THE PHYSICAL BASIS OF PIANO TOUCH AND TONE

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AN EXPERIMENTAL INVESTIGATION OF THE EFFECT OF THE PLAYER'S TOUCH UPON THE TONE OF THE PIANO

BY

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WITH NUMEROUS ILLUSTRATIONS

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PREFACE

"DO you mean to tell me that such poetic effects are produced by means of mere variations in key-speed and in time duration ?" I was asked after a particularly beautiful performance of Schumann's *Kinderscenen* by Harold Bauer. Bauer himself, of course, would be the first to deny the existence of any physical agencies other than those of key-speed and duration. The question, however, is so often asked—and so variously answered—that it prompted a decision to undertake an experimental investigation of the problem in the hope that such an investigation might clear up some of these differences of opinion, and might, at the same time, furnish a stable basis upon which some of our reactions to music could be explained. The scope of the work and the method of procedure adopted in it were far from being as complete and accurate as I should have liked to make them; but they were determined by the fact that the investigation was made as a minor problem of a more general one: the development of an adequate measure of musical talent.

The work on piano touch and tone, however, yielded results of sufficient clearness and practicability to warrant their publication as a separate study; particularly since this subject is a fundamental problem of piano pedagogy, in which its efficient application has been seriously interfered with by the conflict of opinions on the basic relationship between piano-touch and piano-tone. What we actually hear and what we imagine we hear, what we actually do and what we imagine we do, when listening to or playing upon a piano are distinctions urgently needing a clear exposition. Some affirm that the influence of touch upon tone must forever remain a mystery; others hold that the piano action is but a lot of dead, wooden sticks, movable up and down, in only one, fixed way; still others assert that the most subtle shades of emotion are actually transmitted to and through this action by individual spiritual differences of touch. Such confusion is both harmful and unnecessary, since the piano is not a psychical but a physical instrument, and, as such, is entirely obedient to laws that have been formulated, tested, and proved long since.

A preliminary study of the problems connected with the effect of touch upon piano-tone brings to light the facts that the musician rests content with the total effect and does not analyse this into its fundamental components; and that so long as we depend upon personal opinion, as expressed through playing, we cannot bring the problem to any satisfactory solution. Instead of trying to find common ground in the various views held, it is better to adopt the experimental method. This method accepts only those conditions and relationships that can be proved to exist. The problem is solved when we can reproduce at will the action and reaction experimented upon; when, given the conditions, we can definitely forecast results; or, given the results, can determine the causes. Such a method is entirely free from personal bias; it furnishes a permanent record which may be verified, at any time, by subsequent experiment.

In music such proof is not always easily established. No language is so difficult to understand as the language of tones. And no language is so misunderstood; for a tone lives but a moment, and when we would scrutinize it, it is gone. Music, in this respect, differs from all the other arts: its transiency keeps its nature obscure and makes its effects subtle. As a result, truth and error, fact and fancy, have long played a game of hide-and-seek in musical theory, and will continue to do so until we catch the elusive tone and hold it for closer inspection. We must do the same with touch; for touch, as here understood, means movement, and movement means transiency.

Fortunately, both touch and tone can be adequately recorded. When we have so recorded them, we shall have taken the first step in the solution of our problem: the separation of the physical from the non-physical. This division is fundamentally essential. The musician often objects to it on the ground that it robs music of its poetry: "Art is not science," he says. That is quite true, and yet the objection is not well taken. Are we the less able to appreciate the art in a painting because we happen to know, when we chance to think of it, that the picture consists of various coloured pigments and a piece of canvas? Is the poetry of Shakespeare less beautiful because we know the process by means of which the book was printed? The artist need have no fear that art will suffer from scientific investigation. The two points of view are never co-existent. A performance of Tristan is a world of poetry to the adolescent girl; it is "worse than a pig-kill" to a scientist of my acquaintance; it is a fitting environment for her new evening gown to Mrs. Smith; a study in altered chords to the harmony student; a reaction experiment to the psychologist. Moreover, what at one time is the perfection of musical art, may at another time, to the same person, be rates of vibration, sheep-gut, and what not. The objection to a scientific analysis of art is but a reflex of the classical problem of Greek philosophy, which has pointed out the loss of identity that accompanies any division into parts. It is, therefore, an objection outside the field of the scientific investigation itself.

PREFACE

The division into a physical and a non-physical element is not at all times easily made, for there are phases of the one that shade imperceptibly into phases of the other. These demand separate treatment. Our immediate problem will be limited to the purely physical elements of touch and tone, and will exclude all processes which occur before the finger touches the piano-key, as well as all those which occur after the sound-wave reaches the ear. It will include each step between the moment of contact of finger with key, and the impingement upon the ear of the sound-wave resulting from the touch. This defines the problem clearly, and permits an effective application of experimental procedure.

The present investigation is addressed primarily to the musician; the physicist will necessarily find in it much that is repeated and apparently superfluous. He, however, who knows the reluctance with which musicians, both professional and amateur, accept the limitation of all tone-colour on the piano to key-speed and duration, will readily understand the necessity for both repetition and detail. If this book contributes a little to the acceptance of this limitation, its object will have been attained. This it proposes to do by using as a starting point proved laws; by employing, in the experimental procedure, both the affirmative and the negative method of proof; and by presenting graphically the essential physical attributes of piano touch and tone.

I take this opportunity to express my gratitude to Harold Randolph and May G. Evans for the co-operation that made the investigation possible; to George P. Hopkins for assistance in conducting the tests; and to the many teachers who kindly contributed the necessary records for the study.

O. O.

BALTIMORE.

INTRODUCTION

PHYSICAL PRINCIPLES

CLEAR analysis demands accuracy of expression. If some of the contradictory opinions now current with regard to certain phases of piano-tone and touch are to be readjusted advantageously, the meaning of the terms and principles involved must be made as definite and clear as possible. Obviously, all analysis is useless if we continue to use momentum, elasticity, and similar terms in the usual confusing and loose manner. The following list of definitions and axioms is an attempt to define clearly certain properties of matter and laws of dynamics upon which the conclusions drawn in later pages are based. They form the theoretical basis of which the actual experiments described in succeeding chapters are the practical application and the verification.

WEIGHT.—That force which a body exerts upon any support which keeps it from falling to the earth. The greater this force, the greater the weight.

MASS.—The amount of matter (number of particles) which a body contains irrespective of its volume or shape.

INERTIA.—The property possessed by a body by means of which a force is necessary to change the motion of the body.

ELASTICITY.—The property of matter by means of which it returns to its original size and shape after deformation under the action of some force. Steel, water, rubber, compressed felt, and all gases are elastic; clay, lead, and similar substances are inelastic.

RIGIDITY.—That property of matter permitting its shape to be changed only by a great force. Equivalent to stiffness. Applied to muscles it means a contraction preventing motion among the parts of the body.

COMPRESSIBILITY.—The property of matter by means of which its volume may easily be diminished. The opposite of expansibility.

DENSITY.—The mass per unit volume of the substance.

FORCE.—An interaction between two bodies (or parts of the same body) causing or tending to cause a change in the motion of each, either in direction or in magnitude.

We measure all physical phenomena in one or more of three ways: mass, length, and time. Or, in the words of Maxwell, our whole civilized life may be symbolized by a set of weights, a footrule, and a clock.

If a particle or body is moving with a constant velocity, no resultant force is acting.

To produce a change in the velocity or direction of a moving body, a force is required.

If F = the force, and t = the time, the product Ft = the impulse.

If m = the mass, and v = the velocity, the product mv = the momentum.

When a body is under the influence of several forces, the action of each one is independent of the action of the others.

When two bodies receive acceleration from the same force, their accelerations vary inversely as their masses.

Conversely, the accelerations imparted to the same mass by two different forces vary directly as the forces.

There are two kinds of acceleration, change of speed and change of direction.

When two bodies, A and B, interact on each other, the force exerted by A on B is equal and opposite to the one exerted by B on A.

The effect of a force on a material body depends upon three things: its numerical value (intensity), its direction, and its point of application.

The effect of a force on a rotating body is measured by the product of the force by its lever arm, and is known as the moment of the force. The lever arm is the length of the perpendicular dropped from the axis to the line of direction of a force.

The idea of work involves both force and motion in the direction of the force.

The power to strike a blow is due to the momentum of the moving body.

The work done by a purely mechanical force during a displacement from one point to another depends upon the initial and final positions and not upon the path followed.

A force, at any moment, can have but one quantity; this is independent of the manner in which it has been attained.

The general law of mechanical action is stated by the equation $fs = rs^1 + w$, in which f = force applied, s, the distance through which force acts, r, the resistance overcome, s^1, the distance through which its point of application moves, and w, the wasted work.

There are two ways of doing work: first, by producing acceleration, which means increase of kinetic energy; and secondly, by overcoming resistance, which means increase of potential energy. If a system has both potential and kinetic energy, an increase in one is accompanied by a decrease in the other. As matter cannot be destroyed, so energy cannot be destroyed. The principle of the conservation of energy states that in the transfer of energy there is no loss; what one body loses the other gains.

Change of velocity due to uniform acceleration is equal to the product of the acceleration and the units of time; $v = V + at$.

The speed at any instant is the distance which the point would travel during the next unit of time, if the motion were to remain uniform.

The law of the lever is expressed by the equation $P \times ca = Q \times cb$, in which P is the power, Q the resistance, ca and cb the lever arms respectively. That is, in the lever, the power is to the weight in the inverse ratio of the arms.

A moving body has three and only three fundamental properties: mass, speed, and direction.

The fundamental law of force is $F = ma$, where F = force, m = mass, and a = acceleration.

Work = force $\times$ displacement in the direction of force.

Kinetic energy = one-half the mass $\times$ velocity squared ($\frac{1}{2}mv^2$).

Potential energy = resisting force $\times$ the distance it is overcome.

If F is mean force and h the distance through which the body moves, $Fh = C + \frac{1}{2}mv^2$. Since, in the piano-action h, C, and m are constants, v, the velocity of the hammer, can depend only upon F.

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PART I

CHAPTER I

THE INSTRUMENT

The Action

THE action of a grand piano, although it varies in certain details in the product of different makers, is the same in general principle for all grand styles of the instrument now in use. This principle is illustrated in Figures 1A and 1B. A B is a wooden block called a key, so pivoted at C that it can move only in a vertical plane. Beneath each end of the key is a felt pad (D, E), which limits the descent of either end. Fastened on the inner arm of the key is a lever, F, which connects with a second lever, G. This, with the lever, H (itself a bent lever known as the hopper), and the lever, I, forms the compound escapement, which will be explained later. The upper end of H is cylindrical in shape and covered with leather. When the key (ivory-covered end) is not depressed, the upper end of H supports a cylindrical knob on the arm, J, of the hammer, K, which is pivoted at L. It is important to note that the only point in which the hammer (the tone producing body) comes into contact with the rest of the action before tone production is in this one point, x, where the end of H supports J.

When A (the player's end of the key) is depressed, B rises (principle of the simple lever). This causes F to push G up, until the point h comes into contact with M, a stationary (but adjustable) nut for blocking h, which is the end of the bent lever H. When F continues to rise, through continued key-depression, the lever, H, after h touches M, pivots at this point of contact. This causes the end h′ to move in a direction, roughly speaking, at right angles to the vertical movement of the hammer-arm J, and when a given point is reached causes h′ to jump or slide or escape from beneath the hammer-stem. This point is known as the point of escapement and is so adjusted as to operate when the surface of the hammer-head N is about $\frac{1}{8}$ in. from the string, P. The jerk (under playing conditions) throws the hammer over the intervening space against the string, and because of the elasticity of the compressed felt of which the hammer-head is made, as well as the

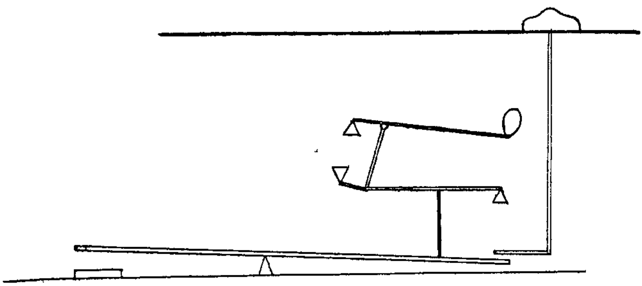


FIG. 1C.

elasticity of the steel strings, the hammer is immediately thrown back. If, in the meantime, the key end, A, has been permitted to remain in its depressed position, the hammer is caught by the check, O, and is gradually released as the end A of the key ascends. If, on the other hand, we wish to repeat the key-depression, the escapement mechanism is so adjusted that the end, h′, re-engages the hammer-arm, J, immediately after it rebounds from the string, whence a second depression of A will again drive N against the string. (This is what is meant by the " repeating " action.)

Fig. 1B shows the action when the key is depressed and the hammer about to strike the string. Figs. 1C

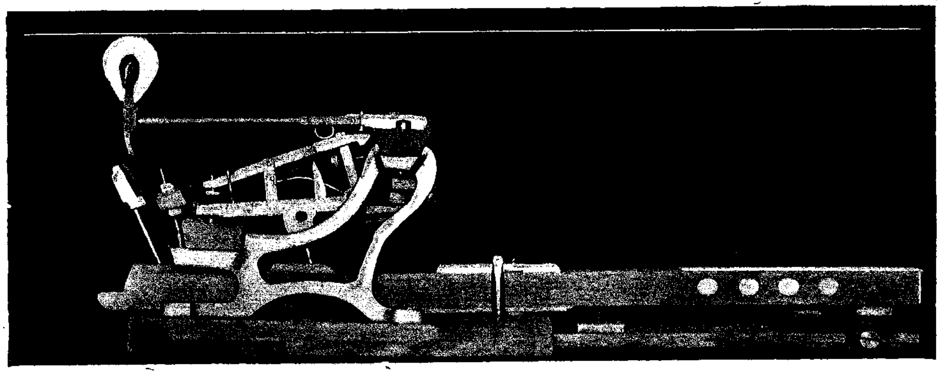


FIG. 1b

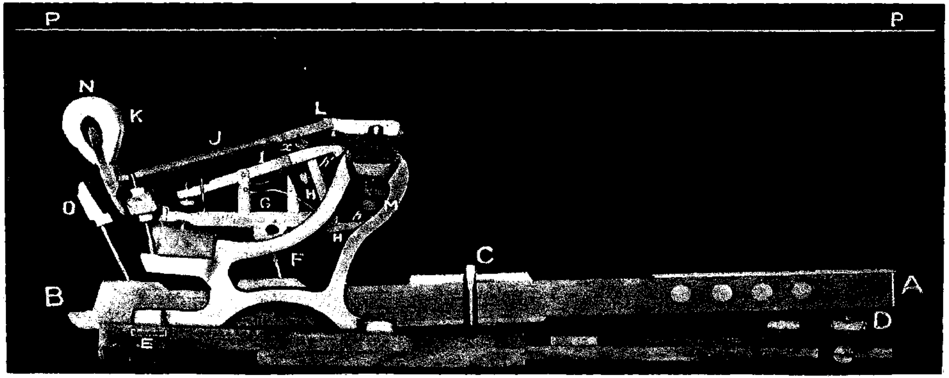


FIG. 1*a*

and 1D illustrate the principle of the piano-action very much simplified.

Every student should study the working of the piano-action on an actual model. This will at once clear up many misunderstandings as to its operation. (The action of any piano is easily removed.)

The mechanism here described is a machine. A machine is a contrivance by means of which force can be applied to resistance more advantageously than when it is applied directly to the resistance. The action of the piano is a machine which enables us to overcome a resistance at one point (hammer

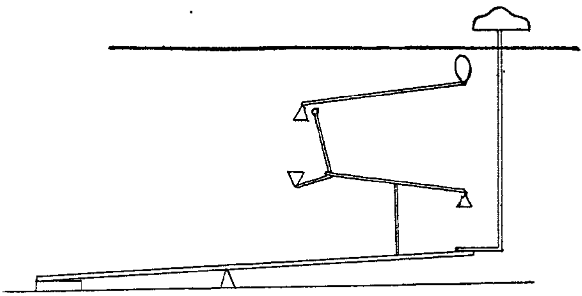


FIG. 1D.

end and strings) by applying a force at another point (the key end). It employs the principle of the lever and is a complex leverage system. Since it is obvious from the diagram (Fig. 1) that the distance through which the hammer end moves is greater than the distance through which the outer key-end (point of application of the force) moves, it becomes clear that the purpose of this machine is to transfer force into speed.

We have seen under the heading "Physical Principles" that the fundamental law of mechanical action may be expressed by the equation $f_1s_1 = rs^1 + w$. Let $rs^1 + w = f_2s_2$: Then $f_1s_1 = f_2s_2$, or

$f_1 : f_2 : s_2 : s_1$. That is, two forces vary inversely as their distances of application. Since, in the piano, a key-depression of $\frac{3}{8}$ in. roughly corresponds to a hammer-movement of $1\frac{3}{4}$ in. the force applied at A must be four times as great in order to secure a corresponding force at P. For it must be remembered that a gain in speed involves a loss in force. No machine transmits more energy than it receives, and no practical machine transmits as much. In other words, there is no machine whose efficiency is 100%. The piano action, then, is a machine which, roughly speaking, changes force into speed in the ratio of 1 to 4, for the distance traversed by the hammer-head is approximately four times that traversed by the key end in the same time. It reverses the direction of application of the forces, the force at the key end being applied downward, that at the hammer end, upward.[1]

The Strings

When at rest, that is, when the ivory-covered end of the key is not depressed, the action of the piano is not connected in any way with the strings (excepting of course the obvious fact that both are in the same case). A connexion is made only by throwing the hammer against the string, which is then set into vibration.

If l be a length of vibrating string, r the radius of the string, d its density, P the stretching weight or tension, and n the number of vibrations per second, it is known that $n = \frac{1}{2rl}\sqrt{\frac{P}{\pi d}}$, in which π is the ratio (3·14159) of the circumference to diameter. This formula expresses four important laws concerning the transverse vibrations of strings: first, that the

[1] The details of the operation of the piano action will be taken up in subsequent chapters.

number of vibrations per second varies inversely as the length, if the tension be constant; secondly, that the number of vibrations per second varies inversely as the diameter of the string; thirdly, that the number of vibrations per second varies directly as the square root of the tension; fourthly, that the number of vibrations per second varies inversely as the square root of its density.

These relationships explain the process of selection used in the strings of a piano. In the treble region we find the thin, short strings, hence a high frequency, pitch, or rate of vibration. As the pitch becomes lower, the strings may become either longer or thicker, or both. Generally speaking, a one-foot length of vibrating string is found in the region of C^2. In the bass region the thickness of the strings is increased by wrapping the steel string once or twice transversely with thin steel or copper wire. Steel is used for all string-cores because of its elasticity, which permits greater freedom of vibration than other metals. It is, moreover, not immaterial whether we increase length or thickness, since, assuming the pitch to be the same, greater length permits more freedom of partial vibrations, which influence tone quality. In other words, a long, thin string produces a better musical tone than a short, thick string.[1]

When a piano is tuned, that is, when the pitch of the strings is altered or corrected, this result is obtained solely by a change in tension.[2]

Since the hammer strikes the string from below, it causes an upward displacement, in consequence of which the string vibrates in a vertical plane.[3]

[1] This partly explains the beauty of tone in a concert grand as compared with other grands.

[2] It is interesting to note that pianos are built to withstand a combined tension of all the strings on a grand piano when tuned to proper pitch of over 50,000 lb. or 25 tons.

[3] Certain exceptions will be noted later.

The number of strings used varies with the pitch. In the treble region when, because of the high tension and shortness, the tone would be weak, three strings to each tone are used. In the region of large C, two strings suffice, and in the lowest register, one string. Not all strings are stretched in the same direction.[1]

THE SOUNDING-BOARD

Every musical instrument may be divided into two parts: a tone-producing mechanism, that part in or by which vibrations are created or produced, and a tone-controlling mechanism, that part in or by which the tone is moulded, shaped, or intensified before being transmitted to the surrounding atmosphere. The piano is no exception. What we hear when a string in the piano is struck is not due chiefly to the vibration of the string but to the resulting vibration of the sounding-board. This is a resonator, a large, thin, slightly convex and carefully constructed sheet of wood, covering practically the entire inner case of the instrument beneath the strings. It is in direct and permanent contact with the supports at the end of the strings, and is joined to the outer case of the instrument, though otherwise free to vibrate.

The vibrations of the string are transferred to the sounding-board which, through its size, intensifies them by setting into motion a much greater volume of air.

A resonator does not create tones. It can reproduce only what the generator transmits. Moreover, partly on account of its own natural periods of frequency, it may not reproduce with equal accuracy all the vibrations which the generator transmits. Thus, what we hear in the piano, as in all musical instruments,

[1] The experiment of using four strings has been made, but it is said without the desired result of enriching the tone quality.

is due as much to the resonator as to the body originally producing the vibrations.

Two kinds of resonators are in use. One responds only to a single frequency or its harmonic partials, as does the Helmholtz spherical resonator; the other responds to tones of various pitches, and combinations of them, as does the body of a violin or the sounding-board of a piano. The duration of a tone, that length of time during which vibrations, through inertia, continue after the initial force is no longer applied, depends upon the speed with which the energy of these vibrations is absorbed by the resonator. That often misused expression, "singing" tone, when applied to the piano, is due to the above-mentioned phenomenon. That is, the tone-quality of an instrument is largely dependent upon the resonance relationship existing between generator and resonator.[1]

The action of the sounding-board of the piano is not due to sympathetic resonance. The fundamental condition of sympathetic resonance—equality in the natural frequencies of the two vibrating bodies—is not present in the piano. The sounding-board does not vibrate because the air waves proceeding from the strings fall upon its surface, but because it is joined to the string through the bridge at one end and thus receives the vibrations directly. If one of two tuning forks of the same frequency be sounded, the other will also vibrate without any other medium of transmission than the air. That is a case of sympathetic vibration. If a tuning-fork be sounded and held in the air its tone is scarcely audible. If

[1] Future improvements in the piano will doubtless include improvements in the sounding board. At present there are three difficulties: if the board is too thick it loses the necessary elasticity, producing a short tone; if too thin it warps or loses its tension and necessary strength. Lastly, the fastening to the case prevents great freedom of vibration. Some of these difficulties have been overcome in modern grands.

placed firmly upon a table, the tone becomes distinctly audible, since the vibrations are communicated to the table, which, acting in turn as a resonator, reinforces them. This is a case of forced vibration, and it is this type of resonance that we find in the piano.[1]

The Pedals

There are three kinds of piano pedals in general use: the *damper* pedal (popularly, though inaccurately, termed loud pedal), the *una corda* pedal (known as the soft pedal), and the *sostenuto* pedal. The first, when depressed, keeps the dampers lifted from the strings, all of which are consequently free to vibrate until their energy is spent or a release of the pedal brings the dampers down upon the strings again. The *una corda* pedal shifts the entire action of the piano sidewise so that the surface of the hammer, instead of striking three or two strings, strikes two or one. The sustenuto pedal keeps any damper or dampers raised which happen to be raised when the pedal is depressed.

The pedals of the piano have two primary functions: to sustain tone and to colour tone. Since the first purpose was devised as a means of enlarging the field of activity of the fingers, this has no influence on the single tone, the central object of the present investigation.[2]

The effect on tone-complex quality is due to the phenomenon of sympathetic resonance, in consequence of which vibrations are set up in other strings than the string which has been struck. Although this certainly affects the quality of the tone-complex, its influence

[1] In a violin the sound heard is not due chiefly to the vibrating string nor to the transfer of these vibrations over the intervening air space to the belly of the instrument. It is due to transmission by means of the bridge which, owing to the tension of the strings, is firmly pressed upon the belly.

[2] Some of the sustenuto effects will be discussed in later chapters.

is entirely beyond the effect of the touch as here understood, and for that reason will not be treated in the comprehensive manner which it otherwise deserves.

The Wrest-Plank

The plank or block which carries the tuning pins is called the wrest-plank. It is made of wood in the older makes of instruments, and of metal, with holes for containing wooden plugs, in the modern makes. The tuning pins, which are threaded to ensure a firmer grip, are driven into these plugs. The wrest-plank is firmly fastened to the frame and case of the piano. Through it no vibrations are intended to be conveyed. Consequently, absolute rigidity, which ensures the maintenance of the string-tension, is a desideratum.

The Bridges

There are two bridges in the piano : the wrest-plank bridge, and the sounding-board or belly-bridge. The former, sometimes called the pressure-bar, regulates the various string levels necessitated by over-stringing ; the latter accommodates the various string lengths at the vibrating end. The sounding-board bridge is important because it transmits the vibrations of the strings to the sounding-board. The exact position of the belly-bridge varies somewhat with the various instruments. It is generally divided into two or three sections, one for each group of strings, according to the manner in which they are overspun or overstrung. In certain pianos the position of the belly-bridge is further determined by the length of string on the far side of the bridge. A position is chosen so that this length bears a desired ratio to the freely vibrating portion on the other side of the bridge, in consequence of which it vibrates harmonically. This is known as the "Duplex" or "Aliquot" scale. Another type of aliquot scale is found in those instruments carrying an extra string stretched above the usual ones and parallel to them.

The wrest-plank bridge determines the point at which the vibrating length of string begins. It is used in any of several forms: a blunt edge above or below the strings, a metal nut, or a hole for each string.

Overstringing is that process adopted in order to accommodate the various lengths of the strings to the size and shape of the instrument. It permits the lower, longer strings to be stretched above and diagonally across the higher strings. When this occurs once, the instrument is said to be single-overstrung; when done twice, it is double-overstrung. The plane of the hammer in these cases is always kept parallel to the string.

The Frame and the Case

The modern piano dates from the time of introduction of metal into its construction. This took place about 1820. Between 1770 and 1820 the complete, all-wood grand piano was perfected. Originally, the metal frame was conceived to overcome difficulties of tuning strings of various metals which were influenced differently by the same change in temperature. Whatever form the metal frame has now assumed, it consists essentially of a great or small number of iron bars set at various angles. The iron frames are situated at the sides of and immediately above the strings. The introduction of metal into piano construction has influenced tone because of the greater elasticity of metal as compared with wood. Below the strings and sounding-board we find the wooden frame, consisting of a series of horizontal heavy wooden bars placed at various angles. They mutually reinforce each other and also reinforce the harp-shaped case. This is either solid wood (mahogany, oak, or black walnut) or in the more recent makes layers, sometimes more than twenty, of maple and oak. The advantage of the layer-process is supposed to be an increase in resonance effect. The entire object in selecting a case and framing is to secure a proper ratio of elasticity and rigidity, enough of the former to permit freedom of transmission of the vibrations, and enough of the latter to ensure stability against the enormous tension of the strings. Generally speaking, the use of metal tends to give the tone brilliance, and the use of wood tends to give it "softness" and "depth". We should therefore expect a combination of metal and wood to produce the best results. Too much or all metal would produce a metallic, clangy tone, too much wood, a dull, thick, and "plump" tone.

All variations in the tone of the piano may roughly be divided into two classes: those resulting from differences in the make of the instrument, and those resulting from variation in the manipulation of keyboard and pedal. Variations of the first class account for variations in the tone of instruments of various makes. It is not our purpose, here, to trace the source or the effect of these variations, since they bear no direct relationship to the effect upon tone by the touch of the player. The tonal variations analysed in subsequent chapters are all variations in class two, that is, differences in tonal effects occurring within the tonal range of any one instrument.

CHAPTER II

KEY-DEPRESSION

Theoretical Analysis

THE action of the piano is operated by the hands and arms of the player. The nature of these bodily movements, their variability and usefulness, on the psychological side, do not concern us here. We have to investigate only their effect upon the action, and through this, upon the sound-complex of the piano. Such an investigation should begin at the point where the player comes into contact with the playing mechanism, in this case the key-end of the action. And the first question becomes: What are the effects of the various forms and gradations of pianistic touch upon the movement of the piano key?

In accordance with the method of procedure outlined in the introduction we shall first examine the theoretically possible effects of touch on the key mechanism, and then consider a number of original records in the light of the theoretical possibilities.

The piano key (the part visible to the player represents less than one-half of the entire key or lever) is a piece of wood about a foot and a half long and seven-eighths of an inch wide. It pivots on a point midway from either end, which makes it a lever of the first kind, that is, one in which the fulcrum is between the power and the resistance. The vertical pin at the fulcrum, with an additional vertical pin at the outer key end, prevents the lever from moving in any plane except a vertical one. Moreover, the felt key pads beneath each end of the key limit the vertical distance through which the key may move to approximately three-eighths of an inch at its extremity. We have, then, a mechanism capable of being moved at its extremities through a vertical arc of three-eighths of an inch and immovable in any other way.

On account of the smallness of the ratio of this arc to the length of the lever arm (9 inches) the arc may, for practical purposes, be considered a straight line.[1] No matter how we hold our hands, how gently or harshly we stroke or strike the key, no matter how relaxed or rigid our arms are, how curved or flat our fingers, we can do nothing else to the key than move it three-eighths of an inch or less vertically downward.[2] This limit is absolutely fixed by the unyielding wooden action, a glance at which will dispel any doubt as to the possibility of other movements.

Since the key when played upon becomes a moving body, the laws governing moving bodies also apply to the key. The three fundamental properties of a moving body, as we have seen, are mass, direction, and speed. For any one key the mass is fixed; the direction for all keys is fixed; the only variable remaining is speed. Consequently, any differences of effect of touch upon key-movement must be differences in speed. There is no other variable. From the fundamental law of mechanical action, we know that in addition to the force the distance through which the force acts influences the work done. The piano key gives as a maximum distance slightly less than three-eighths of an inch.[3] Whatever

[1] Defective action, such as a slight lateral motion due to the wear on the felt packing, need not be considered, since this represents an individual, abnormal, and musically undesirable condition; hence it is of no value for general deductions.

[2] A perfectly obvious fact. Yet what wonderful tonal effects are ascribed to differences in key "manipulation?"

[3] Whatever effect we wish to transmit to the hammer must be transmitted to the key before this reaches the end of its downward

force is transmitted to the key must, in order to be of any musical value, be transmitted within this distance. It may require as little of the distance as is desired, but it cannot require more. Again, any difference in degree of force or its mode of application must show itself in the speed of key-depression, for in the equation $F = ma$, F, the force, cannot vary without similar variation in a, the acceleration, since m, the mass of the key or action, is a constant.

Concerning variations in key-speed, a number of possibilities present themselves. The speed of key-descent may be slow or fast, constant or positively or negatively accelerated, or it may be a combination of these factors. We have, then, a definite indication of the effect of touch on key-movement, namely, speed. If we can record the variations in key-speed, we can record all the differences of the effect of touch on key-movement; for when there is no difference in key-speed there is no difference in touch so far as effect on the key is concerned.

Conversely, any variation in touch which does not influence or in some way change key-speed is useless when evaluated in terms of the result on the action.

Records of Key-Depression

It is possible to record the variations in key-speed in several ways. One that is clear, and that at the same time permits detailed reading of the records without additional measurement, is to fix a piece of smoked glass[1] to the side of the key and record upon this the tracings of a tuning-fork whose frequency is known. As the key is depressed, this will yield the sine curve.

movement. The reason for this will appear from a study of Fig. 1B. The hammer leaves its escapement before the key is fully depressed. Consequently, what the key does below this point does not affect the hammer in any way. This will be more fully explained when we discuss the hammer-stroke.

[1] A microscopic slide serves the purpose very well.

The slightest variation in speed will show a variation in wave length (in this case vertical distance from crest to crest or trough to trough). A horizontal line indicates no motion; an increase in wave length means an increase in speed. Thus, in Fig. 2, reading

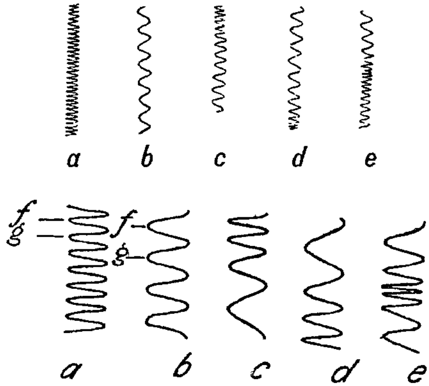


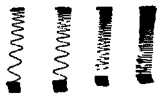
FIG. 2.

from top to bottom, *a* means slow and constant velocity; *b*, fast and constant velocity; *c*, positive acceleration (from slow to fast); *d*, negative acceleration (from fast to slow); *e*, an initial speed, then a decrease, then an increase. The records, Fig. 3 to Fig. 15, were made with a 256 v.d. fork. Each wave length (the vertical distance between two such points as *f* and *g*, Fig. 2) represent $\frac{1}{256}$ of a second.

FIG. 3.

Since F = ma, and m is a constant, an increase in F will result in an increase in a. If we apply a greater force to the key we will get greater key-speed.

Fig. 3 shows the key-movement when initiated by various weights. Thus, *a* is the movement made by the key when a weight of $3\frac{1}{2}$ oz. is applied; *b*, 4 oz.; *c*, 5 oz.; *d*, 8 oz.; *e*, approximately 1 lb.; and *f*, considerably more. The curves show a gradual increase of key-speed from *a* to *f*. The relationship is also shown in Fig. 4, in which *a* is a tone produced with the finger; *b*, with the hand; and *c* and *d* with the arm. As we increase the weight of the playing body (force) we increase key-speed. Therefore, key-speed varies directly with the force. But in making these records the tones produced by the key-speeds also varied directly with the increase in weight. That is, *a* yielded a tone of approximately *pp* intensity; *b*, a tone of *p* intensity; *c*, *mp* intensity; *d*, *mf* intensity; *e*, *f* intensity; and *f*, *ff* intensity.[1]



d c b a

FIG. 4.

It follows that an increase in key-speed means an increase in dynamic tone value; the faster the key is depressed, the louder is the resulting tone.[2]

The Effect of Muscular Relaxation and Rigidity on Key-Depression.—If a relaxed tone-production (meaning the bodily movements made in key-attack) affects the key differently from a rigid tone-production, these differences must reveal themselves in variations in key-speed, since there can be no other variation. Fig. 4 shows the key-depression made for tones made with a rigid wrist and arm, *a* = *pp*; *b* = *p*; *c* = *f*;

[1] This variation can be seen in the remaining figures as well.
[2] Certain partial exceptions will be explained as they are met.

and $d = ff$. Fig. 5 shows the key-depression for tones made with normal pianistic relaxation, $a = pp$; $b = p$; $c = f$; and $d = ff$. [In spite of repeated trials, *fff* could not be obtained for relaxed production, and this shows that the dynamic range of tone-production with rigidity embraces wider limits than that of relaxation.] Both Fig. 4 and Fig. 5 represent non-percussive touches; that is, in both cases the finger touched the key-surface before any movement for tone-production was made. In both figures we get the speed increase with the dynamic increase mentioned in Fig. 3. Comparing Fig. 4 with Fig. 5 we note that in each paired instance, *pp* with *pp*;

d c b a

Fig. 5.

f with *f*, etc., there is practical identity.[1] Many records, duplicates of Fig. 4 and Fig. 5, were made, all yielding the same general result. This means that when intensity is controlled or equal there is absolutely no difference between key-movement initiated with a rigid arm and key-movement initiated with a relaxed arm.[2]

In addition to these, a number of records was made in which the normal kinæsthetic feeling [3] of the player

[1] This was only secured after extended practice in controlling the intensity. Without this practice the average individual produces a louder tone with rigidity than with relaxation. In fact, a shade of this difference is noticeable between Figs. 4 and 5.

[2] For those who still doubt this statement it is hoped the following chapters offer sufficient additional proof.

[3] The feeling present in the usual playing of a composition.

was the sole regulator of intensity. Fig. 6 is an example of such a record. Omitting for the time being the peculiar irregularity, which will be explained later, we notice upon comparing Fig. 6 (rigid) with Fig. 7 (relaxed) that in each case the speed is less when relaxed tone-production is used than when a rigid tone-production is used. As a result the tone produced with relaxation under normal (uncontrolled) conditions is weaker than the tone produced by rigidity.

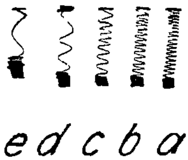


FIG. 6.

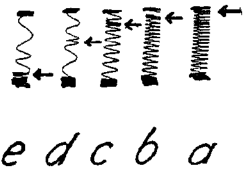


FIG. 7.

The Effect of Percussive and Non-Percussive Touch on Key-Depression.—Since practical piano playing often precludes placing the finger upon the key before starting its depression, it is necessary to differentiate between percussive and non-percussive touches. A percussive touch is one in which the moving finger strikes the key-surface; a non-percussive touch demands that a finger rest on the surface of the key before descent.[1] Fig. 6 was made with a rigid arm

[1] Needless to say, this classification is not always clearly defined, since one class shades into the other. A very slowly moving finger, or one moving through a very small distance, may belong to either class, its assignment depending largely upon the subjective mood of the player.

and wrist, an example of the percussive touch. Compare this with Fig. 4, which was also made with rigid arm and wrist but with a non-percussive touch. The various intensities are the same for the two figures. In the case of the non-percussive touch we notice a gradual increase in key-speed from top to bottom. There is practically uniform, positive acceleration. In Fig. 6, on the other hand, there is a well-marked irregularity. Interpreting the curve, we find that the key begins its descent with a sudden jerk.[1] Thereupon, its speed decreases and again increases. This gives us an interesting insight into the nature of percussive touch. The finger striking the key rebounds slightly from it, or, what is the same thing, sends the key off. The finger then re-engages the key in its continued motion downward and " follows it up " to the key-bed. This " following-up " differs from the usual key-depression, as we shall see later. Figs. 6 and 7, *a*, *b*, *c*, *d*, *e*, show, in addition, how the distance, through which the initial impact sends the key down, increases as we increase the force of the impact ; in *pp*, the key is thrown through a negligible distance ; in *sfff*, it is thrown practically its entire distance of descent, for the dense, apparently blurred, portion of the curve, that momentary retardation after the impact (shown in Fig. 7 by the small arrows), moves further down for each increase in force. A number of deductions may be drawn from this. Since the key, for that part of the stroke above the dense portion, is not in actual contact with the finger, we naturally have no control over it during this distance. Consequently, whatever speed we wish to communicate to the key will have to be transmitted either at the moment

[1] Sudden, as compared to the curve of Fig. 4, for it takes time in all cases to set into motion a body at rest.

of impact or after the finger regains the key. The first is a matter of a moment only; the latter, considerably shorter (for all degrees louder than *mp*) than the usual depth of key-descent. Since, then, we have less space in which to guide the key (consequently also less time), key-control with percussive touch is more difficult than with non-percussive touch. In the latter the finger "weighs" the key down throughout its descent, thus enabling us to gauge the resistance more accurately. The non-percussive touch, then, permits finer control of key-movement than the percussive. In the percussive touches the movement must be communicated to the key almost instantaneously, the word "instantaneously" being used in its usual sense. A comparison of Fig. 5 and Fig. 7 illustrates the same difference. This pair is similar to the preceding pair, Figs. 4 and 6, except that the former, Figs. 5 and 7, represent relaxed tone-production, and the latter, Figs. 4 and 6, rigid tone-production. When these records are studied for dynamic differences, the percussive touches show greater key-speed than the non-percussive touches,[1] for in Figs. 6 and 7 the wave lengths are in the aggregate greater than in Figs. 4 and 5. Further, more clearly defined differences may be seen by comparing Fig. 13 with Fig. 14. We have, then, as the physical reason for the adoption of certain forms of touches, the setting into motion of the action with a minimum of jar or percussion and a maximum of kinæsthetic control. In percussive touches there is no gradual addition of weight. Key-control, in those instances, depends entirely upon the speed with which the finger reaches the key. This means that the psychological factors

[1] This, of course, does not mean that the order cannot be reversed. It merely means, that, other things equal, we normally tend to play louder when using percussive touches than when using non-percussive touches.

involved in percussive and non-percussive touches are different.[1]

Effect of Finger and Wrist Position on Key-Depression.—Finger position we shall divide into the two most common forms: curved or bent finger, and flat or straight finger. The curved finger strikes the key with its nail joint vertical. The straight or flat finger has its nail joint almost horizontal. Fig. 8 shows the curves for flat and curved fingers. The intensity was kept approximately constant at *mf*. *a* represents flat finger, percussive touch; *b* represents curved finger, percussive touch; *c*, curved finger, non-percussive touch; and *d*, flat finger,

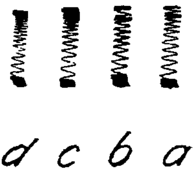


FIG. 8.

non-percussive touch. The greatest difference is again found in the percussive and the non-percussive elements, as is shown by the dark line below the top in *a* and *b*, but not in *c* or *d*. Careful inspection, however, shows also a slight intensity difference in favour of the curved finger. This difference would be too slight to have any practical value if it occurred only occasionally. We find it present, however, in every case of a number of similar records taken, such as *a* and *b* of Fig. 12. Apart from this slight difference of key-speed there is no difference in key-movement when initiated by flat or curved finger;

[1] Since it is only the physical aspect which concerns us here, it will suffice to mention only the fundamental psychological difference. In non-percussive touches key resistance is a sensation, in percussive touches it is essentially an image.

provided both are percussive or both non-percussive touches.

Wrist position we shall divide into high-wrist and low-wrist. In the former case, the wrist is held well above the key-level and descends when the key is depressed. In the latter case, the wrist is held below the key-level, and with a "snap" movement ascends, the fingers at the same time descending. Fig. 9 shows the curves thus obtained. Intensity was controlled approximately at *f*. In this figure, *a* represents low-wrist, non-percussive touch; *b*, high-wrist, non-percussive touch; *c*, low-wrist, percussive touch; *d*, high-wrist, percussive touch. Note again the well-defined difference between

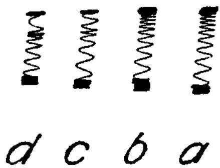


FIG. 9.

percussive and non-percussive touches, shown by the presence of the dark line in *c* and *d* and its absence in the non-percussive touches *a* and *b*. For all practical purposes no difference in key-movement, whether initiated by high or low wrist, exists, the curves for both cases being practically identical. True, there is an occasional slight difference in key-speed, but since this was found to vary, sometimes in favour of the high-wrist touch and sometimes in favour of the low-wrist touch, it cannot be considered a differentiating quantity in the sense here understood.

Key-Depression and Tone-Quality.—Have we a right to speak of a single piano tone as "good" or "bad?"[1]

[1] In the final chapter an attempt will be made to define a standard "good" tone in terms of physical quantities.

In the last analysis, perhaps not; for the so-called quality which we assign to a single tone is almost invariably the result of a combination, either simultaneously or successively, of this with other tones. Nevertheless, although the terms "good" and "bad" are primarily of subjective value only, the long list of adjectives with which we describe even single tones, words the meanings of which are readily understood by many piano teachers, proves the existence of objective qualities which give rise to these descriptive terms. Thus, we know and distinguish on the piano, among many other tone-complexes, the following: harsh, brilliant, mellow, full, singing, round, shrill, dry, metallic, steely, brittle, shallow, poor, ringing, clear, velvety, bell-like, jarring, and strident. Since

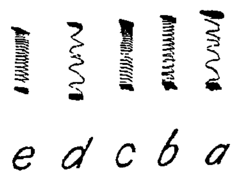


FIG. 10.

the majority of these tone-complexes have a fairly distinct meaning to the teacher, their investigation becomes a necessary phase of our problem, especially because the creation of these various tone-qualities is generally attributed directly to the quality of touch employed. The following records were all made by experienced pianists and teachers who were asked, after producing a tone, whether it had the desired quality—harsh, shallow, or some other quality. Many repetitions were sometimes found necessary before the desired tone-quality was satisfactorily produced, and it should be stated that most teachers found the production of a specific quality difficult for a single tone. This is, in itself, a proof that this tone-quality, generally attributed to a single tone, is due largely to a combination of tones. The descriptive terms were selected by the teachers making the record, and the mode of tone production, that is, the touch employed, was left entirely to the teacher. The records represent the following: Fig. 10, *a*, good tone; *b*, dry tone; *c*, dry tone; *d*, thumped (ugly) tone. Fig. 11, *a*, good tone; *b*, forced tone; *c*, depthless tone. Fig. 12, *a*, shallow tone; *b*, good tone; *c*, forced tone; *d*, good tone; *e*, "harsh" (ugly) tone; *f*, full tone.

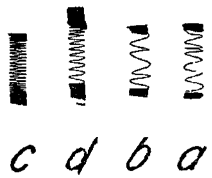


FIG. 11.

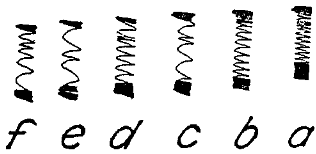


FIG. 12.

A study of these records brings to light the interesting fact that for every difference in quality we have a difference in key-speed. Thus, we find that forced, harsh, ugly, and thumped tones mean great key-speed; good, singing, and full tones mean moderate key-speed; shallow and dry tones mean slow key-speed. But Fig. 3 showed that with every increase of key-speed we have an increase in the dynamic value of the resulting tone. Therefore, all these supposedly qualitative differences as applied to the single tone are merely differences in intensity.

Moreover, we find that the most satisfactory tone is one of medium loudness, the unsatisfactory qualities being at either end of the dynamic range.

Why the ear so often accepts these differences as purely qualitative instead of quantitative will be explained in the chapter on the vibration of the string.

Effect of the Playing Unit upon Key-Depression.—Although in actual piano playing we do not entirely isolate any part of the arm, nevertheless, various members are used more or less independently. Thus, for example, in true hand-staccato, it is largely the weight of the hand that depresses the key. In

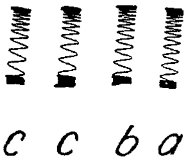


Fig. 13.

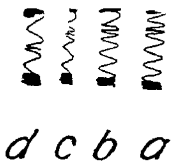


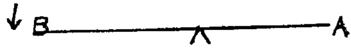
Fig. 14.

cantabile passages the weight of the entire arm is used. The effect of the use of various parts of the arm, and of the arm as a whole, are shown in Figs. 13 and 14. The former represents non-percussive touches, the latter, percussive touches. In both figures, *a* shows the key-speed for the finger as the playing unit, *b* for the hand, *c* of Fig. 13 and *c* of Fig. 14 for the forearm, and *d* of Fig. 14 for the whole arm. Both figures show the increase in key-speed as we increase the weight of the playing unit. This is, of course, the result of the increase in force which an increase in weight produces. In the percussive touches this increase is clearly shown by the various positions of the heavy portions of the curve, the points representing, in *a* and *b* at least, a momentary cessation of all key-movement. (Note also the marked differences in key-movement when initiated by a percussive as against a non-percussive touch, and the considerably greater key-speed for the percussive than the non-percussive touch.)

Variations in Force during Key-Depression.—It is interesting to know whether the force with which we depress a key in playing remains constant (allowing of course, for the accelerating effect of gravity) after key-descent begins or changes during key-depression. If we secure a picture of key-depression resulting from a constant weight standing or dropped upon the key, and compare this record with that made by the hand or arm, we have an index of this force variation. Since the resistance to be overcome (weight and friction of the inner half of the piano-action) remains a constant, a weight acting upon the outer key-end throughout the three-eighths of an inch of key-depression will not show uniform key-speed, but positive acceleration, as a result of the action of gravity. For the weight, in a very general way, at least, may be considered a falling body, and, if we ignore the action-resistance, will show an increase in speed characteristic of falling bodies. This acceleration from one unit of time to the next will show in a gradual increase in the wave length of the curves here secured. A greater increase than this normal acceleration will naturally mean added weight, and a less increase will mean subtracted weight. Fig. 3, *a, b, c, d,* shows key-depression when initiated by weights. When we compare these records with any record made by the player for the softer dynamic degrees, such as *a* and *b* of Figs. 4 and 5, we notice that the curves are practically identical, only the slightest intensity difference being noticeable. Whether the descent is initiated by hand or by a mechanical weight does not affect the increase in key-speed. As we proceed to the louder dynamic degrees, *mf* and *f*, however, *c* and *d* of Figs. 4 and 5, although beginning no faster than *c* and *b* of Fig. 3 respectively, show a considerably greater key-speed as the key approaches the end of its descent. That is, there is greater acceleration for the former than for the latter. Since F = ma, this added acceleration results from weight added after the key has started its descent. For all degrees of intensity, excepting the very soft ones, when we play with a non-percussive touch, we do not use the entire force desired at the beginning of key-depression, but add more and more weight as the key descends. In other words, we set the *key* into motion gradually. In percussive touches, since no such increase in the curves is noticeable, the key is not regulated throughout its descent but only at the moment of impact. Such records throw interesting light upon the problem of key-control, the chief tonal problem of artistic piano playing. They indicate, as we have mentioned before, that the so-called "clinging" or "sympathetic" touch (which is nothing else than a non-percussive touch) enables us, not *per se* to produce a better tone, but by permitting more accurate key-control, enables us to secure just the appropriate key-speed, and through this, the appropriate tone-intensity.

Many other records dealing with miscellaneous minor phases of touch were made. Among them the *martellato* touch, the *strisciando* of the finger and the "slapped" touch. Tones were produced by various articles dropped upon the key, knuckles and fist were used. In all cases where the records showed no differences in key-speed, no differences in tonal quality were heard. In addition, the ascent of the key, usually termed rebound, was recorded. This concerns us only so far as it influences tone. Although key-ascent does not influence the production of tone, it does influence cessation of tone, since the damper cannot fall back upon the string until the key ascends.

This key-ascent may be retarded to any extent desired by the player, but cannot be advanced or increased in speed except for a very slight increase resulting from pressure upon the key-bed. This is due to the elasticity of the felt pad. Other than this there is nothing elastic about the upward or return motion of the key. The word elasticity (applied to the key and not to the finger) is a misnomer. Even the word rebound is somewhat misleading, since it does not accurately express what takes place. The key does not return as a rubber ball rebounds from the ground, but solely because it is the lighter arm of a lever. In other words, excepting of course when the pressure upon the key-bed adds a very slight element of elasticity, the return of the key does not take place because upward forces act at its outer end, but because downward forces act on its inner end. This may be conclusively proved with a model action. If we raise all the parts from the key, leaving this free, it will at once tilt and remain with the outer end (ivory or player's end) depressed. If we lift this with our fingers and let it drop back there will be no rebound, or at the best only a very slight one.

What actually takes place when a key is depressed and then returns to its original position may be seen by the following diagram. Let A B be a lever in which the force acting downward on B is greater than that on A. 

The player depresses A by adding a force greater than B.

This causes A to descend, B to ascend. Now, suppose that the moment A reaches its lower limit the player removes the added force. Then B again outweighs A and causes the lever to return to its original position. The same return would take place if A were held depressed any length of time and then released. Hence, we cannot speak of a rebound in the sense in which the hammer rebounds from the string.

The ascent of the key is further influenced, though again only slightly, by the speed of the rebounding hammer which exerts a diagonally downward force on its catch or buffer and hence on the inner key-arm. When the key, on its ascent, reaches the starting-point, its momentum carries it slightly beyond, whereupon it returns again and gradually comes to rest. That is, the key does not make a single

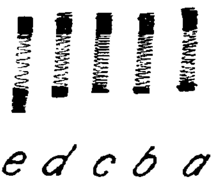


FIG. 15.

depression and ascent, but one pronounced movement of this kind and one or two lesser ones. These latter, of course, have no influence whatever on the tone since this has been dampened when they take place. They are evidence that the piano-action is not a firmly connected unity. None the less, because it is often believed that certain modes of key-release influence tone by varying the manner (speed ?) with which the damper falls back upon the string, a number of records were secured for various types of key-release. These are shown in Fig. 15. They should be read upwards: *a*, shows the curve when the finger is lifted perpendicularly from the key; *b*, when the finger is pulled away from the edge; *c* and *d*, the same for a piece of metal; *e*, for the finger after considerable pressure upon the key-bed. The curves for *a*, *b*, *c*, *d*, show a very slight increase in key-ascent to the middle, then a slight decrease again. This is natural. Gravity is responsible for the slight increase, and the resistance of parts of the action which are re-engaged as the key approaches the upper end of its ascent is responsible for the slight decrease.

Notice the width ($\frac{1}{8}$ in.) of the blurred tops. This is caused by the fact that the key does not immediately come to rest when it reaches its top level, but through the slight elasticity of the felt pads and the "balanced" form of the action is bounced back and forth through a short distance. This also applies to the piano-hammer. The more rapid key-ascent shown in *e* of Fig. 15 results from the upward force which the compressed key-bed pad exerts upon the key. The extent of this compression is shown by the lower beginning of *e* as compared with *a*, *b*, *c*, or *d*.

The differences in key-speed found in these and other records are all so slight as to have no practical effect upon the cessation of tone. It is true that we can retard the ascent of the key and thereby permit the damper to fall back very gradually upon the string. This mode of key-release gives tone-cessation a curious "fuzzy" character, which, because of its unmusical quality, is seldom desirable. The important fact is that, no matter how we release the key, we cannot increase the speed of its ascent. Regardless of touch, the key returns in but one fixed way as soon as the finger leaves it.

Influence of Key-Pressure and Movement after Key-Depression.—This includes the effect of lateral rocking to and fro, the so-called "kneading" or "vibrato" and all other motions made after the key has reached its key-bed. Since the key, once it is depressed, is no longer in contact with the string, any further motion of the key cannot influence the string. The idea that such motions set up air disturbances of their own which affect the ear is entirely fallacious, since these would have to occur, at the very least, 18 times per second to have any pitch value, and in the second place would have to occur with absolute regularity. The one physically possible effect of all such motions on tone is that they rock the entire instrument, hence also the sounding-board. The practical significance of this theoretical possibility will be treated in a later chapter.[1] Here we have to ascertain only the effect of such movements on the key. Of such effects there is none, since all we do is to press the key more firmly against the key-bed, and when employing a lateral movement, we merely help to "loosen" the action and to hasten the day when it will find its way to the factory for repair.

The records reproduced in this chapter are but a few of many that were made. They were selected because they embrace all the differences found. Tested from all angles, and in many practical and even impractical ways, no record was obtained which does not agree with one or more of those here reproduced.

Conclusions

From the results of the above experiments we may conclude the following :—

1. Differences in touch, so far as they affect the vibration of the string, always involve differences in speed of key-descent.

2. Considered with reference to their effect on key-descent, there are but two touches, percussive and non-percussive. These represent qualitative differences in key-movement. All other touch classification

[1] "The Vibration of the Sounding-Board."

or nomenclature represents merely quantitative differences in key-speed.

3. Non-percussive touch permits easier and finer key-control than percussive touch.

4. All differences in tonal quality are due to differences in intensity, with the exceptions noted in later chapters.

5. Such words as *shallow*, *harsh*, *forced*, *dry*, and others of this nature, are merely descriptive of the intensity of the tone.

6. Under normal conditions, rigidity tends to produce greater key-speed (hence louder tone) than relaxation.

7. Under normal conditions, curved finger touches tend to produce slightly louder tones than flat finger touches, though this difference is not always present.

8. The dynamic range of tone-production through relaxation is less than the dynamic range of tone-production through rigidity. Hence, if that portion of the latter which is not contained in the former, is required for a special effect in a composition, rigidity is necessary.

CHAPTER III

FORCE OF TOUCH

KEY-DEPRESSION results from the action of a force upon the key. Chapter II dealt with the variations of this key-movement, produced by variations in touch and tone. This, primarily, had a qualitative end in view, though the conclusions mainly show quantitative variations. In the present chapter we shall seek to determine some numerical values for the forces of touch. Needless to say, the limits of key-resistance set by various instruments are by no means fixed, and consequently the values herein deduced are representative of individual instruments, and not of pianos in general. The absolute values give a fair approximation for other instruments ; the relative values result from certain general principles functioning for all pianos.

The present quantitative evaluation of touch was originally prompted by a young pupil possessing a rather refined sense of kinæsthetic discrimination, who complained of the added resistance which the keys in the bass region offered to her then weak fingers. This added weight is due to the larger size of both hammer and damper in the bass region as compared with the treble. The complaint led to a desire to ascertain, in a general way, the extent of these variations.

The effect of a force upon a material body depends upon three things : its numerical value, its direction, and its point of application. The numerical value of the force acting upon the piano key varies between zero and the limit set by the physiological capability of the player; the direction of the force may be any line in a tri-dimensional space, between the horizontal and the descending vertical; the point of application is limited by the length of key seen on the key-board, about six inches. If the line of action and point of application be constant the effect on key-depression will vary directly with the force. If force and point of application be constant the effect will vary with the direction. Practical piano playing demands that the key be struck from various angles; in other words, it demands various lines of application of force. The effect is greatest when the force acts in a line with key-descent, which on the piano is vertically downward. The effect decreases as the line of application deviates from this vertical, because to change the direction of a moving body, a force is required.[1] Finally, if the line of application and the numerical value of the force remain constant, key-depression will vary with the point of application. The further the point of application is from the fulcrum the greater is the effect of the force. The key lever measures about ten inches from the end of the key to the fulcrum. About six inches is visible as the key-board, and all variations in the application of touch naturally fall within this 6-inch distance.

The following measurements have for their object the quantitative evaluation of vertical forces acting at different points of the key lever. A metal cup, of appropriate size, was placed upon the key. Its weight was regulated by pouring small shot into it, and the key was released by removing a point lightly pressed against the outer surface, which ensured a fairly constant mode of release. The amount of shot was adjusted until the release of the key produced

[1] Thus, when the direction of the hand is changed by key-depressions (the key has only one line of movement) energy is consumed in making this change.

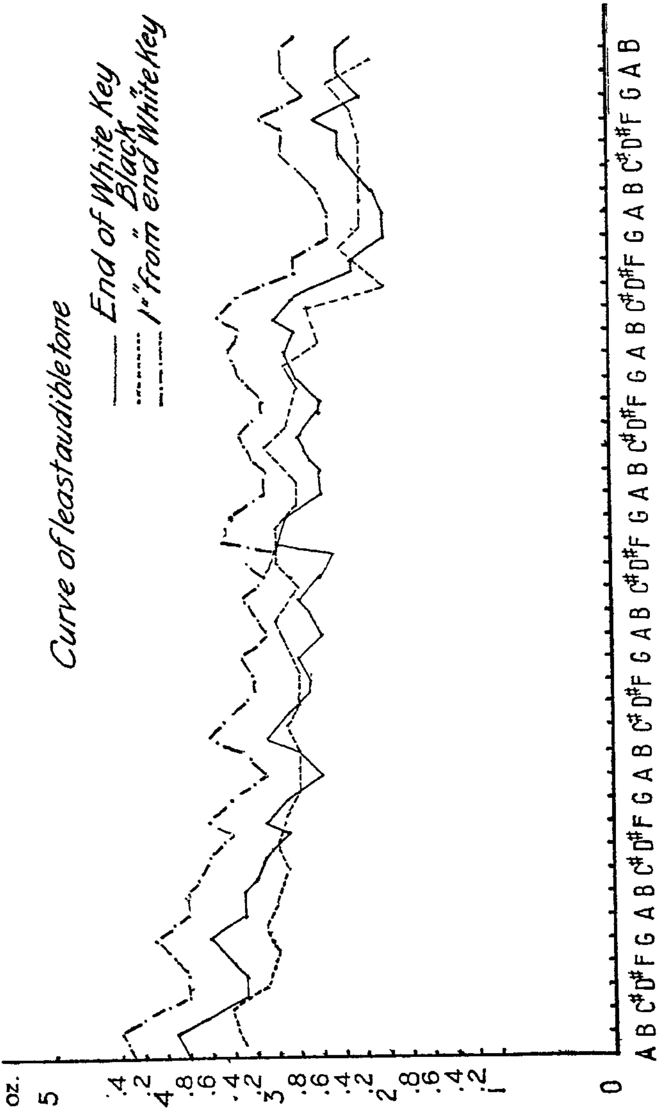

Curve of least audible tone
End of White Key
" Black "
1" from end White Key
oz.
5
.4
.2
4
.8
.6
.4
.2
3
.8
.6
.4
.2
2
.8
.6
.4
.2
1
0
A B C♯ D♯ F G A B C♯ D♯ F G A B C♯ D♯ F G A B C♯ D♯ F G A B C♯ D♯ F G A B C♯ D♯ F G A B C♯ D♯ F G A B C♯ D♯ F G A B

Fig. 16a.

a barely audible tone. The threshold of audibility was set by two observers seated in the usual position at the key-board, and the numbers here used represent the average of several judgments made for each key. Two instruments were tested. Both were used instruments in fairly good playing condition, good representatives of the normal conservatory or student's piano. The following curves are correct to within one-tenth of an ounce. The weight in ounces is shown in Fig. 16A and Fig. 16B in the form of a graph, which presents the variations more clearly than the figures would. The weight in ounces is shown on the vertical axis, the corresponding keys on the horizontal axis. We find a variation for key-depression between 2·1 ounces and 4·5 ounces for the one instrument; 2·3 ounces and 5·0 ounces for the other instrument.[1] Differences in point of application: front edge or end of key, and one inch from the edge, average ·4 ounces for the first instrument and ·5 for the second instrument. This means that if, for example, we wish to play the D major scale, *ppp* through one octave, ascending, beginning on D below middle C and touching each key at its customary point for this scale: D near its outer edge, E near the black keys, F♯ at its edge, G at its edge, etc., in order to secure a dynamically even scale for these instruments, we should have to distribute the weight in ounces as follows:—

No. 1:	2·9	3·2	2·8	2·8	3·0	3·1	2·8	2·6
No. 2:	3·5	3·4	3·3	2·8	3·4	3·0	3·1	3·0

Almost every key demands a different weight from its neighbour if the resulting tones are to have the same

[1] In a number of instruments the lever-arm of the black keys is somewhat shorter than that of the white keys, approximately 8½ inches and 10 inches respectively. This difference is partly compensated for through the individual "weighting" of each key by the piano manufacturer. Otherwise, we should find the dotted line of figures 16A and 16B well above the solid line.

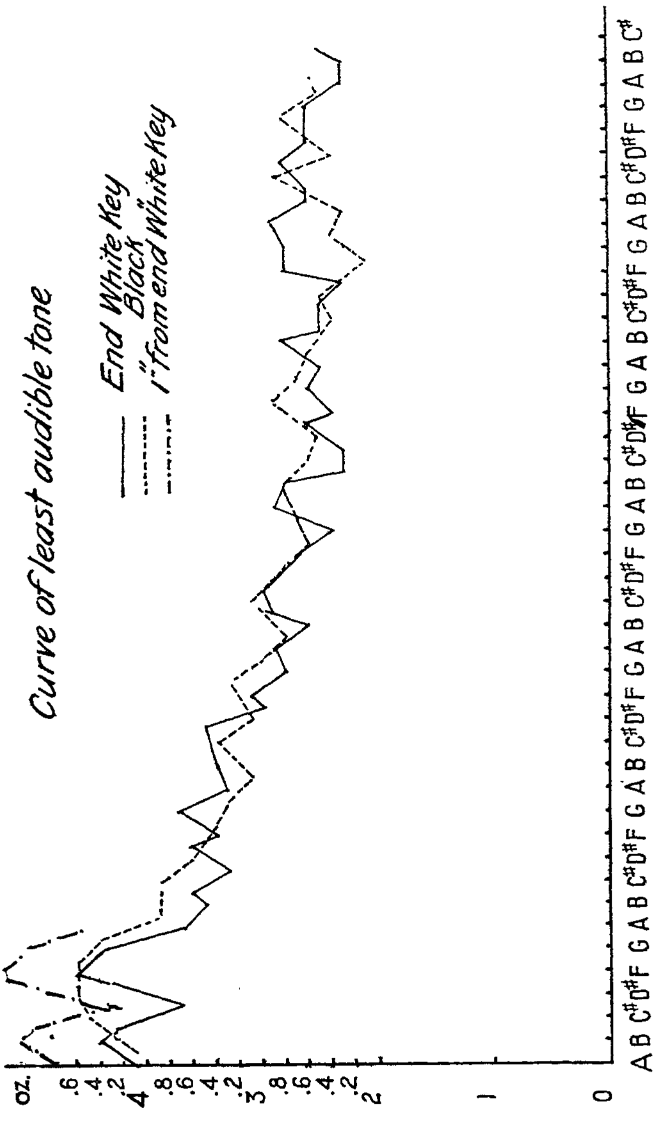

Curve of least audible tone
End White Key
Black "
1" from end White Key
oz.

FIG. 16B.

intensity. Conversely, the same weight used on all the keys will produce a dynamically uneven scale. Thus, a weight of 2·9 ounces on the first instrument will produce no tone whatever on E, A, or B. Again, a weight of 3·2 ounces will produce the softest pianissimo on A, a *p* tone on D, F♯, G, and C♯, and almost an *mp* tone on upper D. Now, these differences, while clearly audible for intensities ranging from *ppp* to *p*, gradually decrease in audibility as we increase the dynamic degrees, and in the *forte* regions, differences of several tenths of an ounce are not discerned.[1] Were it not for this fact, it would be impossible to play a dynamically even scale on any used instrument. On the other hand, the evenness of key resistance is doubtless largely responsible for the technical pleasure derived from playing on a new, or a newly "voiced" instrument as compared with a used one.

Thus far we have established values for the least audible tone only, which, however, is but relatively seldom used in piano playing. The intermediate degrees are much more prominent, but, because they represent subjective generalities, any actual figures which we deduce can be only very approximate. Nevertheless, some idea of the great amount of physical energy expended in the performance of any advanced piano composition may be gained by a rough quantitative scaling of the range of the weight of touch. We have just seen that for the production of the softest tone, a force varying from 2 to 4 ounces is required. If we use 3 ounces as an average and attempt to measure for the same key the force necessary to produce the various intensities used in music,

[1] This is but an application of the famous law of Weber, which states that for equal positive additions to the sensation we must make equal relative additions to the stimulus, or, in other words, to increase the sensation in arithmetic ratio it is necessary to increase the stimulus in geometric ratio.

remembering, always, that the figures are only rough approximations, we get *ppp* = 3 oz.; *pp* = $3\frac{1}{3}$ oz.; *p* = $4\frac{1}{2}$ oz.; *mp* = 6 oz.; *mf* = 10 oz.; *f* = 17 oz. +; *ff* = several pounds to many pounds. These figures apply to a single key-depression. The increase, as is seen, does not represent equal force additions from one dynamic degree to the next. It illustrates, inaccurately, it is true, but none the less clearly, the truth of Weber's general law.

Another factor influencing the weight of touch is the damper, and its controlling device, the damper pedal. In experiments on the instruments mentioned, an average difference of ·5 ounce for one and 1·0 ounce for the other was found between the weight necessary to produce the least audible tone "senza" and "con-pedale". We have a lighter action when playing with pedal than without, for the resistance of the damper has been removed when the pedal is depressed. The drop in the curves of Fig. 16A at the beginning of the three-lined octave shows where the dampers in this instrument end.

The measurements thus far made deal with constant weights. But there is no reason why this weight cannot vary during key-descent. Even a constant weight will produce increasing key-speed owing to the uniformly accelerating effect of gravity. Records made by constant weights are shown in Fig. 3*a*, *b*, *c*, and *d*. Now compare them with the records shown in Fig. 3*e* and *f*. Two points of difference will be noticed: the acceleration in the second group is distinctly greater than in the first group, and it is not constant. But if uniform weight produced key-speed such as that shown in Fig. 3*a*, *b*, *c*, or *d*, then *e* or *f* can only be produced by greater weight. And since the acceleration is greater than that produced by gravity alone, regardless of the actual weight, we may conclude that the player adds weight after key-impact in the touches employed in making these particular records. This phase has been met in various forms in the records shown in Chapter II.

Besides variations in weight resulting from variations in pitch, in point of application, in the numerical value of the force, and in degree of loudness, we have to consider variations resulting from the direction of the force. The effect of a force upon a body depends partly upon the line of application which, as has been indicated, may vary on the piano through 180 degrees. Since the key-descent is a fixed vertical motion, the 180 degrees may be divided into two symmetrical quadrants and the investigation of either quadrant will suffice. Now, the numerical value of a force acting at a known angle through a known distance upon a measurable body is easily calculated, if we assume the resistance to be a constant.[1] Thus, we find the forces required for producing tones of equal intensity by varying the line of application of a vertical force of 4 ounces to be as follows, the table representing a sample instance in which the degrees show deviations from the descending vertical :—

0 degrees . .	4 ounces.
10 ,, . .	4·06 ,,
20 ,, . .	4·26 ,,
30 ,, . .	4·62 ,,
40 ,, . .	5·22 ,,
50 ,, . .	6·22 ,,
60 ,, . .	8·00 ,,
70 ,, . .	11·69 ,,
80 ,, . .	23·04 ,,
90 ,, . .	infinity.

[1] Any force acting upon a body may be resolved into two components, one of which acts in the direction of the motion of the body and the other at right angles to this direction. The latter component does no work and the work done by the former is the product of its numerical value and the distance through which it works. This component equals p cos θ, in which p is the original force, θ the angle which the direction of p makes with the line of motion of the body acted upon. The values deduced in Fig. 17B have been derived from this formula.

A similar instance, using 8 ounces as the force actually producing tone, is shown in Fig. 17A. A vertical descent of a force of 8 ounces produces a tone X. If we strike the key from an angle of 10 degrees, either from the right or left, a force of 8·13 ounces is necessary in order to produce the same tone X. At 30 degrees a force of 9·24 ounces is required. At 60 degrees just double the original vertically acting force will produce the tone X. The manner in which this increase takes place is shown for four weights

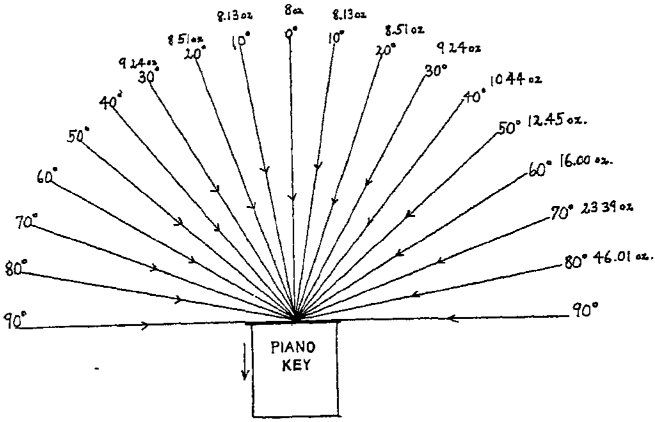


FIG. 17A.

(3 oz., 4 oz., 8 oz., 12 oz.) in Fig. 17B. These curves show very little increase for the smaller angles or deviations from the vertical. The increase becomes much greater for the larger angles. In actual piano playing a wide range of force direction must be used; accordingly, the variations here indicated may help to explain the selection of certain physiological movements of piano technique in preference to others.

As the mode of touch deviates from the vertical type, more force is required to produce the same tonal effect, and since oblique touches are often met

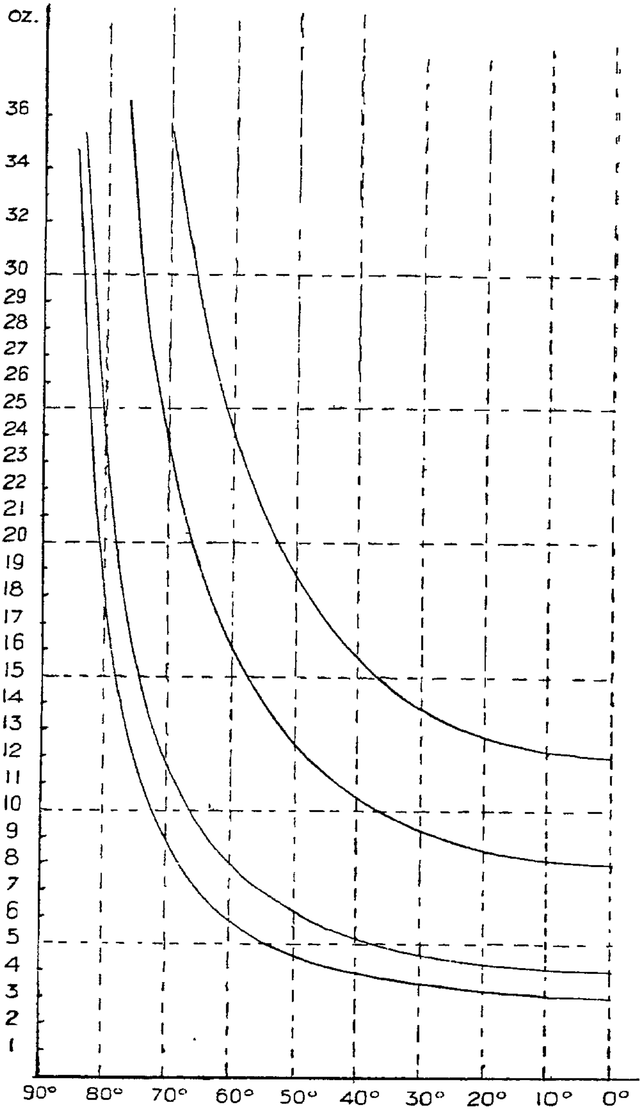

OZ.
36
34
32
30
29
28
27
26
25
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
90°
80°
70°
60°
50°
40°
30°
20°
10°
0°

FIG. 17B.

with in piano technique, only a part of the energy expended by the player is transformed into sound. The further we deviate from the vertical the greater is the loss in force-effect; the further we deviate from non-percussion the greater is the loss in tone-control. Consequently, the sound produced on the piano is not in itself a measure of the energy expended. The numerical value of this energy is always in excess of the tone produced. It varies, as we have seen, from several ounces to many pounds. Even a short and lightly played composition, such as the Chopin D flat Waltz (Minute Waltz), if we use three ounces for single tone production and a *pp* touch throughout, would demand a minimum expenditure of force of 235 pounds. Works such as the Liszt B minor Sonata demand, in a sense, truly a Herculean force; a conservative estimate for this sonata would be 25,000 pounds, with work done of 780 foot-pounds.

The weight or force basis for simultaneous key-depression now becomes clear. When two keys are simultaneously depressed it will naturally require twice as much force as when either key alone is depressed, for three keys, three times as much, and so on. This accumulation may be felt by placing a stick across the entire key-board (white or black keys) and depressing all the keys at once. Therefore, chords demand a greater expenditure of energy than single tones, and the same force applied to a single key and to a chord will produce a louder tone in the former case than in the latter. This distribution of forces is not without some effect upon passages in piano literature in which double-notes or chords alternate rapidly with single notes; for example, as in the accompaniment of the first theme of Chopin's B flat minor Sonata, or the accompaniment of the second theme, first movement, of Beethoven's Sonata Appassionata. If in such places the single key gets the same force as the two or three keys combined, the tonal effect naturally will be uneven. In order to secure an even tonal effect the chords must receive respectively two or three times the force applied to the single key. For it is known that the addition of other tones does not influence the sensation of loudness. A chord of three or six tones, each tone played *pp*, does not seem three or six times as loud as a single tone played *pp*. If it did, the production of a pianissimo ninth or eleventh chord, for example, would be impossible. Consequently, if a passage such as those to which we have referred sounds even in intensity, either the tonal differences resulting from equal force application are too slight to be heard, or the force applied varies rapidly between the single tone and the chord, and thus produces tones of the same

FIG. 17C.

intensity. As we complicate the figure by varying the number of keys simultaneously depressed, we complicate the application of forces; because each group of keys, numerically different from another key or group of keys, demands its own force for the production of a definite tonal intensity. That it is usually the variation in forces, producing the same tonal intensity, and not equality of forces producing unequal tonal intensities, which we find in the actual execution of such passages, may be seen in the above figure, in which *a* represents key-speed for a single key, *b*, key-speed for one of a group of keys played as a chord. Further proof of this force distribution will be found in Fig. 34 in the chapter on Hammer-Stroke. There are times, however, when some intensity fluctuations remain.

The same variation in forces applies to passages divided between the hands, in which one hand has simultaneous key-depressions differing in number from those of the other hand. The " bringing out " of a melody against an accompaniment, when the accompaniment is in the form of chords, is influenced by this distribution of forces, because if each hand plays with equal force, any one tone of the chord accompaniment must receive less force than the tone of the melody. Thus, if the two hands are played equally strongly, the hand having only one key to depress will produce a louder tone than the other hand; and if we wish to produce the same tonal effect for both hands, the hand having the greater number of keys to be depressed must be played with proportionately greater force.

A similar, though less pronounced, variation exists for differences between the hands resulting from the direction of touch and the point of application. If the right hand plays a series of keys with a vertical descent, while the left hand plays a series with a very oblique touch, equal forces for both hands will not produce equal tonal intensities. If, in such cases, equal tonal results for both hands are desired, the hand using the oblique touch must necessarily receive a greater force than the other hand.

This balance of forces is further complicated by the fact that it varies with the dynamic degree. The weights or forces used for the production of the dynamic degrees used in music do not increase in an arithmetical ratio but rather in the manner of a geometric ratio, as is shown in Fig. 3. For the softer degrees a relatively slight increase or decrease in force may alter the balance between melody and accompaniment, whereas, for the louder dynamic degrees, a greater increment will be necessary to secure this alteration in balance. Force and tonal effect, then, do not vary in any constant ratio. We cannot measure the tonal result by the amount of force applied until we know the manner of application of the force.

From these observations it is evident that the best control, and hence the most accurate tone variation measured in terms of force-distribution, is secured by a vertical descent at or near the outer end of the key in a non-percussive manner. The most difficult control, naturally, would be a very oblique descent away from the edge in a percussive manner ; a touch the physical difficulties of which we learned in Chapter II. All problems of piano technique, as far as they influence key-depression, fall at, or somewhere between, these extremes, and part of their difficulty may be explained in terms of the physical qualities of the keyboard.

Summarizing, we find that :—

Key-action, hence key-resistance in a normal instrument is not perfectly even or constant. The variations in the action are small, however, and have only a slight effect on musical results.

The forces used in piano playing vary from several ounces to many pounds.

The degree of force and the resultant sound vary with the point of application, line of application, duration of application, and numerical value of the force. The tonal effect is most direct when produced by a descending, vertical, non-percussive touch near the end of the key. A fixed ratio exists between degree of force and intensity of tone only for the single key and a constant touch, for an increase in the number of keys or force of touch does not, of itself, mean a like increase in tonal loudness.

The practical significance and importance of the contents of this chapter should be neither over-estimated nor entirely disregarded. We need not determine whether directing a pupil's attention to these things will improve his playing, for that, as a pedagogical problem, is entirely foreign at this point. We are not concerned here with establishing the practical value or the effects, in a musical sense, of these force variations. What we establish is their existence. Knowing that they exist, to what degree they exist, and how they vary, we have these facts to draw upon, if necessary, when explaining the physiological or psychological aspects of piano playing. In attempting to reconcile the conflicting opinions held on the question of the personal element in piano playing, nothing is too small to be omitted. For, obviously, an explanation will not be found in gross differences noticeable to any casual observer. It is highly probable, however, that it will be found in fine physical differences which, because of their very minuteness, have escaped the observer, and which he accordingly, with perfect sincerity, attributes to indefinable, non-physical elements.

CHAPTER IV

TOUCH COMBINATIONS

WHEN, now, we consider the results obtained for the single key-depression in the light of practical problems of piano technique, we are not confronted with any new physical variations; for the differences between a single key-depression and the playing of a musical composition, real enough in practice, are almost entirely physiological and psychological in nature. Every piano manufacturer prides himself upon the regularity or smoothness of his action, an evenness perfected in response to the urgent demand of the musician for such an action. Variations from this uniformity are considered defects, to correct which neither cost nor effort is spared. The ideal attempted is an action in which each key is a perfect duplicate of every other key. Consequently, we may formulate as an axiom that whatever happens to any one key on the piano can happen to any other key; or, conversely, nothing can happen to any one key that cannot happen to any other key. This perfectly obvious statement is emphasized here, because if we grant its validity we are forced to admit the truth of certain important conclusions in later chapters, which follow as necessary corollaries.

All devices of piano technique fall into one of two classes: simultaneous or successive key-depression, representing, respectively, the harmonic and the melodic aspects of piano playing. Simultaneous key-depression may vary in but one way—key-speed.

Successive key-depression may vary in two ways—key-speed and time-interval between key-depressions. Accordingly, musical variations of simultaneous key-depression are the result of variations in key-speed; musical variations of successive key-depressions are the result of variations either in key-speed or time-interval, or in both. These physical quantities, key-speed and time-interval, may remain constant, they may change abruptly, or they may vary gradually. For each phase we have appropriate terms. Thus, "*f*," "*p*," since they represent tones of constant intensity, also represent constant key-speed, and a change from one to the other represents abrupt change in key-speed. (Of course, we must remember that the dynamic degrees are not sharply defined areas of tonal loudness, but are merely convenient divisions on a continuous scale.) *Crescendo* and *diminuendo* represent gradual variation in key-speed, the former from slow to fast, the latter from fast to slow. *Andante*, *Adagio*, *Allegro*, indicate constant time-intervals; a change from one of these to another, or the use of such words as *doppio movimento*, *meno mosso*, indicates abrupt change of time-interval; *ritard* and *accelerando* indicate gradual variation in time-interval. Other terms, such as *calando*, *perdendosi*, demand a variation in both intensity and tempo, hence in both key-speed and time-interval.

Since the terms thus far cited, and many others belonging to the same classes, are themselves defined in intensity and tempo, their physical equivalents, key-speed, and interval between key-release and key-depression, are practically expressed in the definition. But there are other pianistic effects and terms, affecting both the harmonic and the melodic aspect of piano technique, which are not defined in terms of intensity and tempo. Such are the various touches and the terms of style and expression. It is our problem, now, in a very brief survey, to find the physical equivalents in key-action of such terms, a detailed account of which demands treatment from the psychological viewpoint.

The investigation of touches, such as *legato*, *mezzo-legato*, *portamento*, *staccato*, requires no experimental procedure, since the differences can be clearly seen, by mere observation, to be differences in the ratio of sound duration to silence duration. Or, expressed in terms of key-action, they are differences in the time-interval between a key-release and the next key-depression. Here, again, we are dealing not with absolute types of touch, as is often believed, but with an unbroken series varying in the ratio of silence-interval to sound-interval, from 0 for a perfect legato to 1 for a theoretically perfect staccatissimo. The terms used are merely convenient, quite general, and sliding divisions on this scale. There is no such thing as *the* mezzo-legato touch, or *the* staccato touch, because the tempo and the character of the passage fix merely one degree of many. Who, for example, can locate the exact point where a non-legato becomes a portamento, or a portamento a mezzo-staccato ?

Let any staccato passage be played in turn in the following tempi: Adagio, Andante, Moderato, Allegretto, Presto. Note the many varieties of touch employed solely to meet the demands of tempo. Play the passage again as follows: *pp*, *p*, *f*, *ff*. New varieties of touch will be employed, this time to meet the dynamic demands. Moreover, no gaps or clearly defined lines of demarcation will be found. All pianistic touches belong to an unbroken, highly complex series, the elements of which shade imperceptibly into each other.

Three other types of producing tones should be mentioned; *martellato*, *glissando*, and *vibrato*. The last-named, though truly not applicable to the piano, is included because it has been used by composers for the piano, for example, by Chopin. Fig. 7*e* shows the characteristic key-descent for *martellato*. This touch depends for its effect upon a fairly great key-speed. *Glissando* depends for its effect primarily upon rapidity of tempo. A series of tones played at a speed of less than 12 per second, ceases to give the effect of a *glissando* though played in the glissando style. The *vibrato* effect on the piano does not exist physically, since it depends upon prolonged manipulation of the tone, which we know is impossible on the piano.

The touch forms used in accentuating a tone of a chord or in "bringing out" a melody against an accompaniment (*melodia marcato*), generally understood as the result of throwing additional weight behind the melody finger, gain their effect by causing the melody key to be more rapidly depressed than the remaining keys.

The physical equivalents of such terms as "*con amore*" and "*affettuoso*" are less easily localized. These are terms most intimately suggestive of the "poetic" or "artistic" phase of piano playing. Yet, if they have any physical effect whatever upon the playing, and this, after hearing our best performers, can hardly be doubted, then this effect, too, must be explained in variations in key-speed and time-interval, for we have no other physical variable than these two. For the purpose of determining the normal effect of various marks of expression, a number of records of pianists were obtained and measured for variations in key-speed and time-interval, or, in musical terms, variations in intensity and tempo. These records brought to light the interesting fact that for practically every term such variations did occur. That is, the effect of every term of expression examined, with a few exceptions to be mentioned later, could be explained in terms of intensity and tempo. The following list illustrates in a general way the physical equivalents of various terms, translated into tonal qualities :—

con abbandono	marked variation in both tempo and dynamics.
affettuoso .	marked variation in both tempo and dynamics.
con amore .	variations in the slower tempi and softer dynamic degrees.
appassionato .	marked variations, abrupt and gradual, in both tempo and dynamics.
con calore .	variations in the slower tempi and softer dynamic degrees.
dolce . .	soft, and in moderate, graceful, or slow tempo.
doloroso .	no effect other than slow tempo.
espressivo .	variations in both tempo and dynamics.
giocoso . .	rapid tempo and detached tones.
lamentoso .	no effect other than slow tempo.
mesto . .	no effect.
pietoso . .	no effect.
religioso . .	no effect.
scherzando .	rapid tempo and detached tones.
con tenerezza .	soft and in slow or moderate tempo.

In other words, except in those cases marked " no effect ", the attempt to play a phrase or composition in the manner indicated by the term always resulted in variation in the intensity and duration of the tones, two purely physical quantities. For the terms marked " no effect ", we are obliged to conclude that no physical variation peculiar to the term exists. At least, none could be found. That is, so far as effect on the tone is concerned, it is useless to write "religioso", "pietoso", "mesto", for a piano passage, since the key-board cannot be influenced thereby. The usefulness of such terms must be sought elsewhere than in the physical field. The same remark applies also to numerous other terms not included in the preceding, necessarily fragmentary, list. On the other hand, many other terms will show, like *espressivo* and *affettuoso*, variations in either dynamics or tempo, or perhaps in both.

How do we know, now, that these physical variations in key-speed and time interval are not merely effects or accompanying phenomena, instead of causes, of the poetic elements? The unqualified answer is found by playing the same phrases without these variations in intensity and duration. In experiments under these conditions, it was impossible to convey any artistic effect as here understood. [Let the reader who doubts this attempt to play a Chopin Prelude or Nocturne, or a Beethoven Sonata strictly with a metronome and at a uniform intensity throughout.] It is true that the player uses other devices (psychological in nature) in addition to these intensity and duration variations, in order to secure the desired effect. These are relatively unimportant, however, and we may safely conclude that all artistic effects *in sound* are secured on the piano by variations in key-speed and in time-interval between successive key-release and key-depression. This includes, without exception, the most subtle poetic effects.

The "meaning" of a phrase, its poetical content, is conveyed to the auditor, not by some individual, even mysterious, touch of the player, but by appropriate variations in the speed with which the latter depresses one or more piano keys. Consequently, the control of key-speed, dynamically and agogically, becomes of vital importance, since it is the technical means of securing artistic effects.

To what extent, the piano teacher should direct the pupils' attention to key-control itself, is primarily a pedagogical problem; the teacher should at least realize clearly that if the pupil secures the desired tonal result, it is because he is using appropriate key-speed, and conversely, that if there are tonal defects, there is also inappropriate key-speed.

CHAPTER V

THE HAMMER-STROKE

Theoretical Analysis

GENERALLY speaking, whatever motion we impart to the piano key is transmitted through the piano action to the hammer. Therefore, if we analyse key-motion we analyse hammer-motion; knowing the one, we can accurately deduce the other. This is true to a great extent. Two factors, however, limit this relationship and make a separate investigation of hammer-stroke necessary. In the first place, the hammer is not rigidly fixed to the remainder of the action, and in the second place the point of escapement is not the point of tone-production. As a result, the hammer, under certain conditions and within certain limits, is free to move when the rest of the action is at rest.

The hammer consists of a head and shank of wood, formerly mahogany or cedar, and in recent years, birch and hickory. The head is covered with a thin strip of leather, over which several layers of specially prepared felt of different degrees of compressibility are fastened, with the most compressible to the outside. The head is set approximately at right angles to the shank. The shank is about 5 or 6 inches in length, and pivots at one end on a horizontal axis somewhat lower than the level of the strings. When at rest, the hammer-shank rests upon the hopper, making approximately an angle of 20° with the horizontal. When in this position the upper surface of the head is about $1\frac{3}{4}$ or 2 inches below the strings. Since one end of the shank is fixed, the hammer movement is restricted to an arc of a vertical circle embraced between the position just described and the position when the hammer-head surface rests against the strings, the radius of the circle being the length of the shank. The hammer cannot be moved in any other direction or through any greater distance when the action is in position. This can be readily observed on a working model. The deductions concerning the constants and variables in key-movement apply also to hammer-movement. Since both direction and distance are fixed, only the speed may vary, and consequently what differences exist must be differences in speed, since this is the only variable. Let us assume, for the present, that the hammer-shank remains in contact with the hopper throughout its stroke. Then a glance at Fig. 18A shows that as we depress the key the hammer must ascend. Since, while the key has traversed a distance of three-eighths of an inch the hammer has moved $1\frac{3}{4}$ inches,[1] the hammer evidently moves about four times as fast as the key. Up to this point we have a clear illustration of the principle of the lever, operating in the familiar form of a see-saw. When such movement takes place, every variation in key-movement is shown in hammer-movement magnified four times. All deductions and conclusions reached in the chapter on key-depression apply also to hammer-movement, when allowance is made, of course, for reversal of direction and when the condition assumed holds true, namely, that the hammer-shank remains in contact with the hopper. This phase, then, does not demand separate experimental investigation. In practice, however, the above condition is not fulfilled at all points of the hammer-stroke. It is true that the hammer-shank cannot get lower than the hopper, but it is not true

[1] Owing to the length of the lever arms.

that it cannot be lifted away from the hopper.[1] It is solely this hammer freedom to which the escapement mechanism owes its proper functioning. The principle of the escapement is illustrated in Fig. 18A.

Let A B be a lever, D a pellet resting on, but not fastened to, the end B. When A is depressed very slowly, D lifts with B; and when A strikes its lower limit, if the movement has been sufficiently slow, D will remain practically at rest upon B. If the descent of A takes place more rapidly, then B comes to a sudden halt, and D, through inertia or momentum, will tend to continue in its ascending path and will leave B slightly, and then fall back upon it. If

FIG. 18A.

the descent of A is still more rapid, the distance through which D is thrown from B will be greater. Exactly the same thing happens in the piano, in which A becomes the key end, B the hopper, and D the hammer.

Press down a piano key very slowly. When it is near the key-bed, a "jerk" will be felt. This is caused by the hopper sliding from beneath the hammer-shank; in other words, it is the point at which the hammer "escaped". If the key-depression has been sufficiently slow, the movement will not have produced any tone whatever, for the hammer will not have touched the string, although the key will have been depressed its entire distance. As we increase the speed of key-depression, a point will be reached at which a tone is just barely produced. When we

[1] When the action is removed from the instrument the hammers may be lifted from or, better, turned on their axes until they pass beyond the perpendicular, where they will remain if released.

continue to increase key-speed beyond this point, the tone becomes louder. The fact that there can be complete key-depression and incomplete hammer-ascent permits a very important conclusion to be drawn; namely, that there is no unbroken connexion between key and string, or tone-production. *The hammer in every case leaves the rest of the action before it reaches the string.*[1] Now the law of the lever says that for every increase in the distance traversed by any point in one arm there must be a corresponding increase in the distance traversed by any point in the other arm. Since the above experiment shows that this is not always the case, for example, above

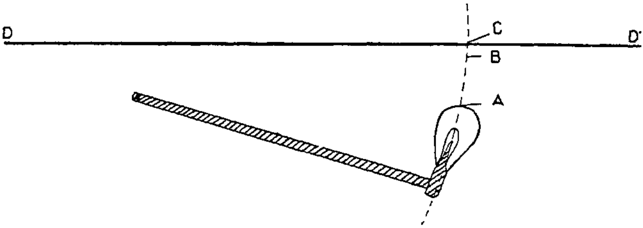


FIG. 18B.

the point of escapement, we cannot apply any laws of the lever to the hammer-action after the hammer leaves the escapement.[2]

Pass a string beneath the hammer-shank and tie this so that the striking surface of the hammer-head rests about $\frac{1}{32}$ of an inch below the piano-string. Now manipulate the key in any manner whatever, and notice that nothing affects the hammer. This is conclusive proof, if further proof were needed, that there is a part of the hammer stroke during which we have absolutely no control over the hammer.

[1] Again, the observation of a working model will make this perfectly clear.

[2] Certain effects of touch on string, as described in works on piano-playing, are explained by assuming the action of a piano to work upon the principle of the lever throughout its course. This is an incorrect assumption.

Let A be the hammer when at rest. Let B be the point of escapement and C the point at which the hammer strikes the string D D′. From A to B the hammer is under the player's fairly direct control. Therefore the act of tone-production takes place, and must take place, between the points A and B. It is assumed, of course, that the forces acting upon the hammer from B to C, namely, friction, gravity, and atmospheric resistance, are constant. Once again, then, as in key-depression, our problem becomes the investigation of variations in hammer-speed, the only variable possessed by the hammer.[1]

Now, a body at any one moment of time can have but one mass, one direction, and one velocity. If a body begins with a velocity of 0 and a uniformly positive acceleration so that at the end of 10 seconds it has a velocity of 100, its velocity at the fifth second will be 0 plus 100 divided by 2 = 50.[2] Again, if a second body begins with a velocity of 100 and moves with uniformly negative acceleration of 10, so that its velocity at the tenth second is zero, at the fifth second this, too, will have a velocity of 50. A third body moving at a constant velocity of 50, will likewise have a velocity of 50 at the fifth second.

Suppose that the fifth second referred to in the above theoretical case corresponds to the point of escapement in the movement of the piano hammer. Then, at the point of escapement we should have the hammer travelling at precisely the same velocity, though this velocity would have been gained differently for each case. Referring to the physical principle of the Introduction, we find that in order to change the velocity of a moving body a force is necessary. We have

[1] For reasons, see Chapter on key-depression.

[2] Or, applying the formula that the velocity at any moment equals the product of the acceleration and the units of time $v = V + at$, we get $v = 10 \times 5 = 50$.

also seen that from the escapement to the string we can exert no force upon the hammer. It follows that we cannot change the velocity of the hammer after it leaves the escapement, and ignoring the very slight retardation due to friction, gravity, and resistance of air, we may conclude that the hammer keeps this velocity through the distance B C in Fig. 18B and reaches the string with practically the same velocity with which it leaves the escapement. Applying this to the case cited, the first hammer-stroke starting at 0 increases to 50 and reaches the string with a velocity of 50. The second begins with a velocity of 100, decreases to 50, and also reaches the string with a velocity of 50. The third begins with 50, remains at 50, and likewise reaches the string with velocity of 50. Accordingly, the effect of this hammer-speed upon the string is precisely the same for the three cases, although this force has been attained in a different manner for each case. Since whatever tonal result we get from the string depends entirely upon the effect of this force, we can thus produce the same tonal result in three totally different ways. Moreover, it is evident from the given figures that the moment we change the velocity at the point of escapement, we change the tone-producing force. This means that the only fundamental physical factor affecting the tone of the piano, so far as this is caused by the vibrating string, is the velocity at which the hammer head travels when at the point of escapement.

Thus far, the examples have dealt only with uniform acceleration, positive or negative. When the acceleration is not uniform, which the figures of key-depression show to be the normal condition existing in practice, the actual calculation becomes more complex, but the fundamental principle remains the same. In such a case, we divide the entire stroke into unit sectors, and if these are sufficiently small, we assume each sector to have either a constant velocity or uniform acceleration.[1]

These differences or fluctuations, however, do not influence tone directly. The sole vital factor is the velocity at the end of the stroke, not the velocity or velocities during the stroke. The same body cannot possess different velocities at the same moment. Any one hammer, in any one stroke, when leaving the escapement, is travelling at one and only one velocity, in one and only one direction, and is capable of exerting one and only one force. It does not matter how this force has been attained, gradually or suddenly, regularly or irregularly; the quantity $\frac{1}{2}mv^2$ proves that the energy possessed by a moving body at any one moment is independent of its mode of generation.

It has been necessary to explain this part in detail, since many incorrect conclusions concerning the action of the hammer on the string have been drawn, even by prominent writers on piano technique. Among them is the fallacy that if we depress the key gradually the string is set into motion gradually. This, of course, assumes that if we begin with little weight and increase this, thereby increasing hammer-speed, that this increase continues after escapement. Why should it continue? Suppose there were no string to stop the hammer, nor a pivot to retain it, then it would always continue to increase in speed, and we should not only have perpetual motion, but even perpetually-increasing motion.[2]

[1] In similar manner, when proving the area of a circle, we assume the circumference to consist of an infinite number of straight lines forming the bases of triangles.

[2] We certainly have no right to assume that because the distance ($\frac{1}{8}$ in.) is so small the physical laws are different for this distance than for greater distances. It is true that the eye does not perceive the physical phenomena at this small distance, but it is absurd to advance that as a proof that these phenomena do not exist.

From these facts we draw three primary conclusions:

1. The only variable in hammer movement is speed.
2. The hammer traverses part of its stroke as a relatively free body, beyond all influence of the player.
3. The tonal result as produced by the vibrations of the string depends solely upon the velocity with which the hammer leaves the escapement.

The Hammer in contact with the String.—If, then, the hammer has sufficient velocity at the point of escapement, it is thrown across the intervening space against the string with more or less force. Since the outside layer of felt is compressible, this reduces the audibility of impact to a minimum. The lower layers yield the necessary elasticity for a rapid rebound of the hammer.

When the hammer is thrown against the string, two things occur: the string is displaced upward, and the felt is compressed. Thus we have both force effects, a change in shape and a change in volume. The hammer exerts an upward force on the string, the string exerts a downward force on the hammer. Now, the law of the conservation of energy teaches us that energy cannot be destroyed; it is merely transferred. Therefore, when the hammer comes into contact with the string, a transfer of energy from the former to the latter takes place. It is in the manner in which this transfer is made that we have the clue to tone-production on the piano.

To overcome resistance, a force is required. The string offers resistance to the upward stroke of the hammer, and, as soon as displacement of the string occurs, a transfer of energy, equivalent to a loss of energy in the hammer, takes place. That is, for each additional unit of displacement the hammer gives up a unit of force.

Now, in discussing the first part of the hammer-stroke, we found that the velocity of the hammer cannot increase after escapement, for no new force can be added, and positive acceleration always means the action of a force.[1] It is still more obvious that the velocity of the hammer cannot increase after reaching the string, because in this case, not only can we not add any force, but the additional resistance of the string must be overcome. Therefore, from the moment of impact, the moment when the hammer touches the string, a decrease in hammer-speed takes place. Any increase is a physical impossibility. Hence, any transfer of energy is negative for the hammer and positive for the string. This question next presents itself: Does the manner of the transfer vary, and if so, how? Since we are dealing with a fixed steel string, we know or can calculate its coefficient of elasticity. This, for the same string, is a constant ratio. That is, the resistance offered to the hammer per unit of time remains the same up to the limit of elasticity.[2] Thus, two equal initial forces will always give up their energy in precisely the same manner.[3] Applied to the piano, this means that when the hammer reaches the string with a certain velocity, there can be but one string-response, which is always the same for every hammer-impact at the given velocity.

Now, when a greater force acts upon the string, one of two things may theoretically occur: the greater force may overcome the same resistance in less time, or a greater resistance in the same time. The first assumes that the resistance remains constant, when as a matter of fact it changes with string-displacement. Of the two theoretically possible actions of a

[1] See Physical Principles.

[2] The interesting variations taking place beyond this point will be treated in the chapter on the vibration of the string.

[3] Of course, the irregularities due to the unstable condition of felt as a striking body are disregarded.

greater force, then, we have in our case an increased resistance, and not a shortened time, with which to deal. The greater the force the greater the resistance overcome. Now, since the coefficient of elasticity, the resistance offered, is a constant ratio, the force must act through a greater distance, because the ratio in which the force loses its energy per unit time remains the same. Therefore, for every increase in hammer-force we have an increase in string displacement, or, as it is technically termed, amplitude. Two unequal hammer-forces cannot produce two tones of the same intensity; two equal hammer-forces cannot produce two tones of unequal intensity. The transfer of energy from hammer to string takes place as follows: the greater the hammer-speed, the more rapidly is energy transferred and the greater is the resistance overcome. The time required for this transfer, consequently, varies within certain limits, since it depends upon the relation of the force of the hammer to the physical properties, mass, tension, and elasticity of the string.

The hammer continues on its upward journey, until its energy has been completely transferred.[1] For an instant, both hammer and string are at rest at the upper extremity of their displacement. The felt of the hammer being depressed, the amount or length of felt surface actually in contact with the string depends upon the depth of depression. It has often been assumed that a good length of contact surface dampens the high, erroneously called inharmonic, partials of the string, and that a less length produces a "harsh" tone. If this were true, all *pp* tones, since only a small part of the felt surface touches the string, would be harsh; and all tones

[1] Not all has been transferred to the string. Part has been lost in producing noises and in overcoming friction and in compressing the felt of the hammer.

produced by hammers with well-worn ridges, and hence long surfaces of contact, would produce "sympathetic" tones. As a matter of fact, the reverse is the case. The difference in tonal qualities is due not to the length of contact surface, but to its hardness, location, duration of the contact, and to the cutting-out of partials with nodes at that point.

When hammer and string have reached the upper extremity of their excursion, the former possesses zero energy, the latter energy somewhat less than the initial impact force of the hammer. The string in turn now exerts a downward force on the hammer; the compressed felt, owing to its elasticity, an upward force on the string. Both forces tend to drive the hammer down, away from the string. If the key has been completely depressed and so retained, the hammer will be caught by the buffer and its energy dispersed through this, as shown in Fig. 1. If the key, meanwhile, has been completely or partly released, the hammer is re-engaged by the escapement mechanism and is ready for a second excursion against the string should the key again be depressed.

The rising of the dampers simultaneously with of the depression of the key, as well as the action the pedals, need not detain us here. These effects will be studied later.

Records of Hammer-Stroke

If, now, we can record the path of the hammer-head, we have practical and tangible proof of the preceding theoretical statements and conclusions. Records of the hammer-stroke may be fairly satisfactorily obtained by attaching an appropriate stylus to the hammer-head and passing beneath this, at a constant speed, a surface of smoked paper. An ordinary kymograph will not do because of its size and, secondly, its slow speed. The experiment requires a specially constructed apparatus consisting of one small vertical cylinder, or preferably several such cylinders, of such size that the paper passed over them will present a vertical surface close to the hammer. By appropriate gearing or belting, a rapid paper or film-speed may be obtained. Needless to say, only a section of the piano-action can be used. This can be made by any piano manufacturer at comparatively small cost. The advantage of such an apparatus is due to the fact that it enables us to record the hammer-stroke without interfering with tone-production. Thus the experimenter actually hears the tone produced and knows whether or not it is what was desired. Imagine the film passed from left to right at a constant speed. Then the motion of

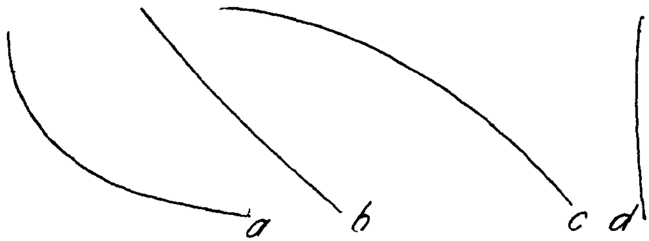


Fig. 19.

a point moving vertically across this film will be projected upon it, deflected toward the left. If the point moves rapidly, the line described will be nearly vertical. If the point moves very slowly, the line described will be nearly horizontal. Any fluctuation in speed during the stroke will be shown by curvature toward or away from the perpendicular. This applies to either an ascending or a descending point. An ascending point beginning slowly and increasing in speed will describe a path such as *a*, Fig. 19. The same point moving with a constant velocity will describe a path such as *b*. A point beginning rapidly and decreasing

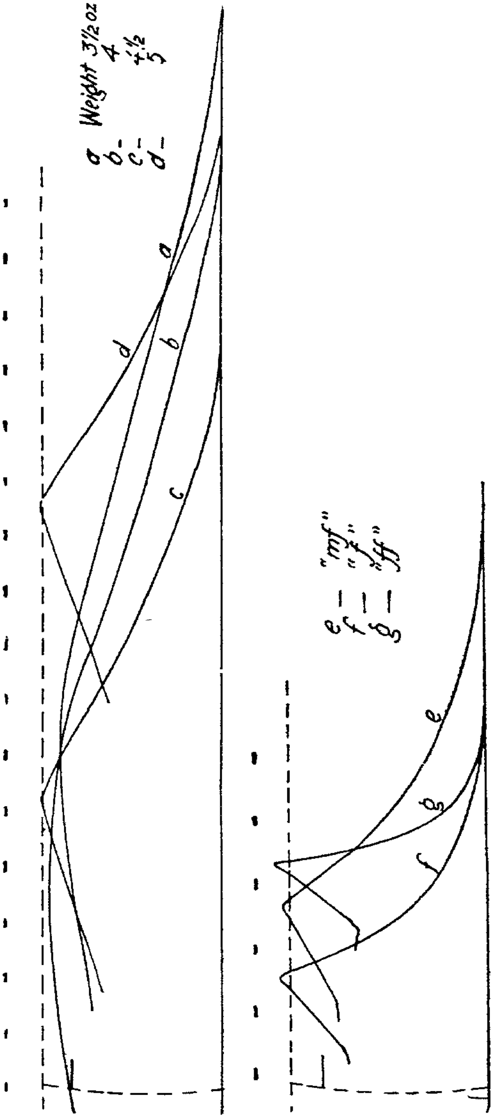


FIG. 20.

in speed will describe a line such as *c*, Fig. 19. When the film is at rest, a point fastened to the hammer-head describes the line at *d*, Fig. 19.[1] In the records used allowance must be made for this curvature. That is, a concavity of this amount or less does not mean increasing speed since the point on the hammer itself moves in a curve. The records should not be read for horizontal differences of less than $\frac{1}{10}$ inch, which is equivalent, approximately, to $\frac{1}{500}$ of a second, since they are not accurate beyond this point.[2] The additional arc on the records shows the path traversed by the hammer when the film is at rest; in other words, it shows the path which an instantaneous hammer-stroke would describe. The short horizontal line shows the point of escapement. The dotted horizontal line shows the string level. Every record is shown on a scale slightly less than one-half of the originals. The great distance, nearly three-eighths of an inch, against the normal of one-eighth inch between escapement and string in some of the records, needs explanation. The escapement was thus set in order that variations in hammer speed between escapement and string contact could be magnified. Many of the observations, of course, are merely reiterations of those made in the chapter on key-depression. They are included, however, as additional proof, and also because they facilitate the comprehension of the remaining records.

Fig. 20 shows increase in hammer-speed from the horizontal slow speed, "*pp*," to the vertical fast speed, "*ff*," with intermediate grades. All records of hammer-stroke are to be read from right to left.

Effect of Muscular Relaxation and Rigidity on Hammer-Stroke.—The effects of relaxation and rigidity

[1] This is the arc of the circle whose radius is the length of the hammer-stem.

[2] The piano-action, scientifically considered, is too coarse a mechanism to permit really fine measurements.

upon hammer-stroke are shown in Fig. 21 and in Fig. 22. In Fig. 22 we find a slight difference, and in Fig. 21 a marked difference. In both cases, however, the hammer-speed produced by a rigid hand and arm was greater than that produced by a relaxed arm.

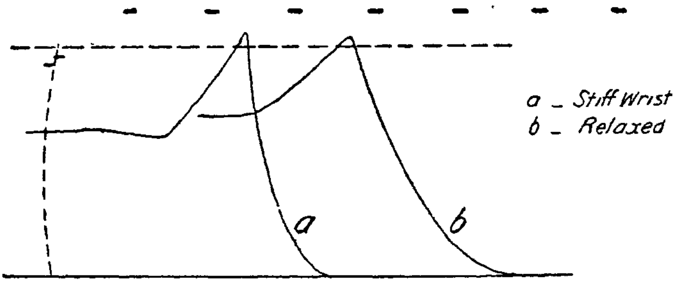


FIG. 21.

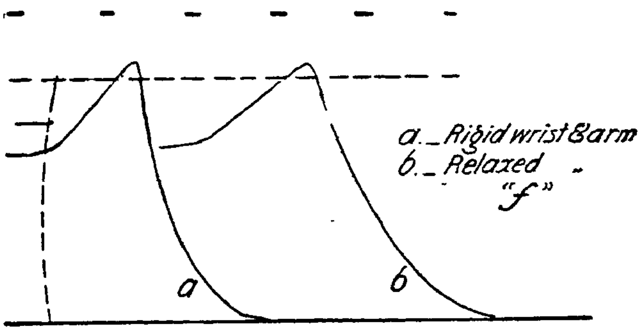


FIG. 22.

Moreover, when we look at the distance which the string is displaced (that part of the curve above the string level) after allowing a little for felt-depression, we find that the greater hammer-speed has caused the greater displacement of string, hence louder tone. Therefore, generally speaking, rigidity tends to produce louder tones than relaxation.[1] This is shown by faster hammer-speed and greater string-displacement.[2]

Effect of Percussive and Non-Percussive Touch on Hammer-Stroke.[3]—Fig. 23*a* shows the hammer-stroke resulting from percussive touch, and Fig. 23*b* that resulting from a non-percussive touch. Note the abrupt beginning of the former and the gradual beginning of the latter. The upper part of the first curve is practically straight, showing no increase of speed. In other words, the maximum hammer-speed is attained before the hammer reaches the

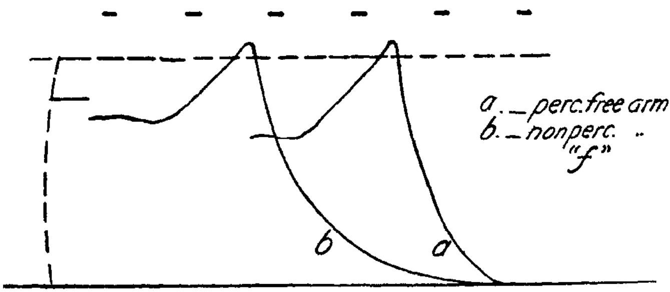


FIG. 23.

escapement. The non-percussive curve, on the other hand, shows a steady increase up to the point of escapement. In addition, we find a difference in intensity, the percussive touch showing the greater intensity. This verifies those records of key-depression which illustrate these touch differences.

The key-depression, moreover, showed during its course a marked irregularity for all percussive touches.

[1] Compare with the corresponding paragraph in the Chapter on Key-depression. This conclusion involves the assumption that amplitude of string-displacement is the physical equivalent of the sensation loudness.

[2] String-displacement will be discussed in detail in Chapter VI.

[3] It will be remembered that the one qualitative difference in key-depression was found to be the result of differences between percussive and non-percussive touch.

Naturally, we should expect to find a similar irregularity in the hammer-stroke. Such an irregularity would result in a hammer-stroke somewhat as follows: Somewhere in its course would be a momentary retardation, which would deflect the curve toward the horizontal. No such deflection, however, was obtained on any of the many records made, nor could any be obtained by special attempts to secure such a stroke. In other words, the retardation which takes place in key-descent does not take place in hammer-ascent. And the subsequent increase in key-speed likewise is not shown in the hammer records. This difference between key-depression and hammer-

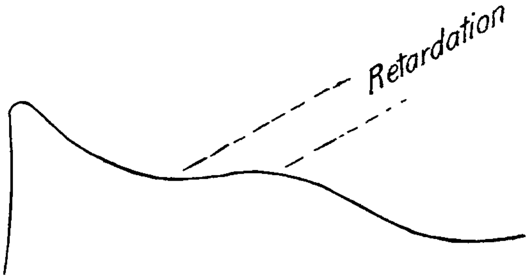


FIG. 24.

stroke can be explained in only one way: that key and hammer are not in contact at and after the point when the irregularity in key-depression occurs. This being so, the important corollary follows: that in percussive touches the hammer is under control of the player through only a part of its stroke, the distance varying with the dynamic degree of percussion.[1] Whatever motion we wish to impart to the hammer in percussive touches must therefore be transmitted before this point where the hammer leaves the key-action.[2] This phase has other interesting

[1] This agrees entirely with the conclusion reached in the Chapter on Key-depression.

[2] Not to be confused with the point of escapement.

features. In Fig. 25, *b* and *c* show, respectively, the curve resulting from a very light, staccato touch and the curve resulting from a so-called "surface" or "shallow" tone. Both are convex almost from

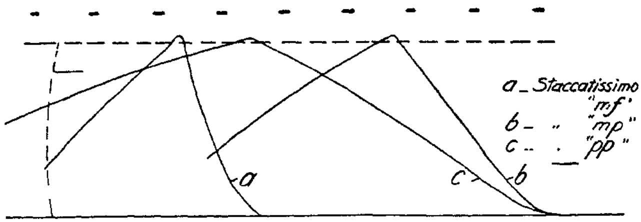


FIG. 25.

the beginning. That is, we have a decrease in velocity. This means that no appreciable force is acting after the moment of impact. To prove this, the piano key was "blocked"[1] at distances first of $\frac{1}{8}$ inch below its surface level and then at $\frac{3}{32}$ inch. Fig. 26

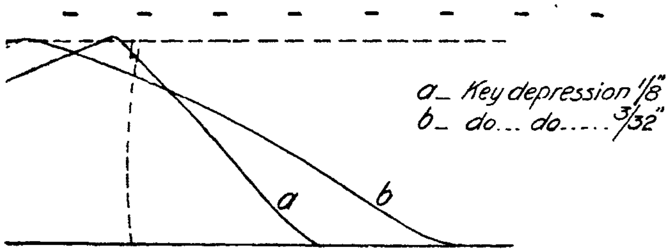


FIG. 26.

shows the resulting curves, when the key is struck "*f*" and "*ff*". These curves, it will be seen, are identical with the curves *b* and *c* of Fig. 25, a condition which proves that in percussive touches, the motion is imparted to the hammer only during the time of impact and not after. This, of course, necessitates

[1] A piece of wood was inserted beneath the key, so that the key could be depressed only $\frac{1}{8}$ in. and later $\frac{3}{32}$ in.

very fine muscular adjustment in order to secure the desired dynamic degree.

Percussive touches are said to produce a "brilliant" tone; non-percussive touches, a "sympathetic" tone. Such differences, when they do exist, are, as we have seen, in no way due to differences in hammer-stroke, as is erroneously believed, excepting the fact,

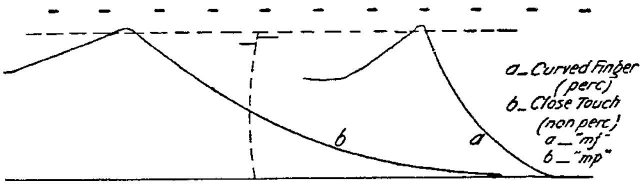


FIG. 27.

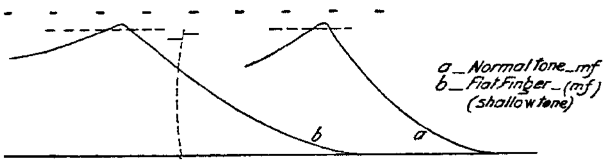


FIG. 28.

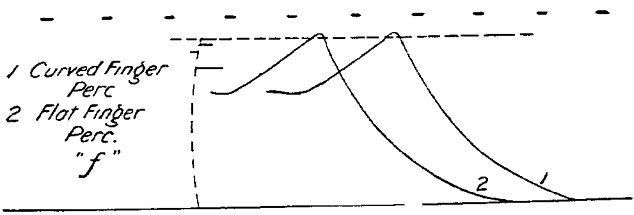


FIG. 29.

of course, that percussive touches tend to produce louder tones. It will be shown later that these differences are due to other factors.

Effect of Hand and Finger Position on Hammer-Stroke.—Figs. 27 and 28 show curves for a bent or curved and flat or extended finger, respectively, the latter representing the so-called "clinging" touch. Both curves show differences of intensity in favour of the curved-finger touches. After extended practice by the experimenter, this intensity difference was largely eliminated and the curves of Fig. 29 were secured. The person making these records admitted, however, that he " felt " the flat finger touch " louder " than that of the curved finger, which merely substantiates the statement that under normal conditions,

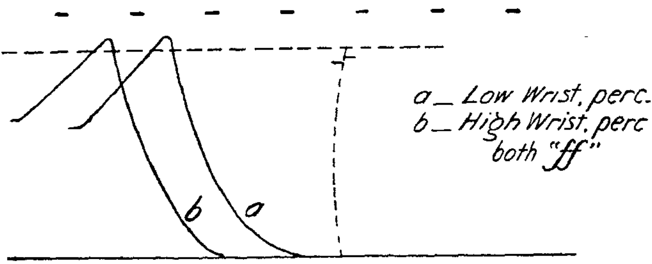


FIG. 30.

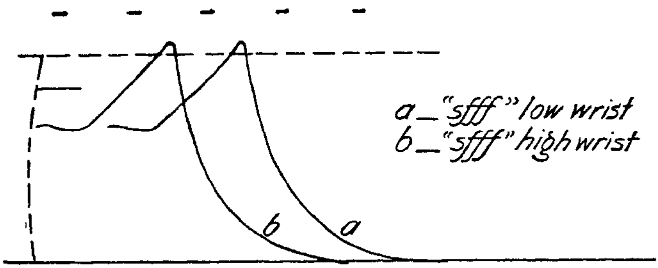


FIG. 31.

when there is a difference, we tend to play softer with extended fingers than with curved ones.

Figs. 30 and 31 show curves produced by a high and a low wrist. As in key-depression, absolutely no difference was found. Upward or downward motions of the arm, then, are immaterial, so far as an influence on the hammer-stroke and hence on the vibration of the string is concerned. When a particular arm or hand movement does produce a particular effect, this is due to other things than the tone resulting from the vibration of the string. The same statement applies to other movements of the arms and hands, such as rotary motion.

Fig. 32 shows the curves obtained by a percussive staccato (a touch in which the hand is thrown against the key and quickly withdrawn) and a non-percussive (so-called "plucked" staccato), a touch in which the

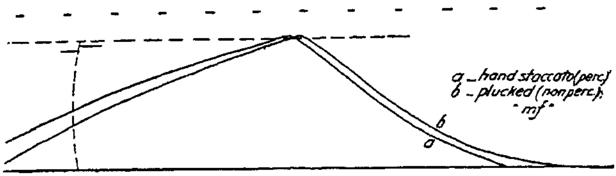


FIG. 32.

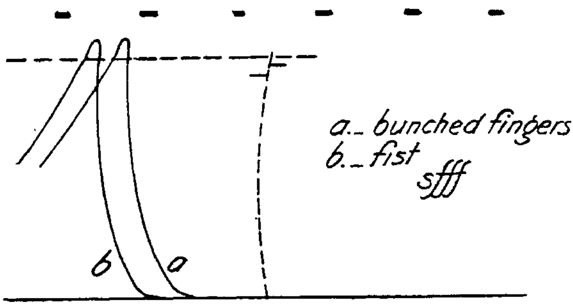


FIG. 33.

finger rests against the key and is then quickly drawn up.

Except for the immediate beginning of the curve, where the percussive type naturally shows a somewhat more abrupt beginning than the non-percussive type, the curves are identical. This identity precludes any difference in the tonal result for these two touches, so far as this is produced by the string.

Fig. 33 shows a curve made with "bunched" fingers (several fingers for the one key) as musically as the dynamic degree used (*sfff*) permitted, and a curve made by using the fist, striking the key a severe blow. The hammer moves in precisely the same manner in both cases.

Fig. 34 shows the hammer-speed for a key when depressed alone, and for the same key when depressed as a tone of a chord. In Chapter III (Fig. 17c) the fact was mentioned that for simultaneous key-depression greater force is used in order to keep the intensity the same. That each key under such conditions receives the same force is shown in Fig. 34, in which Figure the two curves are identical.

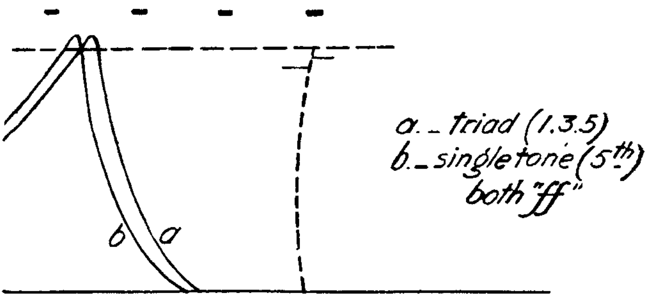


FIG. 34.

The opinion is sometimes held that it makes a difference whether, when the damper pedal is depressed, we play a key *staccato* or *sostenuto*. It is said each produces its own tonal effect. This opinion, evidently, is based upon the assumption that the shortness of the one touch and the sustained pressure of the other is transmitted to the hammer and thence to the string. Fig. 35 shows the curves obtained for these touches. In the records here used there is considerable intensity difference, the percussive staccato being louder than the sostenuto. Apart from this difference, however, the two curves are alike, inasmuch as they both show a straight line for the greater part of the hammer-ascent. We must remember that the parts of the curve after string contact have no significance. Consequently, the differences in these touches is without effect upon hammer-stroke, and hence also upon tonal result. The explanation of the slight difference which may exist will be found when we come to discuss the noise element.

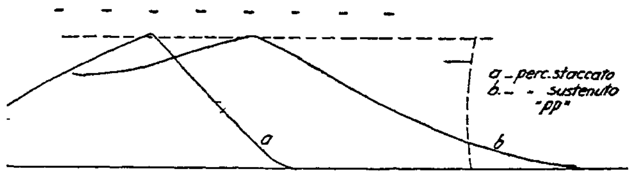


FIG. 35.

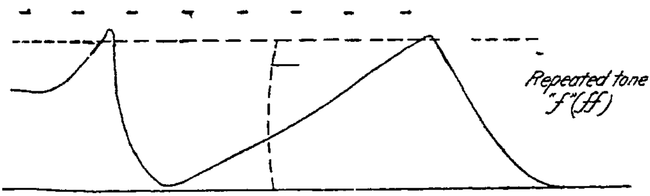


FIG. 36.

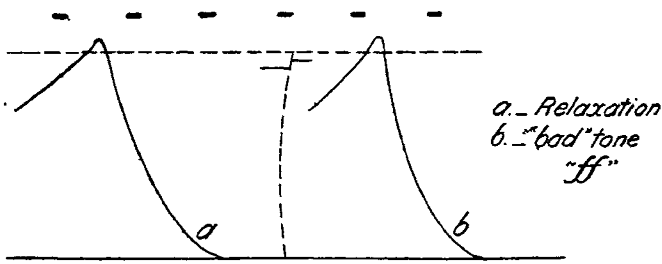


FIG. 37.

Fig. 36 shows the operation of the repeating mechanism by means of which the hammer may be re-engaged and re-driven against the string before it descends completely. The two tones produced here were "*f*" and "*ff*" respectively.

Hammer-Stroke and Tone Quality.—Figs. 37, 38, 39, 40, and 41 show curves for tones of the various qualities named with the Figures. Again, we find a "harsh" tone louder than a "good" tone, since it is represented by greater hammer-speed; we find

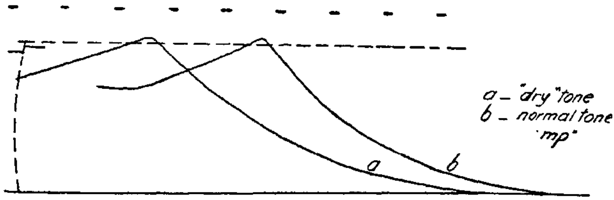


FIG. 38.

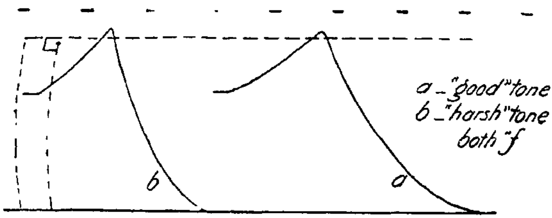


FIG. 39.

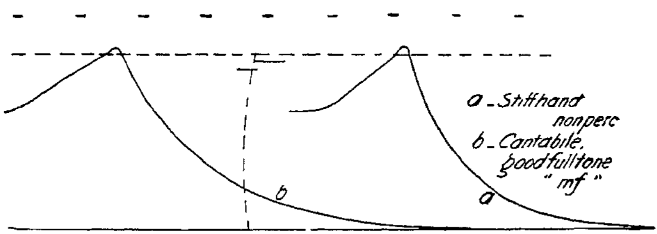


FIG. 40.

a "shallow" and a "dry" tone weaker than a "normal" tone. When by additional experimentation these differences in intensity were corrected, the difference in so-called "quality" vanished in the judgment of the subjects originally making the records.

This bears out the findings in the chapter on Key-depression.

The Hammer-Stroke after Escapement.—A study of the entire series of records showing the hammer-stroke reveals one important fact concerning the path after the moment of escapement. In none of the records do we find concavity, that is, increase of speed [1] after the point of escapement. When the line remains practically straight, we have examples of approximately constant hammer-speed; when the line is convex, that is, bending towards the horizontal as it ascends, reading from right to left, we have decreasing hammer-speed. In no case, then, has there been energy added after escapement, for such an

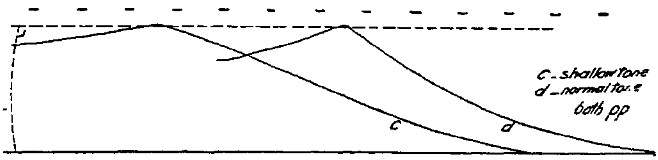


FIG. 41.

addition would result in an increase of hammer-speed. A number of instances among the records of key-depression, however, showed such addition.

Let us now look at that part of the curve above the string level which represents contact of hammer and string, bearing in mind, however, that the records are not sufficiently exact to permit accurate comparison. We find the greatest hammer-speed at the moment when the hammer-head comes into contact with the string. Thereupon there is a decrease in speed. If the hammer strikes the string with great velocity, there is a rapid decrease; if the hammer strikes with a low velocity the decrease is slower. This is shown

[1] It must be remembered that a very slight concavity does not indicate increase in speed since the actual path of the hammer is not a straight line, but an arc of a circle, hence concave in itself.

by the various degrees of convexity of these arcs or curves above the line representing the level of the string. In every case, however, there is convexity, that is, decrease in hammer-speed. If there were increase of speed or even constant speed the curve would have to bend toward the right. The theoretical impossibility of this has already been demonstrated. The records furnish the necessary practical substantiation. Consequently, the statement that with appropriate touch, e.g. that represented in Fig. 40, the string is "gradually pressed" into motion, is shown to be a complete fallacy. There is not and cannot be any "unpercussive" attack of the string, or "gradual" setting into motion of the string.[1] Above all, it must not be supposed that the gradual key-depression resulting from the various forms of "sympathetic" touch is likewise gradually transmitted to the string; for all this gradual preparation takes place before the string is touched, and since, owing to the escapement, it has also ceased before the string is touched, it might just as well not have taken place *so far as its direct influence on the string is concerned.* This is clearly shown in the records, several of which have equal hammer velocities at string level and similar curves above this, regardless of whether this velocity has been attained gradually or suddenly. But similarity of that part of the curve representing contact with the hammer means similarity of string motion, for when the apexes of two curves are identical, the string itself, a physical constant, evidently is set into motion in precisely the same manner. A study of the records shows this to be possible regardless of how the escapement velocity has been attained, for curves totally different at the beginning have similar apexes: compare Figs. 20*e*

[1] Further proof of this will be found when we treat of the vibration of the string.

and 25*b* for example. The quality of string motion is thus shown to be entirely independent of the manner of generating the velocity of the hammer, and to be dependent solely upon the speed with which the hammer leaves the escapement. This the records bear out. Wherever the angles made by two curves at the escapement point are equal, the contact parts of the curves are practically identical.

Duration of Contact.—It is well known that the vibration of a string depends in part upon the nature of the stroke. This, in turn, depends upon the length of time during which the striking body remains in contact with the string. A body in contact with the string for only an instant produces one mode of vibration, and a body in contact for a longer time produces a different mode of vibration. For that reason it is advisable to study the given records in a general way for duration of contact; i.e. the length of time during which hammer and string are in contact. This is represented by the length of horizontal line at string level included between the two sides of the curve. The greater this distance, the longer the contact. We find the shortest distance in the greatest hammer-speed. The distance increases as the force of impact (hammer-speed) decreases. Though the hammer drives the string relatively farther aside in the former case, the transfer of energy consumes less time than in the latter case. In other words, in the production of loud tones [1] the greater force is transferred in less time than in the production of weaker tones. The contact time, then, increases from tones of great intensity to tones of little intensity [2]; or, generally speaking, contact time varies inversely as the intensity, and the entire variation from fortissimo to pianissimo

[1] For vertical string displacement means amplitude, which means loudness.

[2] The effect of this relationship on the resulting tone will be discussed under the vibration of the string.

occurs between approximately $\frac{1}{200}$ and $\frac{1}{300}$ of a second. Mention of this general tendency must suffice here, for the records are not sufficiently accurate to permit detailed calculation, much as this is desired. Nor would the instability of the felt hammer and piano action permit this.

The Hammer after Leaving the String.—In the tracings of records here shown the greater part of the downward or returning stroke of the hammer has been omitted. There are two reasons for this: first, the descending stroke has absolutely no influence on tone; and secondly, to record it here would in some cases lengthen the records to several feet. What actually takes place is this: the hammer when caught by the check is held about $\frac{1}{2}$ inch from the string. When the key is released the hammer falls; and, owing to the manner in which it is held by the action, it does not immediately come to rest, but first describes several gradually diminishing minor ascents or descents. A complete record on a small scale is shown in Fig. 42. Notice that the rebound from the string is considerably more rapid down to the point where the returning hammer engages the buffer than for the rest of the distance. This part is a true rebound, something very different from the ascent of the piano key.

Conclusions

The agreement of the records with the theoretical proof deduced at the beginning of this chapter permits the following conclusions to be drawn:—

1. The only factor directly influencing, or responsible for, the vibration of the piano string is the velocity with which the hammer leaves the escapement.

2. Regardless of the touch employed, regardless also of the manner in which the escapement velocity of the hammer has been attained, there is but one action of the hammer against the string; namely,

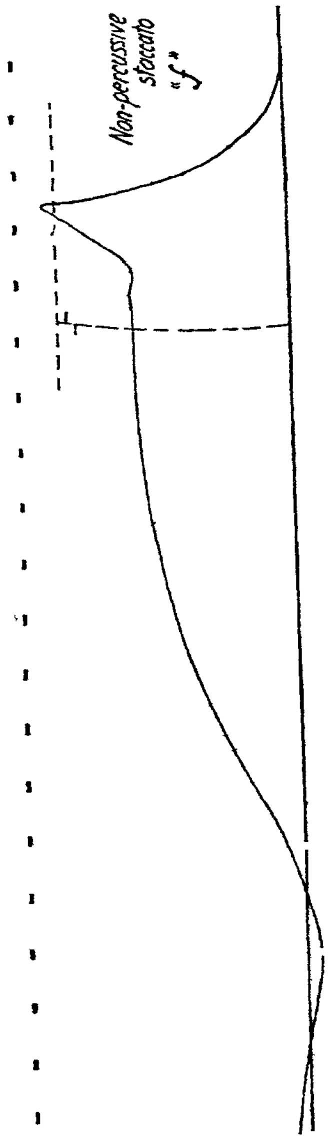


FIG. 42.

a sharp, percussive action. There is no such thing as an unpercussive attack of the string.

3. In no case is it possible to increase the hammer-speed after escapement.

4. In every case there is decrease in hammer-speed from the moment of string-contact. The greatest velocity occurs at the moment of impact. Hence there can be no gradual setting into motion of the string.

5. For every increase in hammer-speed we have an increase in the amplitude of string-displacement.

6. The duration of contact between hammer and string decreases as we increase hammer-speed, or, what is the same thing, it decreases as we increase the intensity of the tone.

7. All qualitative differences, such as "harsh", "dry", or "singing", are the result of differences in hammer-speed, and therefore differences in tonal intensity or loudness.

8. Rigidity and curved finger touches tend in general to produce greater hammer-speed than relaxation and flat finger touches. And since greater hammer-speed is the equivalent of greater tonal intensity, the former produce louder tones.

9. Normal hammer-action takes place in a period of time very approximately between $\frac{1}{10}$ and $\frac{1}{150}$ of a second for the softest and the loudest tone respectively. Therefore all tone gradations, as far as these depend upon intensity, must take place within these limits.

10. In order to produce the least audible tone, the hammer must have a velocity of about 5 feet per second; for a *fortissimo* tone, the velocity is about 40 to 60 feet a second.

PART II

INTRODUCTION

IN Part I we sought to analyse the physical mechanism of piano touch and tone; in Part II we shall seek to analyse the sound produced by this mechanism from the moment of its generation in the piano to the impingement of the sound waves upon the ear of the listener.

When a single piano key is depressed and a tone produced, the sound heard is generally considered a simple unity, a "one-ness". As a matter of fact, however, this is far from true. The sound is physically very complex, and with a little training, which incidentally, is most desirable for the pianist, the ear can distinguish a number of the elements of this sound complex. It will be convenient to list these elements as follows:—

I. Tonal Elements:

A. Vibration of the String Struck
1. Fundamental tone
2. Partial tones
3. Beats between 1 and 2
4. Beats among partials

B. Vibration of other Strings
1. Sympathetic resonance
2. Forced resonance

C. Vibrations of the Sounding Board
1. Natural frequencies
2. Forced frequencies

D. Sound Propagation
1. Diffusion
2. Reflection
3. Interference
4. Resonance

II. Noise Elements :
A. Hammer-String percussion
B. Finger-key percussion
C. Action noises
1. Key-bed percussion
2. Friction noises

D. Noise Propagation
1. Diffusion
2. Reflection
3. Interference.

This analysis does not exhaust the elements of variability. Taken as a whole, the piano sound-complex varies again, as we shall see, with numerous other attributes, such as the pitch region or duration, which are here understood as more or less foreign to the tone-complex itself. Our problem, therefore, becomes first a study of the nature of piano sound and what may be called its internal and external variability, and, secondly, a study of the effects of pianistic touch upon this sound-complex and its physical variations. And since the mechanical forces are transformed into sound at the contact of hammer and string, we shall begin with an analysis of the vibrations of the piano string.

CHAPTER VI

VIBRATION OF THE STRING

Theoretical Analysis

STRINGS may be made to vibrate by bowing, as in the case of the violin, by plucking, as in the case of the harp, or by striking, as in the case of the piano. The quality of the resulting tone depends partly upon the mode in which the string is set into motion. Strings of various material are used for producing musical sounds, such as the gut strings of the instruments of the violin family and the harp, and the metal strings of the piano. The quality of the resulting tone depends partly upon the material of the string.

The strings of the piano are made of carefully prepared steel. They vary in length and thickness, the shorter and thinner being used for the tones of the treble region, the longer and thicker for those in the bass region. In order to reduce the length of the string necessary for the production of very low tones, the bass strings are wrapped with thin copper or steel wire, some once, some twice. This wrapping makes the string thicker, but at the same time gives greater flexibility to the string than it would possess if the steel string itself had the diameter of the wrapped string. It gives, however, less flexibility than an unwrapped string of the same pitch, but necessarily greater length. When a piano string is stretched between two points and, either by plucking or striking it, is made to travel back and forth, that is, to vibrate, it produces vibrations which, if wide enough, the ear takes up as a tone.

Fortunately, instruments such as the monochord have enabled us to study and analyse rather minutely what actually takes place when such a string vibrates. This study and analysis has led to the formulation of several fundamental laws :—

1. The stretching weight or tension being constant, the number of vibrations in a second varies inversely as the length of the string.

2. The number of vibrations per second varies inversely as the diameter of the string.

3. The number of vibrations per second varies directly as the square root of the tension.

4. The number of vibrations per second varies inversely as the square root of the density of the string.

Moreover, we know that :—

1. The duration of a tone depends upon the length of time during which the vibrations, sufficient to produce tone, continue to reach the ear.

2. The intensity or loudness of a tone depends upon the width of the excursions of the string.

3. The height or depth of a tone, its pitch, depends upon the number of vibrations per second.

4. The quality, timbre, or "colour" of a tone depends upon the form or shape of the vibrations. Thus in Fig. 43, which illustrates various types of vibrations, *b* represents a shorter sound than *a*; *c* represents a higher sound than *b*; *d* represents a louder sound than *f*; *e* represents a different tone-quality from *a*; *d'*, a crescendo and diminuendo.

Since we know that the pitch of a tone depends upon the number of vibrations or waves reaching the ear per second, in other words, upon the frequency of the waves, it is evident that a vibrating body, yielding a curve such as *e*, Fig. 43, must give forth more than one tone, for the smaller waves or vibrations are greater in number per unit of time than the larger ones. In such a case we hear what is known as a complex tone. All tones used in music are complex.[1] We have no musical instrument which when sounded produces but a single tone, a tone of one pitch. Consequently, we should expect a complex curve to result whenever the vibrations of the tone-producing body of any musical instrument are recorded. It will be

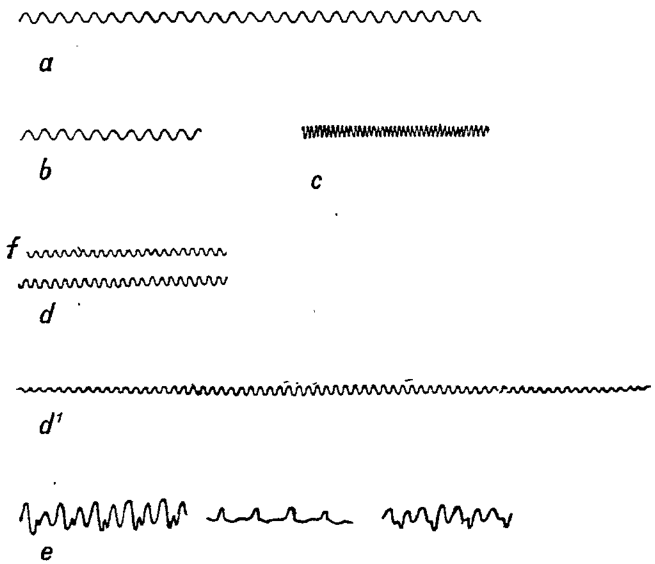


FIG. 43.

shown later, as far as the piano is concerned, that this is invariably true.

The most important law concerning tone quality is Ohm's law,[2] which states that all varieties of tone quality, no matter how complex, are analysed into combinations of simple tones. Later, Fourier[3]

[1] The tone of a tuning-fork is normally a pure tone. The curve produced by such an instrument is shown in *a* of Fig. 43. The tone is considered musically uninteresting.

[2] George Simon Ohm (1787–1854), a German Physicist.

[3] Jean Babtiste Fourier (1768–1830), a French Physicist.

developed a theorem by means of which any complex vibration could be analysed into its proper component simple vibrations. However, because two vibrations differ in shape, they need not necessarily produce tones of different quality, since the differences in their wave form may be merely differences of phase,[1] and it is generally accepted as true that differences of phase *do not* affect tone quality.

In Chapter V we traced the operation of producing a tone on the piano to the point where the hammer displaces the string. We have to find out now what happens to the string when so displaced. The string is forced upward by the hammer, and a wave runs along the string from the point displaced to either end.

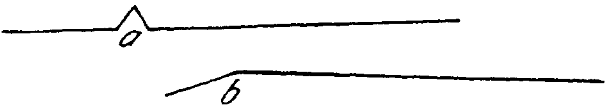
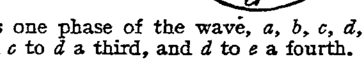


FIG. 44.

Because the tension of the piano string is very high, this wave progress takes place very rapidly. Moreover, as a result of the softness of the felt hammer and its graded compressibility, these waves are not marked. The soft felt displaces the string in the manner of *b*, Fig. 44, whereas a sharp, hard point would displace it as at *a*. The hammer rebounding from the string leaves the latter free to vibrate. It is a well-known fact that a string thus free, vibrates not only as a whole but also in parts. That is, a string vibrates as at *a*, Fig. 45, at the same time vibrating as at *b*, *c*, *d*, *e*, and in yet other ways. But

[1] The phase of a wave may be illustrated as follows :—



from *a* to *b* is one phase of the wave, *a*, *b*, *c*, *d*, *e*, from *b* to *c* another phase, *c* to *d* a third, and *d* to *e* a fourth.

each one of these wave lengths produces its own tone, because pitch, we learned, depends upon the length of the string; *b* produces the upper octave of *a*, *c* the fifth above *b*, *d* the fourth above *c*, *e* the major third above *d*. For example, if *a* produces the C below middle C, *b* will sound middle C, *c* will sound the G above, *d* the C above the G, *e* the major third above the C or two-lined E.[1]

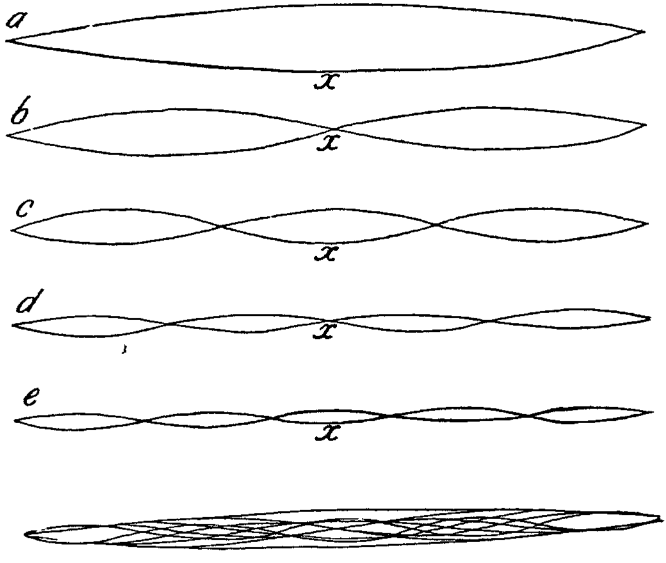


FIG. 45.

Again, looking at Fig. 44 we see that the greatest displacement of the piano string at the moment of impact is at the point of hammer-stroke. But amplitude means loudness. Therefore, those tones whose natural width of vibration corresponds to this point will be loudest at the moment of impact. If we study Fig. 45 we notice that a point *x* is moving through a relatively great distance in *a*, while it is

[1] The presence of these tones may easily be detected by resonators.

not moving at all at *b*, it is moving somewhat at *c*, and not at all at *d*. Years of experimentation have led the piano manufacturers to select a point between $\frac{1}{7}$ and $\frac{1}{9}$ the length of the string [1] as the point for the hammer-stroke yielding the most satisfactory quality of tone-complex for musical purposes. This point will permit the fundamental, 1st, 2nd, 3rd, 4th, and 5th partials to vibrate. The tones corresponding to these frequencies are key-note, octave, 12th, double-octave, major-third above, and octave of the 12th. The string cannot freely vibrate in sevenths because the point at $\frac{1}{7}$ from the end must be at rest, and if the hammer strikes the string at this point it obviously cannot be at rest. Higher partials than the 6th are weak, though they are present in the tone-complex.[2]

These partials, however, are not of equal intensity; they are not, strictly speaking, the same in number or intensity for any two strings in the piano; and they do not retain either their absolute or their relative intensities from one moment to the next. But every piano tone-complex consists of a fundamental and various upper partials of constantly changing intensities. The number of these partials and their relative intensities give the tone-complex its colour or quality.

When the hammer strikes the string with little force, it is able to overcome but little resistance. Hence, it displaces the string but slightly; and, since loudness of tone depends upon this displacement, or amplitude of vibrations, we naturally get a soft or weak tone. Such a tone might be represented as in Fig. 47*a*. Now, suppose the piano hammer to strike the string with somewhat greater force. There will be greater displacement, and, as a result,

[1] The distance of the hammer striking-point from the end of the string is not exactly the same for all strings in any one instrument, nor for various instruments.

[2] With sufficiently refined apparatus the presence of as many as 34 partials has been detected.

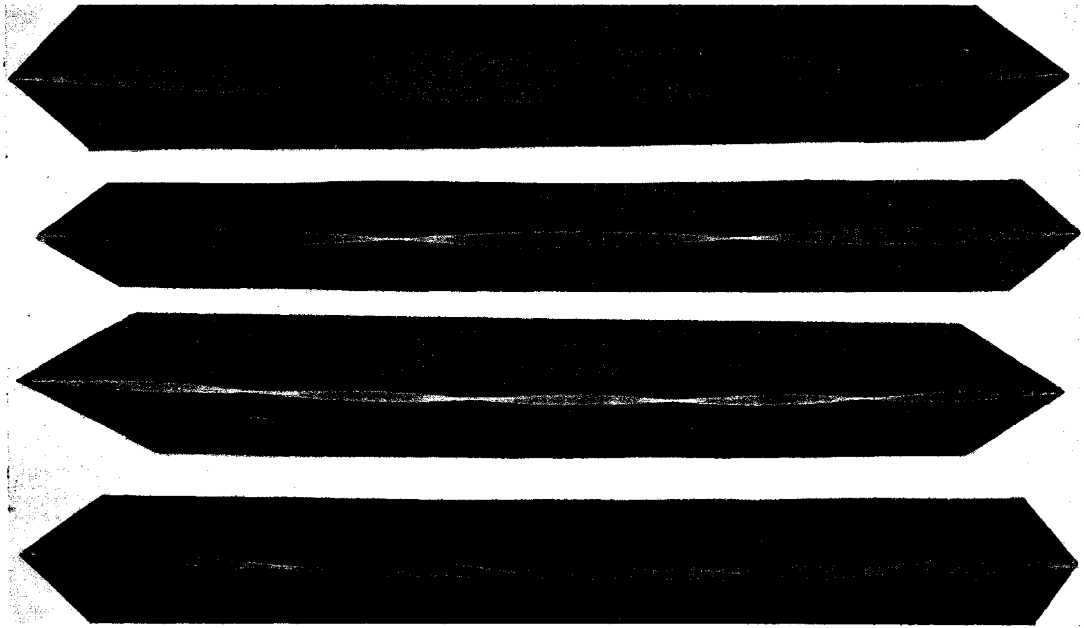


FIG. 46. PHOTOGRAPHS OF A VIBRATING STRING, SHOWING THREE FORMS OF SIMPLE AND ONE OF COMPLEX VIBRATION

[face p. 96

a louder tone. Let it be represented by Fig. 47*b*. A still greater hammer-force will result in still greater displacement, and the resulting tone may be represented as in Fig. 47*c*. Now, it is evident that below a certain amplitude no tone is audible, since the waves are too minute to affect the human ear. Otherwise, there would be no waves too soft for us to hear, which is, of course, not true. Suppose in our figures that we represent this point by the line which we shall call the threshold of audibility (T.A.).[1] What is below this line is too weak to be heard. Then in Fig. 47*a*

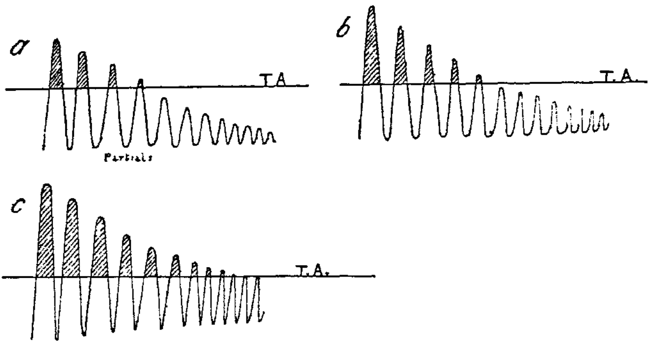
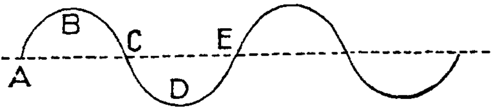


FIG. 47.

we have a tone consisting of a fundamental, 1st, and 2nd partial, and a weak 3rd partial; in *b* we have a tone consisting of a fundamental, 1st, 2nd, 3rd, and 4th partials of various intensities; and in *c* we have a tone with all partials present up to and including the 9th. Since the colour or quality of a tone-complex depends upon the number and relative intensity of the partials present, we get three tone-complexes of different quality. From this we can formulate an important law: that for every difference in intensity there is a difference in the quality or colour of piano tone-

[1] Needless to say, this varies with the individual, pitch, and distance.

complex. The diagrammatic illustrations used are purely theoretical and do not represent the actual, more complex relationships as we shall find them later. The principle, however, is the same. The vibration of the string is further complicated by the fact that its own speed varies during the course of a vibration. The string travels at a maximum speed when it reaches its point of displacement. Its speed decreases until it reaches the end of its excursion in either direction. For a theoretical moment its velocity at this point is zero. The return excursion from extremity to centrality of position shows gradually increasing velocity with a maximum velocity at the point where the string passes its original position of rest. Thus, if we project a simple vibration, as follows:



the string has a maximum velocity at A; negative acceleration to B; zero velocity at B; positive acceleration to C; negative acceleration to D; zero velocity at D; and positive acceleration to E. Thereupon this series repeats itself, each time of course with diminishing absolute energy, until finally the string comes to rest. This internal speed variation does not influence pitch but does influence intensity. The string travels faster for a loud tone than for a soft one. It does not make more vibrations per second, of course, but because it still makes the same number, and yet has to travel a greater distance (amplitude) for each vibration, it certainly must move at a greater velocity. This variation in velocity then must always occur with a variation in amplitude.

Tension, likewise, has an effect upon tone-quality. The greater the tension the clearer and longer does the tone tend to be. A low tension reduces the elasticity of the string and consequently affects the tendency to vibrate in parts. On the other hand, it permits the fundamentals and lower partials to predominate. The resulting tone is somewhat dull and heavy. Extremely high tension results in a preponderance of upper, higher, partials, and gives the tone a metallic colour.

This relationship between intensity and tone-quality will be better understood if we seek its corollary in colours. Thus, if we mix yellow and blue, we get green ; by adding more yellow or more blue we change the tint of the green. We have a new colour, a change in quality, obtained not by adding a new element but merely more of an old element, that is, a change in quantity or intensity. Precisely the same phenomenon occurs in piano-tone ; a physical addition of quantity results in a subjective difference of quality.

Since the resistance which the string offers to the hammer is the same for each successive hammer-stroke, and since the physical properties of the hammer are likewise invariable,[1] it is manifestly impossible to produce different forms of string-vibration if the hammer-force remains the same. A study of Fig. 47 will make this clear. If the hammer-strokes are the same, the string displacement is the same, and consequently the same number of partials of the same intensity will result. For if this were not so, the same force would have to produce various effects upon a body whose properties remained constant, a statement which contradicts the most fundamental law of dynamics. In other words, whenever the velocity with which the hammer reaches the string remains the same, the form of the resultant string-vibration remains the same. That is, for any one degree of

[1] Excepting, of course, the so-called "wear" of the hammer.

intensity we can have but one tone quality. In the piano, *two tone-complexes of equal intensity cannot differ in quality for the same string.*

Duration of Tone.—These two fundamental laws of string-vibration, when applied to practical problems in the piano, become complicated for a number of reasons. Chief among the latter are the changes of quality in piano tone-complex occurring from one moment to the next. It is a well-known fact that the piano is incapable of sustaining any tone at a uniform intensity. The tone reaches its loudest point practically at the moment of impact (the instant after is really more exact), and then diminishes in intensity. This variation is accompanied by complexity of tone colour. Not only does the tone-complex change in intensity, it likewise changes in quality from each moment to the next, in accordance with the laws deduced in the preceding paragraph. This diminution in tone is the result of the transfer of energy which takes place within the string as a whole, its internal molecular resistance, the resistance of its end-pins, and the resistance of the atmosphere. In terms of the movement of the string, this decrease means decreasing amplitude of vibration. The vibrations, scarcely audible at the moment of impact, become inaudible later on; those plainly audible become scarcely audible.

This diminution may vary in speed and also in quality; it may be regular or irregular. In other words, the amplitude of the vibrations may decrease an equal or unequal amount for each unit of time. Naturally, any irregularity would tend to complicate the tone-quality still more. Since the hammer has left the string before the entire string has been set into uniform motion, we may expect to find irregular diminution when we record the vibrations.

Limit of Elasticity.—The laws of elasticity teach us that the displacement of an elastic body is directly proportional to the force, within the limits of elasticity.[1]

If a force of 1 causes a displacement of 2, a force of 2 will cause a displacement of 4. Applying this to the piano we have the string displacement varying directly as the force, as far as the elastic properties of the strings are concerned. And the physical properties of the string being constant, they cause the ratios among the fundamentals and partials to remain constant. In other words, if the elasticity of the string alone influenced tone colour, we should have a series of tone qualities increasing by a constant ingredient, and not varying by changed relations within. That is, as we increased the displacement of the string we should add B to A; to A and B we should add C; to A, B, and C we should add D. But the relation of A to B in any case would remain the same. In practice we find no such simple arrangement. Other factors contribute to tone quality on the piano. They are: the duration of the stroke, the material of the striking body, and the place struck.

The Duration of the Stroke.—As a result of friction, displacement, inertia, and elasticity of the hammer-head, the hammer remains in actual contact with the string for a certain time, which we shall call the duration of the stroke. The tendency of any body which rests against a vibrating body is to "damp", that is, to destroy the vibrations. Naturally, the longer this contact lasts the more effectively will the vibrations be destroyed. The weakest vibrations are the first to be destroyed; then follow the stronger vibrations. A very short contact time permits a string to vibrate in small as well as larger segments;

[1] The limit of elasticity is the point at which a permanent alteration in molecular structure takes place; the point at which a stretched string or a bent stick fails to return to its original shape.

a longer contact time destroys these smaller vibrations. But the vibrations of the small segments produce the high upper partials, those of the larger segments produce the lower partials, and that of the whole string produces the fundamental. Hence, with a very short duration of stroke we should expect a tone rich in high upper partials, and with a longer duration of stroke a tone with fewer upper partials. Helmholtz, in his *Sensations of Tone*, has shown that this is actually so.

By referring back to the records of hammer-stroke we see that the more rapid the stroke, the shorter the contact time. Consequently, loud tones (the equivalent of great hammer-speed) will contain more, and more intense, upper partials than the soft tones (the equivalent of slow hammer-speed), because the duration of stroke is less in the former than in the latter case. Needless to say, all such variations in contact time are very small, ranging approximately between the limits of ·001 and ·005 of a second, for the middle and lower regions; but this is ample time to produce tonal differences when we consider that fraction in relation to the rate of vibration of the string.

Given the same intensity (force of stroke) for all strings, each string will have its own contact time in relation to its vibration time. Suppose the duration of the stroke to be $\frac{1}{500}$ second. For a string making 30 v.d. per second, the ratio of contact time to vibration time, which is the factor determining one phase of tone-complex quality, will be $\frac{3}{50}$. For a string of higher pitch, making, for example, 150 v.d. per second, the ratio of contact time to vibration time equals $\frac{3}{10}$, for a string making 500 vibrations the ratio equals 1; for a string of 1,000 v.d. it equals 2. Which means that in the region of the contra octave, for the theoretical force selected, the hammer would remain in contact with the string for $\frac{3}{50}$ of one vibration, in the small octave for $\frac{3}{10}$ of one vibration. Near C² it would remain in contact with the string for just one vibration, and an octave higher the contact time would equal two vibrations. But we know that a change in the ratio of duration of stroke to vibration time results in a change in tone-quality. This may be seen from the following table, deduced by Helmholtz, showing the varying intensities of the upper partials for various intervals of contact time :

	$\frac{3}{7}$	$\frac{3}{10}$	$\frac{3}{14}$	$\frac{3}{20}$	instantaneous
Partials	near c″	near g′	below c′	below c′	
1	100	100	100	100	100
2	99·7	189·4	249	285·7	324·7
3	8·9	107·9	242·9	357·0	504·9
4	2·3	17·3	118·9	259 8	504·9
5	1·2	0·0	26·1	108·4	324·7
6	0·01	0·5	1·3	18·8	100·0
7	0·0	0·0	0·0	0·0	0·0

The fractions at the head of the columns indicate the ratio of the hammer-contact time to the string-frequency.

Because of this variation in contact time, the elasticity of the felt hammers changes for variations in pitch. We find the more elastic hammers in the bass region, where the duration of the stroke may be relatively great and the more rigid hammer surfaces in the treble region where shortness of duration time, on account of the high vibration frequency, is essential. Such differences as these tend, by keeping the ratio of contact-time to vibration-time an approximate constant for any one degree of force, to neutralize the qualitative tone differences which would otherwise result.

The Material of the Striking Body.—These qualitative tonal variations are still further complicated by the material of the striking body, the felt of the hammer. This changes in hardness for every change in string displacement, for as the string is driven aside it compresses the felt, which in turn becomes harder. The effect of the compressed felt upon the string, when the latter is at the end of its displacement, is different from the effect of the uncompressed felt at the beginning of string displacement, for the hardness of the acting surface has been changed. Fig. 44 illustrates what happens when a string is set into motion by a perfectly hard (steel) hammer and a very soft one (soft felt or rubber). These are the extremes. The variations in the hardness of the felt still produce these same differences in string movement, though, of course, such differences are much less pronounced. Now, the resultant tones of longitudinal waves thus produced are high, being roughly comparable to the high, partial tones of the transverse vibrations. The unstability of the felt makes a numerical analysis of these qualitative differences impossible.

The Striking Place.—The striking place of the hammer, unlike the factors we have just discussed, is a constant for any one string, and consequently no qualitative differences in the tones of that string can possibly be due to the striking place. However, its location, $\frac{1}{7}$ to $\frac{1}{9}$ of the length of the string from the end, affects the "characteristic piano tone-quality" by eliminating all partials having nodes at this point. Only a small part of all the clang-tints, or tonal qualities, which the piano string can give forth can be obtained on the piano by means of the hammer.[1] Yet, within these relatively narrow limits, there is

[1] It is theoretically possible that among the future improvements upon the piano will be one which permits such a shifting of keyboard and action that the hammer may strike the strings at different places. The field of tone colour would be much enlarged thereby.

still room for rich varieties in quality as a result of variations in intensity.

Pitch.—The quality of a piano tone is further influenced by pitch. Thus the treble region of the piano differs in quality from the middle region, and both of these from the bass region. The explanation is simple. A short string cannot vibrate in as many parts as a long string. This means that the strings in the treble region do not produce as many upper partials as do lower strings. Greater tension, too, means less amplitude, and a quicker return of the

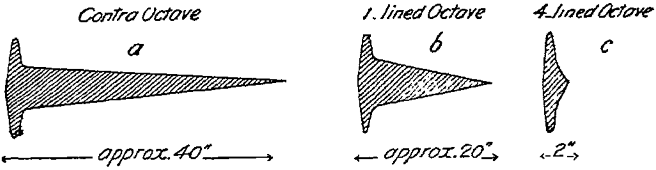


FIG. 48.

string to its position of rest. Hence the duration of the tones in the treble region is much less than the duration of those in the bass region. We have then, not only initial qualitative differences for every difference of pitch, but we also have qualitative differences during the life of a tone which are due to pitch, for the abrupt diminuendo of a tone gives it a character different from that of a very slow diminuendo.[1] Representing these differences diagrammatically we should get for the bass tone a figure such as *a*, Fig. 48, for the middle region one such as *b*; for the treble, one such as *c*.

RECORDS OF STRING-VIBRATION

If these theoretical deductions are true, then, when we obtain actual records of the vibration of the piano string we must find:

[1] Not a little of the charm of certain piano compositions is the result of the composers' effective application of these pitch differences of quality.

1. A different curve for every difference in intensity.

2. The same curve (excepting phase differences) for the same degree of intensity.

3. More complex curves for loud tones than for soft tones.

4. More complex curves for low tones than for high ones.

5. Changes in the curve during the duration of a tone.

6. Marked differences as we approach the limit of elasticity.

In order to secure tracings of the movements of a vibrating piano string, a stylus may be attached to the string and the vibrations recorded on an appropriately prepared surface. The stylus in such a case represents a point of the string. There are, unfortunately, two important sources of error to guard against in this method, the creation of false wavelets by fluctuations in the stylus itself, and the obliteration of essential characteristics by friction between the stylus and the recording surface. One cannot be overcome without increasing the other. Thus, if we make the stylus more rigid we increase friction, and if we make it more flexible we increase its own fluctuations. For this reason it was necessary to experiment with a number of styli, varying in material, size, shape, and rigidity.

The curves obtained with a perfectly rigid stylus naturally cannot contain stylus fluctuations. Some light at least may be thrown upon the fluctuations of a flexible stylus by attaching this to a vibrating body whose exact mode of vibration is known (such as a tuning-fork). In spite of these precautions, however, the records shown in this chapter are not sufficiently clear or accurate in detail to permit any analysis into the component partials. Nevertheless, the method employed satisfied the demands of our problem, which was merely to show the central tendency of variations in intensive and qualitative differences resulting from pianistic touches, and not the precise nature of them. Read figures from right to left.

Three strings in different regions of the piano were used, the "f" below middle C, the "F" an octave lower, and the contra "F" the lowest F on the keyboard. Two classes of measurements were made, one showing variations in the duration of the same tone, the other variations in the vibrations of the string,

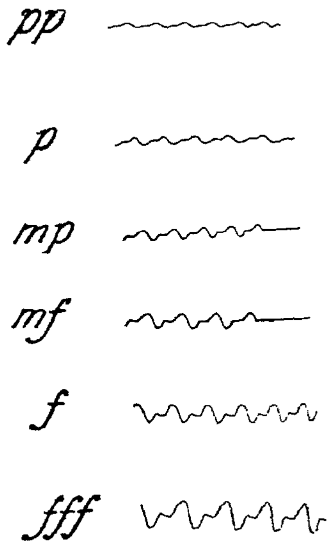


FIG. 49.

immediately after hammer-impact, produced by intensive differences and differences of touch. The records were obtained by passing a piece of smoked glass over the point of the stylus. The latter was attached to the string at a point $\frac{11}{26}$ of the length of the string for "f", $\frac{13}{31}$ for "F", and $\frac{3}{7}$ for "F_1".

Effect of Intensity on Amplitude.—The first group of records, Fig. 49, shows the effect of intensity on the amplitude of the vibration of the string, which was, in the case here shown, "f" below middle C. As we increase the intensity of the stroke, the distance through which the string is displaced increases. In other words, the amplitude varies directly as the intensity. The curves of Fig. 50 were made when the string was repeatedly set into motion by the same force, and prove the converse of this: that the same force will always produce the same string displacement. Whatever differences in intensity are transmitted by the player to the key and hammer, the hammer in turn transmits to the string, as the records of Fig. 49 show. But since amplitude is the physical basis for the sensation which we call "loudness", these differences are only differences in loudness.

FIG. 50.

Effect of Intensity on Quality.—Fig. 49 also proves the statement that for each change in intensity of tone-complex, there is a change in quality of tone. The latter, as we know, depends upon the presence and relative intensities of upper partials. These will show in little curves or wavelets along the main curve, which corresponds to the fundamental tone. In 1, 2, 3 of Fig. 49 there is no evidence of irregularities in the curve, excepting the one distinct one in the middle. In 4, however, a magnifying glass will show traces of such irregularities. In 5 they are plainly visible, and in 6 they alter the contour of the curve. This gradual increase in the amplitude of these small curves means an increase in loudness of the upper partials. In degrees less than " mf ", for example, the higher upper partials are too weak to register with the methods here employed. As we increase the dynamic degree, the partials become more and more distinct, adding their own tones to the fundamental and hence influencing the quality of the tone-complex as a whole. A great number of records were taken, and in no case was it possible to obtain as complex a curve for the lesser dynamic degrees as

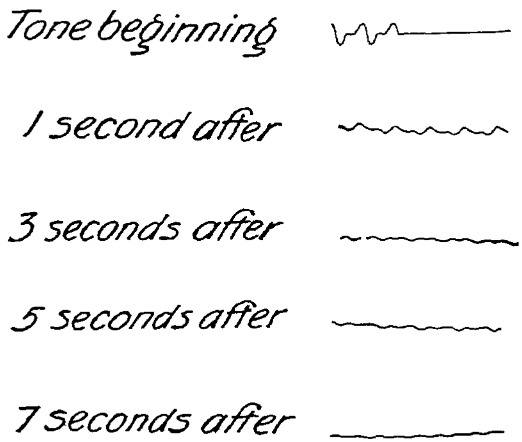


FIG. 51.

for the greater. For every degree of intensity, then, we have a corresponding string-vibration which means a change in tone quality.

Effect of Duration on Vibration.—Since the piano tone cannot be sustained at constant intensities, intensive and qualitative variations must occur during the life of a tone. Such variations are shown in Fig. 51 and Fig. 52, recording respectively small *f* and contra *F*. First, there is the gradual decrease in amplitude which means a diminuendo. This decrease in tone does not occur evenly, for in Fig. 51

the amplitude of the curves on the original record are in inches ·11; ·05; ·02+; ·02; ·01. Since the time interval between any two successive records was a constant (2 seconds) we have a much more rapid decrease of tone immediately after the beginning than afterwards. In fact, within a fraction of a second the tone has dropped to within one-half of its original loudness. Thereupon, it "dies out" much more gradually.

The qualitative variations occurring during the life of a tone are shown in the various degrees of complexity of the curves in Fig. 51 and Fig. 52. Naturally, the most complex curve is also the loudest. Just as the partials rise above the threshold of audibility as we increase the tone, they drop below this threshold as the tone diminishes, until, when any tone is scarcely audible, the curve recorded is a close approximation to a very weak sine curve—a curve free from all upper partials. This proves that, on the piano, every tone-complex passes through a series of qualitative changes depending in number and kind on the initial intensity. For every loud tone-complex this series will be both longer and richer in variety than for a weaker tone-complex, since the former has to pass through a greater number of intensity gradations before it drops below the threshold of audibility.

Effect of Pitch on Vibration of String.—A comparison of any curve for the *f* string, with that for the *F* string, using the same intensity degrees, will show clearly differences due to pitch variation. The complexity of the curves increases as we pass from higher to lower pitch. The highest string being considerably shorter than the others, does not vibrate as freely in small parts. Hence it produces fewer upper partials and must be represented by a relatively smooth curve. The curve for the lowest string, on the other hand, shows the presence of numerous and strong partials. We do not find the same ratio for both strings between partials and fundamental;

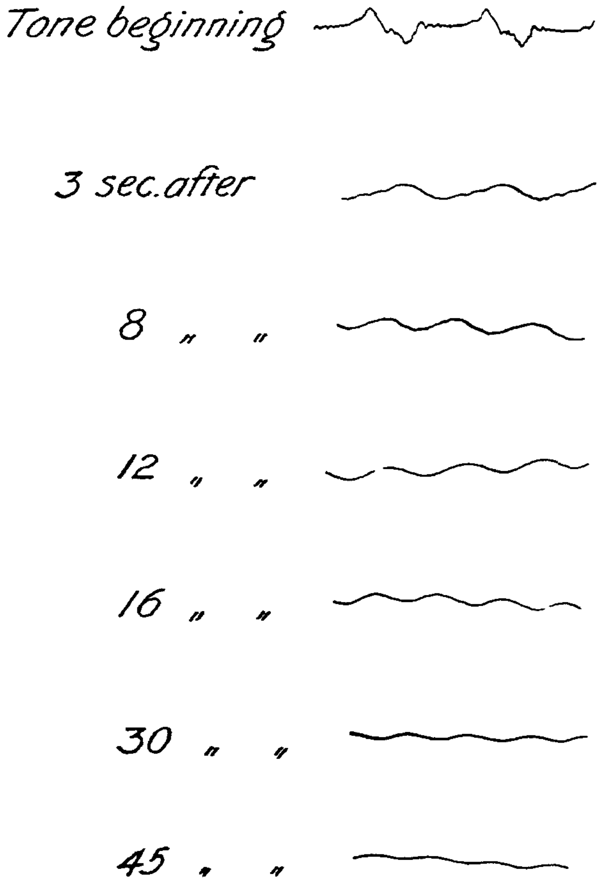


FIG. 52.

one does not increase in proportion to the other. As we go from high to low, the intensity of the partial increases more rapidly than that of the fundamental.

This is not the only effect of pitch on the vibration of the string. Besides beginning differently, strings of various frequency "die out" in various ways. The tonal life of a short string is much less than that

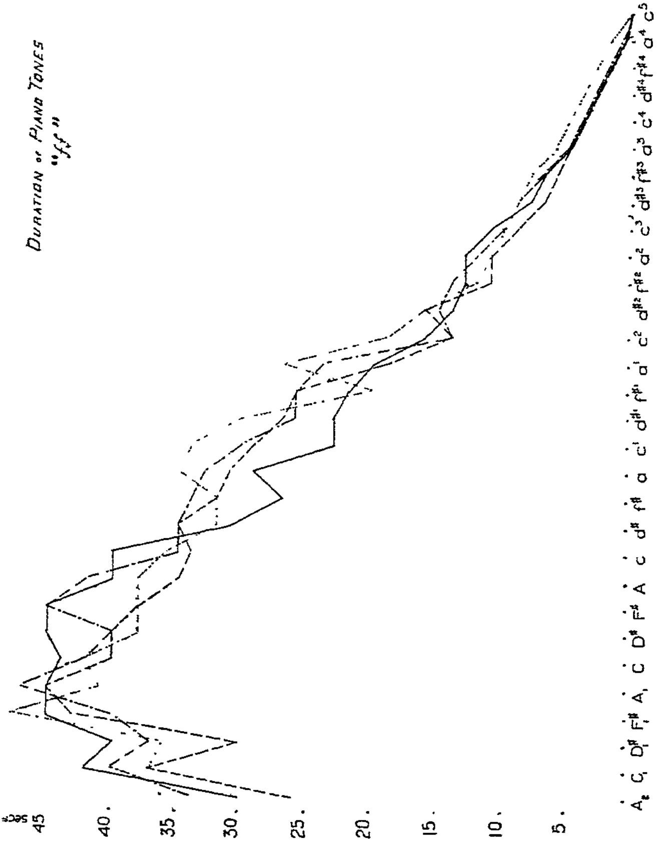


Fig. 53.

of a long string.[1] This may be seen by comparing Fig. 51 with 52. The duration of a tone, other things equal, varies directly with the length of the string. This may be seen in Fig. 53, which represents the

[1] This explains the absence of dampers for the very high tones.

approximate curves of duration[1] for a series of "ff" tones sounding in four pianos of rather good tonal quality in rooms with normal reverberation.

The Effect of Muscular Rigidity and Relaxation on Vibration of String.—Since it is generally assumed among pianists and teachers that "set" muscles produce a "poorer" tone quality than relaxed muscles,

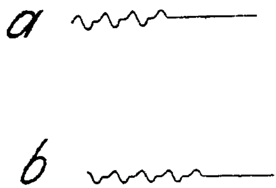


FIG. 54.

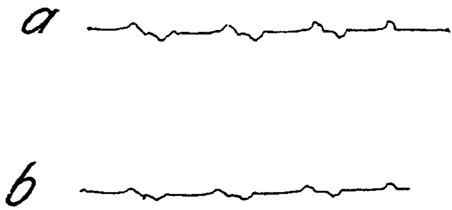


FIG. 55.

records of the vibrations of the string were taken for both forms of touch. They are reproduced in Fig. 54 and Fig. 55, one pair for the string "f" and one for "F_1". Again we notice what was shown in the records of both key-depression and hammer-stroke, namely, that

[1] The duration is the average of a number of judgments made by an observer seated at the keyboard. There were no disturbing noises of any kind.

muscular rigidity tends to produce a louder tone than does relaxation. This is shown by the amplitude of the curves, *a* and *a* recording the vibrations as the result of a rigid tone-production, *b* and *b* as the result of a relaxed tone-production. The amplitudes of the former two curves are greater than those of the latter two. Hence, the resulting tones are louder. This difference was not present in all the records taken, but whenever any qualitative difference was present it always showed the rigid tone-complex the louder.[1]

Effect of Percussion and Non-Percussion on Vibration of String.—The records for key-depression showed a decided qualitative difference between percussive and non-percussive touches. The records for hammer-stroke showed a slight difference. The records of vibration of the string show no difference. Fig. 56 shows the vibrations for "f" and "F", obtained by percussive and non-percussive touches. The two forms of touch produce precisely the same vibration form in the string. In the two records for the upper string, even the intensity is the same. In the records for the lower string the percussive touch is slightly louder (greater amplitude) than the non-percussive touch. This, it will be remembered, agrees with the tendency mentioned in the chapters on key-depression and hammer-stroke, namely, that when there is any intensity difference between these forms of touch the percussive is louder than the non-percussive. If additional proof were needed of the fact that there is no unbroken connexion between the player's finger and the string, the records for percussive and non-percussive touch would furnish

[1] The cases where no physical difference was found, and in which the subject still held that a difference existed, though the difference was not noticeable to a trained musician who could not see the player, can all be explained under the psychological aspect of touch and tone.

such proof, because here we have a distinctly characteristic motion imparted to the piano-key and no trace of this motion imparted to the string.

Effect of Quality of Touch on String-Vibration.—In order to ascertain whether or not the manner of touch such as "unsympathetic", "forced", or "surface" touch has any effect on the vibration of

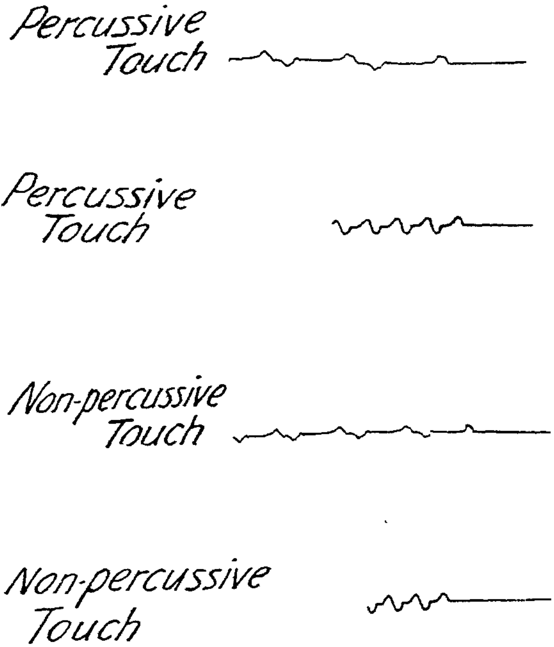


FIG. 56.

the string, a number of records were made for various forms of touch. Fig. 57 and Fig. 58 show some of the results obtained. The records were made by experienced pianists. Fig. 57 shows a curve made with normal relaxation, the so-called "sympathetic" touch producing a good "singing" tone. The other curve was made by "forcing", producing a "harsh", "unsympathetic" tone. When we compare the curves we find that they are identical in form and different in intensity. The "forced" tone was somewhat louder than the "good" tone. Again, we have a difference in intensity.[1] Fig. 58 shows the vibration for a full, round tone (made with relaxation)

FIG. 57.

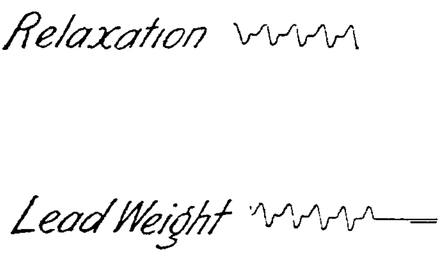


FIG. 58.

and that for a tone made by dropping a fairly heavy (lead) weight on the key. Notice that the curves are qualitatively identical. Here we have a case where all that the pianist can possibly do to make

[1] The differences between these curves and some of the preceding ones made on the same string are only differences of phase and do not affect tone-quality.

a beautiful tone was done. On the other hand, we have the most "impersonal" tone production, a lead weight dropped upon the key. Yet, as far as the effect on the piano string is concerned, it is the same for both cases. The experiment was tried repeatedly, always yielding the same result, a result obtained also by other variations of touch. In other words, the greatest possible variations in the manner in which the player attacked and depressed the key made not the least variation in the form of the vibration of the string other than variations in amplitude. Since tone-quality largely depends upon the form of this vibration, we may conclude that, aside from variations in intensity, no difference in quality exists so far as the vibration of the string is concerned.[1]

The difference in phase referred to in the preceding paragraphs demands a little further explanation. Fig. 59 shows the curve when the string is struck a second time immediately after the first time. The vibrations from the first stroke have scarcely diminished when a second stroke renews them. Suppose, now, that the string is just about to ascend on one of its vibrations when the hammer re-engages the string. Naturally, since hammer and string are moving in the same direction, the resultant force will be the sum of the separate forces. This is what occurs in *a* of Fig. 59. The string is about to ascend as the hammer re-engages it, producing a greater displacement. In *b* of the same figure the hammer chanced to strike the string as the latter was descending. In such a case the two forces are acting in the opposite directions, and produce a curve of less amplitude. On the other hand, the sum of the two equal loops of curve *b* equals the sum of the large and small loop of curve *a*. The fact that these curves are

[1] The effects of touch upon tone-quality are traceable to other factors.

different from each other does not mean that they produce tones of different quality, because, as Fig. 59 shows, the differences may be due to variations in phase only. Such differences in phase are easily discernible. However, although two different curves may contain the same number and intensity of partials, any one curve can be composed of but one definite series of partials. Hence, when two curves are alike they can produce one tone-complex and one only. Although Fig. 59 shows that two curves of different amplitude may yet be tones of equal loudness,

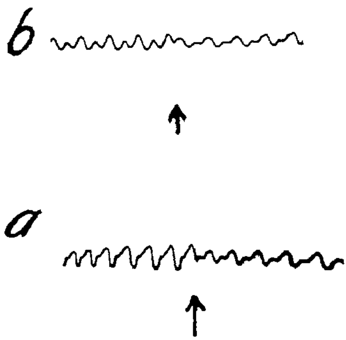


FIG. 59.

it also shows that every such increase in amplitude means a change of form—what is added to one wave must be taken from another. Consequently, when we have two curves differing in amplitude, and yet having the same wave form, we know that one tone is louder than the other, and that both are of the same quality.

Extreme Vibration of the String.—The observations made in the preceding sections of this chapter are true for all vibrations of the piano string from pianissimo to fortissimo. In practice, however, a string is often struck such a forcible blow that a distinct change of tone quality suddenly occurs. This degree of intensity we might call *sfff*. (Rachmaninoff, for example, in his C♯ minor Prelude, calls for *sfff*.) It forms the one exception to the normal string-vibration. In the experiments with fortissimo tones, it was repeatedly found very difficult to secure clear tracings. The form shown in Fig. 60 was usually obtained. Such a curve can only be produced if the string vibrates out of its normal vertical plane. This seems to be what actually happens. Moreover, it vibrates very regularly in the new plane, which is parallel to the cross-section of the string, as may

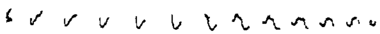


FIG. 60.

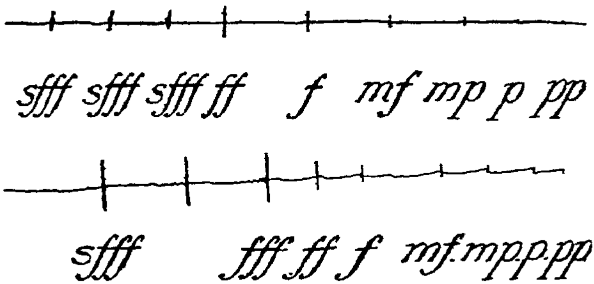


FIG. 61.

be seen by the regularity with which the "skip" in the curve of Fig. 60 occurs. In other words, the manner in which the string is fastened in the piano, the properties of the string itself, and the manner in which it is set into motion, combine to set a limit to its free, vertical displacement. When the string is driven beyond this, something similar to torsion takes place and causes it to vibrate in a different manner. No matter how much additional force we add beyond fortissimo, we cannot increase the vertical displacement of the string. This is shown in Fig. 61, which records the amplitude of the vibrations of the strings " f " and " F " for the various dynamic degrees indicated. Beyond *ff* the amplitude does not increase. When such extreme vibrations are recorded upon a moving slide we get the curve of Fig. 62. This is interesting for two reasons: it shows for " f " below middle C the same amplitude as the ordinary " ff " curve, but in addition we find that it no longer retains its former shape, but begins to approach the form for the lower strings.[1] That is, high partials become increasingly

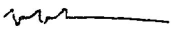


Fig. 62.

Fig. 63.

Fig. 64.

prominent, and hence the quality of tone is different. But this is not all. By counting the number of " gaps " in the curve of Fig. 60 we find that there are 6 gaps to 7 parts of the curve proper, which produced a high (unmusical) partial of its own.

The cross-sectional vibrations, as they may be called, occur regularly, repeating their path just as the transverse vibrations. Fig. 63 which shows

[1] This proves that these wavelets are not the result of stylus fluctuations.

this fact may be better understood by imagining the string cut in two, while vibrating, and one end tracing its motion on the smoked glass. The reader, in looking at Fig. 63 is looking directly along the string. The lowest dash (left column, practically a point) represents the vibration for *pp*, the dash above this, the vibration for *p*. Counting upward in this manner the next dash corresponds to *mf*; the fourth to *f*; the fifth to *ff*; the sixth and seventh to *sfff*. Up to and including *ff*, we have normal increase in amplitude with vertical vibration only. For *sfff* the vertical line in the right-hand column is replaced by an approximate loop. As the left-hand column of Fig. 63 shows, it was impossible to obtain this mixed vibration for the low F string, because this demanded a force which threatened to break the piano hammer. Fig. 64 gives several clearer records of the form of the cross-sectional vibrations for the upper string ("f" below middle C). As is readily seen, this form closely resembles the mirrored capital letter P in script.

The details of the foregoing analysis of the vibrations of the piano string, both moderate and extreme vibrations, should not be accepted as proved until further, more extended, and a mechanically more accurate study of this phase has been made. However, the records show the one possible condition under which we can have a change in tone-quality without a change in amplitude of string vibration. This dynamic degree (*sfff*), however, is beyond the range used for normal purposes, and hence finds very limited use in artistic piano playing.

Other Modes of String-Vibration.—The fact that the mechanical construction of the piano permits only a few of the many possible vibration-forms of the string to be utilized has already been mentioned. In addition to the types of string-vibration obtained by varying the force of hammer-impact, two other types are used, namely those corresponding to the "una corda" pedal, and the harmonic use of the string. When the *una corda* pedal is depressed, the action of a grand piano is shifted laterally so that a different, naturally softer, part of the felt hammer surface comes into contact with the string. The result is a tone of veiled quality similar to the *con sordino* tone of the violin group of instruments. This softness of tone is in part the result of the damping of the higher partials by the softer felt. Accordingly, we should expect a somewhat smoother curve for such a vibration. Figure 65 shows the curve obtained

FIG. 65.

with the *una corda* pedal on a piano the hammers of which were sufficiently worn to make the difference between *una corda* and *tre corde* fairly pronounced. On a new instrument, if the harmonic vibration of the third string be damped, no difference between *una corda* and *tre corde* is heard because the hardness of the striking surface of the hammer remains unaltered. The curve of Fig. 65 is interesting because it shows the smaller wave in the centre less clearly defined than that in the records thus far studied. This curve begins to approach the sine curve more closely, and hence produces a physically, not musically, somewhat purer or softer (less rich) tone.

Another type of string-vibration used in the piano is the harmonic vibration of the string, which is an example of sympathetic resonance. In this case, the string vibrates not by being set into motion by the player, but in response to the vibration of some other string bearing the proper relationship in frequency to it. The third string, where there are three strings to each tone, when we play *una corda*, vibrates harmonically. And when the damper pedal is used, many strings vibrate harmonically. Fig. 66*a* and *b*, shows the curve for strings so vibrating, *a* for small *f*, *b* for contra *F*. Here we have a really qualitative variation in tone, an addition of a tonal element which can only indirectly be traced to intensity. Since, however, the use of this vibration form depends upon either the *una corda* or the damper pedal, it cannot directly be influenced by the key-board touch of the player, and hence forms no exception to the general

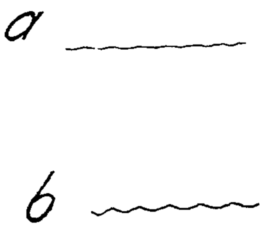


Fig. 66.

rule that the sole variations in tone through touch are intensive. A possible exception is found when the player silently depresses certain keys in order to secure the harmonic vibrations of the corresponding strings. But these and other similar types of key-manipulation are special forms which act only as accessories. The principle remains unaltered.

Sources of Error.—Since most of the records here reproduced were made with a rigid stylus,[1] we may disregard as a source of error stylus fluctuation. There remains the possibility that friction has destroyed

[1] A stylus so cut that fluctuations in a vertical plane were practically eliminated. Needless to say, hundreds of trials were necessary before the friction was sufficiently reduced.

the essential characteristics of the curves. As far as the deductions made in this chapter are concerned, this defect may be, in general, ignored. This is true, in the first place, because the method used was sufficiently refined to record very soft tones (see Figs. 51*e*, 52*g*) ; and, consequently, any vibrations not recorded would probably be too weak to reach the ear and thus to influence quality. In the second place, the records obtained agree perfectly with the theoretical deductions and the records of key-depression and hammer-stroke, which argues for their reliability. In the third place, several styli of various materials, rigidity, and shape were used, permitting comparison ; and again, the same stylus was used in order to keep fluctuations constant. In the latter case differences in two curves could hardly be due to fluctuations of the stylus. Nevertheless, the records obtained are not accurate in detail, and are meant to show central tendencies, not absolute values.

Complexity of the Piano Tone.—The complexity of the vibration of a piano string may be observed with the eye aided by a magnifying glass. If a beam of bright light be thrown against a part of a piano string which has been covered with lampblack so that only a fine horizontal line remains exposed, a most interesting and quite wonderful play of lines may be seen when the eye is so placed as to catch the reflected ray. In addition to the maximum string displacement, a number of smaller displacements, constantly changing, are seen. Fine lines seem to run back and forth, some more rapidly than others, and all within the two apparent edges formed by the maximum transverse displacement. An incomplete picture of this phenomenon may be seen in Figs. 67*a*, *b*, *c*, *d*, which shows photographs of one of the G strings below middle C, in vibration ; *a*, immediately after tone-production (*ff*) ; *b*, a little

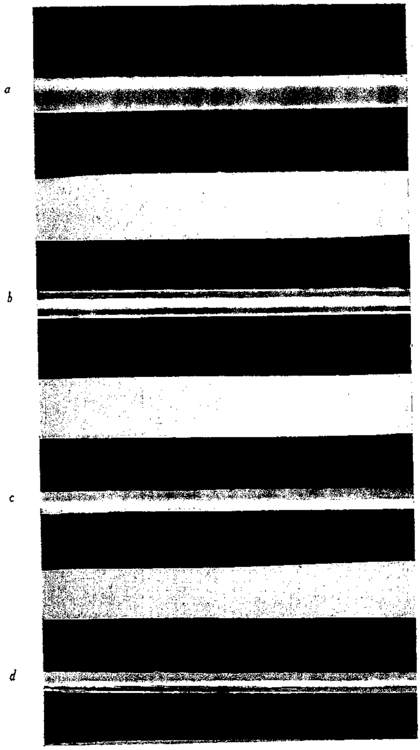


FIG. 67

[*face p. 124*

over a second later, *c* about $2\frac{1}{2}$ sec. after *a*; *d* about $3\frac{1}{2}$ sec. after *a*. In the first picture, the brightest line is at the top edge and a faint line at the lower edge. In *b*, several faint lines are seen between the extremes, and the brightest line which, in *a*, was at the top, has now descended to a point near the middle. *c* shows the bright line at the lower edge. *d* shows the same line beginning its return upward; it is just leaving the lower edge. This motion continues with modifications until the string comes to rest. In addition to a bright line there are other, fainter lines running back and forth in the vertical plane at greater or less speed, too faint for the photographic method here adopted to portray.

Needless to say, these movements vary with each string, and somewhat with each degree of intensity. The fact that there are lines of various brightness is also significant, for the brighter the line the longer has the string remained at rest in its vertical plane. Since the play of lines is continuous, but does not repeat itself from moment to moment, it follows that the character of the vibration of the string also changes from moment to moment. This is additional proof of the changing quality of a piano tone. The records also indicate the irregular diminuendo of the piano tone; they show that in a very short time after its production the amplitude has dropped to about half of the original. Then it decreases much more slowly.

A number of general observations was made in order to ascertain the effect, if any, of variations in touch upon the vibration of the string when observed in this manner. The results were in accord with those obtained by the stylus method. In other words, when the intensity was the same, the mode of string-vibration, as seen in the line movements referred to, was also the same.

Conclusions

From the records obtained showing the vibration of the string, we may conclude that, so far as the mechanically rather unrefined method of procedure permits analysis :—

1. For every degree of pitch there is a different quality of tone-complex.

2. For every degree of intensity there is a different quality of tone-complex.

3. The same degree of intensity always produces the same quality of tone-complex when measured in terms of string-vibration.

4. The vibration of the string is independent of the manner of touch, excepting for variations in intensity.

5. The duration of tone varies with pitch as well as with intensity.

6. The quality of a tone-complex changes from each moment to the next.

7. The mode of vibration of the string changes radically as we approach the limit of elasticity of the string.

8. Tone-production with " rigid muscles " produces greater amplitude of string-vibration than relaxed tone-production ; hence it produces a louder tone-complex.

9. Percussive and non-percussive touch normally produce no difference in string-vibration. When there is a difference, percussive touch produces the greater amplitude.

10. When intensity remains constant, the string vibrates exactly the same for " harsh ", " brittle ", " full ", " good ", and " bad " tones. Hence, such qualitative differences cannot be caused by the vibration of the piano string.

CHAPTER VII

THE VIBRATION OF THE SOUNDING-BOARD

THE vibrations of the piano string are transmitted through one end of the string to the bridge. The latter is a block of wood appropriately shaped to receive the various lengths of strings corresponding to variations in pitch. It is firmly fastened to the sounding board and acts as the connecting link between string and sounding-board. The latter consists of a series of carefully selected pine boards about $\frac{1}{4}$ inch thick. These are firmly joined to make a wooden plate of the shape and size of the piano case. In order to keep this plate from "sagging" in the course of time, it is given a slightly convex form, and is reinforced by from 8 to 12 strips of wood which are attached transversely to its lower surface. The sounding-board is then fastened permanently to the outer case of the instrument. We have to investigate, therefore, a vibrating plate with fixed edges.

Although the complete analysis of vibrating plates is a very complex and difficult problem, certain general laws have been definitely proved. These may be summarized in this statement: the vibration of a plate varies with its size, shape, thickness, position, and material, and with the mode of generation.

From this fact, the complexity of the vibrations of the piano soundboard may readily be imagined. The latter is of irregular shape, of various thicknesses (since the bridge and ribs are firm), and must respond to tones of various pitches. No sounding-board at present in use fulfils all requirements equally well. The thicker we make the board the more we reduce its displacement, and hence the shorter do we make the tone-complex. The thinner we make the board the more we increase its tendency to sag, and hence to destroy the quality of the tone-complex. Moreover, each board has its own natural periods of vibration, which means that it will respond better to some pitches than to others.[1] This last-mentioned phenomenon is illustrated by the curves of Fig. 53, which show the duration of tones selected at equal intervals for the entire pitch region. With perfect construction there should be a steady decrease from bass to treble. Instead, we have numerous crests and troughs. Since all tones were struck with the same force, these differences may be assumed to be in part the result of differences in resonance. If we assume the strings to be of uniform variation, the longest tones will be those most nearly corresponding to the natural periods of vibration of the sounding board, the shortest ones those having a frequency not possessed by the sounding board. Of course, since we are dealing with a case of forced resonance,[2] the sounding board responds in a greater or less degree to all the tones; however, the difference within these limits is often sufficiently pronounced to influence the quality of the tone-complex. This anyone can observe by slowly playing "fortissimo" each tone throughout the pitch region; some sounds of beautiful richness will be found, others of duller quality, a difference, however, that might also result from variations in felt or in strings.

The "tone" that we "hear" when listening to a piano is not that produced by the vibration of the string, but that produced through the vibrating string by the vibrations of the sounding-board plus the phenomena discussed in Chapter X. Hence,

[1] This is the result of resonance, which is explained in Chapter X.
[2] For explanation see Chapter X.

a survey of the vibrations of the sounding-board is necessary. On the other hand, we may dispense with an experimental procedure, since, regardless of the process of reinforcement and selection which the tone undergoes at the hands of the sounding-board, these variations are beyond alteration by the touch of the player, and it is the effect of touch upon tone with which we are primarily concerned.

The sounding-board can add no new vibrations to those which it receives from the strings. It merely transmits them to a larger surface of air. Tone production, so far as it may be influenced by the touch of the player, ends with the nature of the vibration of the string.

The vibration of the sounding-board is limited by its fixed edges. Within these limits, however, as we have indicated, there is variety of response. On the other hand, the relation of the vibrations of a given sounding-board to tones of the same pitch, produced on the same instrument, is a constant. It does not respond differently to the same tone. This definiteness of response explains why we attribute to the string the sound which we hear. As a matter of fact, the tone produced by the vibrations of the string alone, as may be observed on the monochord, has very little similarity, indeed, to the piano tone heard when reinforced by the sounding-board.

Not all parts of the sounding-board vibrate with the same degree of freedom. Generally speaking, the points of least vibration are those near the fixed edges, those of greatest vibration near the relatively free centre of the board. This scale, however, is further complicated by variations in thickness; for instance, such points as the application of the bridges and the ribs. And since the bridge is firmly fixed throughout its length to the sounding-board, the vibrations which it transmits are not transmitted through one point only, but through all points, although not equally through all points. For each string vibration we have the complex vibration of the entire sounding-board. This in turn varies for tones of various pitches and intensities, but remains constant, on the other hand, for any one tone, enabling us to grade the tone as desired. A certain force produces a certain effect.

The vibrations which the sounding-board transmits to the adjoining air are, therefore, exceedingly complex. The air next to various parts of the sounding-board is not set into vibration in precisely the same manner for all parts of the board. This complexity would, perhaps, influence the tone quality were it not for the equalizing effect of certain phenomena treated in Chapter X.

CHAPTER VIII

TONE COMBINATIONS

UP to the present point our inquiry has dealt almost entirely with the single tone. This apparent restriction was advisable for two reasons: the single tone is fundamental; and every physical attribute of any combination of tones can be traced to some attribute of the single tone. Analysis will make this clear.

The condition of tone-combination most closely approximating single tone-production is the successive sounding of two tones with a greater or less interval of silence between. Physically speaking, this is merely a repetition of the process which accompanies the production of a single tone at a greater or less duration, higher or lower pitch, or at a greater or less intensity. No new physical qualities are introduced. The same condition prevails when the second tone begins just as the first tone ends. These two examples, the second of which is diagrammatically illustrated in A, Fig. 68, illustrate non-legato and legato, neither of which contains any physical element that is not present to the same extent, and in the same form, as in the single tone.

As soon as two such tones overlap, the second beginning before the first ends, we touch upon an inexhaustible field of tone-colour. Even for the same two tones a different combination results from each variation in the degree of overlap, because the piano tone is never constant, but changes its contour from each moment to the next.[1] This variation may be

[1] See Chapter VI, pp. 124 f.

seen in Fig. 68 B, C, D. The differences in the heavily shaded portions show the differences in the co-existing tones or tone-complex.

The overlap is not the same for differences in pitch, because the duration of a tone (hence its rate of decay) varies for every variation in pitch.

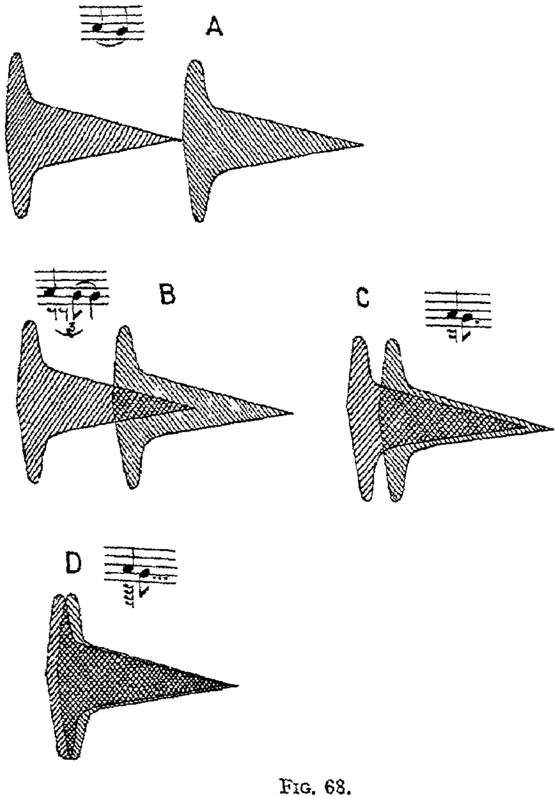


FIG. 68.

In other words, two pairs of tones of equal intensity and equidistant apart (in duration), but in different pitch regions, will not result in the same colour combination, because the amounts of co-existent tone will differ. Two tones in the great octave, for instance, will overlap when played *forte*, if the second is sounded a quarter-minute after the first. In the fourth-lined octave two tones played *forte* at an interval of five seconds will not overlap. In the former case we have co-existing tone, in the latter, we have not. These differences are shown in Fig. 69 A, B, C.

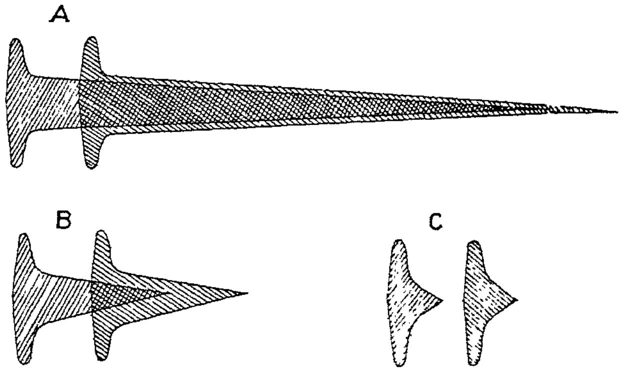


FIG. 69.

When the time-interval between the two tones becomes zero, we have perfect overlap, or the condition resulting when two tones are struck simultaneously. Again our resources of tone colour are greatly enriched, since a new colour is produced with the slightest variation of intensity in either tone, or in both tones, apart from all the varieties of pitch changes which we have discussed. Tones struck simultaneously illustrate the condition known as harmony, as opposed to melody. Harmony in a physical sense, therefore, is nothing more than simultaneous melody; and melody is merely successive harmony. Qualitative differences in co-existent tones resulting from intensive variations are shown in Fig. 70.

Now, since a single tone on the piano may vary in intensity, pitch, or duration, but in no other fundamental way—a fact proved both positively and negatively in the preceding chapters—it follows that any other tone taken separately, cannot vary in any other way; for all the keys and strings of the piano operate on the same principle. It is known that we do not play a group of keys in the same manner as we play a single key. But it is entirely wrong to assume that this difference introduces physical elements not present when a single key is depressed. We cannot in any way alter the mechanism of the

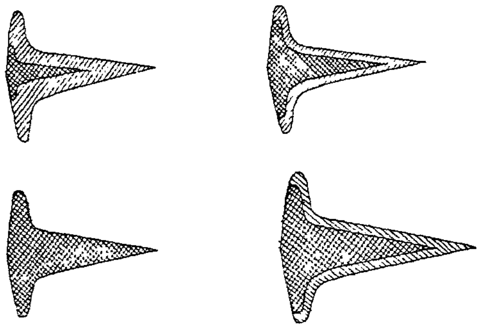


FIG. 70.

piano by touch. The attributes of the individual key remain constant; what we change is the relationship of the attributes of one key and the resulting tone, to those of a second or third key and tone. And the only physical qualities here present are pitch, duration, and intensity. Therefore, whatever variation of tone-combination exists, whether it is purely qualitative or not, must be produced by variations in one or more of these three fundamental attributes, to which every device of piano technique may be reduced. All dynamic variations, including the artistic "bringing out" of a melody against an accompaniment, are variations in tone intensity. All rhythmic variations, including the finest shades of rubato, are variations in duration (time-interval). In practice any one form seldom appears separately, the three types of variation—intensity, duration, and pitch—generally occurring concomitantly.

As we increase the number of tones sounded, we complicate and refine the colours, but we do not add any new fundamental element. Three tones are produced precisely in the same manner as two, four as three, so far as the physical aspect of touch or tone is concerned.

There are, however, certain physical phenomena beyond the direct influence of the player, the result of combinations of tones, which cannot be said to exist for the single tone.[1] These are beats, summational tones, and differential tones. When two tones whose frequencies are nearly equal sound simultaneously, certain fluctuations or pulsations of intensity are produced. This is a primary condition similar to the secondary condition of beats discussed under reflection in Chapter X. When these beats occur at a slow rate, they are heard separately; when, however, they become so rapid that the ear cannot separate them, they give the sound a disagreeable roughness. When they increase still further in number, they produce the musical effect known as dissonance. Also, when two tones are produced simultaneously, they create tones other than their own. The pitch of one of these tones is the difference between the frequencies of the two constituent tones, and the tone is known as a "difference

[1] In the last analysis they are present also in the single tone, for, musically speaking, there is no single tone. Every musical tone is complex, and the fundamental and partials contain in miniature the phenomena here referred to.

tone"; the pitch of the other, the "summational" or "combinational" tone, is the sum of the frequencies of the two constituent tones. Both beats and these additional tones contribute their share to the quality of the tone-complex. But it must be remembered that these new tonal elements are themselves possessed of only the three attributes, pitch, duration, and intensity, and that the intensity of beats and additional tones depends upon the intensity of each of the constituent tones. *Any change in tone-quality of any combination of tones is the result of a change in tone-quality of one or more of the constituent tones, which, in turn, is the result of variations of intensity, pitch, or duration.*

The variety of tone combinations is further enriched by the use of the pedal.[1] The damper pedal enables us, first, to prolong a tone or tones which we could not prolong by holding the keys with the fingers, and, secondly, to add other tones to the tone-complex than those corresponding to the keys struck with the fingers. In a physical sense, and in sound, the prolongation of a tone by means of the pedal is identical with the prolongation by key-depression. The difference is purely a technical matter, and need not detain us here. The other effect, that of colour, is distinctly a physical addition. It is a conspicuous and beautiful example of free resonance.[2] Thus, when the pedal is depressed, and a string is made to vibrate, other strings, twice, three-times, four-times, one-half, one-third, one-fourth, etc., as long, also begin to vibrate "sympathetically". The "sympathetic" vibrations of a string one-half as long as the string struck are shown in Fig. 66*a*.

[1] The sustenuto pedal has the same prolongation effect in principle as the damper pedal, but only possesses the colour effects of the latter to a small degree.

[2] Contrast this with the forced resonance of the sounding-board.

Naturally, each one of these added tones enriches the original tone, so that a tone-complex of great beauty results. But here again the strength of these "harmonics", as they are called, depends upon the intensity of the original tone or tones, and since the relative intensity of the partials is fixed for any one instrument, and is entirely beyond control of the player, except in intensity, all pedal effects of colour are entirely the result of intensive differences of touch. Even the differences noticed when the moment of pedal depression is either retarded or advanced may be traced to intensive differences. A pedal depressed early in the life of a tone produces rich "harmonic" colour, because the intensity of the original tone is great. A pedal depressed late in the life of a tone produces less effect because the original tone is itself weak.

The extent and variety of these tonal additions through the use of the damper pedal are realized when we remember that this pedal device causes from two to ten or more tones to sound when a single key is depressed, and that each one of these tones can vary as did the single tone which we have discussed. Moreover, pedal-action is dependent upon pitch, intensity, and duration for its effect; close and dispersed harmony, chords, and arpeggios, soft and loud tones, produce each its own effect. Not only that, the tones which the damper pedal adds have not all the same duration or intensity. Consequently, their rate and manner of decay will vary, adding yet other elements to the variability of the tone-complex.

The beauty and richness, as well as the variety of pedal effect are readily demonstrable. A few examples which any one can observe for himself, will give a glimpse into this field of tone colour. Silently depress the key corresponding to Contra C and hold it. Play an arpeggio of the C major triad, ascending and descending once or twice, through two or three octaves, *forte*. Release the pedal immediately. The single string (Contra C) will now sound the major triad.

Silently depress all of the white keys in the contra octave. Play, as before, a C major arpeggio. Release the pedal immediately. A very beautiful, ethereal tone-complex will be heard from the low octave, the keys of which are still held.

The damper pedal may even produce melodic effects. The closing measures of MacDowell's "To a Wild Rose" are these:

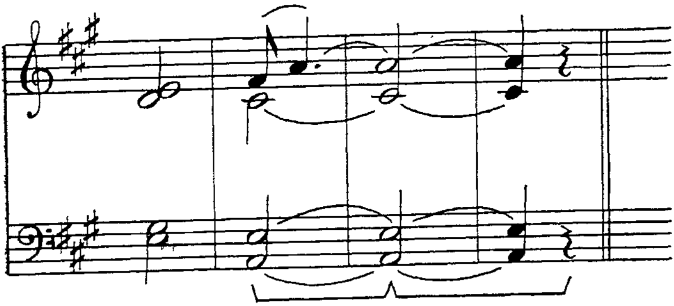


FIG. 71.

If the damper pedal be taken as the F♯ is played and be then released at the beginning of the next measure, the ear hears the F♯ apparently descend into the E, resolving the dissonant seventh chord into the major triad—a subjective, not physical, melodic resolution made entirely with the pedal.

These examples will suffice to show the qualitative tone possibilities of the damper pedal.

A study of the use of the pedal emphasizes again the importance of intensity gradations. To lay down the general law that the pedal must not be held through a change of harmony is wrong. Whether or not the effect will be musical, will depend, among other things, upon the absolute and relative intensities of the component tones of the tone-complex. The subtle pedal effects which lend the art of some of our pianists such a charm, are secured less, perhaps, by variations in the length of pedal depression than by appropriate variations in the intensities of the tones during pedal depression. The effect, for example, of the accompaniment of Chopin's "Berceuse", is not primarily due to a pedal held throughout each figure, but to the intensity, at which the notes of this figure are played. If the tones are soft enough, and then the pedal be held, a beautiful veil will be thrown over the composition. Not that duration of pedal is unimportant; we find this point discussed at length in all treatises on the pedal, yet we seldom find the important bearing of tonal intensity upon the use of the pedal emphasized. Pedal effects, then, do not introduce any difficulties into our analysis, since pedal effects, too, are seen to be the result of variations in the pitch, duration, and intensity of the tones themselves, these being, finally, the three basic elements that determine all laws of pedaling.

The effect of the *una corda* pedal upon tone colour is different. This pedal shifts the entire action [1] sidewise so that a comparatively unused part of the felt hammer strikes only two of the three strings for each tone. Two effects result. The softer felt tends to dampen the partial vibrations of the string, thus softening the tone-quality [2]; and the third string, since it is tuned in unison with the others, vibrates harmonically as a result of sympathetic resonance and adds its tone to the other. A combination of such tones obeys precisely the same laws as tones

[1] Of course a grand piano is meant. On an upright piano the pedal action works on a different principle.

[2] Also, in part, on account of variations in the noise element.

produced without pedal. We have merely altered the basic tone-complex. The variations which this may undergo must be produced in the same manner in which the variations of the basic tone of three strings was produced, for the key and hammer action, once the soft pedal has been depressed, are constants. The effect of the *una corda* pedal on a new instrument is never so pronounced as that on a used instrument; because, in the former, all parts of the felt hammer possess the same degree of elasticity. Therefore, we do not alter the striking material as we do in the case of the used hammer.

Tones, then, can be differently combined only by varying pitch, duration, or intensity. There is no further physical variant either for simple combination or for the most subtle dynamic, rhythmic, or " poetic " shading. This conclusion applies as well to a Beethoven Sonata as to a few tones, for physically speaking, a Beethoven Sonata is but a combination of many single tones, of definite pitches, durations, and degrees of intensity.

The question may be asked: " If this be true, why do we differentiate between the playing of a mechanical player-piano and that of an artist? " The answer is that the player-piano has not yet reproduced accurately all the physical sound elements which constitute the piano sound-complex, and on the other hand has added sounds of its own, such as the " whirr " of the motor and roll. If the playing of the artist is to be accurately reproduced, impact noises, among other things, and not merely the tonal elements must be reproduced. The fact that player-pianos have not yet solved the problem entirely is not an evidence of some subtle influence which defies recording, but merely an indication of mechanical imperfection which, so far as physical elements are concerned, may eventually be overcome. For it is entirely wrong to suppose that the physical variations alone are too coarse to explain the artistic side of piano playing. They may be coarse, but in the hands of the artist they may be, in fact, they actually are, extremely fine. We need only consider the analysis of the sound-complex on page 89 to see what great variety of combinations of elements are possible for the single tone. And when this tone itself is but a small part of a musical phrase, the possible combinations are greatly multiplied. In order better to realize this richness of purely physical variety, let us select at random, a comparatively simple example: two measures from the E minor Nocturne of Chopin.

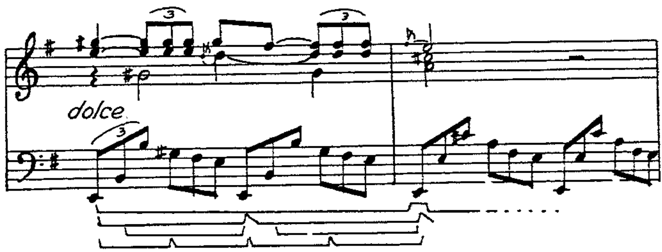


FIG. 72.

The passage may be played with the following variations:—

Dynamic:

R.H. Accentuation of the highest notes, the middle or the lowest, as melody.

Accentuation of two tone lines at the same time as contrasting melodies.

Crescendo and diminuendo in any one or more melodies.

L.H. Throughout *ppp*, *pp*, or *p*.

Accentuation of the upper B first measure, C# second measure, as a sort of bell effect.

Accentuation of the descending diatonic figure as secondary melodic fragment.

Accentuation of the lowest E.

Agogic:

Delay upon almost any beat or sub-beat in the first measure.

Delay upon several points, such as the first beat, the second, for the introduction of the G♯, and the first beat of measure two, for chord emphasis and melodic distribution of the grace-notes.

Pedal:

With or without the *una corda* pedal, using the damper pedal in any of the methods indicated in the figure.

Even if we use only one of the variables enumerated, keeping the remaining ones constant, we produce a specific tone-complex for each separate variation. Moreover, the degree to which the player introduces these variations, whether the accentuation or retardation be slight or pronounced, again produces an entire series of tone-complex gradations. Here, then, in two measures alone, variations in intensity and duration readily permit more than a score of possible executions, none of which will overstep the bounds of musical propriety, and each of which contains some element of artistic shading.

If we approach the problem from the other side, that of actual records made by prominent pianists, we shall find further evidence in support of the assumption that the artistic or poetic phases of piano playing, so far as they affect our ear, are due entirely to variations in intensity and duration. In each record of artistic playing we find these variations. The following tables and graphs illustrate some differences in duration. Table 1 represents the first two measures of Chopin's Nocturne in G major, Op. 39, No. 2, the notation of which is shown in Fig. 73A. The figures of this and of the succeeding tables were deduced as follows: that time-interval occurring most frequently for the note-value most often used (in this case the eighth-note), was selected as the standard time-value for that note-value. Then the percentile deviation of all the other notes from this value was calculated. The left-hand column shows the values as written by the composer, the right-hand column the deviations as played.

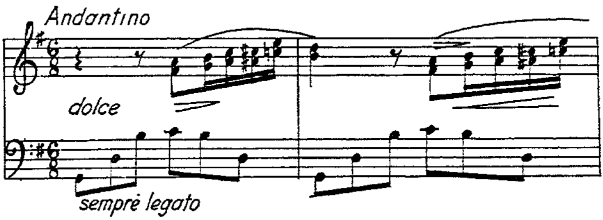


FIG. 73A.

TABLE I.

right hand.

·40	·40
·20	·20
·20	·175
·20	·20
·20	·25
1·20	1·35
·40	·50
·20	·20
·20	·15
·20	·20
·20	·20

left hand.

·45	·50
·45	·35
·45	·40
·45	·45
·45	·45
·45	·35
·45	·45
·45	·40
·45	·45
·45	·50
·45	·40
·45	·45

TABLE II.

MELODY right hand.

·32	·38
·32	·33
·48	·48
·16	·19
·16	·16
·16	·15
·16	·20
·16	·25
·48	·42

TABLE III.

note	·5	·5
rest	·5	·45
note	·5	·5
rest	·5	·45
note	·5	·5
rest	·5	·40
note	·5	·65
rest	·5	·40
note	·5	·90
rest	·5	·15
note	·5	·90
rest	·5	·50
note	·5	1·50

The considerable amount of deviation is seen more clearly if we array the figures in the form of a graph, such as the following, Figs. 73B and C, in which the dotted line represents the note values as written,

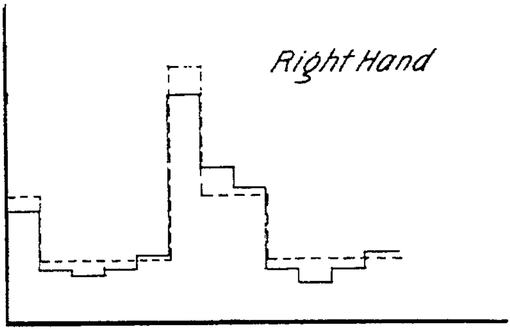


FIG. 73B.

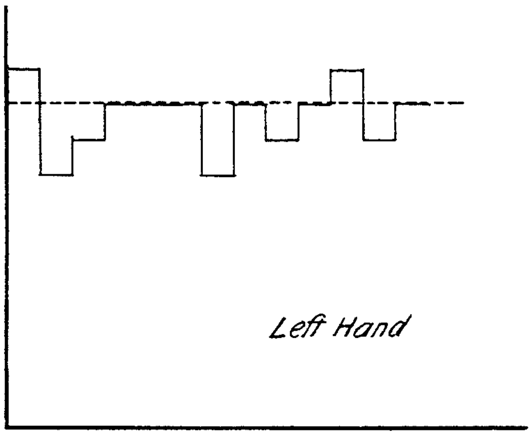


FIG. 73C.

and the solid line their value as actually played by the particular artist making this record. The spaces between the lines show the amount of deviation. Table II represents the melody tones of the first few measures of the slow movement of Beethoven's "Sonata Pathétique", Op. 13, Fig. 74. The standard time unit adopted is the most frequently found value for the sixteenth note of the accompaniment. When

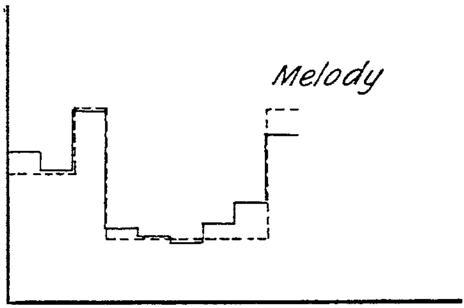


FIG. 73D.

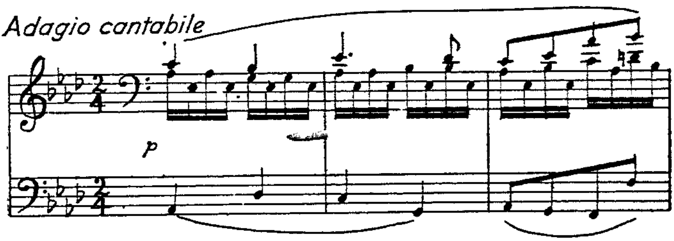


FIG. 74.

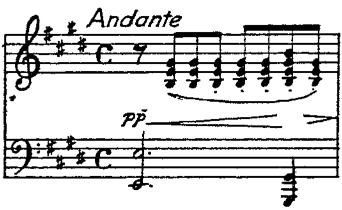


FIG. 75.

thus measured the record gives the percentile array shown in Table II. This deviation is also shown for Fig. 75. Even in this relatively simple and uniform passage we find such deviations. Thus Table III shows the results when we analyse the first measure (uppermost note) of Mendelssohn's "Rondo Capriccioso".

Many more records could be quoted. Those selected are typical instances, made by the best-known artists, and do not represent extreme cases. They suffice to show that in each instance there is variation from the printed score. At once the objection will be made that just because such records record only the physical elements of the pianist's art, and not the "personal" element, we are able to distinguish between the playing of an artist and the reproduction of his playing by a player-piano. This objection has been answered elsewhere. Moreover, be that as it may, what we establish here is that every artist does so deviate from the printed score, and what is more, no two artists deviate in the same way; that is, these deviations are "personal" through and through; the artist is directly reflected in deviations in intensity and duration. Finally, experiment has shown also that when these dynamic and temporal deviations are eliminated, the "poetic" or expressive character of the performance is lost entirely. All of which points to a scale of intensity and duration, that is, to a purely physical basis, for artistic effects on the piano.

And when, finally, the problem of artistic shading is adequately investigated, the poetry of the pianist's art, as is indicated in the records described here and in preceding chapters, so far as poetry is transmitted by sound, will be found in just these fine gradations of intensity and duration, not in the manner in which fingers and hands are used, nor in any psychic element mysteriously transmitted through the key to the tone.

CHAPTER IX

THE NOISE ELEMENT

INASMUCH as we do not find in music a theoretically pure tone-complex, that is, one produced without noise, the analysis of the noise element becomes a necessary part of our inquiry. In wind instruments the noise element is present in the hissing of the air, in bowed instruments in the scraping or scratching of the bow, in percussive instruments in the percussion or impact of one part of the instrument against another. It results from non-periodic vibrations.

In order to establish the influence of the noise element upon piano-sound, as produced in normal playing, it is necessary to separate the noise element from the tonal element. This can be done by damping the entire set of strings with numerous small sandbags, felt, and weights. The damping must be continued until all indications of pitch vanish.[1] This procedure was followed in the experiments here described. Later on, as the various noises were investigated, each one of these was isolated in its turn by appropriate manipulation of the parts of the piano-action. No attempt was made to eliminate the vibration of the sounding-board or the reverberation, since both factors are present in normal playing.

If we exclude the unstable noises, such as sympathetic resonance, etc., outside of the instrument, which are largely due to local conditions, and instead, consider those noises present in great or small degree when

[1] A good test is to play a chromatic scale *f* or *ff* throughout the compass of the instrument. If all pitch elements have been eliminated, an observer will not be able to tell whether an ascending or a descending figure has been played.

any piano is played under any conditions, we may conveniently divide these noises into four parts :—

A. The impact of the finger upon the key (absent in all non-percussive touches).

B. The impact of hammer against string.

C. The impact of key against key-bed.

D. Friction noises of the action, including the impact of the rebounding hammer.

The most important of the four noise elements, is the impact of the hammer against the string. The piano manufacturers have reduced this noise to a minimum by the use of felt of appropriate compressibility and elasticity. The noise of impact, however, has not been entirely eliminated, by any means, a fact which appropriate damping of the strings vividly illustrates. This noise is one of the results of the transfer of energy taking place when the hammer sets the string into motion. Since the object of the hammer is to transmit this energy to the string, and not to produce noise, the noise-impact, physically speaking, represents so much wasted work. A part of the energy possessed by the hammer-head at the moment of impact is lost in producing this noise. The string itself, then, has slightly less energy transmitted to it for tone-production than the hammer originally possessed. This same principle applies to the other noises as well. Wherever noise is produced in the transfer of energy, a corresponding consuming of energy must occur.

The character of the hammer-impact noise may be described as a dull thud. It is readily audible, when isolated, throughout the dynamic range from "*pp*" to "*ff*". Its intensity, and therefore audibility, varies with the dynamic degree; it is weakest when a soft tone is produced. Generally speaking, for a normal ear, under normal conditions, it is audible for a *pp* degree only close to the instrument, audible, let us say, to the player; for the degrees *p* and *mp*, it can be heard anywhere in the classroom; while for forte and fortissimo, it is audible throughout a medium-sized recital hall. Naturally, then, the loudness of the noise increases with the loudness of tone, when tone is produced. Two tones of different intensities are therefore accompanied by noises of different intensity, or, in other words, for every degree of tone a fixed degree of noise is present. This, of course, excludes the exceptional condition due to permanent alterations in the felt hammer-surface resulting from extended use.

The noise of hammer-impact occurs simultaneously with the beginning of tone. It is very brief; and

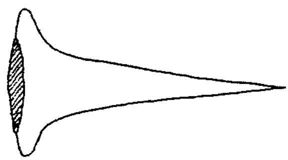


FIG. 76.

after the very instant of sound-creation, the tonal element continues unaccompanied by the impact noise. Since no tone on the piano can be produced without this noise, since, moreover, the intensity of the noise varies directly with the intensity of the tone, and finally, since for all degrees of normal playing the noise is audible, it follows that the quality of the sound-complex of the piano is partly due to the impact noise and is not purely tonal, as is generally believed. The effect of this noise on tone may be diagrammatically illustrated by Fig. 76, in which the shaded portion represents the noise element, the unshaded portion the tonal element.

Next in importance is the noise of finger-impact, the result of the finger striking the key-surface. It depends upon the touch employed. Apart from the fact that in non-percussive touches this noise is entirely absent, the variations in percussive touch enable us to increase or decrease this impact noise. There is a direct relation between the manner of touch and the intensity of finger-impact.[1] Thus the impact noise produced by a rigid hand and arm is louder than that produced by a relaxed arm, though the actual arm-speed be the same. That is, if the speed of arm-descent is approximately the same, the relaxed tone-production will be accompanied by less impact-noise than the rigid tone-production. As far as finger-speed itself is concerned, this varies directly with the impact noise. Now in the chapter on hammer-movement we learned that a soft tone could be produced by striking the key a sharp blow, necessitating a key-descent of only $\frac{1}{8}$ inch. Of course, the blow must have considerable force in such a case, and as a result, we get a decided impact noise. But this yields only a small amount of tone, and it is well known that noise is an undesirable element, which tends to impoverish "good" tone quality.[2] Consequently, the sound produced above will be musically unsatisfactory. But the so-called surface or slapped tone is produced in just this manner, which explains the disagreeable quality of tones of this category, including "shallow", "depthless", and other tones of like kind.

This unsatisfactory quality is due, not to any peculiarity of touch, key-action, or tone itself, but to the unæsthetic ratio of noise to tone; too much of the former, and too little of the latter. That this is generally true was amply verified by experiment. Every "slapped" key-depression showed a maximum

[1] See Fig. 32, Chapter IV.

[2] Otherwise we should not have the painstaking effort of piano manufacturers to eliminate noise, by cushioning every joint and buffer.

noise and negative hammer-acceleration, and every negative hammer-acceleration, when percussive touch was employed, resulted in a "slapped" tone effect. A tone of the same intensity, measured accurately by key- and hammer-speed, but produced with a non-percussive touch, lacked this disagreeable quality entirely.

Another factor which influences finger-impact, is the nature of the striking body, the finger-tip. Every experienced teacher has noticed that certain fingers, well rounded and padded ones, produce an acceptable tone more readily than pointed, tapering fingers. It is quite true that other factors [1] influence the tone control in such cases; nevertheless, there is also a slight difference in the impact-noise, which is louder for the tapering, softer for the padded fingers.[2] Of course, such differences will often vanish with good training and altered use of the finger.

The finger-impact noise is the first sound made in playing the piano. It occurs before the beginning of tone, and for this reason remains audible in every case of percussive touch. The difference in impact noises explains why a normal ear can readily distinguish percussive from non-percussive touches, when the keyboard is not in view. The former is heard as a double sound, the latter as a single sound. The character of this noise is that of a light snap. It differs in quality from the hammer-impact noise, and is perhaps the most influential and characteristic, though not necessarily the loudest of all the noises. It may be diagrammatically shown in connexion with the tonal element as in Fig. 77, in which the shaded portion represents the finger-impact noise, and the unshaded portion, the tonal element.

[1] Circulation and nerve sensitivity, for example.

[2] The noise made by the finger nail striking the key surface is not included, since this manifestly, is always to be avoided.

The finger-impact noise explains several "tonal" qualities which are attributed to certain forms of touch. Thus, the familiar "plucked" staccato used by a number of well-known pianists for certain effects is a non-percussive touch.[1] Naturally, this will produce a different sound from the usual hand-staccato, in which the hand is thrown against the key and immediately withdrawn, since the finger impact-noise is absent in one and present in the other. Some differences between the sounds produced by a high and a low wrist, by rigidity and relaxation, may also be explained by the presence in varying degrees, or the absence of, finger-impact noise. It is important

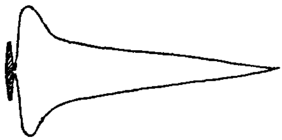


FIG. 77.

to note that practically all forms of touch used for the production of "good", "sympathetic", "beautiful", or "singing" tone, are forms of touch in which either no finger-impact noise at all, or a minimum of such noise is present. And in most cases where disagreeable "tones" are produced, the finger-impact noise is well marked. Moreover, when the form of touch is retained but the impact-noise reversed,[2] the "good" tones become less agreeable, the disagreeable tones more agreeable. The explanation, then, of a number of supposed qualitative differences in tone is to be found, not in the tone, but partly in the accompanying noise production of the finger when it strikes the key.

[1] The fingers touch the keys before playing and the hand is then jerked back.

[2] Impact-noise added to those forms of touch ordinarily not possessing it, and eliminated from the forms ordinarily possessing it.

A third noise element is that resulting from the impact of the key upon the key-bed. As a rule, an increase in finger-impact noise results in an increase in key-bed impact noise.[1] In point of intensity the latter is less than the former, and may be disregarded for dynamic degrees less than *mf*. Even above this degree its effect upon the sound-complex normally is slight. This is due not alone to the quality of the noise itself, which in this respect closely resembles the noise of hammer-impact, but also to the fact that the noise occurs simultaneously with hammer-impact noise and tone-production, and is consequently difficult to distinguish as a separate noise element. The various forms of touch have no effect upon this noise apart from intensive differences, and extensive experimentation leads to the conclusion that although the noise varies slightly with key-speed, these variations contribute only to a very small extent, if at all, to the so-called tone-colour. Nevertheless, the key-pad may be used to illustrate the effect of the noise element on the tonal qualities in general. If the felt pad beneath a key be removed and a wooden disc of proper size and thickness substituted, we obviously have not altered anything about the action or tone itself. The tone so far as touch and string-vibration are concerned can still be produced as before. However, under this condition it is quite impossible to produce a musically satisfactory tone, because we have altered the ratio of noise to tone too much. If tone-complex quality were independent of the noise element, and purely tonal, we should still be able to produce a "good" tone when we increase the noise as indicated. The quality of the tone-complex that we get is poor, and may be described as dull or thick. This is but additional proof of the

[1] There are certain exceptions.

well-marked influence of the noise element on tonal qualities, for in the experiment as made we have increased the noise element only, and any difference in the sound-complex is therefore due to this change, when touch and intensity remain constant.

The final group of noises consists of friction noises and the thud of the rebounding hammer and inner key-arm. A popular belief exists that chords played staccato with the pedal held sound differently (some say shorter) than the same chords played sostenuto with the pedal. Now, if the conclusions reached in the first part of this book are true, it is manifestly impossible for this difference to be due in any way to the vibration of the string. The only remaining influence would be the noise element. If we depress eight or ten keys, without causing the tones to sound, hold them for a moment, and then release them, there will be an audible rattle or scraping, due to the friction of parts of the action and the impact of the rebounding hammer and the returning key. This noise, of course, is also present when tone is produced, though in such a case it is obscured by the tone. In sostenuto touches, on the other hand, this noise is largely absent, since the keys are held depressed. Although there is, then, a difference in noise elements between staccato and sostenuto touches, this difference is insufficient to warrant the conclusion that when keyboard and player are not visible, the two touches can still be discriminated. After much testing it was found that these touches cannot safely be discriminated by sound,[1] unless the listener is very close to the instrument. In such

[1] When the damper pedal is not used, the impact of the falling damper should be added to the noise accompanying the cessation of tone. While this has no physical influence on preceding tone, it may have on succeeding tone. This noise may be heard by lifting several dampers from the strings with the fingers and then releasing them.

a case the presence and absence of the noise element is the deciding factor.

The emphasis here placed upon the noise element in piano playing may appear to be exaggerated, for under normal conditions of tone-production the average pianist and listener are seldom aware of the presence of noise. The observations made apply to a single key. Naturally, this noise element occurs with every key-depression, and increases when several keys are depressed simultaneously. The amount of noise present in the performance of a composition such as the March Militaire of Schubert-Tausig, a Chopin Polonaise, or a Liszt Rhapsody, is surprising to all who hear it for the first time. In such cases the compositions can be recognized in an adjoining room separated from the piano by a solid wall. This recognition is due to the rhythm, it is true, but suppose a similar test with appropriate compositions to be made on a violin whose tonal element had been eliminated. Recognition would obviously be impossible, for not only would the noise be less but it would scarcely be intermittent. This proves the influence of noise on the rhythmic force of piano playing, and also demonstrates how well the piano, compared with string instruments, is adapted to predominantly rhythmic music. It explains, for example, why a march played on the piano is much more effective, as a march, than the same composition played by a string orchestra, unless in the latter case the orchestration contains special rhythmic effects, such as *pizzicati*.

Naturally the amount of noise varies with the style of composition played. If we place the works mentioned at one end of the scale, such compositions as Chopin's Berceuse would come at the opposite end. Thus, throughout the range of practical piano playing we have noise audibly present. We cannot ignore the influence of this factor, though it is undesirable. The less so, since when we change the noise, we change in part the "tonal quality", as popularly understood. Within certain limits, these changes can be definitely forecast. This is ample proof that the noise element plays a measurable part in the formation of piano "tone" and the adoption of piano touch.[1] The inter-relation between the various noise elements may be represented as in Fig. 78, which represents, in a very general way, a staccato,

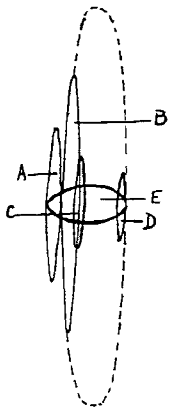


FIG. 78.

percussive touch, played "*f*": A, finger-impact noise; B, hammer-impact; C, key-bed percussion; D, thud of returning action; E, friction noises. The dotted line represents the beginning and the duration of tone. The audibility of the individual noises varies with the touch. Thus, for example, in staccato, D follows B and C so closely that it is not separately distinguished. If the key returns slowly,

[1] Needless to say, these influences vary with different instruments, with the distance of the listener from the instrument, and with the usage of the instrument. Use tends to increase the noise element in all instruments, and "overhauling" a used instrument means little more than reducing the noise element again.

D is largely eliminated. In non-percussive touches A is absent. In "slapped" effects A is high and B low, altitude representing intensity.

Practically all the important noise influences act only at tone-beginning, since at the moment when the action comes to rest, action-noises cease. This leads to the question as to whether those words with which we are accustomed to qualify piano-sound, such as "harsh", "brittle", etc., apply to the beginning of the sound-complex or to the tone-complex at any moment of its duration. If the above deductions on the effect of the noise element be true, then that part of the sound-complex after sound-production must be free from all noise influences; and if, on the other hand, the qualitative differences apply only to the beginning of the tone, this is a further indication, though not proof, that the noise elements are responsible for these differences.

It can easily be shown that most qualitative terms apply to tone-beginning only. By plugging the meatus of the ear (with fingers or appropriate wax form) and arranging a convenient signal, immediately after tone-production, at which the plugs may be quickly removed, it will be found that these qualitative differences vanish and the tones heard can be discriminated only in point of intensity.[1]

Tonal-Noises

The separate treatment of the tonal and noise elements was necessary for a clear presentation of the questions involved. Not all noises, however, which play a part in music are as readily distinguished from tones as those which we have just discussed. In the chapter on touch combinations we learned that the pianistic touches are not sharply defined types, but shade into one another. We find a similar

[1] Care must be taken to control reverberation properly.

condition existing with regard to tone and noise. The explanation that the former is caused by regular and the latter by irregular vibrations is true but not absolutely defined. For it is often difficult to say where regularity stops and irregularity begins, or in sensorial terms, where tone stops and noise begins. If we depress a piano key in a low octave we hear a relatively rich (that is, clear-cut) tone. If we strike three adjacent keys, the dissonance increases and makes a clear recognition of the constituent tones more difficult. If, now, we depress an entire octave of adjacent keys, or better, two or three octaves, the normal ear certainly hears a sound closely approximating a noise. Where has the transition occurred? Or we might proceed from the other end. With the damper pedal depressed, rub two pieces of sand-paper together, clap, cough, or make some other noise near the instrument. A number of strings will immediately begin to vibrate sympathetically, showing that the tones whose frequencies correspond to those of the various strings thus vibrating, were all present in the noise made. And if we had a sufficiently great number of pitches, we could reproduce many noises by compounding the component tones.

By cutting a number of small sticks of appropriate wood, (walnut, rosewood, or box) to the proper length or thickness, the phenomena of the tonal noises may be still better heard. A series of such sticks when dropped in a bunch will produce the customary noise of impinging wooden sticks, a noise in which the ear detects no tone, or at best very little. If these same sticks are then dropped one by one, each gives forth a tone. Of course, this tone is not so pure as the tones produced on our musical instruments, but it is none the less heard as a tone, and if the pieces of wood have been cut to produce the tones of a scale, a clearly defined melody can be played by dropping them in an appropriate order. (The earlier types of the musical instrument known as the xylophone had, and some modern forms still have, wooden slabs for tone-production.)

Thus we see that noise shades gradually into tone or vice versa. In every piano tone-complex a certain noise element (other than those noise elements which we have been studying) is present. It varies in degree with the number of tones, their pitch, and their intensity. These tonal-noises, as they may be called, are important, for tone and noise are our two most fundamental æsthetic concepts in music.

Reviewing briefly the deductions made in this chapter, we find that :—

1. A number of "tonal qualities" are partly the result of noise qualities.

2. "Good," "sympathetic," or "beautiful" tone, means, in part, a sound-complex with a maximum of tonal elements and a minimum of noise elements. Conversely, "poor," "shallow," or "dry" tone, means a minimum of tonal elements and a maximum of noise elements.

3. The most marked differences in sound-complexes occur at the beginning of sound.

4. The elimination or reduction of the noise element is one of the reasons for the adoption and rejection of certain forms of touch.

5. The most characteristic difference in touch, when measured in terms of the noise element, is that between percussive and non-percussive touch.

6. Generally speaking, rigidity tends to produce more noise than relaxation.

7. The noise element is one of the chief vitalizing factors for rhythmic force in piano playing.

8. For degrees less than *p*, noise is of little effect on tone colour. Above this point, its importance increases with the dynamic degree.

CHAPTER X

THE PROPAGATION OF SOUND

THE vibrations which the sounding-board receives from the string, altered by it, are given off to the surrounding air. We have now to trace the progress of these waves from the time when they leave the instrument to the time when they reach the ear of the listener. Do they reach the ear in the same manner in which they leave the piano, or do they undergo change in their passage from the piano to the listener?

Among well-known phenomena of sound are those of diffusion, reflection, interference, and resonance. Diffusion is the spreading out of the sound wave as it moves out from its source. If we imagine a sound produced in a perfectly homogenous medium, this spreading out will take the form of a smooth spherical wave.[1] Naturally, there must be an increase in area as the wave moves from the source—an increase as the square of the radius of the sphere. Moreover, since the wave is not energized anew, it decreases in intensity as it increases in area, and we have, as our first law of diffusion: the intensity of the sound varies inversely as the square of the distance of the sounding body from the ear. The general tendency of sound to decrease in loudness as we recede from the source of sound is a universally known phenomenon. The second law of diffusion—that the intensity of the sound depends upon the density of the medium traversed—does not bear upon our problem, since

[1] A similar phenomenon, occurring, however, in only one plane, may be observed by dropping a pebble into a quiet body of water, whereupon concentric, widening, circular waves will recede from the point of impact.

musical tones are here considered as produced in closed auditoriums, where variations in atmospheric density and motion (direction of the wind) are relatively negligible factors.

Reflection is the changing of the direction of waves, and occurs whenever sonorous waves meet a fixed obstacle. The reflection always takes place according to the law that the angles of incidence are equal to the angles of reflection. If the reflecting surface be plane, waves diverging from any centre in front of it are reflected as from a theoretical centre symmetrically situated behind it. If the reflecting surface is complex, that is, is made up of a number of plane surfaces, each one of these reflects the waves as a separate plane surface. Curved surfaces may be considered as made up of an infinite number of plane surfaces, and, as such, are obedient to the law referred to.

The most familiar instance of reflected sound is the echo. We have an echo whenever the duration of the original sound is short enough, and the distances between source, reflecting surface, and observer, are great enough, to separate the original sound from its reflection (echo) by a great or small interval of silence. If, now, a second reflecting surface be placed opposite and parallel to the first, and the sound be produced between them, it will be reflected back and forth, and will give rise to what is known as multiple echo. Multiple echo may also be produced by the reflection of the original wave from objects at various distances from the source. One form of this latter kind of echo deserves attention, since indirectly it has significance for our problem. If we use an electric spark as the sound producing body, and place a number of parallel reflecting surfaces at regularly increasing distances from it (a long staircase answers the purpose), the multiple reflection gives the original electric snap (a noise) distinct tonal qualities, and thus changes the nature of the sound heard. In musical auditoria, however, clearly defined echo plays an insignificant part, because the dimensions of the halls are not sufficiently simple or great.

A second condition resulting from the reflection of sound waves is known as interference. Since the reflected waves traverse the same medium as the unreflected waves,[1] but in different directions, there must be interference. A remarkable attribute of this interference is that it does not affect the actual propagation of either or any set of waves. The interference does affect, however, the physical qualities of any one wave at the point of interference. When two systems of waves traverse the same medium, the actual motions of each particle of the matter is the resultant of the motion due to each separate system. When these component motions occur in the same direction, the resulting motion equals their sum; when the directions are opposite, the resulting motion equals their difference. Thus, if a returning wave of condensation coincides with an outgoing wave of condensation, their energies are added; and we have an augmentation of the intensity of the sound. If, on the other hand, a wave of condensation coincides with a wave of rarefaction, their energies are subtracted; and we have a diminution of the intensity of the sound. An ear stationed at the point of interference would in the first case hear a loud sound; in the second case, a weak one. In fact, if perfect reflection were practically possible, interference could just double the intensity or reduce it to silence. Such extreme variations are not met with in practice, but we do meet many degrees of variation between the extremes. When a number

[1] No tone produced in music produces but a single wave. Even the shortest staccatissimo sends out a train of waves.

of these fluctuations in intensity occur, they produce what are known as "beats". When, in turn, these beats occur in sufficiently rapid succession [1] to become inaudible as separate fluctuations, they lend a peculiar character of roughness to the sound, which has a decided effect upon its quality.

A third condition produced by reflection, and one which directly concerns us here, is reverberation. Reverberation is the result of multiple echo and irregular reflection. Primarily, it is the result of the overlapping of one series of echoes or interference with other series.

It may best be expressed as confused propagation of residual sound. The complexity of reverberation is realized when we consider that each surface of each obstacle is constantly reflecting any living sound, and that these reflections vary with the shape, size, and material of the reflecting bodies. This complexity is so great that if a sound be maintained constant for five or six seconds in an ordinary hall the reflections in this time will have occurred in every conceivable manner, causing the sound to be fairly homogeneously distributed throughout the hall. For very short tones, this diffusion of residual sound remains incomplete. Moreover, since tones of various pitches have waves of various lengths, each wave length will produce a series of reverberation phenomena peculiar to its own pitch.

Resonance is that condition which results when the waves from one vibrating body meet another body whose natural period of vibration is equal to that of the first body, or stands in some simple numerical ratio to it. The second body will then begin to vibrate "sympathetically". The various types of reflection which have been mentioned do not increase the actual amount of sound generated. Resonance,

[1] Over 16 to 20 per second.

on the other hand, alters the total amount of sound in the space of the auditorium, and always results in an actual increase in sound. If a second body vibrates through resonance, it will continue to vibrate after the first body has come to rest. Such sympathetic or free resonance may occur with noises as well as with tones. Every musician has had the experience of trying to locate—often in vain—the rattling of some article in the room which invariably responds to a certain tone.

It has been necessary to devote attention to the phenomena of diffusion, reflection, and resonance, because their effect upon the so-called quality of piano-tone-complex is very generally underestimated. Not an inconsiderable part of the attributes which we assign to the tone itself before, or as it leaves the instrument, is in reality due to the changes which the tone undergoes after leaving the instrument and before reaching the ear. The influence of diffusion may conveniently be grouped into three classes: super-normal diffusion, resulting in a weakening of desirable tonal elements; normal diffusion, resulting in a musically appropriate duration of the sound; and sub-normal diffusion, resulting in an intensification of the undesirable elements of the sound-complex. We have super-normal diffusion and a corresponding decrease in tonal beauty when a tone is produced in the open air or a very large auditorium; we have normal diffusion and a corresponding beauty of tone when the tone is produced in a hall of so-called good accoustic properties; and we have sub-normal diffusion when the ear is placed close to the instrument, a point at which the impact and action noises, and the weak high partials, impoverish the musical tone quality.[1]

[1] In chamber music concerts the mistake is sometimes made of seating the audience too close to the players. The unavoidable scraping noises of the instruments considerably lessen the beauty of the tone-complex in such a case.

The most important change, however, which the sound undergoes after leaving the instrument is due to reflection, and of the three classes of reflection, to reverberation. In analyzing the effects of reverberation upon tone-quality, we are here less concerned with the component reflections than with the duration of the phenomena and its rate of decay. Assuming, for the sake of analysis, the same sound to be produced in three rooms, one with prolonged reverberation, one without reverberation, and one with normal reverberation, what are the physical changes which the normal tones undergo ? [1] In Chapter IX we learned that the piano sound-complex consists, in brief, of a number of noise elements of short duration and tonal elements of long and short duration. In a room with prolonged reverberation each of these elements is prolonged well beyond the moment when the original source ceases to give forth sound. Thus, a momentary snap, such as an electric spark, would continue to re-echo for as long, perhaps, as several seconds. The noise elements and so-called inharmonic high partials of a sound-complex are likewise prolonged. But we have seen that our musical ear strives to eliminate both noises and very high partials on account of their undesirable effect on beauty of tone-quality. Therefore, when we have super-normal reverberation, we intensify, by prolongation, the undesirable sound elements, and hence impoverish the musical value of the sound. In a room without reverberation we have the opposite extreme. All sound ceases as soon as the original source ceases to vibrate, since there is no reflection. The only waves are those coming directly from the vibrating source. The result of such a condition is to give us, first of all, a clear picture

[1] Extensive observations were made under these three conditions. However, since the method of approach to the problem was largely psychological, the results must be described under the psychological aspect of tone, and only a few general remarks are included here.

of the sound as it actually leaves the instrument.[1] The noise elements have practically no duration, and the length of the tonal attributes is equal to their length of vibration-time. The result is that we increase the purity of the tone, for by reducing the time for which the musically undesirable elements of the sound-complex sound, we practically eliminate them. It follows that if our concept of a musically beautiful tone demanded only physical *purity*, a tone produced without reverberation would be such a tone. As a matter of fact, this is not the case. Our musical ear demands other attributes than purity of tone.

Tone-production under conditions of normal reverberation is modified to an extent which experience has shown to be musically desirable. The physical basis of such a condition is a moderate prolongation of both noise and tone in such proportion that their duration permits them to influence the sound-complex, and yet not to cause a "blurring" by too much overlapping. This is the condition which exists in halls with good acoustic properties.

When the reflection of sound is controlled, either by chance acoustical properties of the hall or by deliberate adjustment for experimental purposes, some interesting effects occur. The phenomenon of the whispering galleries is a familiar example of the great variation in intensity of sound at various points, ranging from points of silence to points of fairly great maximum intensity. Practically every hall, theoretically speaking, is an imperfect whispering gallery, and hence has its regions of minimum, medium, and maximum intensities.

Reflection also affects pitch. It is possible to change the apparent pitch of a complex tone as much as an

[1] All physical measurements of piano sound, if we attempt to measure it irrespective of reflection, must be made in a room from which reverberation has been eliminated.

octave by slightly altering the position of the listener when reflection is properly controlled. This change of pitch is in reality a change of quality. It is the result of certain resonance effects of the hall. Thus, if the listener stands at a point which is the focal point of reflected waves whose length equals that of the octave of the fundamental tone, this octave becomes proportionately louder and the fundamental proportionately weaker, and if the difference in intensity (the scheme of reflection) is sufficiently pronounced, we actually hear a change of pitch.

This incomplete survey of the propagation of sound will suffice to show that any or all of the tonal attributes: pitch, intensity, duration, and quality, may be, and actually are, altered considerably after the original sound waves leave the instrument. For purposes of musical analysis it is useless to photograph these changes, since they vary with each hall, with the size of the hall, its shape, materials, and furnishings (including the audience), and likewise with different points in the same hall. In view of these facts, we should proceed very carefully when assigning certain tone-qualities to the touch of the player or to the original tone-complex. In many cases these tone-qualities are produced not by the player or directly by the instrument, but by the propagation of the sound through the auditorium.

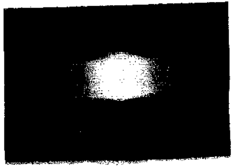
If, after the analysis in the foregoing chapters, we still wish to define a so-called "good" tone in physical terms, we should be obliged to say: a tone-complex of a fundamental and partials, about four to seven. The fundamental should be loudest, the partials diminishing in intensity as we recede from the fundamental. Neither fundamental nor partials should be too strong or too weak. The entire tone-complex should be of sufficient duration to be clearly audible as an agogic extension. Moreover, a really "good" tone would include the absence of all noise elements. It will be seen at once that a tone-complex such as that we have just described can find but very limited use in piano playing. We can, however, look upon such a tone-complex as the purely physical ideal. But because this ideal is never really reached in practice, many authors and teachers maintain that we should demand of the pupil, not the production of a good tone, but the production of a suitable tone. The pupil should ask: is it adapted to the particular passage? Does it harmonize with its tonal environment? Certainly from the interpretive side this viewpoint is to be preferred.

In order to verify the fundamental variations shown in the results obtained for the vibration of the piano string, a few photographs were made, for which an improved form of vibrating reflector, invented by Preston Edwards, was used. This consists essentially of a small mirror mounted on a tuned rod and placed before the mouth of a resonator. The torsional vibration resulting serves the purpose of greatly magnifying the vibration, so that a beam of light, when reflected from the vibrating mirror, makes a considerable excursion, the amplitude of which may be further increased by increasing the distance of the recording surface from the mirror. When properly adjusted, this device is very sensitive, and will show minute variations in intensity.

Since the resonator used vibrated only for one pitch, the photographs are not pictures of the complete piano-sound, which, as we have seen, is a highly complex thing. The pictures show the variations for one pitch, which in these cases was the fundamental. All the illustrations were made under constant conditions, so that the secondary phenomena discussed in this chapter could not influence the variations. The light bands in the pictures represent the path

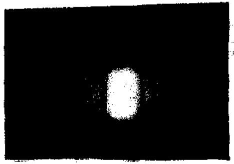
FIGS.

79

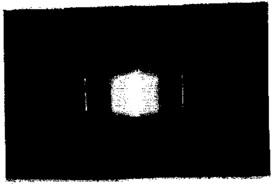


FIGS.

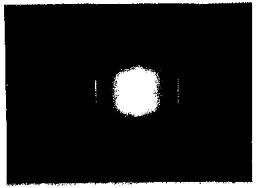
80



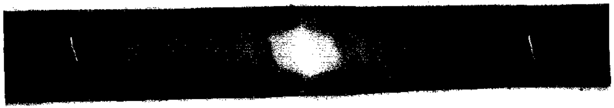
81*a*



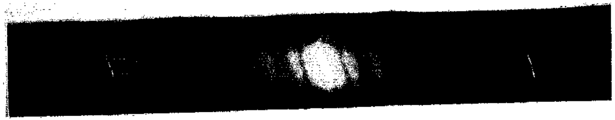
81*b*



82*a*



82*b*



traversed by the reflected ray of light. Horizontal distances are equivalent to amplitude of vibration, hence loudness of tone. The brighter the streak of light, the longer has the ray of light remained at rest in that particular point. Accordingly, a perfect diminuendo should show a band of light growing steadily dimmer as we recede from the central point in either direction. On the other hand, the irregular diminuendo property of the piano tone should show strips of brightness upon a paler background. Such a difference is at the same time proof that the vibrator used did not contribute vibrations of its own to those of the air. Fig. 79 shows the picture of a moderately loud tuning-fork tone allowed to diminish freely. Fig. 80 shows the same for a piano tone. The absence of irregularity in the former, and the streaks seen in the latter, show the marked difference in the nature of the two tones used. In Fig. 80 three levels are seen at which a steady diminuendo was broken. And the most marked of these, indicated by the bright central portion, is less than half of the original intensity, and was reached immediately after tone-beginning. Fig. 81*a* shows the reflection for a curved finger touch, Fig. 81*b* that for a tone of the same intensity (as nearly as the subject could control intensity) made with a flat finger. A very small difference in intensity, in favour of the curved finger tone, is noticeable. Accordingly, the curved finger produced the louder tone. A similar distribution is shown in Fig. 82, where *a* represents a tone made with a rigid arm, and *b*, a tone made with a relaxed arm. The wider displacement in *a* indicates a louder tone for rigidity than for relaxation.

Besides agreeing with the conclusions drawn in the other chapters, these figures, since they are based on a more sensitive method of procedure than that used for the string-vibration, show that where differences are so small that they are ordinarily not clearly noticed, they may yet exist and influence our judgments. For the ear is itself a very sensitive instrument. Thus, a tuning-fork, vibrating on an ordinary resonator with an amplitude of vibration considerably less than one twelve-hundredth of an inch, nevertheless produces a readily audible tone. Hence, in recording sound waves, we need not expect always to find wide differences, but must remember that a very minute difference may be sufficient to account for our reaction.

Moreover, the concha and the external meatus of the ear themselves form a resonator as a result of which the loudness of pitches of appropriate frequencies is materially reinforced. This may be strikingly shown by placing the cupped hand immediately behind the ear while tones in the high treble region of the piano are sounded at moderate intensity. The loudness is then often increased to a more or less painful degree. One of the many theories explaining the so-called characteristic qualities of the various tonalities is based upon this natural resonance property of the ear.

What we actually do, then, when playing the piano, is to produce sounds of various pitch, intensity, and duration. Nothing more. Certain forms of touch are effective only because they enable us to secure a proper relationship among these variables. The quality of a sound on the piano depends upon its intensity; any one degree of intensity produces but one quality, and no two degrees of intensity can produce exactly the same quality. If A plays "poetically" and B does not, then, as far as the single tone is concerned, A plays sounds of different intensity from those of B; and if B could play sounds of the same intensity as A, B would play just as poetically as A.

What we imagine we do and hear is a different question, the answer to which awaits the outcome of an experimental investigation of the physiological and the psychological aspects of the problem. The division into the physical and the non-physical is necessary for an explanation of the conflicting theories and opinions. Whether or not piano pedagogy can profit by thus differentiating between the constant elements, those physical attributes which vary according to constant physical laws, irrespective of the individual, and those psychological attributes which vary with the individual, is not our question here. But it is safe to say that in any pedagogy the distinction between cause and effect is an important one. A certain hand- or finger-motion is often taught because it produces a certain tonal quality, and in actual practice we find that other types of touch can produce the same tonal quality. Relaxation is taught for its effect upon physical piano-tone, but rigidity can produce the same tone. A certain finger-stroke produces a certain tone, not because that stroke is correct and all other strokes are incorrect, but because the finger reaches the key with an appropriate force. A relaxed arm produces a certain tone, not because the arm is relaxed (for the action of the piano cannot be affected by a muscular condition), but because the arm condition permits better control of force. This explains the various modes of using arms and fingers adopted by the concert artists for producing the same tonal quality.

If tone-quality depended directly upon type of arm or finger movement, then one arm and hand position for all pupils would be essential. If, on the other hand, it depends upon the force of stroke, arm and hand positions may be varied in order to secure appropriate force, thus taking into consideration the not inconsiderable differences in anatomical formation.

Again, if good tone-quality resulted directly and entirely from relaxation, then relaxation would be the *sine qua non* of piano playing. As a result, we should find it impossible to play, musically effectively, a very great portion of piano literature. For all piano playing demands some degree of rigidity, and, in many cases, a great degree of rigidity.

In the data secured in this analysis we have the concrete material which, in one form or another, is at the bottom of every art. And since sensation is the first link in the complex chain of neural response, and depends entirely upon the concrete objective material of the physical world, an analysis of this physical element is a logical and necessary beginning. Without the wooden keyboard and the metal strings there could be no pianism, either artistic or inartistic. Such an analysis, moreover, gives us a clue to the answer of the question : How do these physical variants produce the emotional response in the auditor? In the first place, variations in pitch, intensity, and duration, as we have seen, cover a wide range and involve very fine gradations; and in the second place, there is no reason why these variations cannot suffice for the production of the psychological reactions. The popular conception that they are too coarse or not sufficiently subtle is based upon ignorance of the true complexity and great variety of physical piano-sound and of the sensitivity of the ear.

Is all piano playing, then, merely a variation in the physical attributes of tone? Yes and no. So far as auditory stimulation is concerned, yes. So far as total stimulation is concerned, no. Every pianistic effect existing for audition, including the most subtle shades of emotion, can fully be explained in terms of the physical attributes. And when these fail to explain all the effects, this does not establish the presence and operation of other mysterious, super-psychological stimuli; it means, merely, that piano playing as an art is not entirely auditory in character, but appeals also to other sense departments. Chief among these are the kinæsthetic and the visual senses, which, in the music appreciation of to-day, are of very decided importance.

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Any book on general physics will contain the essentials of mechanics and sound. For more detailed treatment the reader is referred to the works listed under the separate heads. The omission of all books on piano touch and technique is the result of the attempt to exclude any psychological phases of the subject, and the chapters in such works devoted to the piano-action are more reliably duplicated in the books on piano-manufacture that are included here.

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