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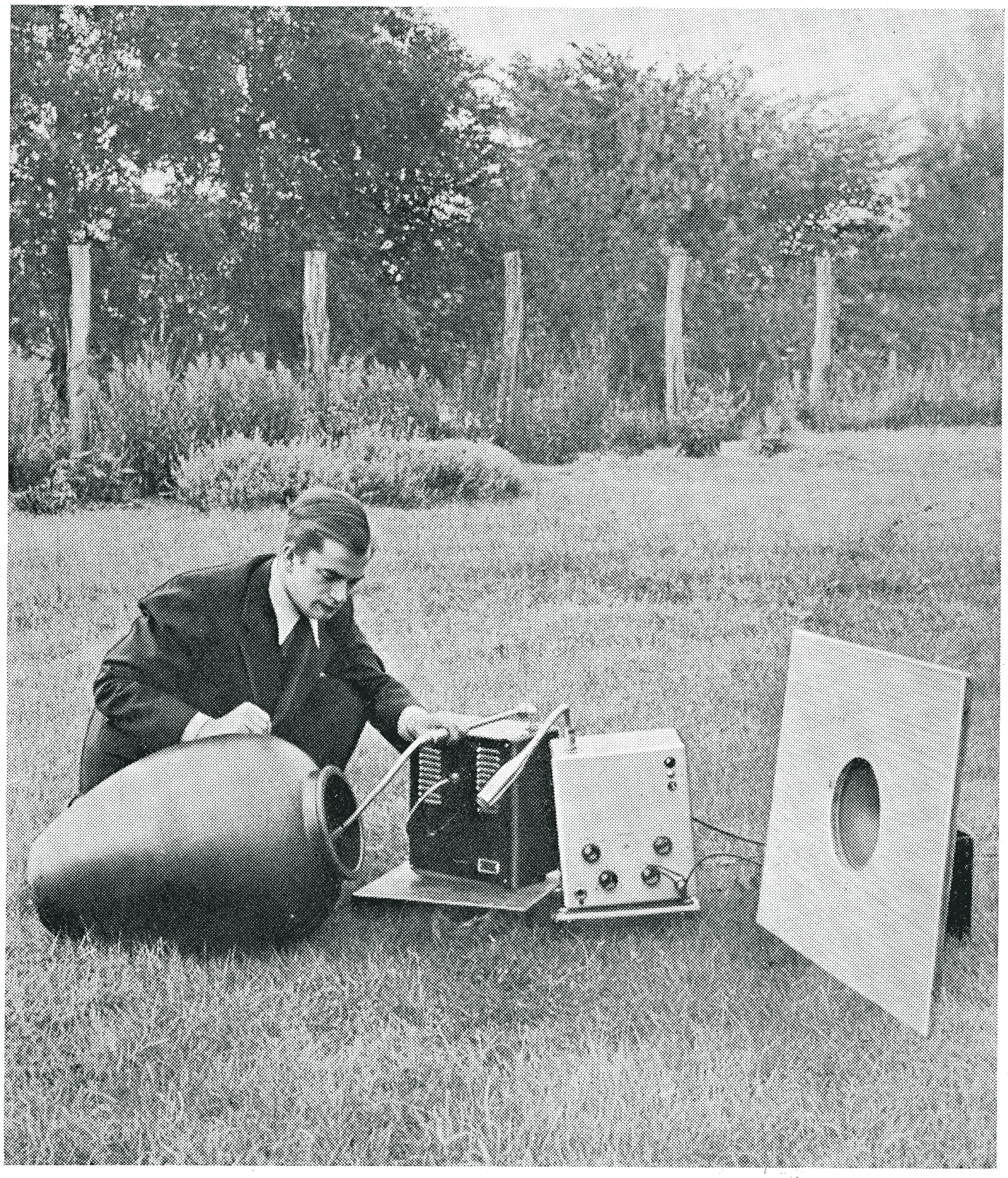
Teletechnical, Acoustical and Medical Research



No. 3 July 1952

Cover: Measuring resonance curve of model of antique resonator.

A NEW DEVICE FOR REVERBERATION MEASUREMENTS OF ROOMS AND LOUDSPEAKERS

Summary

A special selector switch is described which in conjunction with the high speed level recorder makes it possible to record a complete sequence of reverberation curves on the one diagram. It is shown how these can be interpreted to judge the quality of at room's acoustics, the presence of flutter echo, and other phenomena. It is further shown how the universal selector can be used for investigation of room acoustics in accordance with the "Impulse Glide Method" developed by the British Broadcasting Corporation. Further, it is shown how the universal selector can be used for recording articulation diagrams in large lecture halls, for the demonstration of artificial reverberation produced by resonators, and for the automatic recording of the sound insulating properties of walls. Finally, a completely new method for the evaluation of a loudspeaker's quality is shown, the frequency characterictics and dynamic qualities being demonstrated on the same record with the help of the universal selector.

Ever since the turn of the century, when W. C. Sabine, with a touch of genius, defined a room's reverberation period as that time in which the sound energy was damped to 10^{-6} of its original value, the reverberation period has been the primary and most important index of a room's acoustical goodness. As time has passed, the requirements of satisfactory acoustics have made it necessary to establish narrow limits, based on a great mass of investigations, for the size of the reverberation period for different rooms as a function of room dimensions, use and sound frequency. Fig. 1 shows a single diagram in which all these experiences have been collected.[1)] The measure of the reverberation period has thus become an important procedure in all investigations of room acoustics.

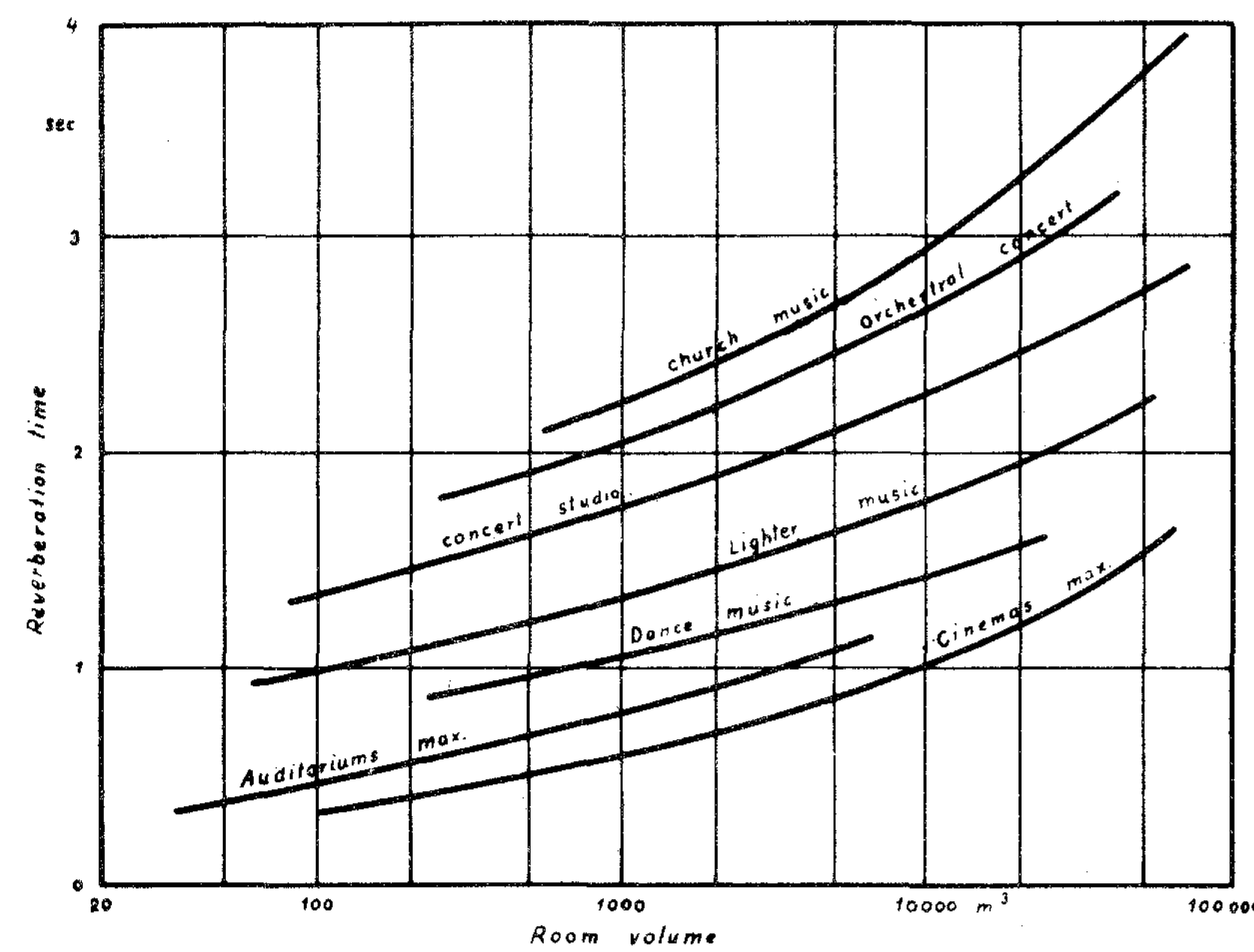


Fig. 1. Optimal reverberation time at medium frequencies.

When a sound source is started up in a room, the sound intensity will rise in a great many small steps, owing to reflections from the walls, until a steady condition is reached, when the energy absorbed by the room is equal to the energy radiated by the sound source. If the latter is suddenly switched off, the sound pervading the room will not die away immediately, but will fade off more or less according to the absorption capacity of the room. All variations of sound intensity naturally occur discontinuously, but where there are many reflections the curve will be smooth. As the sound energy absorbed in a room will be largely proportional to the sound intensity there, it must be obvious that both the rise and fall of the sound will be exponential functions with respect to time.

If the reverberation curve is recorded with logarithmic ordinates, for example in db, it will, if purely exponential, be recorded as a straight line. If some regions of the sound field in a room are less damped than others (flutter echoes, etc), the reverberation curve will diverge from a straight line. Fig. 2 shows some typical reverberation curves recorded with a level recorder with high writing speed, with both linear and logarithmic potentiometers. The reverberation times found from these curves are indicated.

The reverberation time T depends on the room's volume V, the wall area S and its absorption coefficient α. As an approximation, the reverberation time can be expressed in Sabine's original formula as

$$T = \frac{0.16\ V}{\Sigma \alpha\ S} \text{ sec}$$

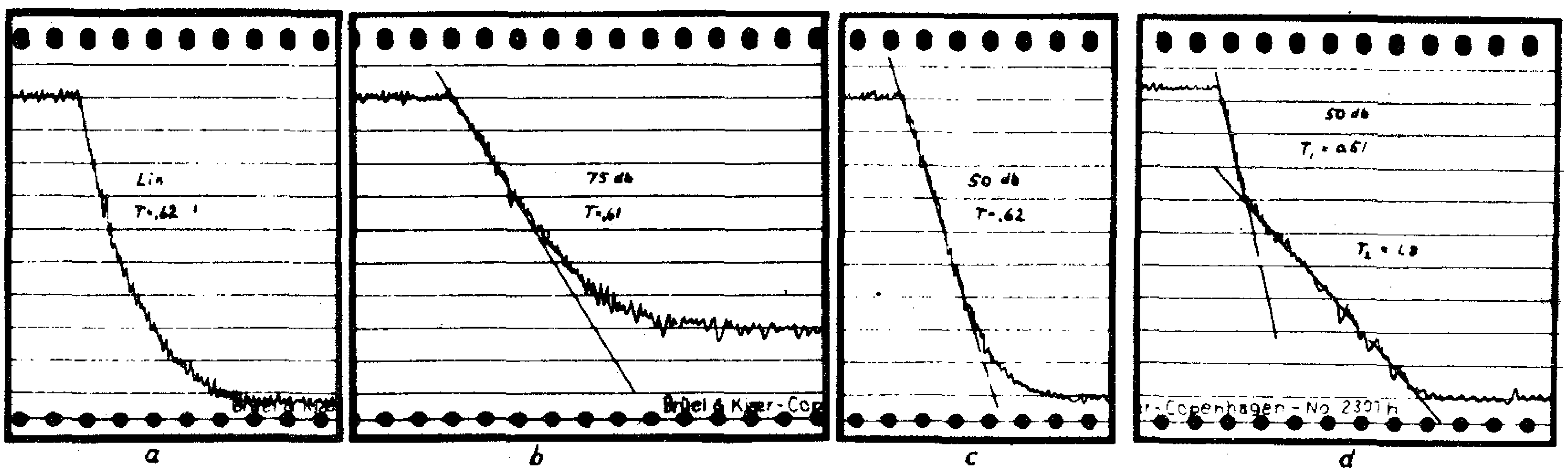


Fig. 2. Typical reverberation curves recorded with the High Speed Level Recorder type 2301.
(a) with linear potentiometer. Reverberation time $T = 0.62$ sec. Paper speed $P = 100$ mm/s.
(b) with logarithmic 75 db potentiometer. Reverberation time $T = 0.61$ sec. $P = 30$ mm/s.
(c) with logarithmic 50 db potentiometer. $T = 0.62$ sec. $P = 30$ mm/s.
(d) Radio studio (see fig. 3) with typical flutter echo, registered with 50 db potentiometer. $T_1 = 0.51$ sec, $T_2 = 1.8$ sec. $P = 30$. mm/s.

Volume and superficial area are expressed in m^3 and m^2 respectively (if cubic ft. and square ft. are used, the constant will be 0.05 instead of 0.16). α is the absorption coefficient of the wall material, defined as the ratio between the sound energy absorbed and that which strikes the wall. The formula presupposes uniformly distributed sound intensity over the whole room, that is, a pure exponential reverberation curve. These conditions are almost never satisfied in ordinary rooms, so that as a rule considerable divergences are observed between the measured reverberation curves and the calculations based on Sabine's formula.

In the course of time of number of suggestions for other formulae and methods of calculation have been put forward. It has proved impossible to establish a simple formula, but on the other hand the form of the reverberation curve can be calculated for simple room shapes with the aid of wave theory, when the room's shape, the wall material's absorption coefficient and the phase characteristics as a function of frequency are all known.[2] The calculations are exceptionally complicated and cannot be used with the normal types of room encountered in practice.

One technique which is often used is to calculate the quantity of absorption material with the help of Sabine's simple formula. The placing of the absorption material and to some extent the shape of the room are worked out according to rules established by experience, supported in the case of very thorough investigations by simpler wave theory calculations. When the room is then finished, exact reverberation measurements are taken, and the curves' slopes, that is, their reverberation periods, are estimated. Furthermore, careful note is made as to whether the reverberation curves in their logarithmic form are relatively straight, as it has been demonstrated that all tendencies to uneven sound distribution, flutter echoes, and so on, which are disturbing from an acoustical point of view, are shown as deviations from the straight line in the reverberation curves. Fig. 2d shows a typical example of a reverberation curve from a

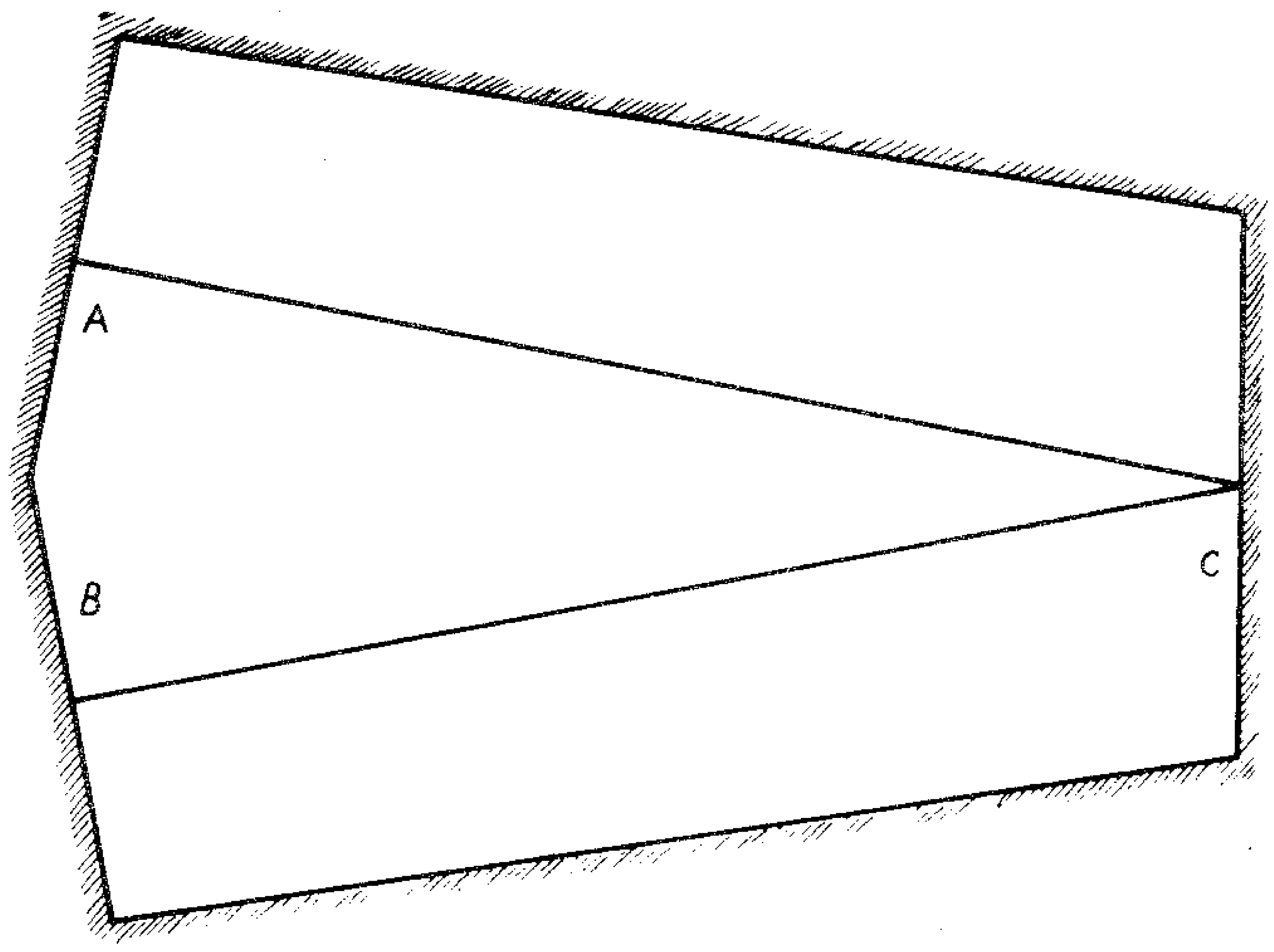


Fig. 3. Horizontal section of a radio studio indicating sound waves with extended reverberation due to the vertical walls A, B and C having too poor absorption for frequencies around 2ooo c/s. The measurement shown in fig. 2 (d) was taken during the building of the studio, and the effect is now removed by increasing the absorption of wall B.

radio studio with bad acoustics, the double slope being caused by a series of wave trains proceeding between two opposing vertical walls with poor absorption. These wave trains experience considerably less damping than other sound waves striking absorbing surfaces, so that they become dominant in the room at a lower level. This condition is illustrated in fig 3, which shows the radio studio of fig. 2d with these bad acoustics, and the direction of the sound waves causing the extended reverberation.

An excellent and much used set-up for measuring reverberation times is shown in fig. 4. One or two loudspeakers are placed in the room to be measured, and connected to a tone generator specially developed for acoustical measurements. A microphone, for example Condenser Microphone type 4111[3], is placed at a good distance from the loudspeakers, and supported on and coupled to Microphone Amplifier type 2601[4]. The measuring set-up is placed outside the room being investigated, and consists as shown of Tone Generator type 1012[5] and High Speed Level Recorder type 2301. The tone generator is equipped with frequency modulation (warble tone), with variable modulation frequency and band width. The voltages from the microphone amplifier are recorded in the set-up's most important instrument, the High Speed Level Recorder type 2301, which records voltages in db as a function of time.

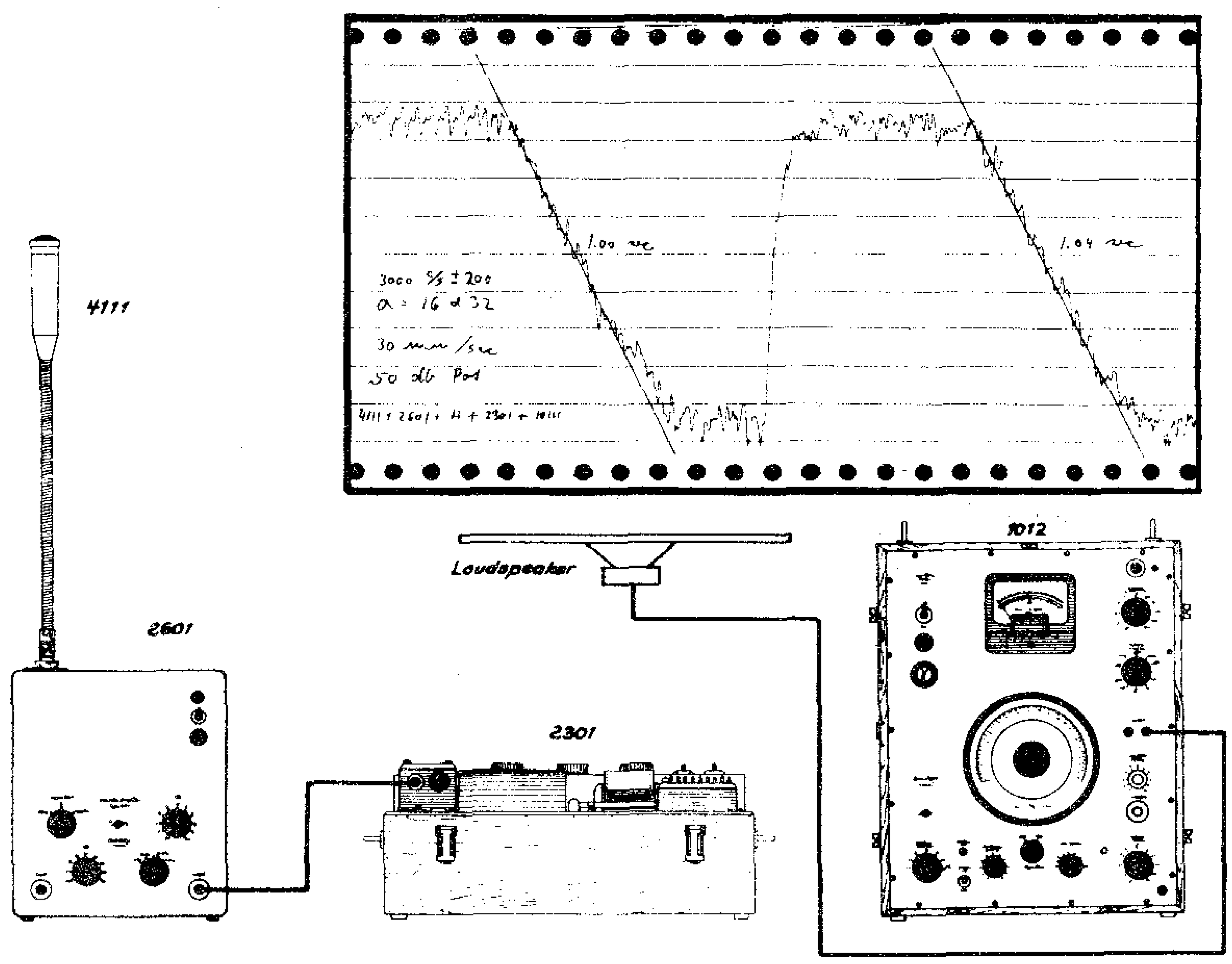


Fig. 4. Set-up for recording reverberation times, consisting of loudspeaker, B. & K. Condenser Microphone type 4111, Microphone Amplifier type 2601, Beat Frequency Oscillator type 1012 and High Speed Recorder type 2301.

This apparatus has frequently been described previously[6], so only the most essential details will be repeated here. The apparatus records on waxed paper, and has 9 different writing speeds, varying from 50 to 1ooo mm/s, and 10 different paper speeds, varying from 0.003 til 100 mm/s. A number of interchangeable potentiometers are available with ranges from 10 to 75 db, as well as a linear range. The effective paper width is 50 mm. Two axles are found on the end of the recorder, near the gear box, one of which rotates with a speed of 75 r/m, and the other can be varied from 75 to 0.0075 r/m in 9 steps. A sketch of the recorder's main construction is shown in fig. 5.

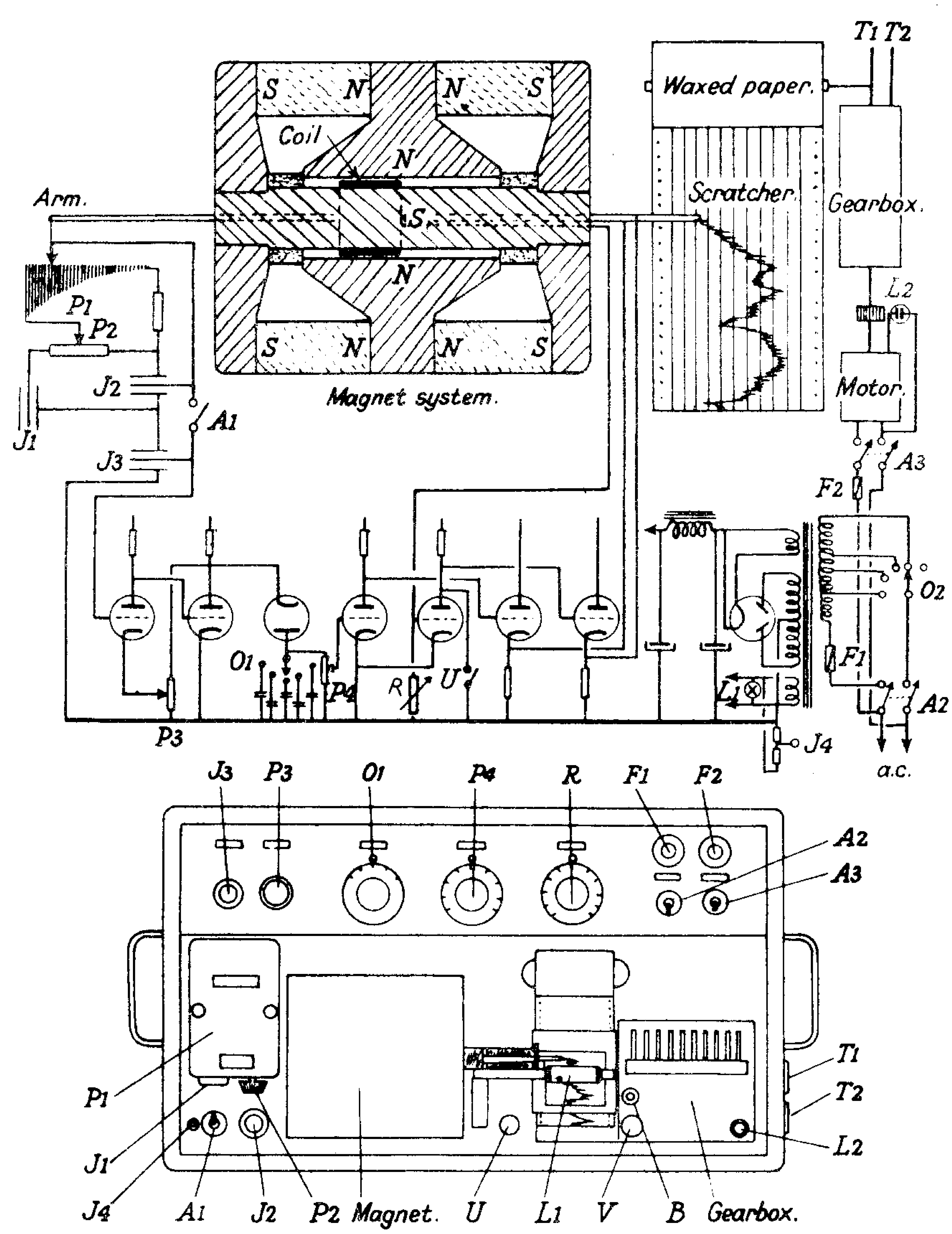


Fig. 5. Principle of the High Speed Level Recorder type 2301.

For ordinary routine measurements 2 to 3 reverberation curves are made for each frequency, with intervals of $^1/_3$ octave as maximum. The bandwidth of the warble tone is preferably adjusted to $^1/_3$ octave of the lowest frequency measured, and kept constant with higher frequencies. The modulation frequency is chosen between 4/T and 8/T, where T is the reverberation period of the room [7] For a thorough investigation, however, a much greater number of curves is required, with a lesser frequency interval, and the work of both recording and estimating the reverberation periods, as well as studying and comparing the individual reverberation curves, often becomes very lengthy. Furthermore, a very considerable amount of recording paper is used in these careful experiments.

For example, a thorough investigation of a theatre auditorium requires measurements throughout the significant frequency range of 60 c/s to 8000 c/s, giving approximately 500 curves, and this range of curves should be recorded in 3 or 4 different spots. In a theatre auditorium whose reverberation period is very short, it is desirable to record with high paper speed, at least 30 mm/s, and if one is quick with one's fingers, each curve can be carried out on 10 cms of paper, which gives a total requirement of 200 metres of recording paper for this measurement. The recording of the curves alone can be done in about 8 hours, for by rational planning of the work, a measurement involving adjustment of the frequency, starting the tone signal, starting the paper, stopping the tone signal, stopping the paper and noting down the frequency, can all be done in 15 sec. Estimation of the curve's slope, even when carried out with the Protractor type 2360, which is shown in fig 6, takes at least 30 sec. when done carefully, that is, another 16 hours, giving a total of at least 24 hours.

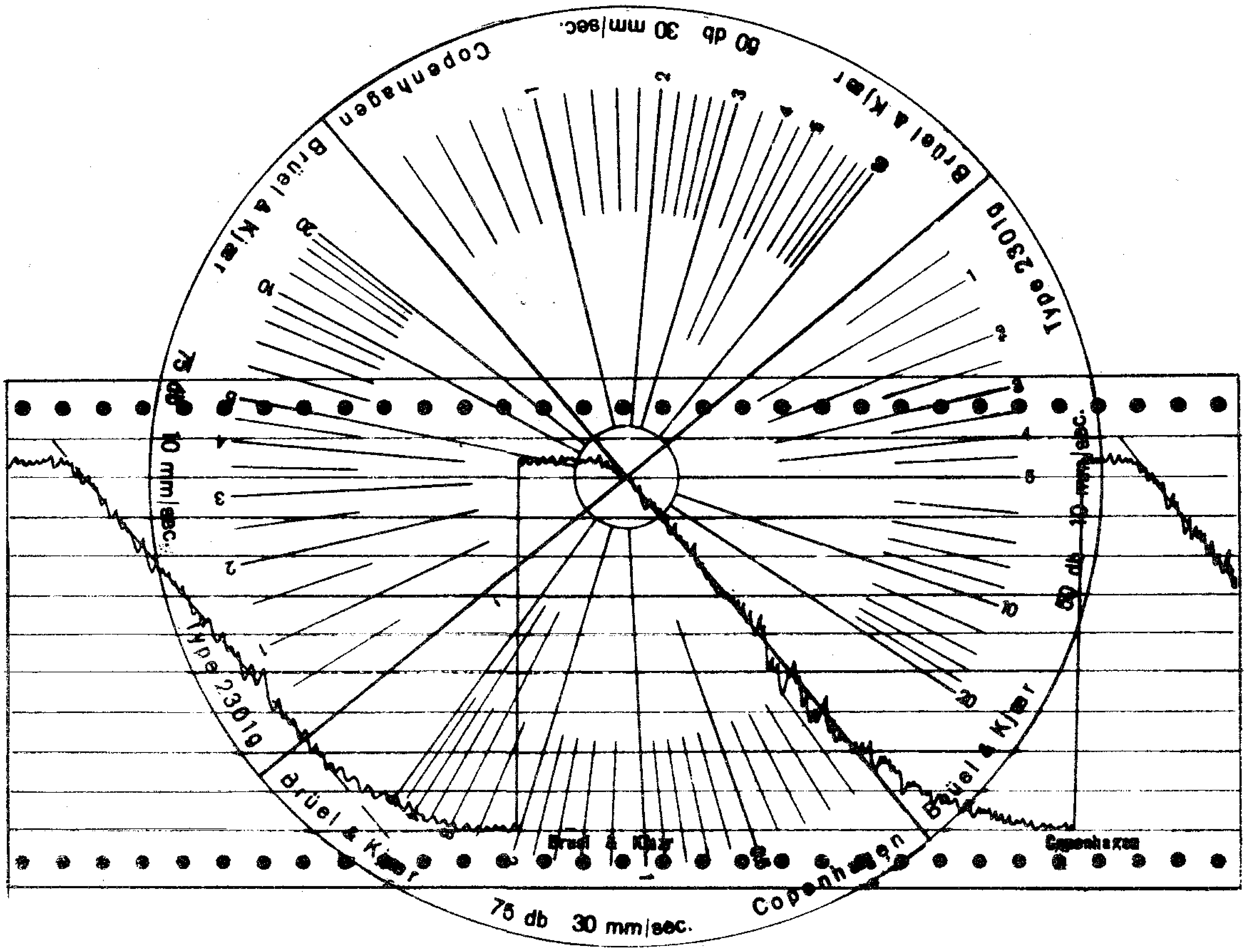


Fig. 6. Estimation of reverberation times with the Protractor type 2360. The protractor has four quadrants, which cover the following combinations: 50 db and 75 db potentiometers with paper speeds of 100 - 30 - 10 - 3 - 1 - 0.3 and 0.1 mm/s. The protractor is placed directly over the reverberation curve as shown in the figure, and the reverberation time, or some multiple of 10 reverberation times, is read in seconds where a horizontal paper line through the centre of the protaractor cuts the edge.

The expense of the paper and the time which goes to the recording and measuring of the curves is, however, of minor importance in many cases where a large and costly building construction is involved, but the long recording rolls cause endless filing problems, for if any real benefit is to be obtained from the measurements, it should be possible to find quickly a series of curves for a definite frequency band for a particular measurement. Unfortunately no good filing system for these long rolls has been discovered to date. When reports are being made out, copies of a number of reverberation curves need also to be included, to show in the most comprehensive way the characteristic deviations for different frequencies and measuring positions. These important enclosures also cause a great deal of difficult work on being extracted, copied, stuck on the report and put in order, when they have to be taken from long rolls.

In order to overcome these disadvantages the Universal Selector type 4406 has been constructed. Figure 7 shows a photograph of the device from in front and behind. The device is intended for coupling between the level recorder and the tone generator (beat frequency oscillator), as shown in fig. 8, so that the universal selector on the one hand completely takes over the manual control of the reverberation measurements, such as switching off and on the loudspeaker and shifting the frequency, and on the other hand makes it possible to use the recording paper in the form of a loop or endless belt in such a way that all the reverberation curves are recorded close up to each other, the distance between the curves corresponding to a given frequency interval. The recording paper loop of course makes one complete rotation with each curve, taking up the appropriate recording position with each new curve. A typical example is shown in fig. 9.

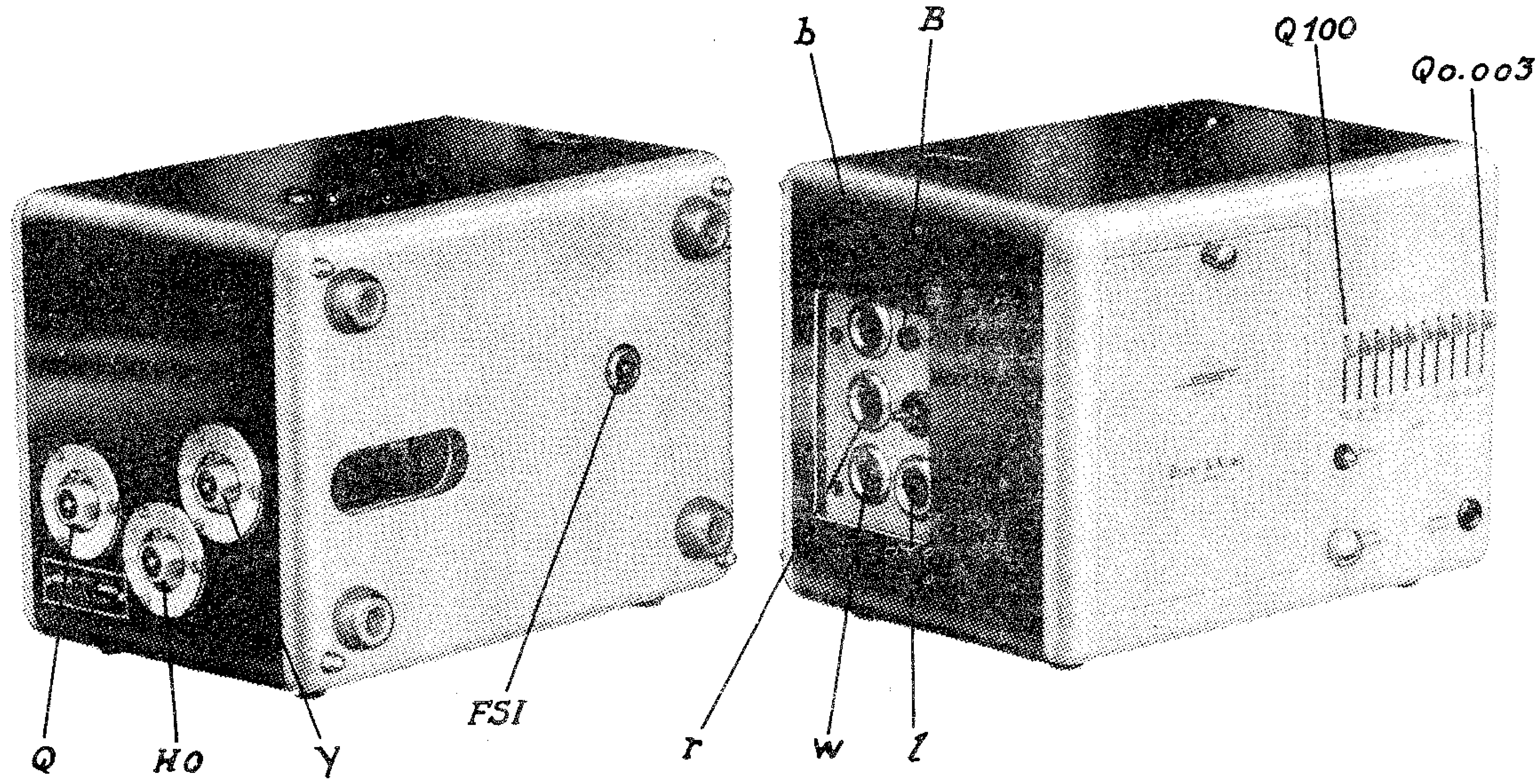


Fig. 7. Photograph of the Universal Selector type 4406. To the left shows the back view, to the right, the front view. The various connections and controls are indicated.

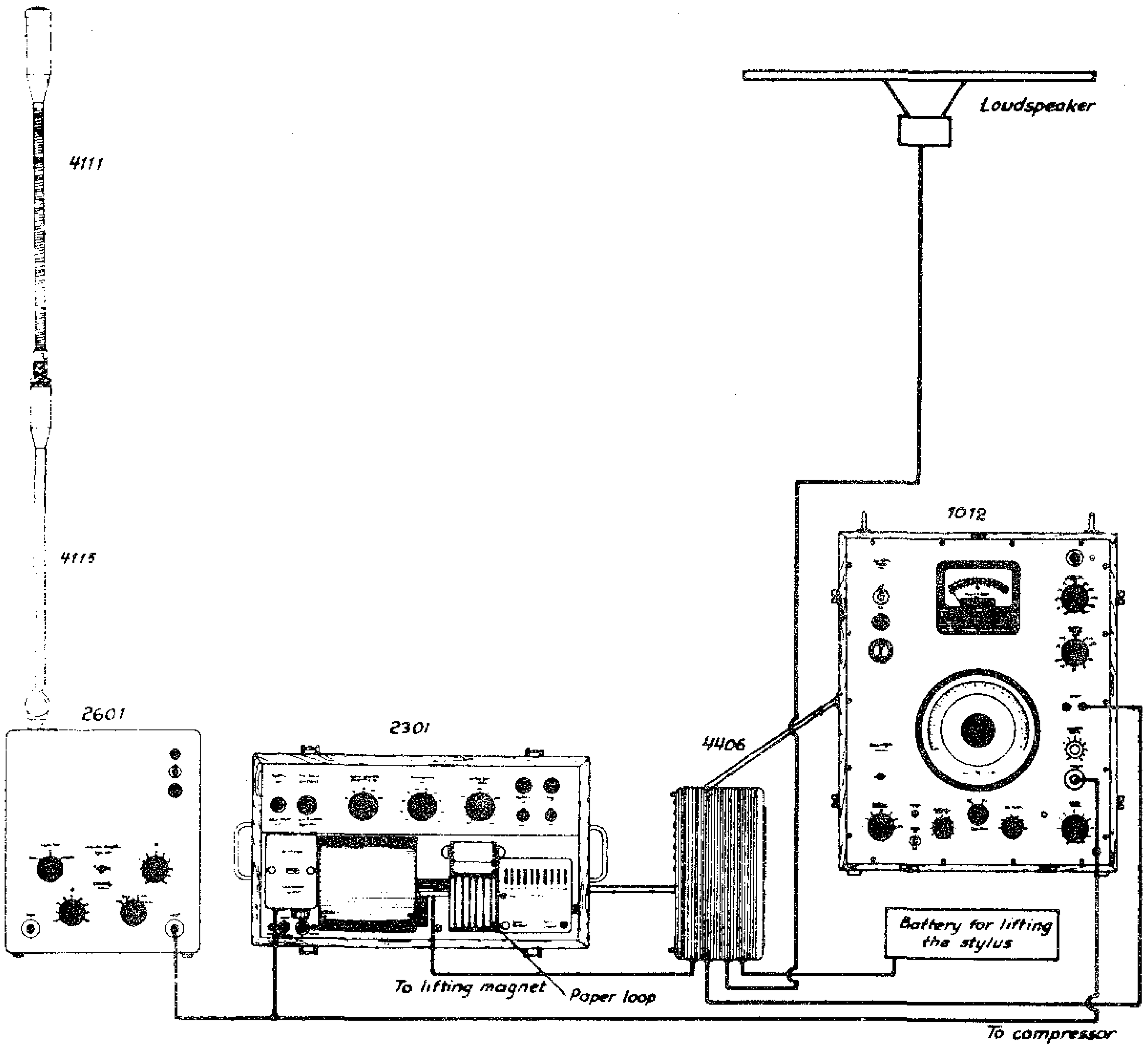


Fig. 8. Set-up for automatic recording of the reverberation curves with the Universal Selector type 4406 as controlling mechanism. The figure also shows how the antomatic volume regulator is used so that all the reverberation curves commence from the same level.

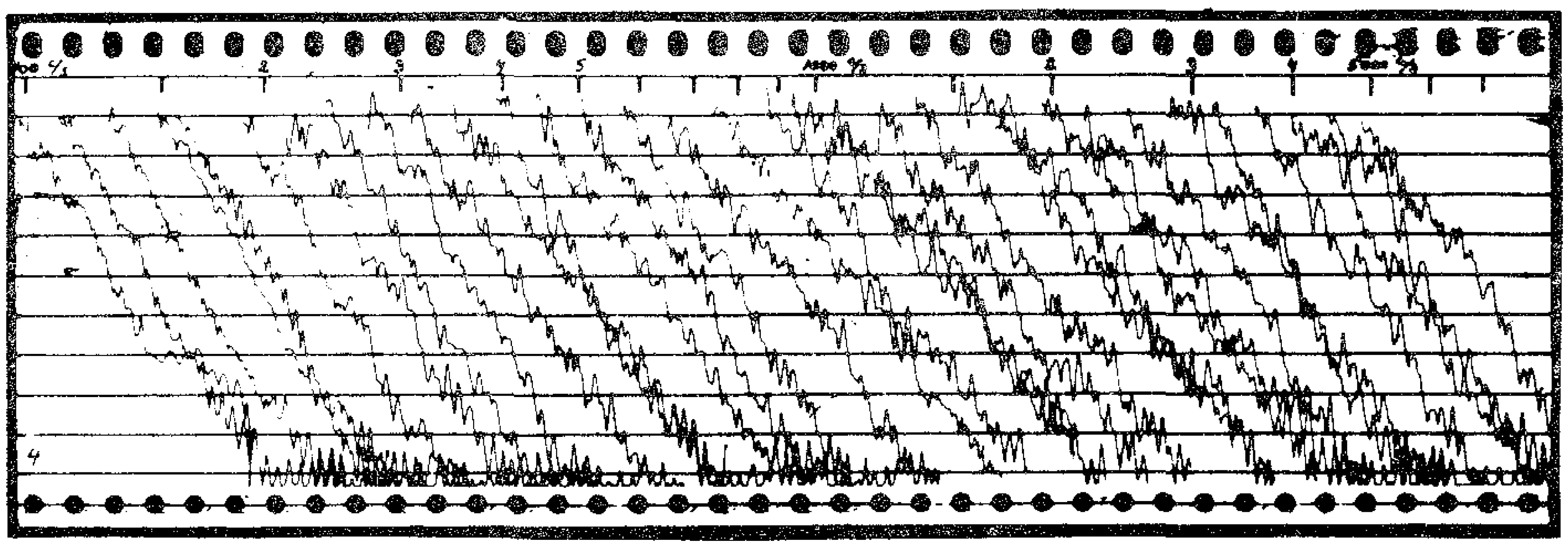


Fig. 9. A series of reverberation curves recorded with the set-up of fig. 8. Paper speed P = 30 mm/s. Loop length L = 24 cms. Potentiometer Pot = 50 db. Writing speed W = 300 mm/s. Gear wheel settings X3 and Y4. Curve spacing D = 5.83 mm/curve. Time interval t = 8 sec. Frequency range 100—5ooo c/s. The frequency scale marked is effective from the commencement point of the curves.

Construction of the Universal Selector.

The principle of the universal selector is shown in fig 10, where it will be seen that the X axle (T_1) in the level recorder controls two camdiscs through a coupling axle, the one camdisc controlling the loudspeaker current and the other controlling the current to a small lifting magnet, which puts the writing point on the recorder out of and into operation. The recording paper, stuck together to form a loop, must move in synchronism with the camdiscs, so that the reverberation curves are recorded at the same point on the paper when the selector's motor is disengaged. The length of the loop is thus determined by both the paper speed chosen and the speed of rotation of the camdisc axle. The most usual lengths of loop are 24, 25, 75 and 80 cm, but also loops with a circumference of 2.4, 2.5, 7.5 and 8 metres can be used in more exceptional cases.

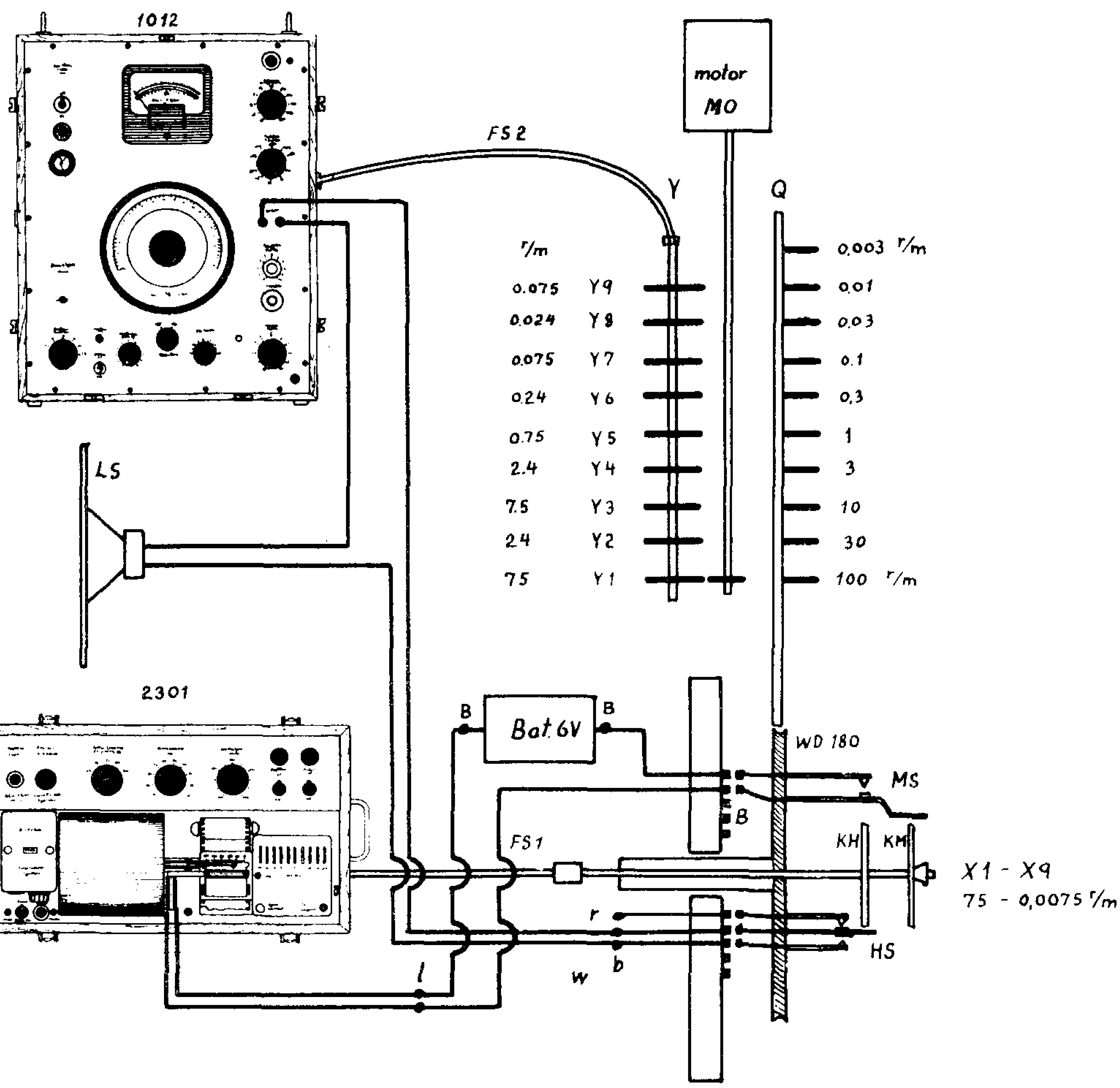


Fig. 10. Principle of the universal selector. HS is the loudspeaker contactor, MS is the contactor for the writing point's lifting magnet. KH and KM are the camdiscs controlling respectively the loudspeaker and lifting magnet contactors, Mo is the motor, WD is the worm-drive with 180 teeth, B is the slip-ring system with slip-contacts to HS and MS, FS1 is the flexible axle coupling the selector to level recorder's X axle, FS2 is the flexible axle coupling the selector to the BFO's frequency drive. The Y axle has 9 speeds of rotation. The worm-drive axle Q has 10 different speeds of .otation. B is a 6 volt accumulator or battery for the lifting magnet.

Separation of the individual reverberation curves takes place by means of the contactors MS and HS turning very slowly. The turning takes place by means of a worm-drive with a ratio of 1:180, operated through a gear-box by the selector's motor. 10 different displacement speeds are available, from 0.3 sec to 3 hr for a rotation of 1°. The tone generator type 1012 is connected to the selector's axle Y by means of a flexible shaft, Y being also driven by the selector's motor, and having 9 different possible speeds of rotation, making it thus possible to traverse the tone generator's frequency range from 0—20.000 c/s with 9 different speeds between 14 sec. and 38.5 hr per traverse. As both the tone generator and the displacement worm-drive are driven by the same motor, the displacement of the curves on the recording paper and the shifting of the tone generator's frequency are always in step. As a result of the many possibilities for different speeds of both the tone generator's frequency scale and the displacement worm-drive, it will be possible to have up to $9 \times 10 = 90$ different frequency scales on the recording paper.

As one is interested in recording only the reverberation curve, and does not wish to have noise and peak effects from each curve filling up the paper, a little lifting magnet is incorporated on the level recorder, which lifts the sapphire point from the recording paper. The current to the lifting magnet can be very exactly adjusted with the outside camdisc KM in relation to the camdisc KH, which controls the loudspeaker current. The period during which the current to the lifting magnet is cut off can also be varied continuously. Fig. 11 shows a photograph of the lifting magnet, camdiscs and other details.

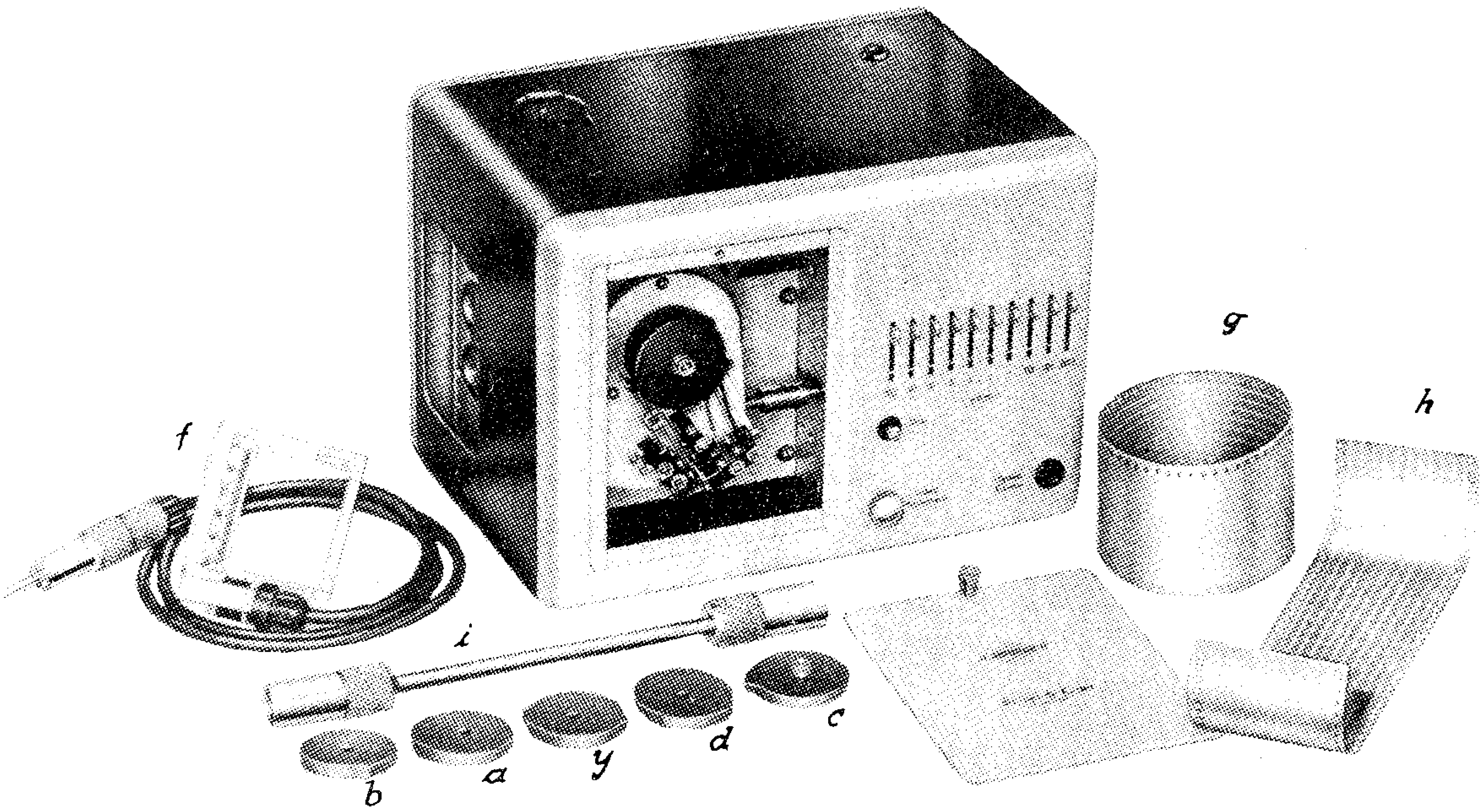


Fig. 11. Photograph of the universal selector's contact mechanism: (a) camdisc for reverberation measurements, (b) camdisc for impulse measurements, (c) camdisc for two impulses, (d) camdisc for two long impulses, (e) camdisc for lifting magnet with variable period of interruption, (f) lifting magnet, (g) 24 cm closed paper loop, (h) 24 cm loop opened at join, (i) flexible axle.

The universal selector is mechanically coupled to the level recorder by means of a short flexible shaft, and it might be feared that the elastic torsion would give too great an uncertainty in placing the reverberation curves. If for example the elastic uncertainty in the mechanical coupling were 2°, with an 80 cm loop moving at 100 mm/s this would give a shift in the individual curves of approximately 4.5 mm. Tests have therefore been carried out of the exactness of the arrangement, and the result is shown in fig. 12. It will be seen that the greatest uncertainty is at most 0.4 mm, corresponding to an angular error of less than 0.2°, and an exactness of timing of better than 4 millisec.

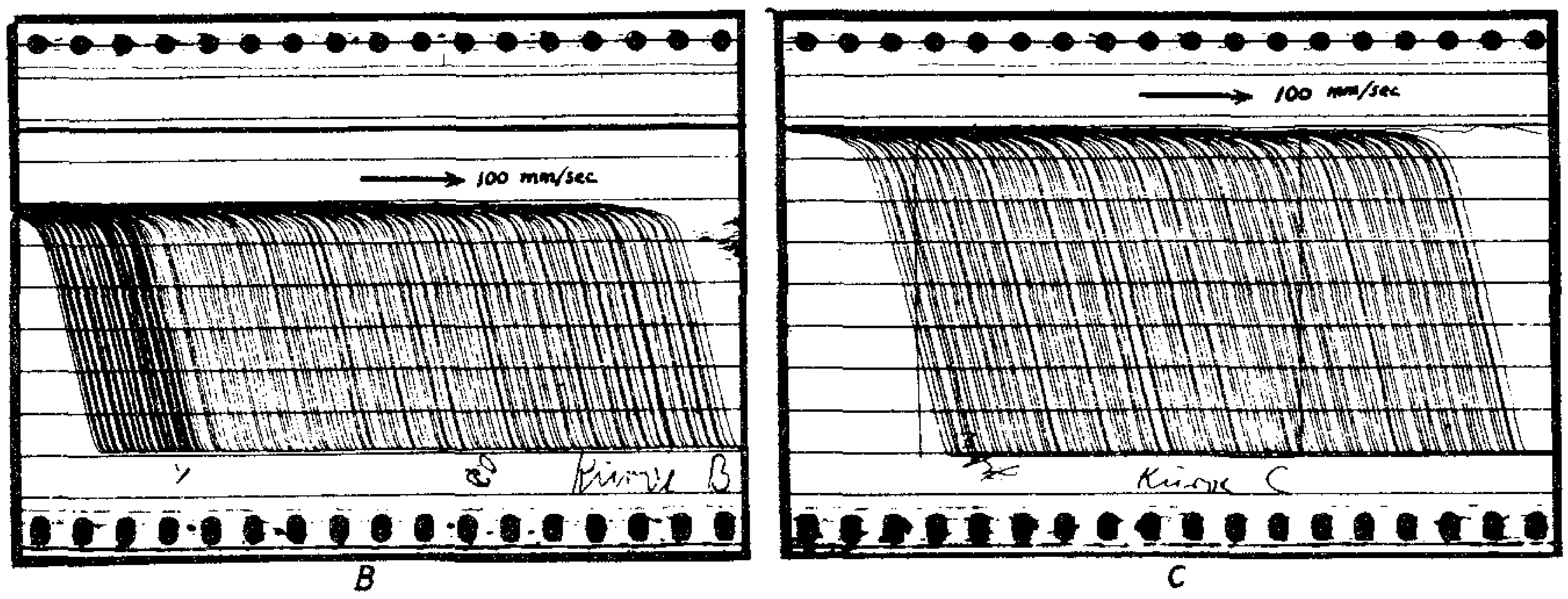


Fig. 12. Precision test of camdisc's movement with rigid shaft connection between recorder and selector (B) and the usual flexible axle (C). Paper speed 100 mm/s. Loop length L = 80 cm.

Reverberation Measurements.
The measuring set-up for the automatic recording of reverberation curves in a room has already been shown in fig. 8. That camdisc which switches on current to the loudspeaker half the time and interrupts it half the time, is used. The camdisc to the lifting magnet is set by experiment so that the reverberation curves are drawn in their whole length, but not more. Warble tone is used according to rules given previously, and the paper speed is so chosen that the slope of the reverberation curves lies between 20° and 60° from the level axis, as it is considered that a slope of 45° gives the maximum accuracy of measurement of the slope. To show the actual characteristics with this method of measurement, several of the recordings reproduced in the illustrations here have been taken in the same room, with corner placing of loudspeaker and microphone. The room is rectangular, with dimensions 5 m × 2.5 m × 3 m. Fig. 13 shows the same set of curves recorded with different writing speeds of respectively 70 db/s and 140 db/s.

Generally speaking one can calculate that if a writing speed twice as great as that corresponding to the reverberation time is chosen, the most reliable result will be obtained, as in that way one will be certain that the reverberation curve's slope will not be affected by any limitations in writing speed, while at the same time the curve is not obscured by unessential details, such as quick changing differences in level due to interference etc. In fig. 13 one can note the great variation in detail which almost completely obscures the curves recorded with high writing speed, while the curves recorded with a speed of 70 db/s appear more distinct and clear without losing such important features as, for example, the slight curvature. Fig. 9 shows the same curves, but recorded with the even greater writing speed of 200 db/s.

Reverberation time as function of frequency is shown calculated from these curves in fig. 14. The measurements should be made from the point where the slope of the curves starts. It is seen that the reverberation time is around 1.0—1.5 sec. A reverberation time of 1.1 sec corresponds to an average slope of 54 db/s, so that the writing speed of 70 db/s used in the upper curve of fig. 13 must generally speaking be considered too slow to be on the safe side. If it is desired to study the reverberation curves more closely along their whole length, from maximum level to noise level, it will often be an advantage to choose a 75 db potentiometer rather than a 50 db one. Fig. 15 shows such a recording over a great frequency range. It will be seen from the curves that with the loudspeaker used, the output above 55oo c/s has been too weak to permit the compressor in this case to hold the commencement level of the curve to the same value. If a commencement level of only 3 to 4 db lower had been chosen, it would have held.

The adjustment of compressor and microphone amplifier is quite simple. First of all the level recorder's volume control is adjusted so that full deflection corresponds to an input voltage of at least 10 volts with the 50 db potentiometer (about half control), then the microphone amplifier's amplification is so adjusted that the noise level of the room, microphone or amplifier can just be recorded. The warble tone is adjusted to the correct value and the volume control in the tone generator turned full up, while the compressor volume control is turned right down. The meter on the tone generator will give full deflection, and the maximum level will have been reached. If the compressor volume control is turned up a little, a point will be reached

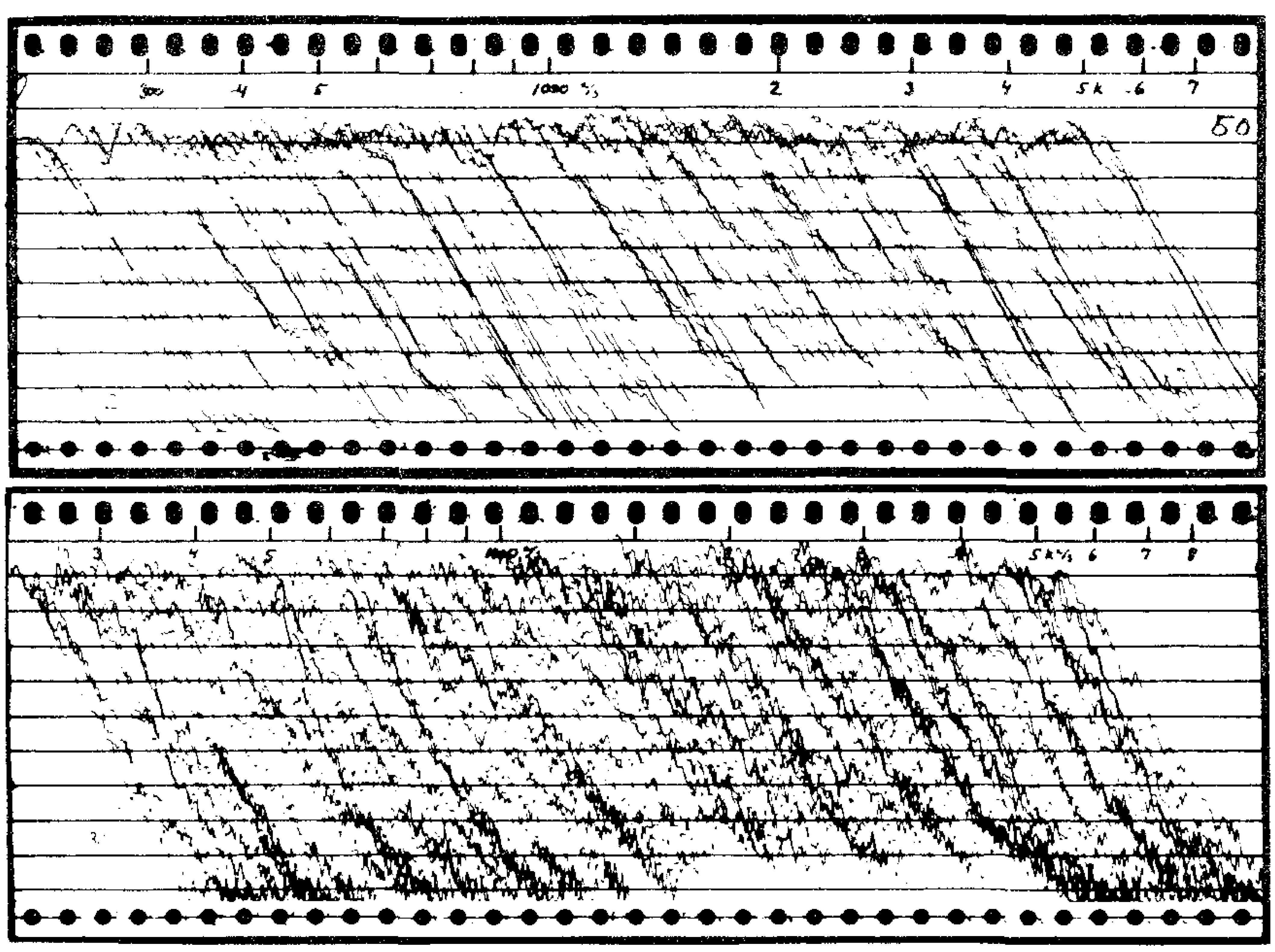


Fig. 13. Reverberation curves recorded with different writing speeds. Upper record 70 db/s, lower record 140 db/s. Potentiometer Pot = 50 db. Paper speed P = 30 mm/s Loop length L = 24 cm. Gear-wheel settings X3 and Y5.

where the compressor will control the tone generator's output voltage downwards, which will immediately be seen on the voltmeter. Now slowly traverse the frequency range one wishes to measure, and note whether the compressor always works so as to keep the voltage to the loudspeaker down a little under maximum. If there are frequency ranges where the instrument gives maximum deflection, one must turn up the compressor volume control, so that the meter keeps at least 1 db below full deflection for all frequencies. If the loudspeaker used has a bad frequency characteristic, and reverberation measurements are required over a large frequency range, the output level will often be rather low, so that the reverberation curves are only registered for a level of about 25 to 30 db. It is therefore important that the loudspeaker has a relatively good frequency characteristic.

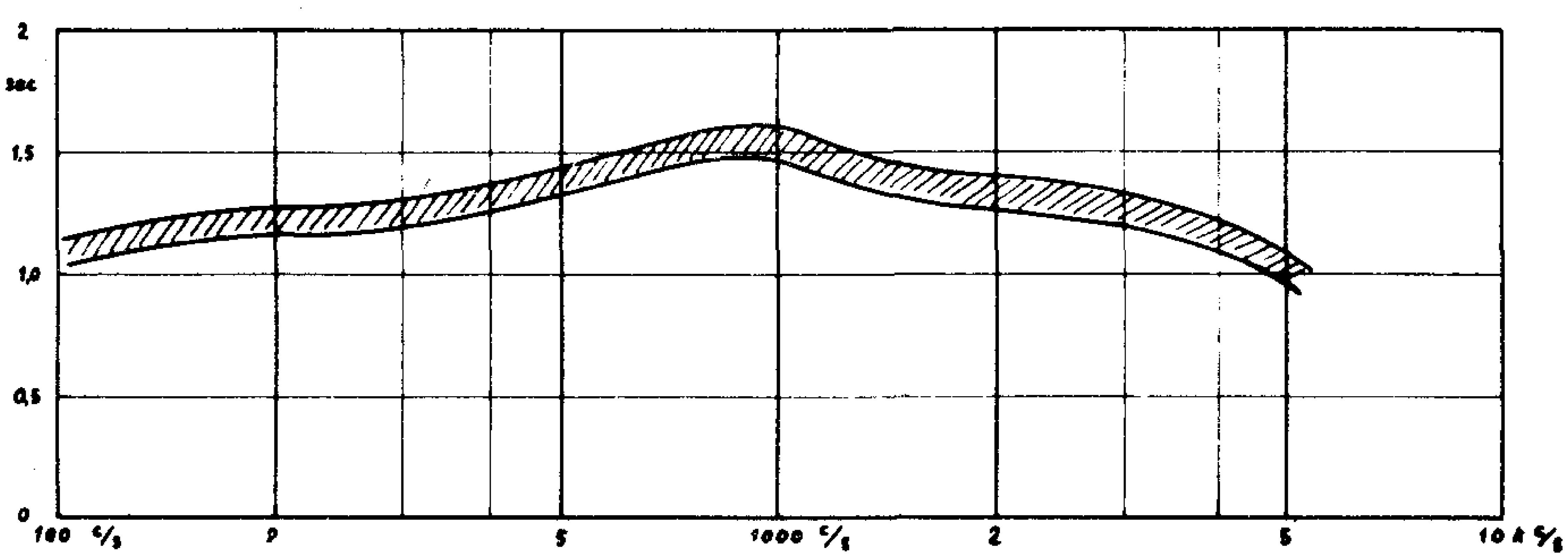


Fig. 14. Reverberation times as function of frequency, calculated from figs. 9, 13 and 15.

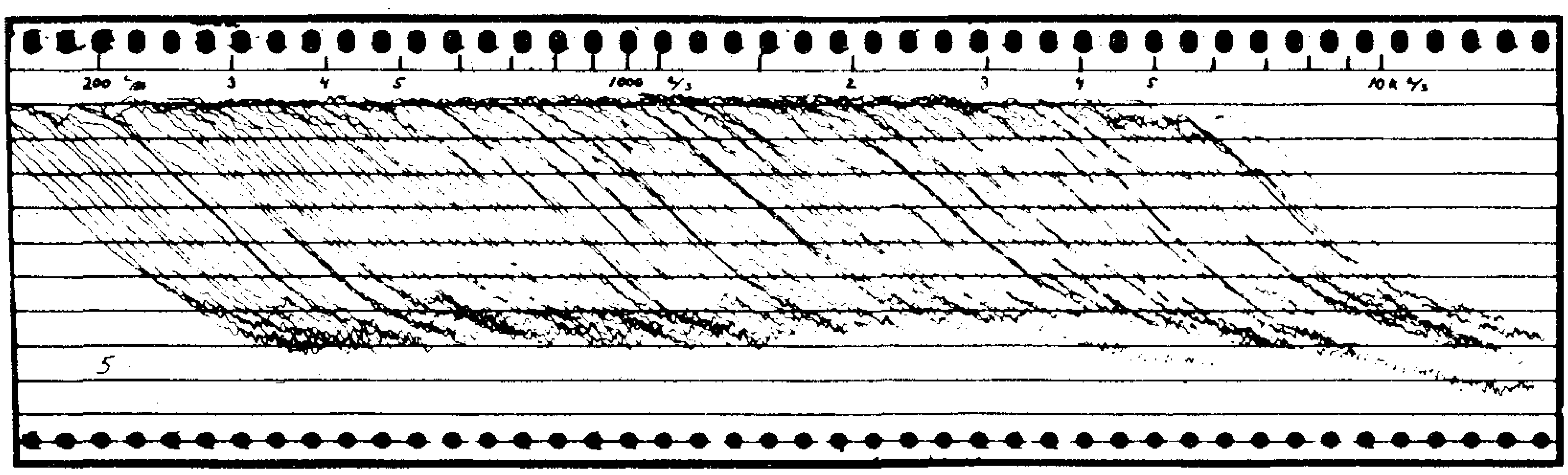


Fig. 15. Reverberation curves recorded with 75 db potentiometer over a wide frequency range. The compressor has not been effective for frequencies above 55oo c/s. P = 30 mm/s. W = 70 db/s. L = 24 cm. Gear-wheel settings X3 and Y5. 120—6ooo c/s. The writing speed here has been chosen too low, there being too few fluctuations.

The possibility of using the compressor in the Beat Frequency Oscillator type 1012 so that all the reverberation curves start from the same level is a very valuable property. This is illustrated best in fig. 16, which shows a series of curves taken under the same conditions as the upper curve section in fig. 13, but without making use of the compressor. It will be seen that the curves' very variable starting level gives an unclear mixing of the individual curves and makes the reading of the frequency uncertain. Fig. 17 shows a series of reverberation curves taken in a workshop with a highly sound-absorbent ceiling. The workshop has parallel end-walls of glass, and for certain frequency ranges very powerful flutter echoes. These are outlined in the figure. The curves are recorded with warble-tone and automatic volume regulation. The reverberation time is determined for the recorded curves as is shown in the lower part of the figure. Further, the reverberation times are determined for these sound waves which travel between the vertical end-walls and produce the characteristic flutter echoes. It will be observed that the damping of these flutter echoes is considerably lower than the damping of the main part of the sound in the room.

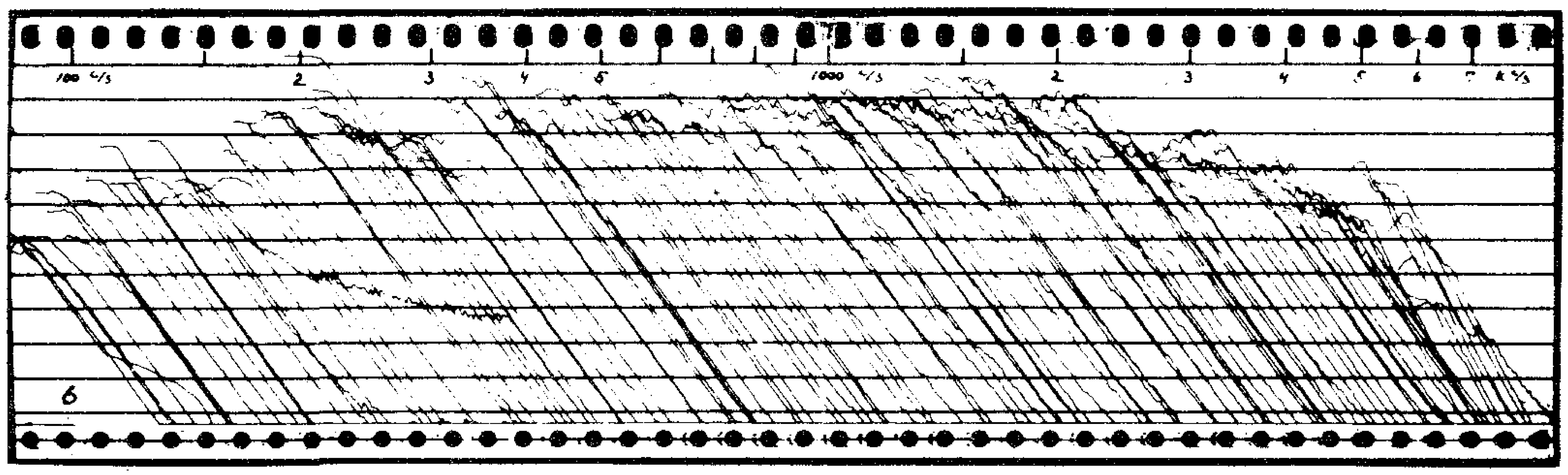


Fig. 16. ***Reverberation curves recorded under the same conditions as in fig. 13, upper record, but without compressor. The very variable starting level is seen. Pot = 50 db, P = 30 mm/s, L = 24 cm. Gear wheel settings X3 and Y5. Frequency range 70—58oo c/s. (One of the curves is spoiled on account of noise from a passing train).***

The automatic volume regulator has not operated correctly for the higher and lower frequencies. This is clearly seen on the curves by a fall in the output level. This is due to the fact that in these measurements a somewhat higher output level was chosen, so that curves could be recorded over at least 40 db. But the loudspeaker's frequency response has been too poor for both the low and high frequencies to permit that effect being maintained which was necessary to yield the level started with at 1ooo c/s. With the recording of reverberation curves it is often an advantage not to depress the level too low, but rather accept a variation of output level at the extreme ends of the frequency range, so as to carry out the measurements on a higher level. This is particularly important if the natural noise level of the room is high.

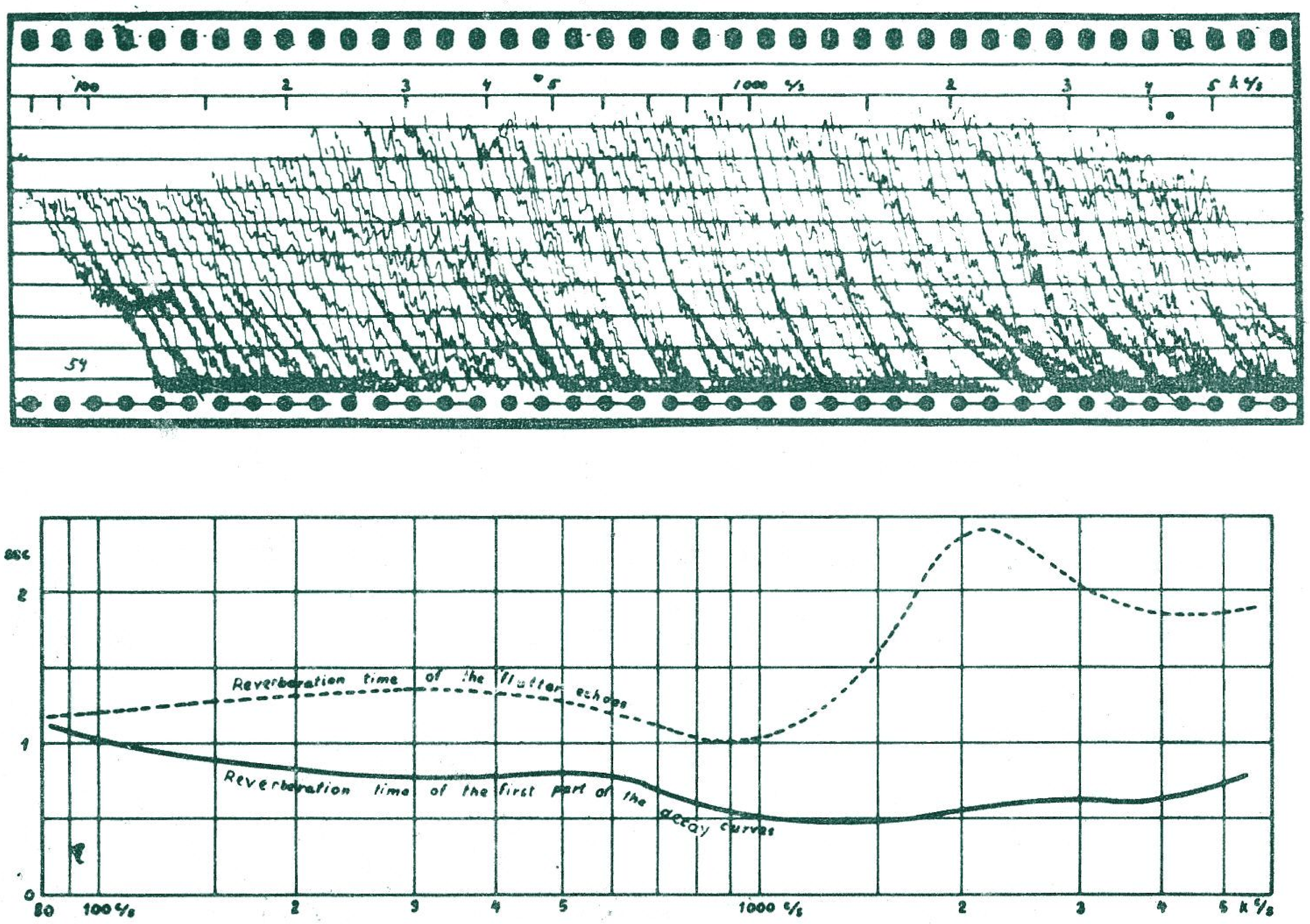


Fig. 17. *Reverberation curves taken in a work-shop with powerful flutter echoes. Warble tone and automatic volume regulator. The flutter echoes are indicated by the inserted lines. P = 30 mm/s, L = 24 cms, W = 200 db/s. Frequency range 80—4800 c/s. The reverberation times of the first part of the decay curves, and the flutter echo reverberation times, are shown in the diagram.*

Continued in No. 4

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