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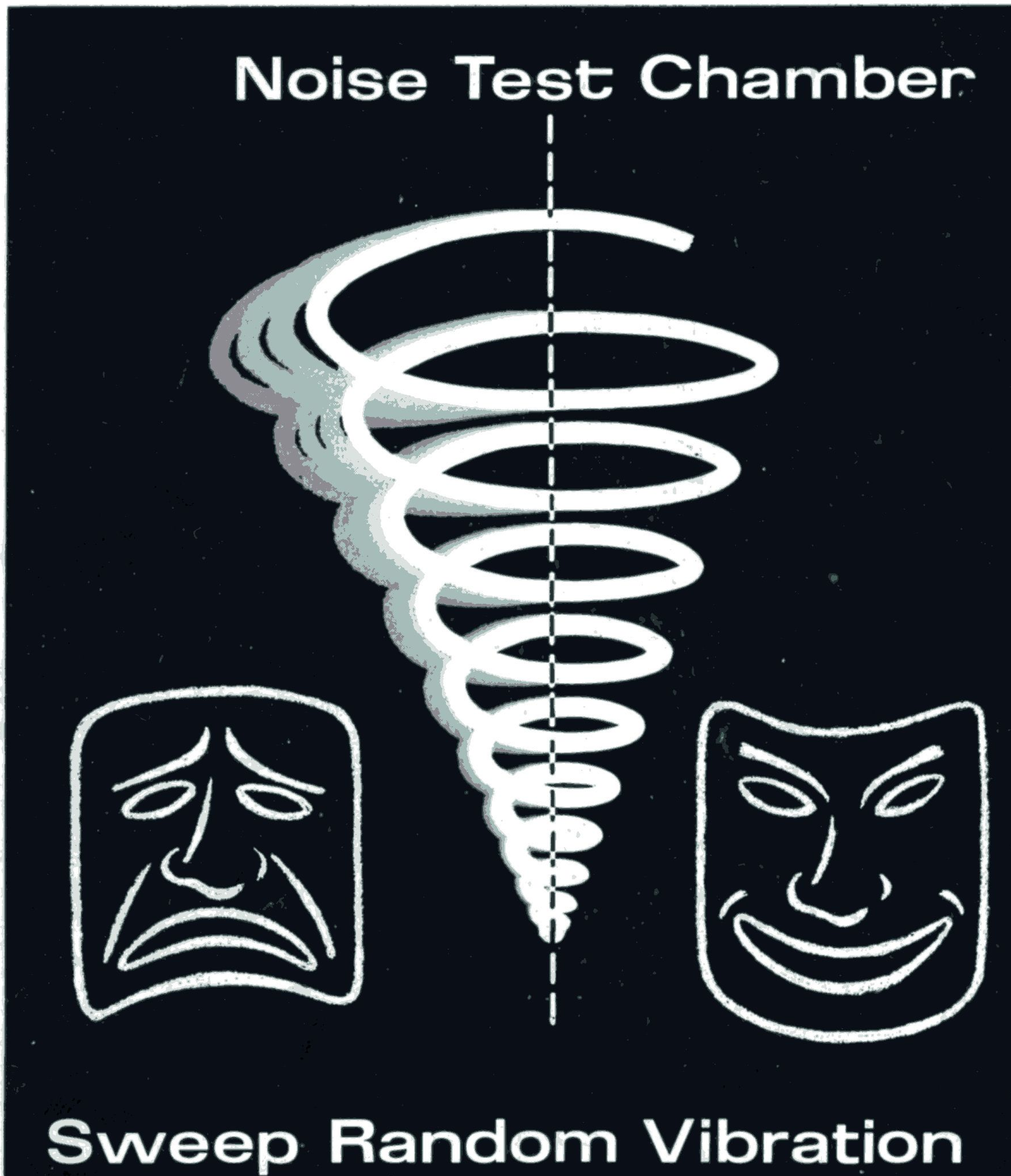

No 2 1964

PREVIOUSLY ISSUED NUMBERS OF BRÜEL & KJÆR TECHNICAL REVIEW

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TECHNICAL REVIEW

No. 2 – 1964

K. LARSEN & SØN - LYNGBY

Design and Use of a small Noise Test Chamber

By

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ABSTRACT

After pointing out the desirability of general noise control and of obtaining noise power data on commonly used office equipment and household appliances various methods of noise power measurements are described. Accuracies to be expected from measurements in anechoic as well as in large reverberation chambers are briefly discussed and the development of a small noise test chamber at Grünzweig & Hartmann, W. Germany outlined. This test chamber is very well suited for the production testing of relatively small equipment,—and may also be used to estimate the sound power radiated from the test object. Finally some suitable measuring arrangements used in conjunction with the Noise Test Chamber are described.

SOMMAIRE

Après une introduction montrant la nécessité générale de mesures de bruit, et la désirabilité d'études de la puissance sonore produite par les machines de bureau ou les appareils électroménagers d'usage courant, l'article décrit diverses méthodes de mesures de puissance sonore. Les erreurs auxquelles il faut s'attendre lors de mesures en chambres anéchoiques ou en grandes chambres sourdes sont discutées, et la réalisation d'une petite chambre d'essais par la société Grunzweig & Hartmann, Allemagne Fédérale, est décrite. Cette chambre d'essais est spécialement bien adaptée aus essais industriels d'appareils de faible dimensions et permet la mesure de la puissance sonore totale rayonnée par l'appareil en essais. Enfin quelques équipements complets de mesure utilisables avec la chambre d'essais sont décrits.

ZUSAMMENFASSUNG

Für die Beurteilung einer Lärmquelle ist es wünschenswert, deren Schalleistung zu kennen, da diese im Gegensatz zu den unmittelbar meßbaren Schallfeldgrößen nicht durch die akustischen Eigenschaften des umgebenden Raums beeinflußt ist. Die klassischen Meßverfahren sind nur im schalltoten Raum oder im Hallraum durchführbar. Für Lärmquellen mit kleinen Abmessungen hat Firma Grünzweig & Hartmann eine Meßkammer entwickelt, die besonders für die Produktionskontrolle, z. B. für kleine Elektromotoren, für Haushaltgeräte usw. geeignet ist. Sie besteht aus zwei Hälften, von denen eine mit reflektierenden, die andere mit absorbierenden Wänden versehen ist. Der Raumquerschnitt zwischen den Hälften kann als eine definierte Meßfläche angesehen werden, durch die die gesamte abgestrahlte Schallenergie strömt. Der hier gemessene Schalldruck ist ein brauchbares Maß für die Schalleistung.

The quality of modern office and household equipment is actually judged differently by different people. Some might judge the quality according to the look of the equipment. Others study the technical specification sheets. Still, other people look for rigidity, compactness, ease of handling, practical to store away etc.

However, in later years where the "general noise level" in an office and an ordinary household has been increased manyfold due to all the various machines and appliances considered necessary, one of the "qualities", that is nearly always looked for, is the noiselessness of the specific item.
Manufacturers of sound measuring equipment have therefore, during the past decades, developed various instruments which are intended for use by the manufacturers of f.inst., household appliances, to control the "noiselessness" of their products. A typical example of such a sound measuring instrument is the Noise Limit Indicator made by Brüel & Kjær. The functioning of this equipment, its development and background has been described in the B & K Technical Review No. 2-1963.
However, though the Noise Limit Indicator may be considered the most versatile and convenient apparatus for the production control of products with

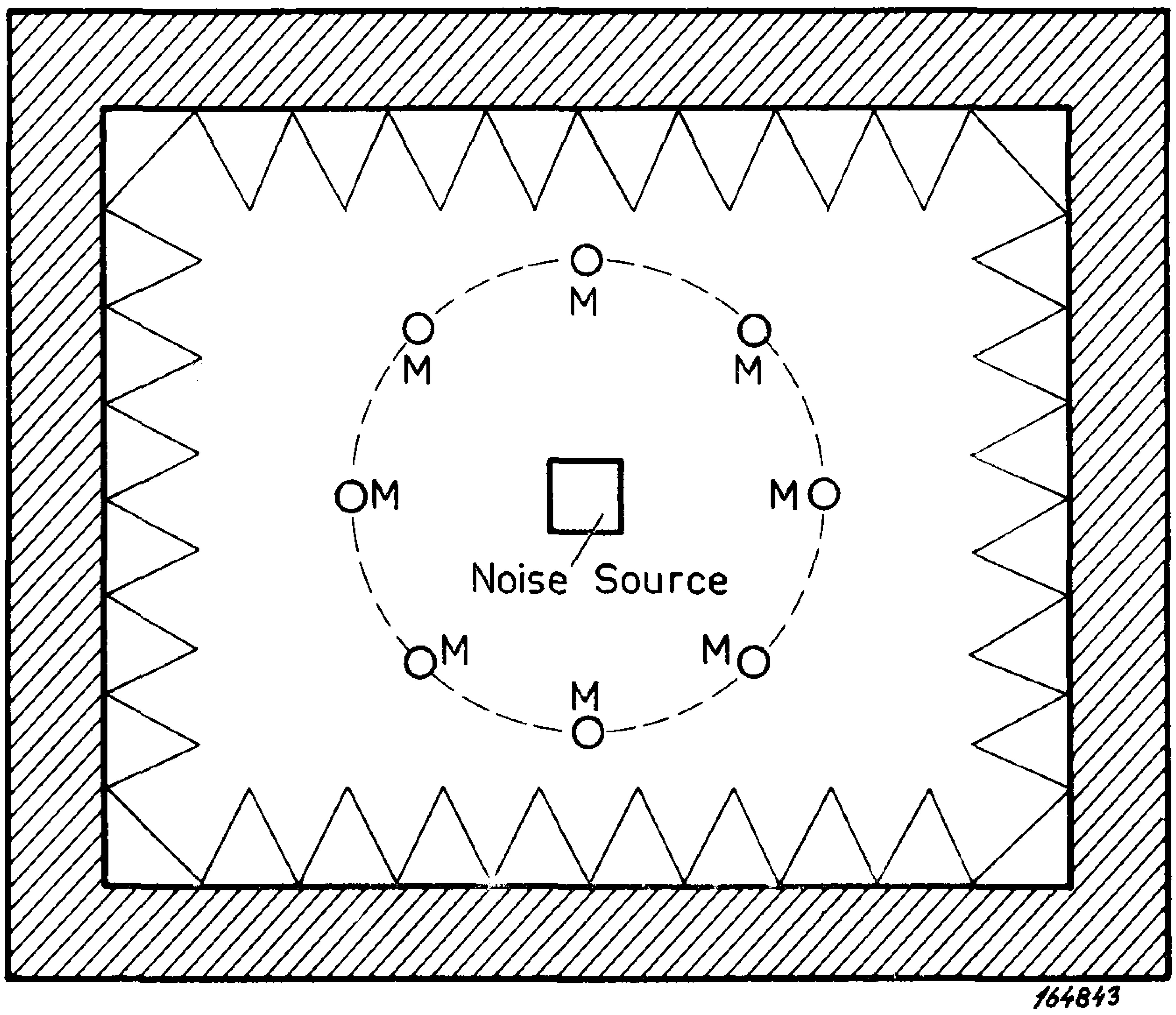

Fig. 1. Free field sound power measurements.

regard to their noise and vibration characteristics, a less refined instrument may in many cases do the job satisfactorily. Sometimes it may even only be necessary to use a high quality sound level meter. Examples of a few practical measuring arrangements are given at the end of this article. On the other hand, production control of the noise emitted from various small machines always requires a suitable *measuring chamber*. Two kinds of such chambers have up to now gained importance: The completely anechoic chamber, and the reverberation chamber.

The anechoic chamber is generally used when it is desired to control the directivity of the emitted sound. If, for example, a particular specimen radiates sound only from a very limited area of its surface, it may be sufficient to treat only this area to achieve the desired noiselessness. Then only the sound radiated from this area will be important from the point of view of noise control. Also in the development of new products it will be important to determine their radiation characteristics and the total radiated sound power. The knowledge of the total acoustic (sound) power, in f. inst. octave bands, emitted from a noise producing specimen is extremely important to the noise abatement engineer. From this the sound pressure level at various distances away from the specimen and under various environmental conditions can be directly estimated,—at least in the socalled "far field". The far field is the sound field so far away from the source that the phase differences between the sound radiated from various parts of the source can be considered negligible. This seems to be the case at distances of one or more wavelengths away (see also the bibliography cited at the end of the article), or at 3 to 4 times the largest linear dimension of the noise producing specimen,—which ever is the greatest.

When sound power measurements are made in anechoic chambers (or outdoors) this requires a complete space integration of the sound intensity over a sphere containing the noise source Fig. 1. However, due to the lack of a commercially available sound intensity meter the intensity has to be calculated from the formula $I = \frac{p^2}{z}$ where I = intensity, p = sound pressure and z = acoustic impedance at the place of measurement. To avoid complex calculations involving phase differences between the sound pressure and the particle velocity the microphone positions should be in the far field where $z = \varrho_0 c_0$ (impedance of the air). Normally at least 12 microphone positions around the test object are necessary.

If the noise is radiated from a large specimen, and the surrounding medium is not completely sound absorbing sound pressure fluctuations due to "standing wave" effects will be present and complicate the averaging. Actually, even very good anechoic chambers will cause some reflection at low frequencies, and if the noise radiating specimen is of a type that radiates more or less pure tones serious inaccuracies may be present in the measured result. A simple estimate of the maximum error will show this clearly:

Assume, f. inst. that the anechoic chamber in question has the dimensions $4.5 \times 5 \times 5$ m^3 and an absorption coefficient of 99 %. For a particular microphone position the sound pressure will consist of the direct sound + the sound reflected from the 6 surrounding surfaces*), see Fig. 2. To determine that part of the sound pressure which is contributed by the reflections it is convenient to assume the noise producing object to be a "point source" of

*) Due to the high absorption at the walls of the anechoic chamber (99 %) only the first order sound reflections are considered in the estimate.

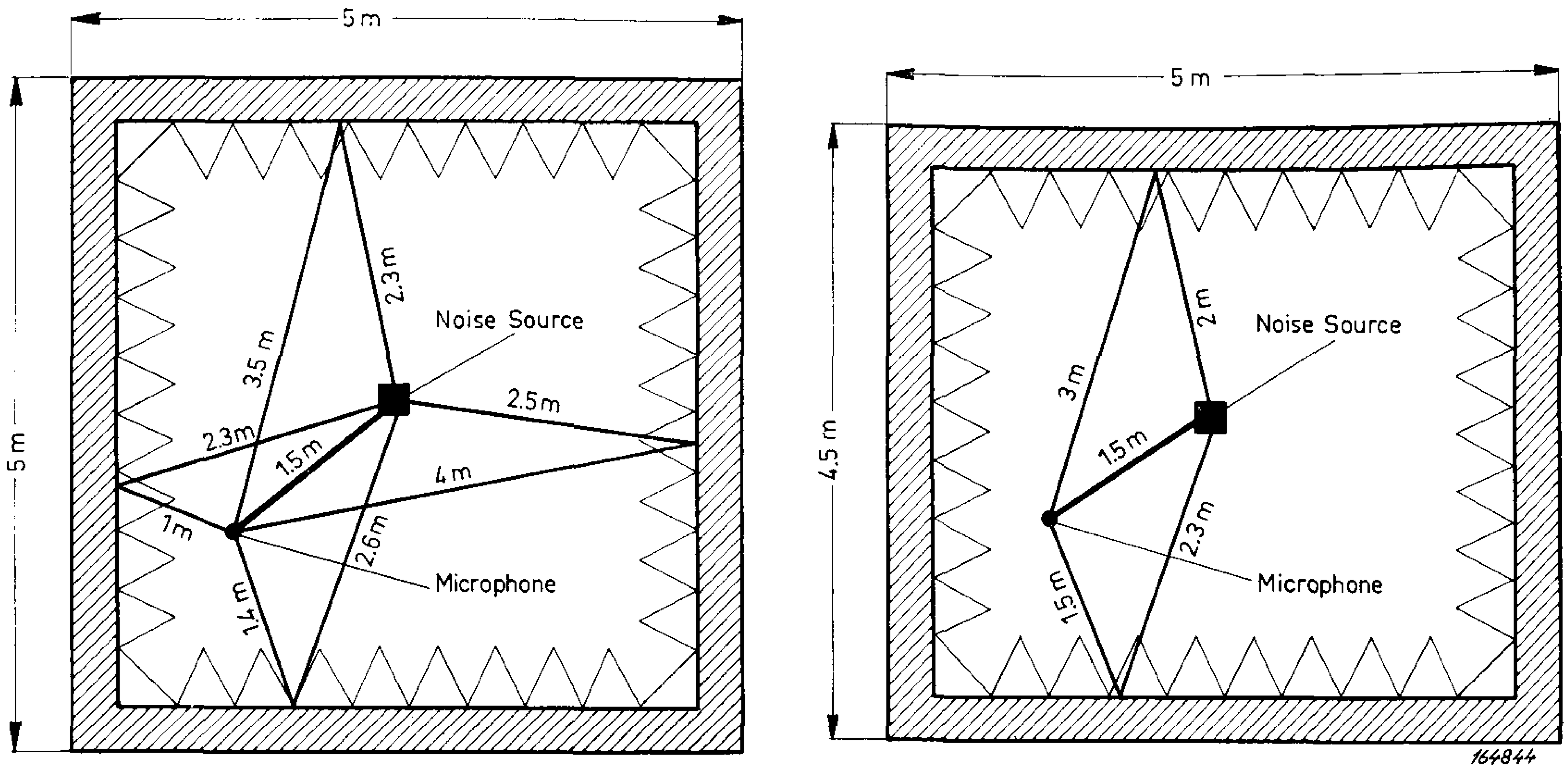

Fig. 2. Example of first reflections causing errors in measurements in anechoic chambers.

sound and to estimate the length of the sound path from the source via the reflection to the measuring microphone. As the absorption factor is $\alpha = 1 - R^2$ where R is the sound *pressure* reflection factor, R = 0.1 in this particular case. Now assuming the worst case, namely when all the sound pressures add in phase, as well as an average length of the reflected sound path of 4.7 m and a direct path of 1.5 m (Fig. 2) the following result is obtained:

Direct sound: $$p_1 = \frac{q}{r} = \frac{q}{1.5}$$

Reflected sound: $$p_2 = \frac{6 \times R \times q}{d} = \frac{6 \times 0.1 \times q}{4.7}$$

Thus

Relative Error: $$= \frac{p_2}{p_1} = \frac{6 \times 0.1 \times 1.5}{4.7} = 0.19$$

where q is a "source factor".

The error in the sound pressure level measurement may therefore be as much as + 1.5 dB and — 1.8 dB. If the distance between the source and the measuring microphone is increased the error due to reflections is also increased. On the other hand, if the distance is decreased errors due to phase differences between the sound pressure and particle velocity may enter into the calculations, and also the assumption of a "point" source may no longer be realistic. In practice errors of some 2 dB are considered reasonable. If errors greater than this are obtained by moving the microphone in a small area around the measuring point more microphone positions are considered necessary.

It might be worth mentioning at this point that the anechoic chamber might consist of f. inst. one reflecting surface (a floor, the ground) while all the other surfaces are completely sound absorbing. The test object should then be

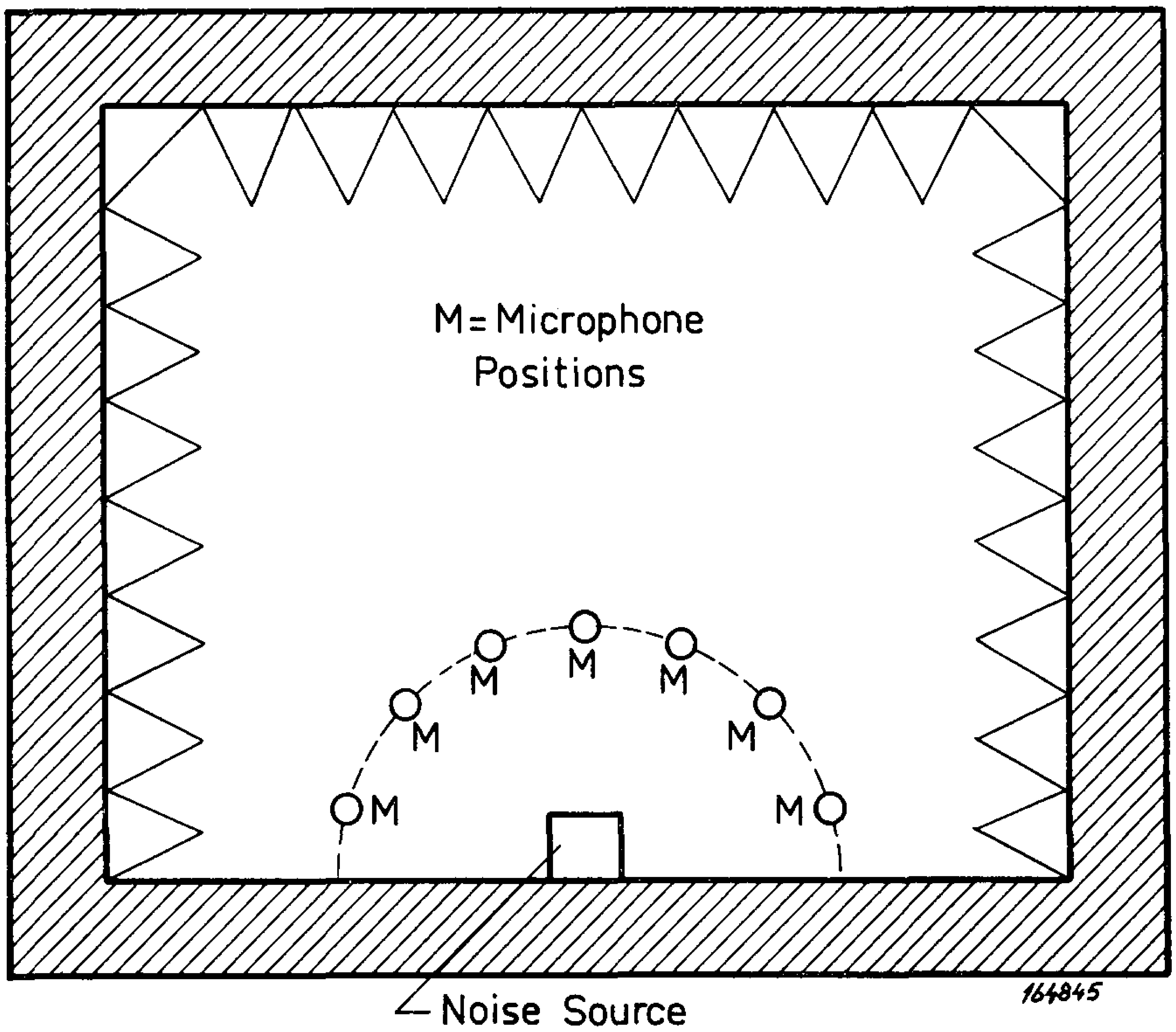

Fig. 3. Example of a "semi" anechoic room having one reflecting surface.

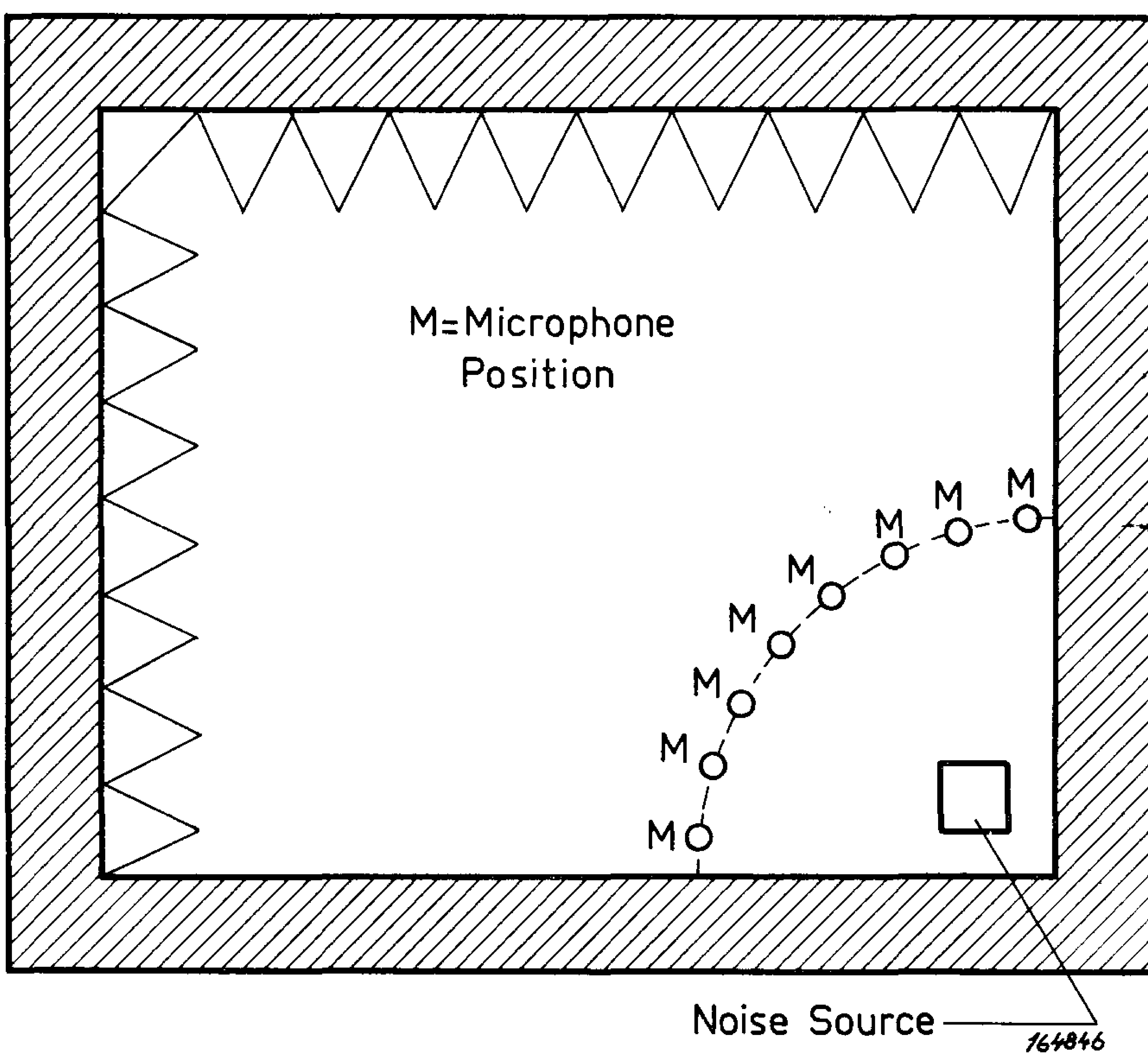

Fig. 4. "Anechoic" chamber with three reflecting surfaces.

placed at least one wave-length away from the reflecting surface, and the integration need only be carried out over half a sphere, Fig. 3. The errors due to reflections are in this case increased considerably due to the highly reflecting floor, and the averaging of the sound pressure over the various areas may be more complicated.

An interesting type of "anechoic" chamber has been designed by Maa in Peking. Here three surfaces are reflecting while the three others are completely sound absorbing. In this way, if the sound source is placed in the corner, Fig. 4, the "anechoic" chamber consists of 1/8 of a sphere. The "simulated" chamber is thus 8 times as big as the actual chamber, and integration need thus only be carried out over 1/8 of a sphere! Again the position of the test object relative to the corner must be carefully chosen when sound power measurements are to be made (the distance from all the three walls in the corner to the test object should be at least one wavelength, ref. 4). Also the sound pressure level will fluctuate considerably with position. If calculations similar to those described above are carried out for this chamber inaccuracies of around 100 % are easily obtained. On the other hand, it would not be realistic to assume that all the sound pressure contributions add in phase and, furthermore, very often the noise source emits a more or less continuous sound spectrum. The errors obtained in practice are therefore normally smaller than those predicted from the above type of estimates.

It is clear from the foregoing discussion that the determination of sound power from measurements in anechoic chambers is fairly complicated and involves a great number of measurements. The other method of sound power measurements mentioned in the beginning of this article, namely the reverberation room method, requires considerably less measuring efforts. By suitable design (and size) of the reverberation room, it may only be necessary to take measurements at one point. This of course, requires that the sound field in the room is completely diffuse, i.e. does not vary very much from place to place. A reverberation chamber that fulfils these requirements is relatively complicated to achieve, and also the size of the chamber must be great (> 200 m^3). The building-up of a diffuse field can be understood from simple considerations, see Fig. 5. In the figure a suitable construction of a reverberation room is shown and also the path of a single "sound ray" is sketched. It is seen that by avoiding parallel surfaces the "ray" will travel around the room in different paths until it is completely absorbed. Due to the reflective properties of the walls, floor and ceiling a great number of reflections occur before a complete absorption has taken place. Conditions quite different from those existing in the "anechoic" chamber, where only the first order reflection was considered important, are thus present in the reverberation room.

The addition of the sound pressure contributions from all the various "rays" at a certain point constitutes the total sound pressure in that point. Considering the various paths and lengths of path of all these "rays" a random averaging effect is obtained and a "mean sound pressure level" measured directly.

When, however, a *standing wave* is set-up, i.e. when a "ray" travels the same "route" all the time and the length of the "route" is equal to an integral multiple of the sound wavelength the sound pressures will add in a very specific manner. The occurrence of these room resonances may disturb the diffusity of the field, and especially at low frequencies, more measuring positions are then necessary. (At low frequencies relatively few distinct room resonances are present, and the space averaging effect (diffusity) is therefore considerably smaller than at higher frequencies where the wavelengths are small and thus a great number of room resonances are built up and averages at "random".)

A good reverberation room should only show sound pressure level variations of $\pm$ 1 to 2 dB with position of the measuring microphone if the noise is of

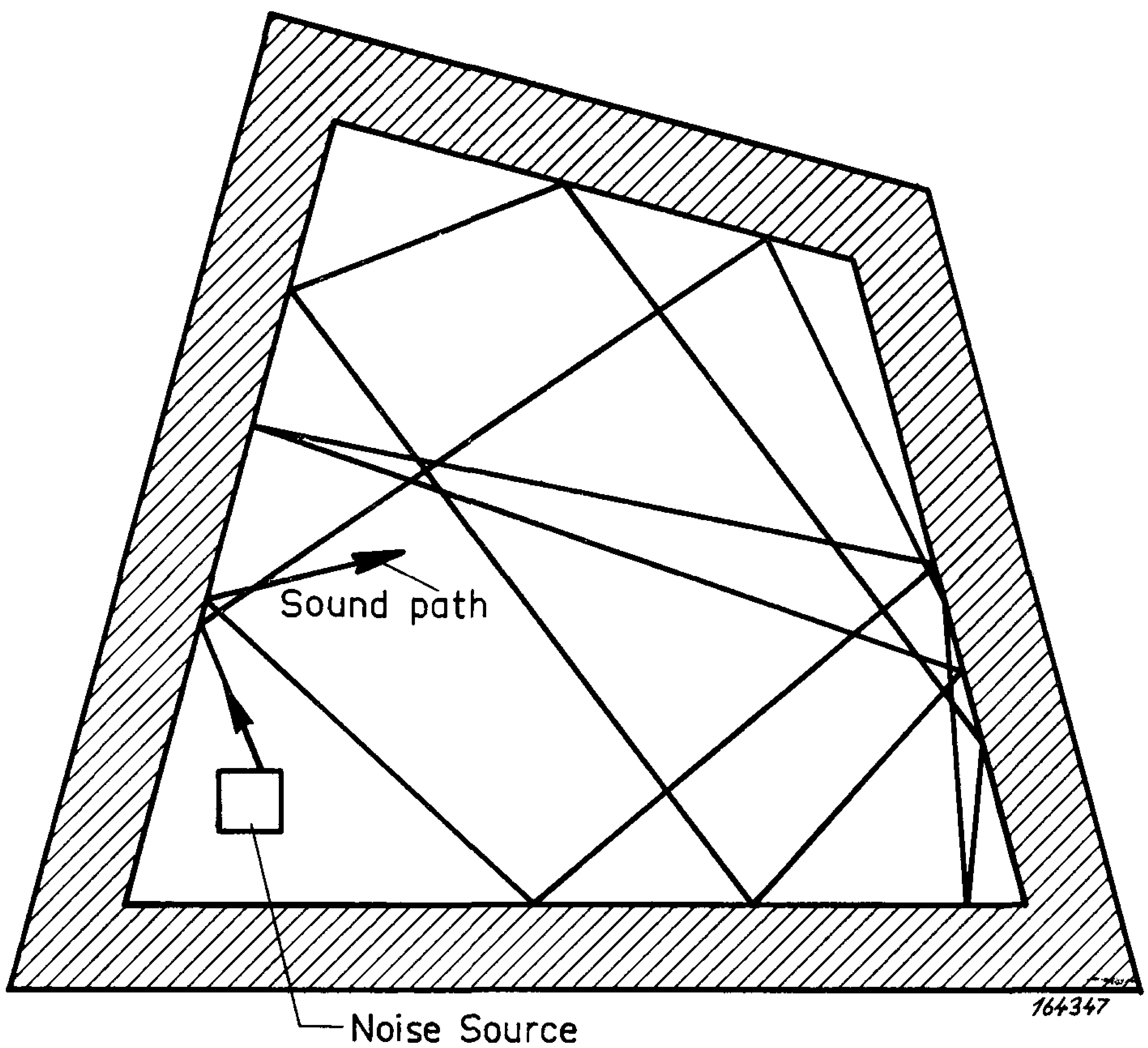

Fig. 5. Illustration of how sound "diffuseness" is obtained.

the continuous spectrum type (see Ref. 2 and 5). However, if the sound emitted from the test object consists of discrete frequencies spread at more than 1 octave level variations of up to some 8 dB may be expected (Ref. 1). From the knowledge of the total room absorption A and the square of the sound pressure the sound power can then be calculated

$$(\text{S.P.} = \frac{p^2}{\varrho_0 c_0} \times A)$$

In all practical sound power determinations the power is thus found from the sound pressure, calculating the sound intensity ($\frac{p^2}{\varrho_0 c_0}$) and multiplying this intensity with the corresponding absorbing area,—or from comparison measurements with a well defined "standard" sound power source.*) An obvious

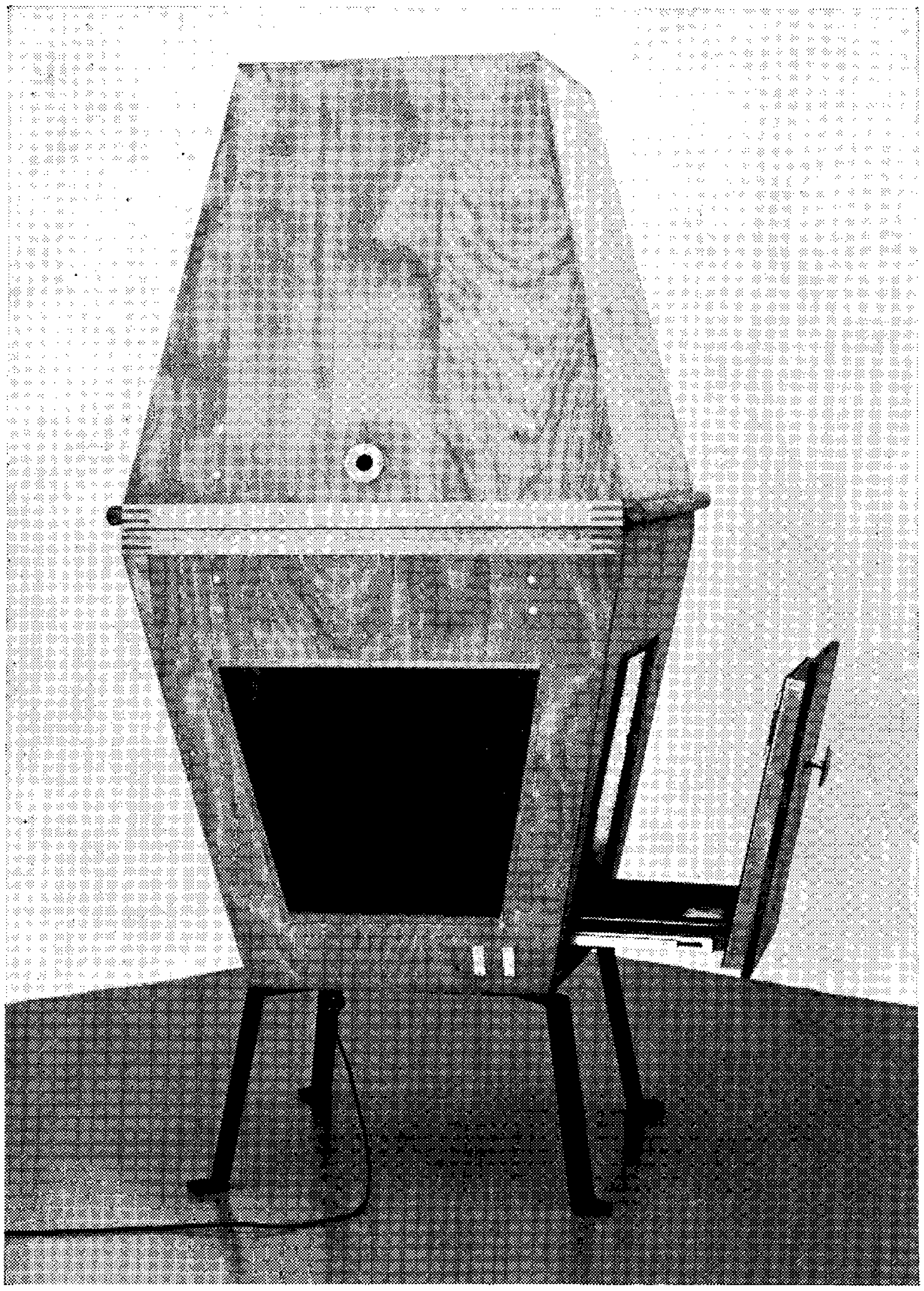

Fig. 6. Photo of the Noise Test Chamber developed at Grünzweig & Hartmann A.G.

requirement for simple calculation is that the acoustic impedance of the absorbing area is known (and preferably not complex).

If now a duct could be made where the sound absorption took place only at the duct termination, and the sound pressure level variation over the terminating area could be made small the determination of the power radiated from

*) In the ASHRAE standard (and other works on sound power measurements) the use of a reference power source is recommended. If, however, the room constant (see bibliography) and the absorbing area of the measuring room could be determined accurately enough the direct method of power calculation would be preferable.

a test specimen placed in the duct would be extremely simple. Actually, this is the philosophy behind the development of the Noise Test Chamber at Grünzweig & Hartmann A.G. Figs. 6 and 7.
Due to its physical dimensions only relatively small noise producing objects can be tested in the chamber. However, when noise measurements are to be made on greater objects it is common practice to test the machine in a position representative of its ultimate mounting.

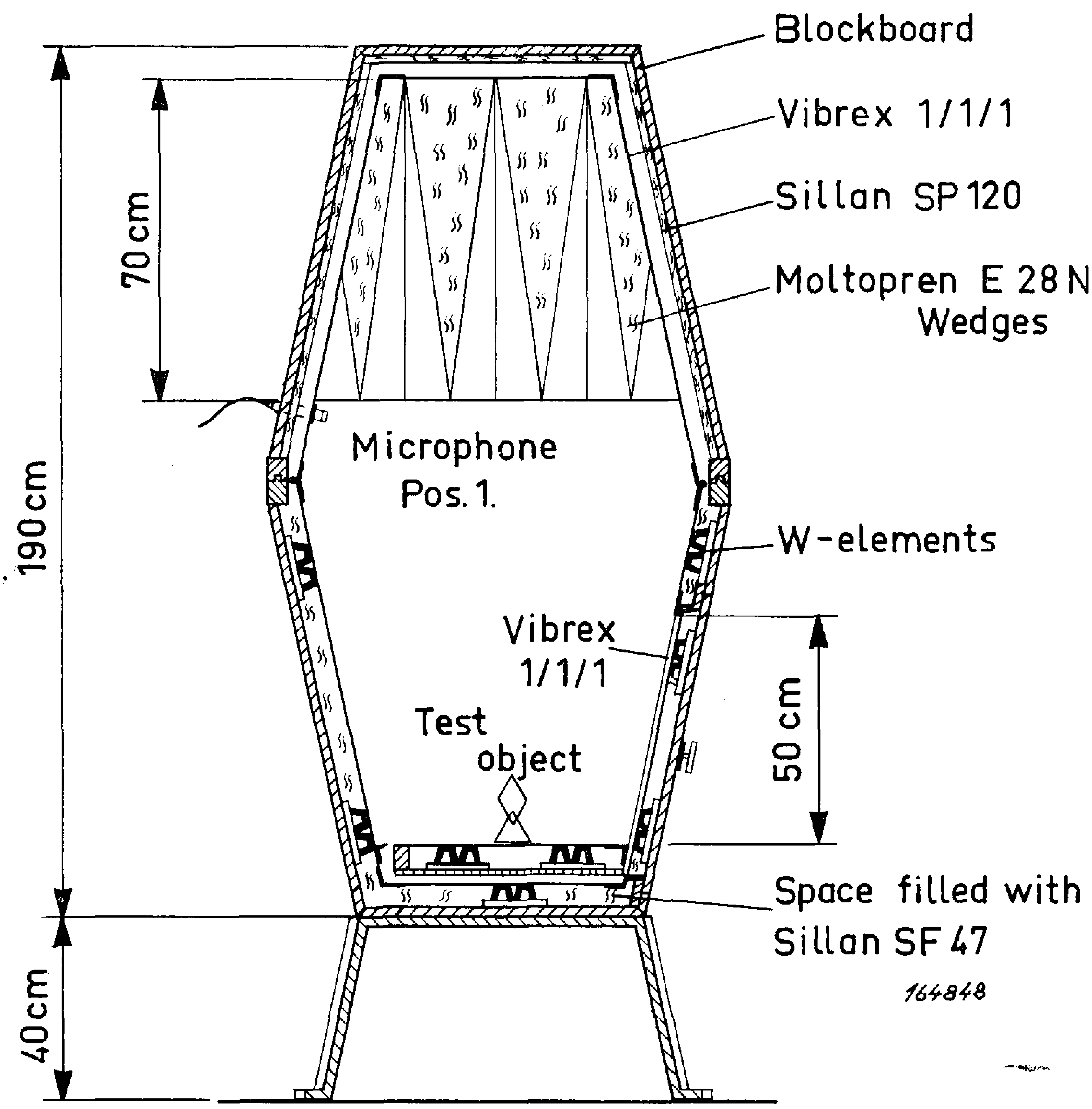

Fig. 7. Sectional view of the Noise Test Chamber.

The "principle of operation" of the Test Chamber is very simple. The test specimen is placed in one end of the "duct" (chamber) which is constructed with acoustically hard (non-absorbing) walls and terminated at the other end by a completely sound absorbing area. Thus, all the sound energy radiated from the test specimen is absorbed in the termination, and by measuring the sound pressure at the absorbing termination, the absorbed energy can be calculated when the area and the acoustic impedance of the termination is known. As the absorbed energy = radiated energy, a single measurement of

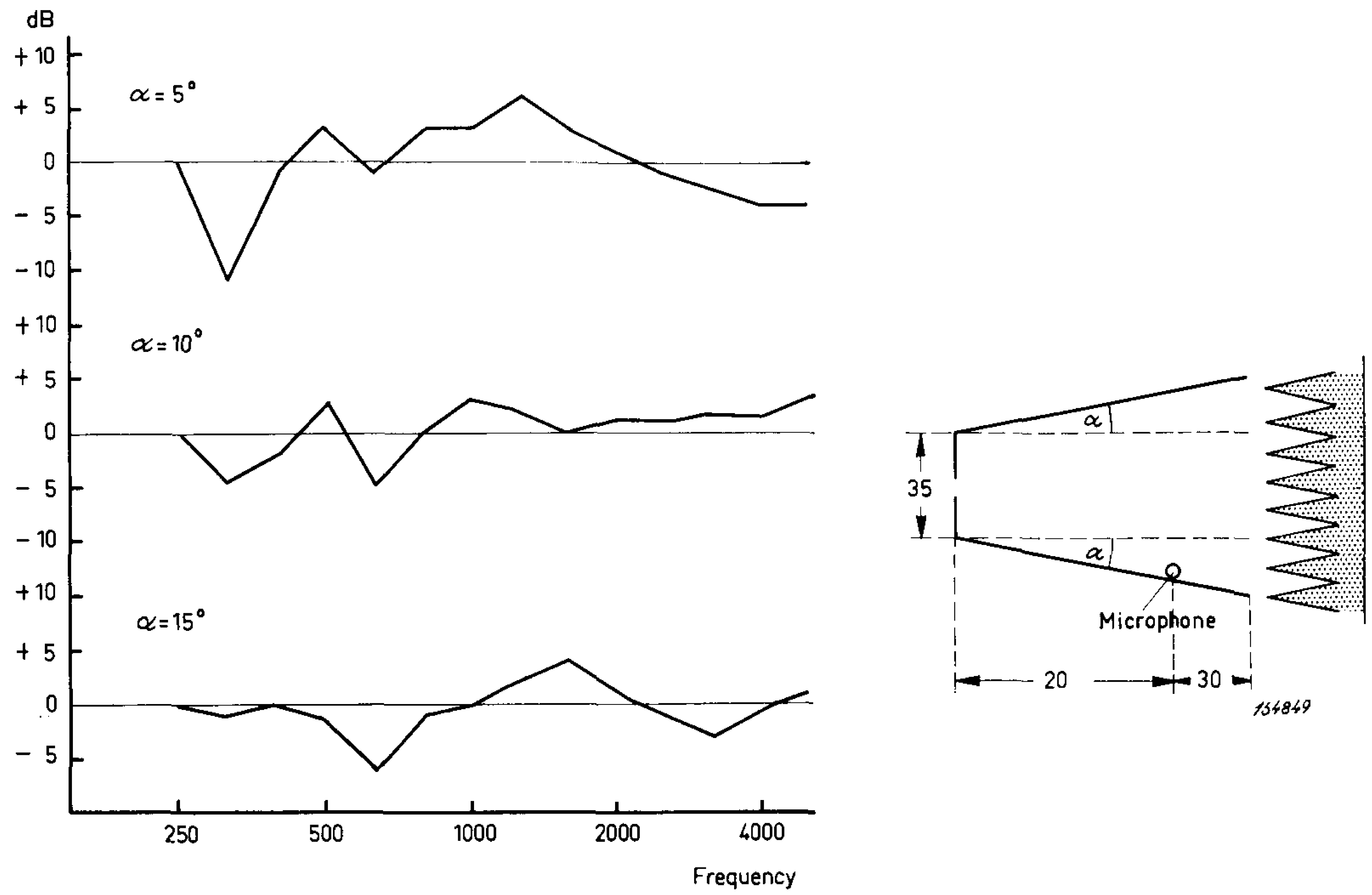

Fig. 8. Results of sound pressure measurements at the walls in the Chamber for various "opening angles".

the sound pressure level at the termination is all that is required to determine the radiated acoustic power from the particular test object being checked.
A number of investigation have, however, been necessary to ensure correct functioning of the chamber. Firstly, the sound field at the walls in the duct

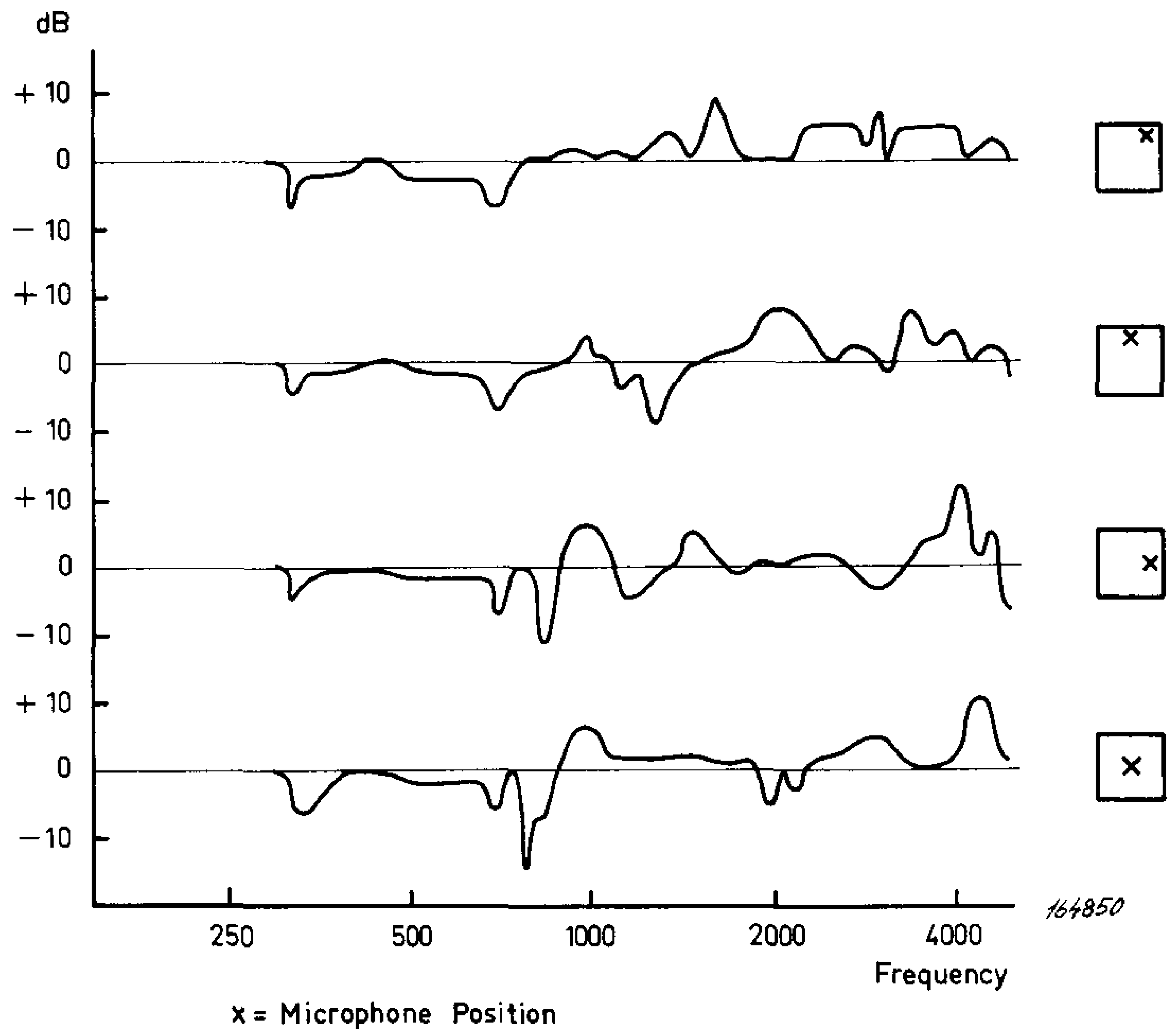

Fig. 9. Results of measurements at various places in the chamber cross sectional area.

was measured for various "opening angles", Fig. 8. In the figure the variation in sound pressure level at an arbitrary point at the duct wall is shown as a function of frequency. From these measurements it was decided to use an "opening angle" for the duct of 10°, which gives frequency response deviations smaller than $\pm$ 5 dB. Fig. 9 then shows the deviation from the ideal sound

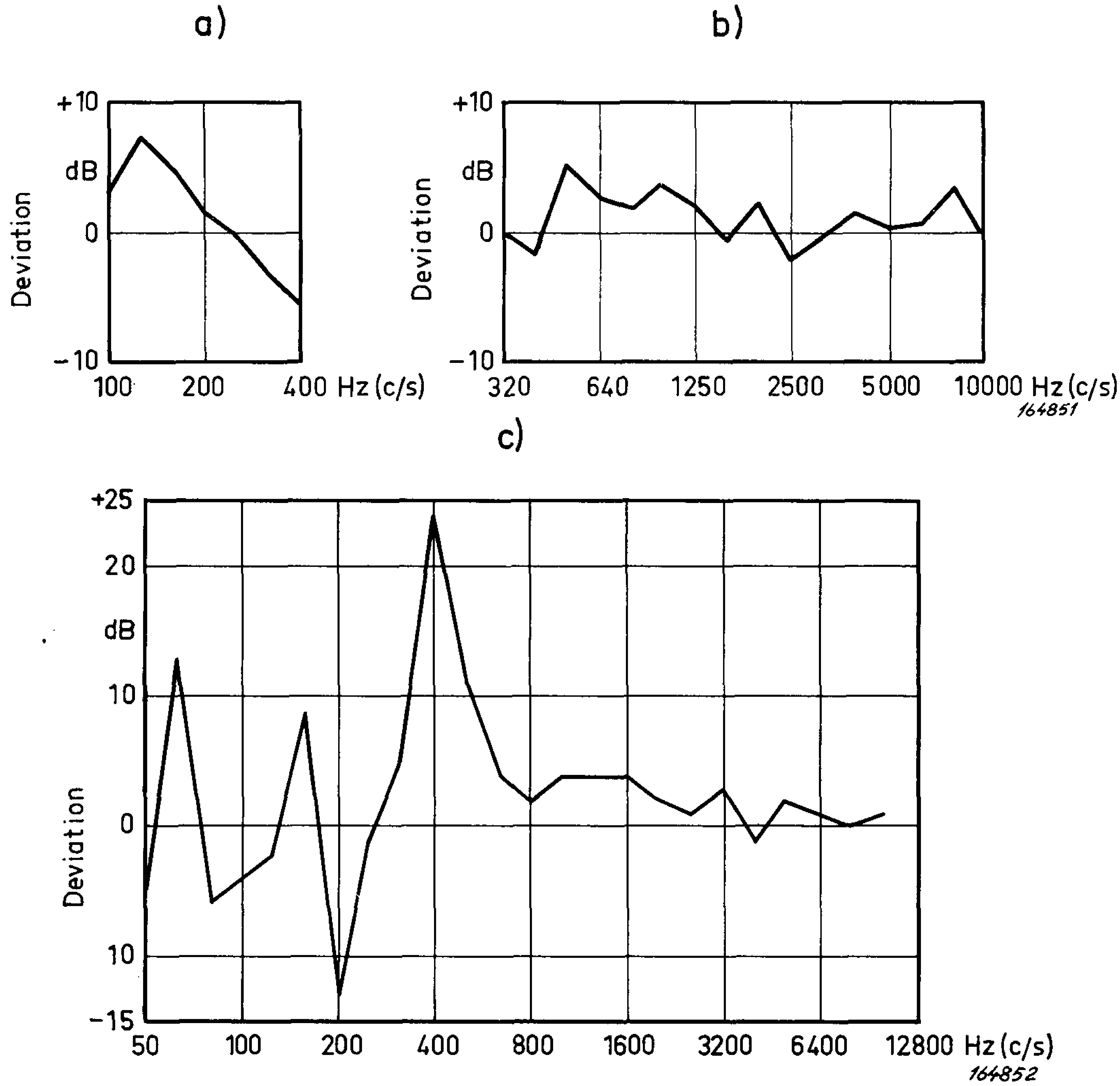

Fig. 10. Comparison of sound power data measured in the Noise Test Chamber and in a reverberation chamber ($V = 188$ m^3)
a) Sound Source = Third octave bands of random noise.
b) Sound Source = Mechanical rattling mechanism.
c) Sound Source = "Pure" tones from horn.

pressure distribution vs. frequency for pure tones at various places in the duct's cross-sectional area with correct termination and an "opening angle" of 10°.

It has been found that by placing the microphone in one of the corners of the chamber (duct) reliable measurements of sound power can be made at higher frequencies, i.e., at frequencies where the human ear is most sensitive to disturbing sounds.

This has furthermore been verified by comparing results obtained from measurements in a large reverberation chamber with results obtained from measurements in the Noise Test Chamber, Fig. 10. It can be seen that the results obtained from measurements in the Test Chamber deviate by less than some 5 dB from the "true" sound power level in the medium and high frequency range.

The cross-sectional area of the chamber termination is 8000 cm^2. Thus the total radiated power in each octave band is found by multiplying the intensity $\left(\frac{p^2}{\varrho_0 c_0}\right)$ in W/cm^2 by 8000.

Sometimes it is not the radiated power, but the sound pressure level at a certain specified distance away from the test object that is to be specified. By subtracting 12 dB from the level measured in the Test Chamber described above, the result of measurements in a G & H Chamber can be reduced to indicate the average S.P.L. at a distance of 1 m away from the source when the source is placed in a free field. The subtraction of 12 dB is necessary because in the G & H Chamber the total sound energy is concentrated within

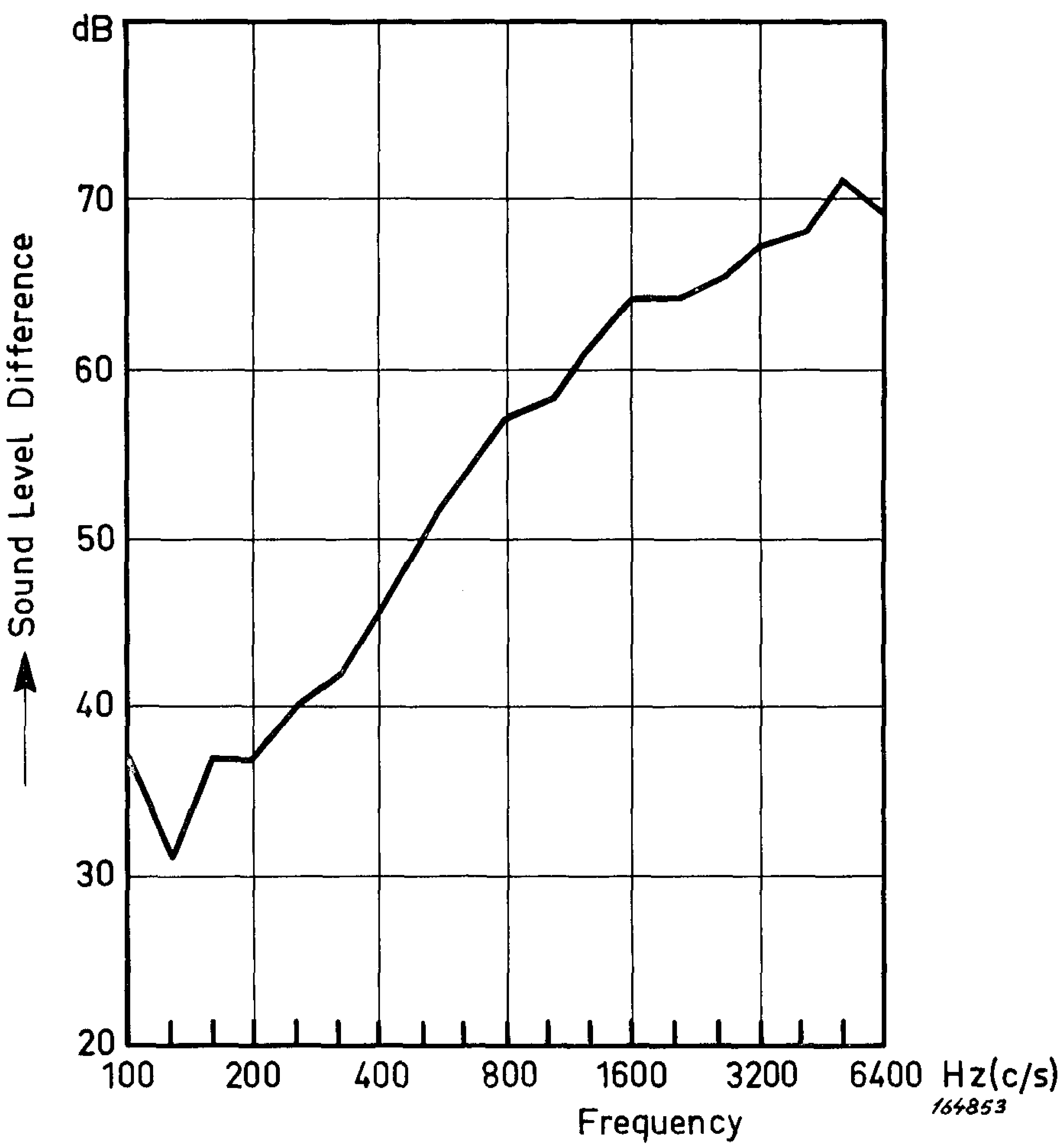

Fig. 11. Typical sound insulation properties of the Chamber measured by means of 1/3 octave bands of random noise.

the cross-sectional area of the duct instead of being spread out on the surface of a sphere with a radius of 1 m.

The microphone built into the chamber is isolated against mechanical vibrations. Also it may sometimes be necessary to isolate the object under test from the chamber and where it is placed, due to undesired radiation from the acoustically hard chamber walls when vibrations are transferred from the test object to the chamber. A soft rubber plate or foam nylon may be used for this purpose.

However, because such materials are good sound absorbers at high frequencies, the rubber (or foam) area should not be greater than absolutely necessary to mechanically isolate the test object from its "foundation" (chamber end).

To isolate the measuring chamber itself from ambient noise a double-wall construction has been used. The inner wall is made of Vibrex-sandwich metal plates which exhibit very high internal damping properties, and sound insulation properties as illustrated in Fig. 11 have been obtained. Also the high internal damping of the sandwich-plates tend to reduce the transmission of mechanical vibrations which could possibly upset the measuring result.

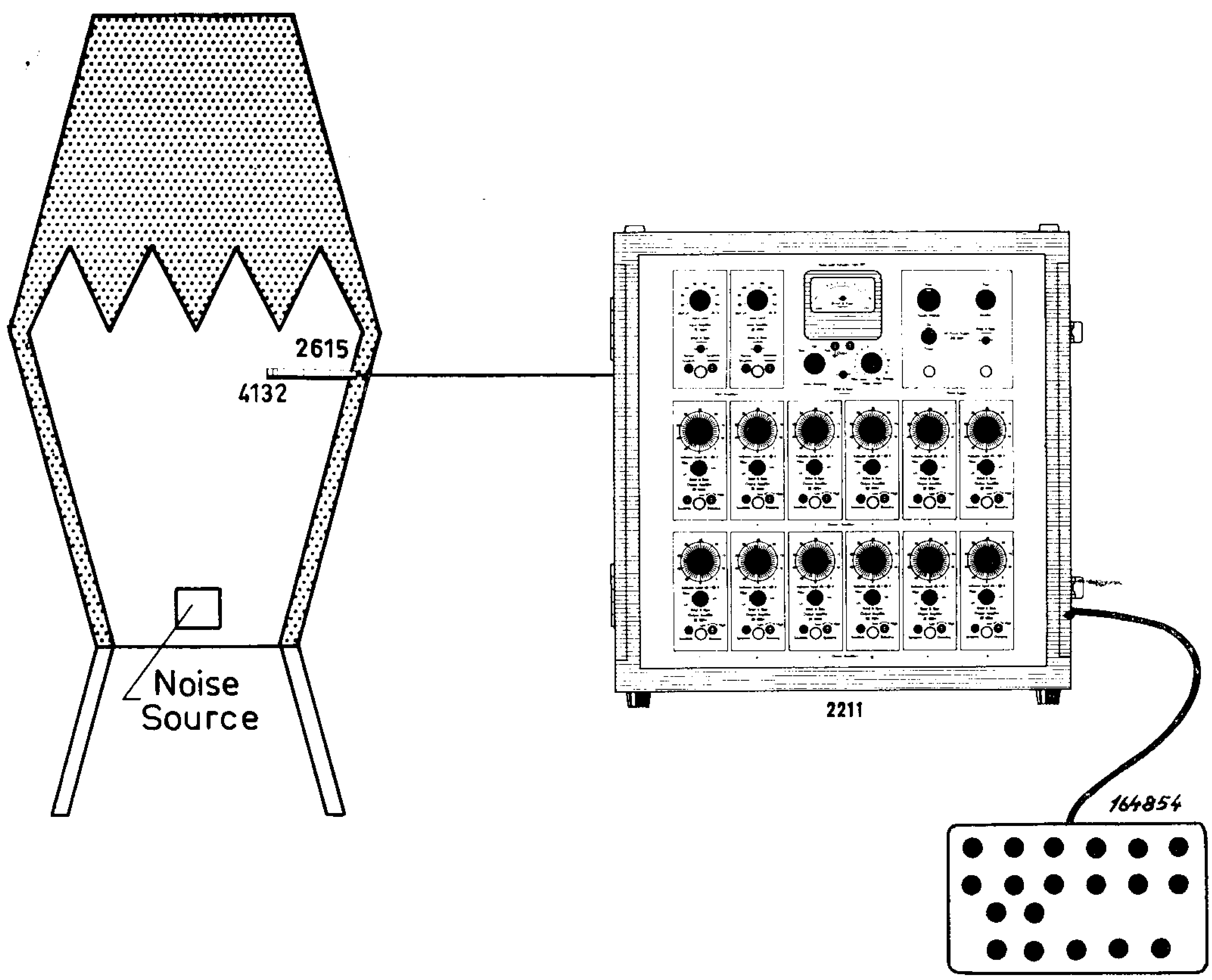

Fig. 12. Measuring arrangement suitable for the production control of noise radiated from small appliances.

The chamber is fitted with a window (of a construction which gives a very high sound insulation) and can be illuminated so that it is possible to watch the behaviour of the test object during measurements. A special mains voltage connection arrangement allows the test object to be powered from the mains during test. In the standard model the opening through which the test-object is placed in the chamber is 51 × 48 cm. If the test chamber is mounted in a place where the mechanical vibrations of the floor tend to disturb the measured results it can be isolated from the floor by means of ordinary vibration isolators.

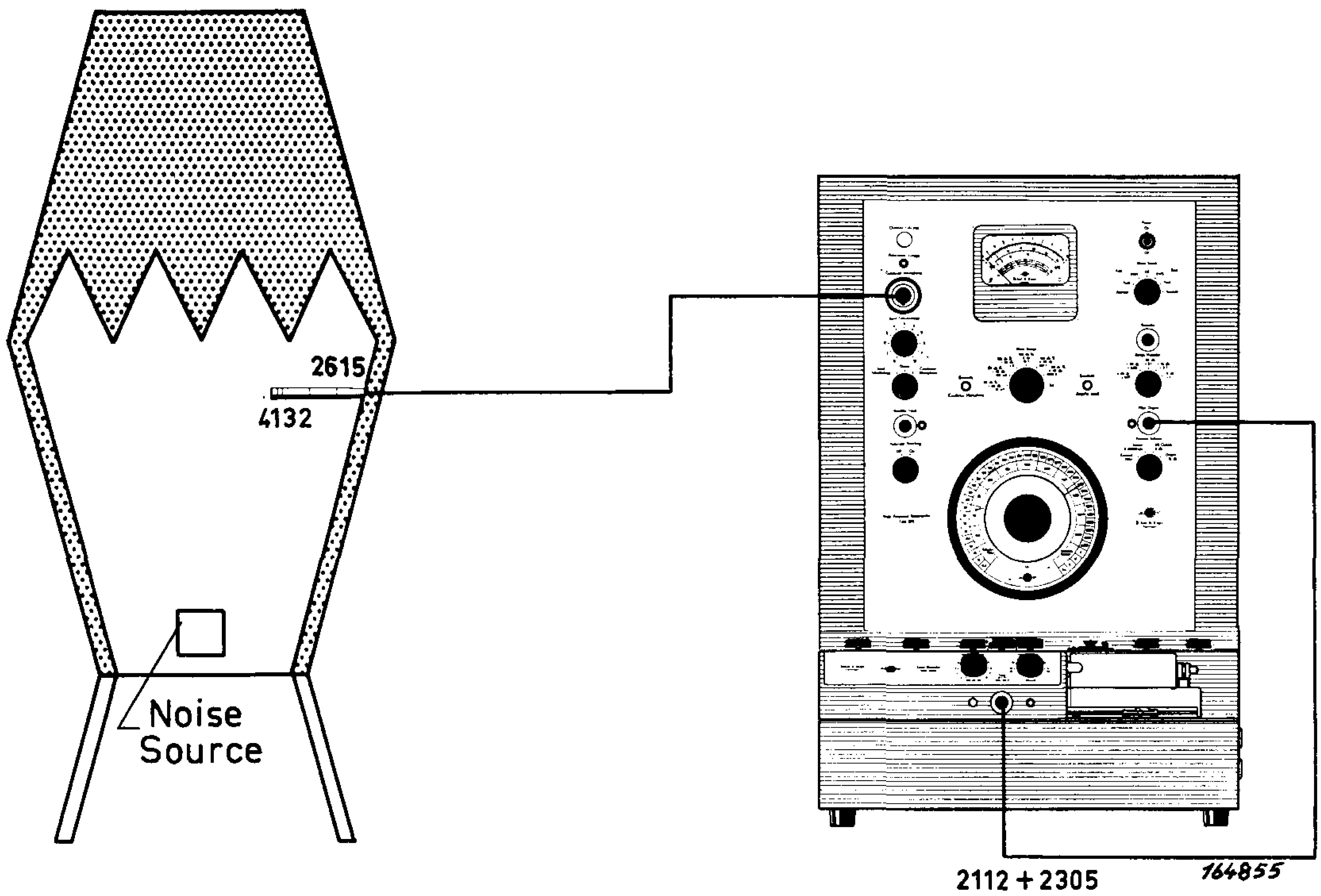

Fig. 13. Arrangement by means of which a written spectrogram can be recorded automatically for each test (or test specimen).

Finally, some typical measuring arrangements which are used in conjunction with the test chamber will be briefly outlined. Fig. 12 shows a complete production control arrangement consisting of the Test Chamber and the B & K Noise Limit Indicator Type 2211. This instrument divides the input signal from the microphone into 12 frequency groups. The groups can be chosen freely and may be 1/3 octave or 1/1 octave wide according to which is considered necessary for the test in question. All groups are supplied with separate level regulators and indicators, and the level is normally preset, by the engineer in charge of the test program, according to data obtained from laboratory investigations. As soon as the noise emitted from the test object exceeds the preset level in one or more of the frequency groups, the corresponding indicator lights up. In this way an extremely rapid and well defined noise check

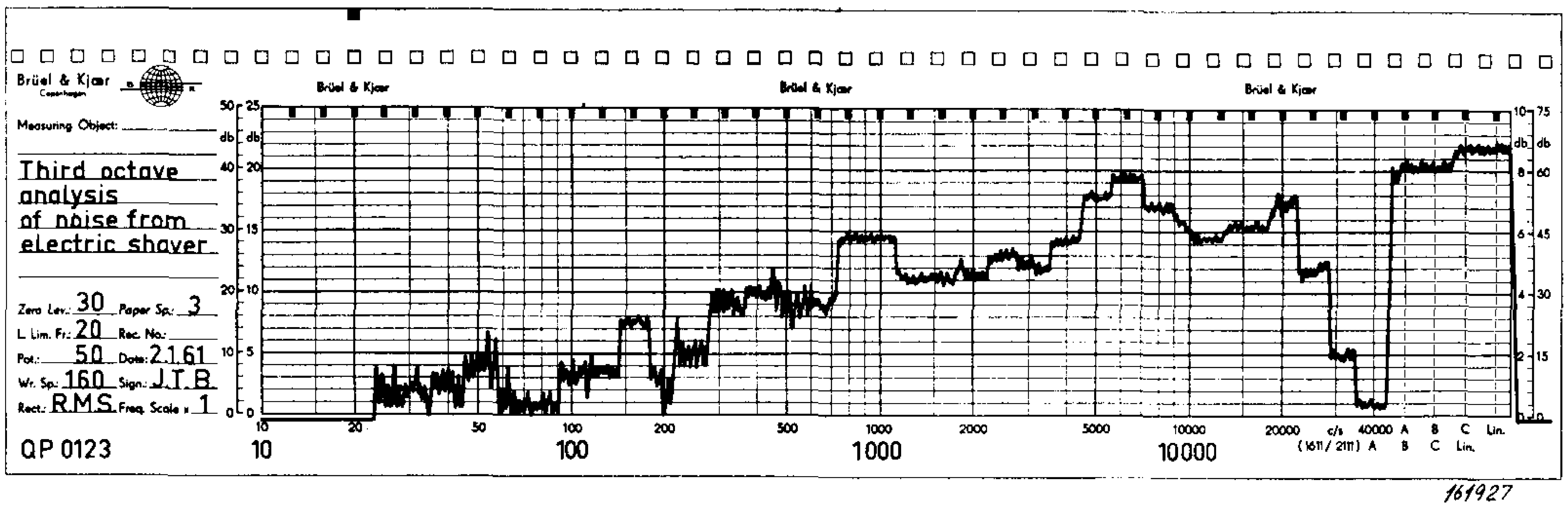

Fig. 14. Typical 1/3 octave noise spectrogram obtained from measurements with an arrangement of the type shown in Fig. 13.

can be carried out. Should it be required to obtain a written record of the noise spectrum produced by each of the objects under test, the Noise Limit Indicator can be substituted by an Audio Frequency Spectrometer and Level Recorder, Fig. 13. The Spectrometer can be automatically driven from the Level Recorder so that a complete sound pressure level vs. frequency curve can be recorded automatically on precalibrated chart paper. The frequency analysis can be made either as 1/3 octave analysis or as 1/1 octave analysis according to the setting of the Spectrometer function selector. Fig. 14 shows a typical 1/3 octave spectrogram obtained from measurements on an electric shaver.

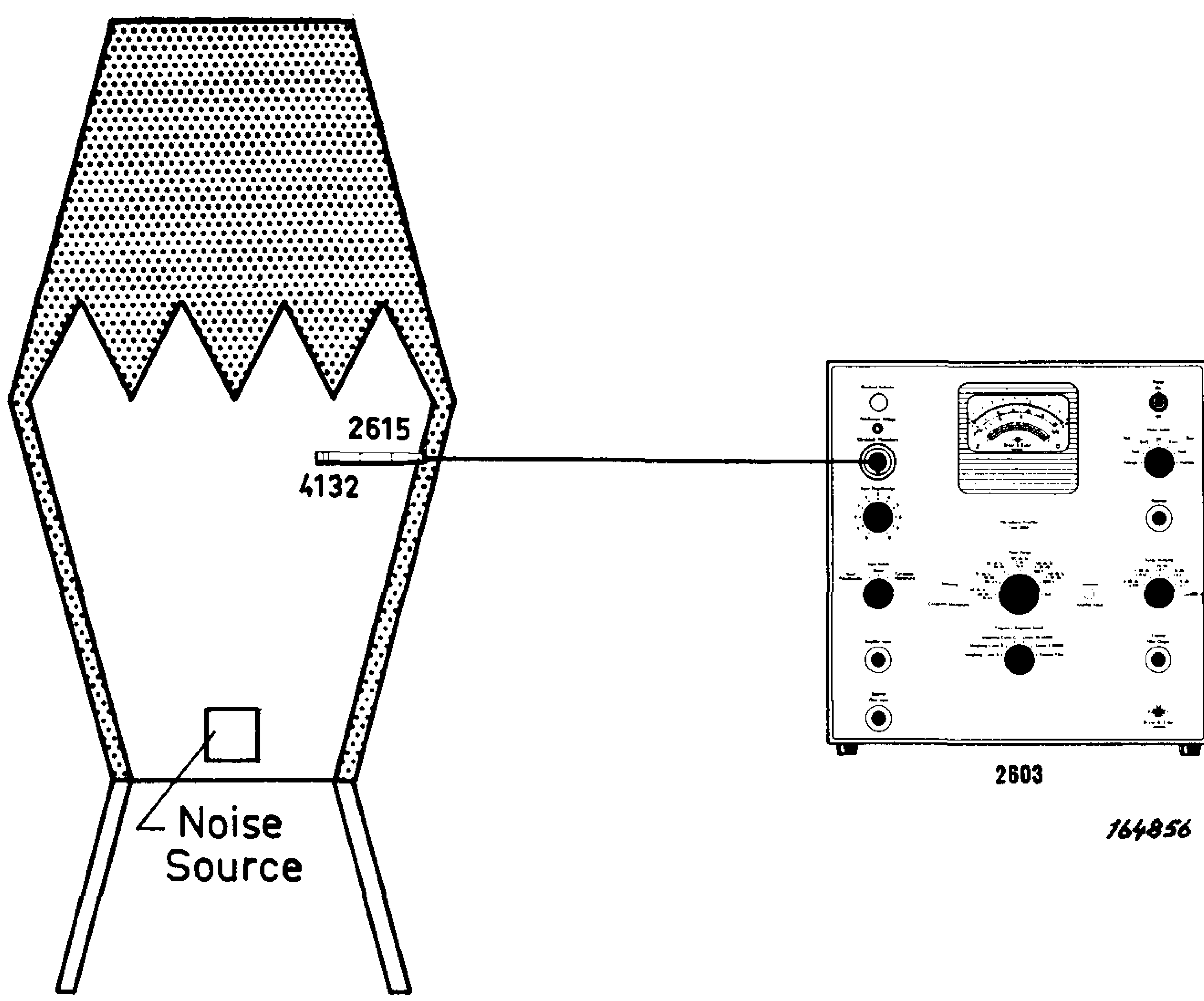

Fig. 15. Measuring arrangement suitable for determining the o v e r a l l *sound produced by the test object. This arrangement can, if desired, be extended to an arrangement as shown in Fig. 13 by adding a Band Pass Filter Set Type 1612 and a Level Recorder Type 2305.*

It may be mentioned at this point that normally spectrograms of the type shown in Fig. 14 are measured on the prototype of the product, and from the spectrogram the allowable noise limits are determined. These limits are communicated to the production control engineer who uses them to adjust a Noise Limit Indicator. The Noise Limit Indicator is then employed in the actual production control process.
If it is considered unnecessary to control the *spectrum* of the noise emitted from the product, and that an *overall sound level* measurement will be sufficient for the production control, this can be made by means of the arrangement shown in Fig. 15. Here the Noise Limit Indicator (or Spectrometer + Level Recorder) is substituted by a Microphone Amplifier. In this case it is necessary for the operator to watch the deflection of a meter pointer and ensure that the deflection is smaller than some pre-determined value. The setting of the Amplifier (frequency weighting, sound level range) is normally carried out by the control engineer.
In the foregoing text the design and use of a small size Noise Test Chamber has been discussed. Even though the production control of noise must be considered to be in its infancy it is reasonable to assume that this kind of control will gain widespread use in the future. People are in general becoming more noise reduction minded than ever, and the number of noise producing elements in daily life is increasing rapidly. If effective noise control is not performed, it might be a doubtful pleasure to live with all the technical advancements which may be achieved over the coming decades.

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An Introduction to

Sweep Random Vibration

By *Jens T. Broch,* Dipl. Ing. E.T.H.

ABSTRACT

The "historical" background of random vibration testing is reviewed and concepts related to this kind of test technique described. Various kinds of spectrum equalization used in wide band random tests are outlined and the advantages and disadvantages of the different equalization methods briefly discussed. Due to the complexity and cost of wide band test systems less complex substitutes for the test have long been sought. One such substitute originally proposed by M. W. Oleson of the Naval Research Laboratory (U.S.A.) seems very promising. This is the method of sweep random vibration which actually constitute a compromise between a wide band random test and a sweep sine test. The basic ideas underlying the test are described with specific emphasis on the probability distribution matching in linear resonances. In an Appendix the actual setting up of a sweep random vibration test is outlined.

SOMMAIRE

Après un court historique de la technique des essais aux vibrations aléatoires, les principes qui y sont utilisés sont décrits. Les différentes méthodes employées pour l'égalisation spectrale en essais à large bande sont rappelées et leurs avantages et inconvénients sont discutés brièvement. En raison de la complexité et du coût des systèmes d'essais en bande large des méthodes moins exigantes en équipement ont été à l'étude depuis longtemps. Une telle possibilité qui a été originalement proposée par M. W. Oleson du Naval Research Laboratory (USA) semble particulièrement prometteuse. Il s'agit de la méthode des vibrations aléatoires en bande balayée qui se présente comme un compromis entre les essais en large bande et les essais en régime sinusoïdal à fréquence glissante. Les idées fondamentales de cette méthode sont décrites, une attention spéciale étant donnée aux distributions d'amplitudes obtenues sur résonances linéaires.
La réalisation pratique d'un essai aux vibrations aléatoires balayantes est indiquée en appendice.

ZUSAMMENFASSUNG

Mechanische Schwingungen können gefährliche Schäden an Luft- und Straßenfahrzeugen sowie an stationären Maschinen verursachen. Die Schwingprüfung ist hier ein vorbeugendes Mittel. Ursprünglich wurde sie ausschließlich mit sinusförmigem Signal durchgeführt. Mit der technischen Entwicklung treten in zunehmendem Maße stochastische Schwingungen auf, deren Nachahmung auf dem Schwingprüfstand das technische Problem der Entzerrung entgegensteht. M. W. Oleson vom Forschungslaboratorium der US-Marine hat vorgeschlagen, anstelle eines breitbandigen Signals schmalbandiges Rauschen anzuwenden. Unter bestimmten Voraussetzungen läßt sich hiermit die gleiche Beanspruchung erzwingen wie mit einem breitbandigen Signal. Ein geringerer technischer Aufwand ist der Hauptvorteil des neuen Verfahrens, zu dessen Durchführung Brüel & Kjær die Steuergeräte Typ 1040 und 2501 entwickelt hat.

Introduction.

Equipment used in conjunction with reciprocating engines and units otherwise subject to shock and vibration have for many years been tested for their ability to withstand such environments. Specific shock and vibration test specifications have been issued by various authorities in an effort to ensure that the product operates properly under these conditions, and a great amount of research and development has been carried out to make the specifications effective enough without being too stringent.

The seriousness of malfunctions is greatest in moving, manned vehicles where human life is at stake. It is therefore quite natural that the development of vibration test techniques and specifications are closely connected to the development of fast moving vehicles like automobiles, aircraft and space vehicles.

As long as the vehicles were powered by reciprocating engines and the speed was not *too* high, vibration testing was carried out by means of sine-wave vibration signals of relatively low frequencies. As the ability of the vehicles to move faster and faster was developed, the frequency range over which vibration tests had to be carried out increased and the test-technique became more and more refined.

The advent of jet-propulsion of high-speed aircraft, and rockets, however, introduced a completely new type of vibration environment. It was no longer satisfactory to test the critical units (or complete structures) by means of slowly sweeping sinusoidal vibration signals. The vibration excitation of the jet, and the air turbulence caused by very fast moving structures, shows characteristics which are widely different from "simple" periodic motion. The excitation frequency spectra of these types of vibration environments are more or less continuous, and the instantaneous amplitude distributions can only be described with the aid of probability concepts. This called for a completely new test technique, *the technique of random vibration.*

In June 1955 C. T. Morrow and R. B. Muchmore (USA) presented a paper "Shortcomings of Present Methods of Measuring and Simulating Vibration Environments" at the Diamond Jubilee Semi-Annual Meeting of the Applied Mechanics Division of the ASME in Boston. In this paper it was suggested that "facilities for applying complex waves to vibration tables should be made generally available as soon as possible", and that proper random vibration test specifications should be derived on the basis of measured vibration environment. Two methods of producing a random signal to control the vibration exciter (table) were mentioned. One was to use tape-recorded, actually measured vibration signals, and the other to use an electronic noise generator with a flat power spectral density spectrum and possibly "shape" the spectrum. To-day, random vibration test specifications are issued from various sources and the specifications are in general based on the use of an electrical, wide-band noise generator as signal source. However, the actual test technique has been subject to considerable changes in the years which have past, and even if the art of random vibration testing is relatively young it has reached a stage of surprising complexity.

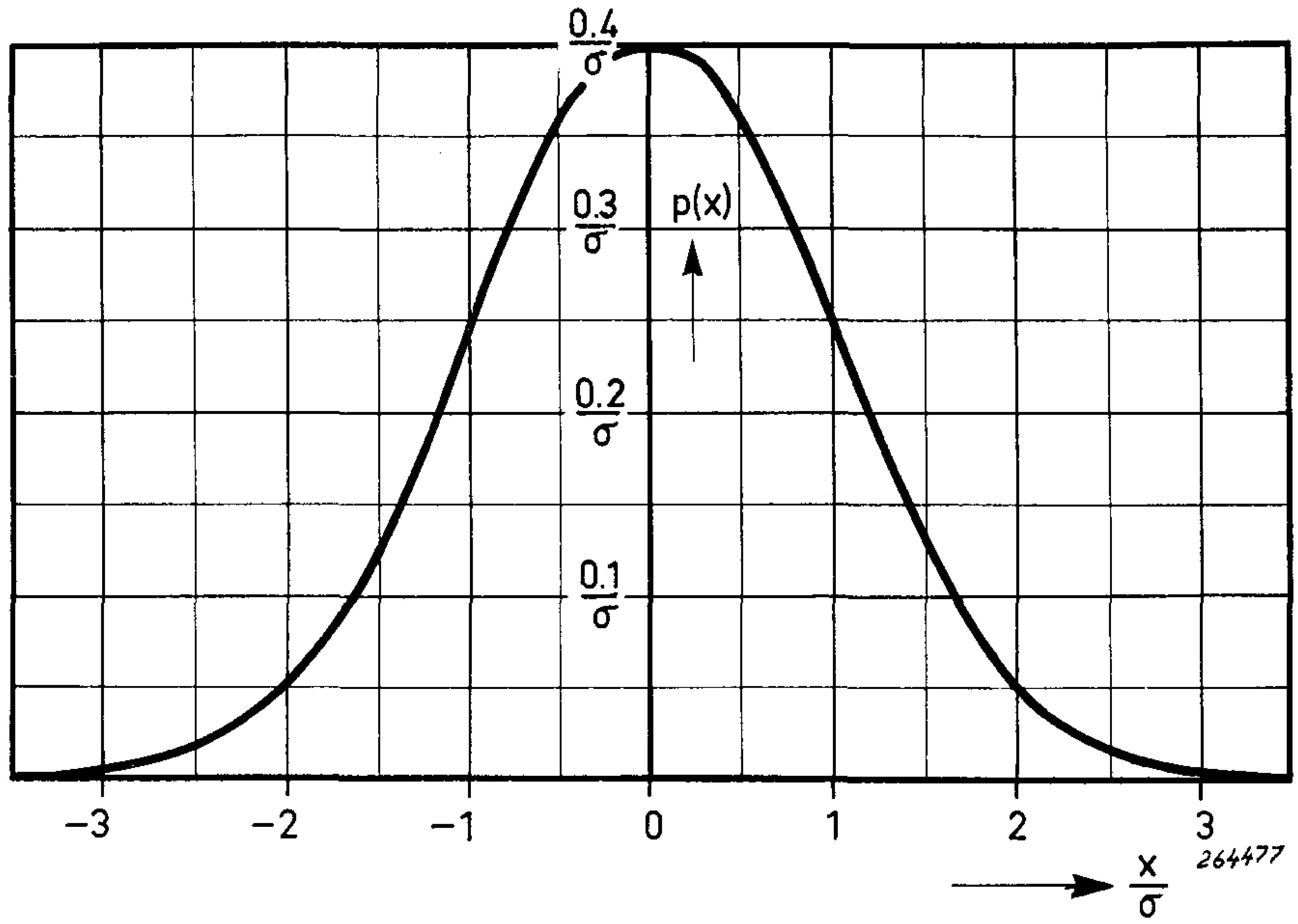

Fig. 1. The Gaussian (normal) probability density function.

Probability Concepts for Random Vibration.

Random motion of a mass can be the result of a very large number of impacts of, say, gas molecules upon the mass, the impacts occurring by chance, and not obeying any periodic law. If the number of events is large enough the *instantaneous* acceleration of the mass will follow a Gaussian (normal) probability law as long as linear relationships hold true. The probability density curve of the instantaneous acceleration is shown in Fig. 1. However, the probability density of occurrence of the *instantaneous* acceleration (or velocities, or displacements) will, from a malfunction point of view, not be the most important characteristic to know. Because malfunctions are almost always caused by acceleration, velocity or displacement *peaks* or in the case of fatigue damage, by the number of high level stress reversals, the *peak distribution* of the motion as well as the actual *frequency of occurrence* of the peaks are two utmost important characteristics. When a single specimen resonance with a relatively high Q-value is being studied these two characteristics are given in that the peak distribution follows, very closely, the so-called Rayleigh-distribution*), Fig. 2, and the frequency of occurrence is simply the resonance frequency. The total number of stress reversals is then equal to the resonance frequency times the period of time (in seconds) that the specimen is exposed to the random vibration environment.

Spectrum Characteristics of a Wide Band Random Vibration Test.

As mentioned earlier in this article one of the typical characteristics of random vibration is that the frequency spectrum is continuous in contrast to the typical line spectrum of periodic motion.

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*) See also B & K Technical Review No. 3-1963.

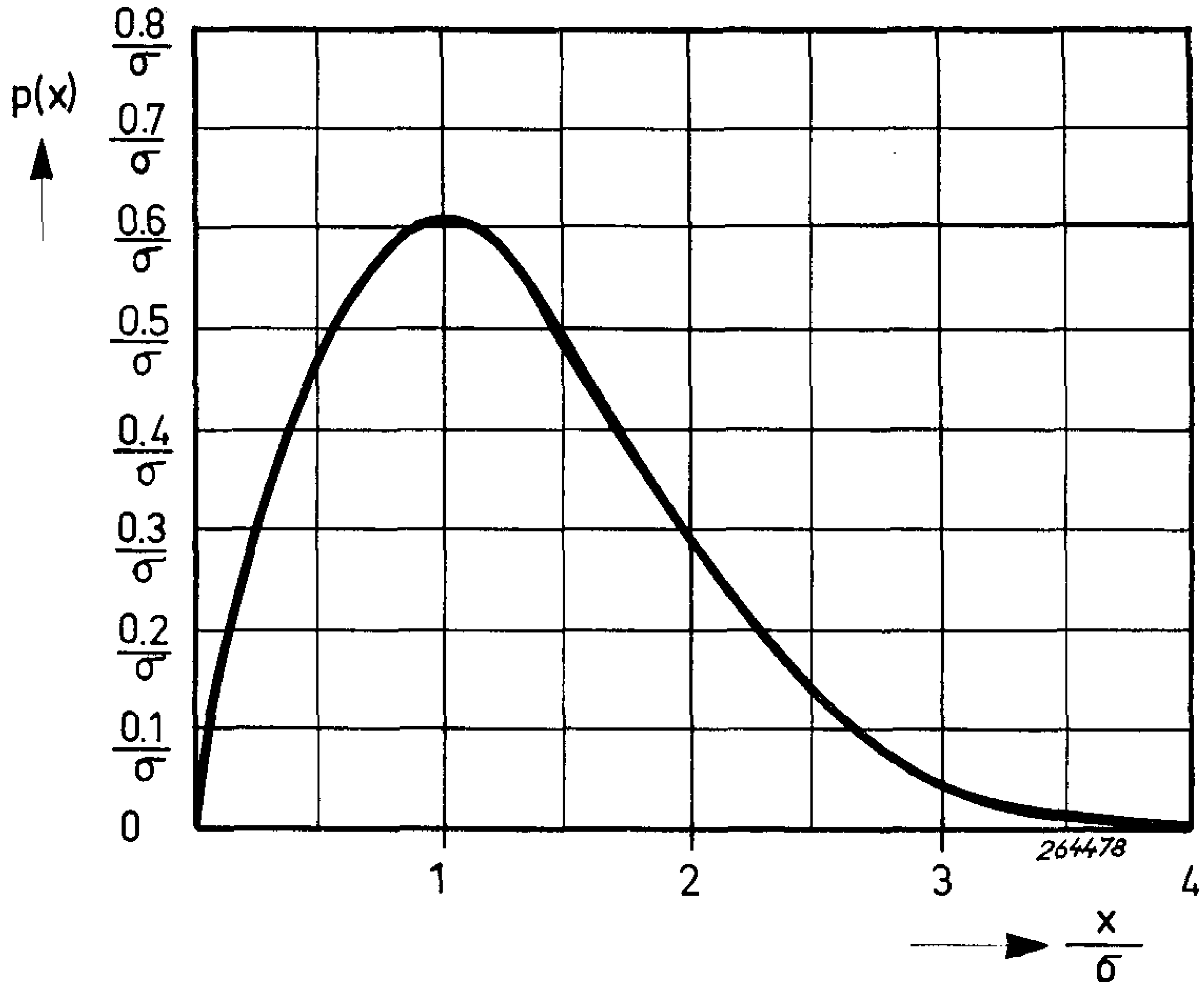

Fig. 2. Rayleigh probability density curve.

Now, what happens when a wide-band continuous spectrum is applied to an electrodynamic vibration machine upon which a certain test specimen is mounted? If the vibrator does not have a mass which is very much greater than the mass of the specimen, the specimen resonances will "work back" on the machine causing the motion of the vibrating table to exhibit a peak and a notch in its vibration spectrum at each specimen resonance, Fig. 3. This means that the excitation of a particular resonance is different from that assumed on the basis of the vibrator input signal spectrum.

During the course of time various methods have been developed to compensate electronically for these peaks and notches. The first method is fairly straight forward and consists of using a number of "peak-notch" equalizers in cascade. Each such equalizer should exhibit the inverse response of one resonance as measured on the vibration exciter table when the system is uncompensated. By using as many equalizers as there are resonances it is possible to achieve a response similar to that given in Fig. 4 (equalized). This shows the resulting vibration of the shaker table when both the frequency non-linearities of the vibration machine itself and those due to specimen resonances are ideally compensated for.

The time spent in adjusting for a particular test is, however, rather great, and other, more feasible methods of compensation have been sought by the producers and users of random vibration test equipment.

One such method is the so-called multiband equalization technique. It involves splitting the test frequency range into a number of discrete filter bands and adjusting the attenuation (or amplification) of each band individually. The adjustment can be performed manually or automatically. In this way it is also a relatively simple matter to "shape" the test frequency spectrum according to any given test specification or for the purpose of further test research.

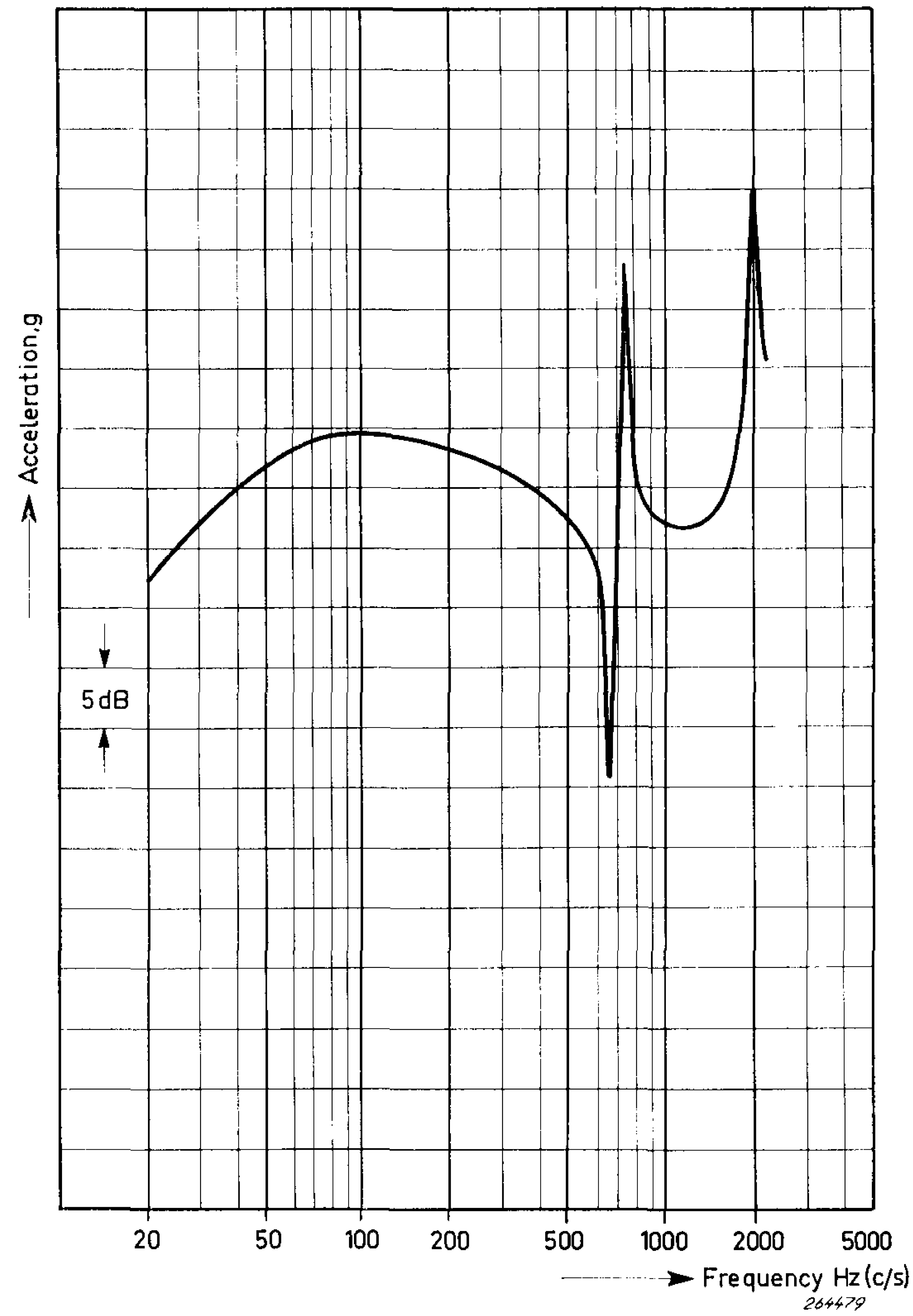

Fig. 3. Typical acceleration level vs. frequency curve measured at the vibration exciter table of an unequalized random vibration test set-up.

A disadvantage of multiband systems is that for a relatively accurate "peak-notch" compensation of complex test specimens a vast number of filters is required. Also, the setting-up time of the manual systems is quite considerable. This time is minimized in the automatic multiband systems, which, on the other hand are rather complex and expensive. *However, one great advantage of using automatic equalization is the automatic correction for the effect of amplitude nonlinearities which is obtained in this case.*

Sweep Random Vibration.

In general wide band random vibration testing is very costly and means to substitute this by a less costly test have been sought ever since its first introduction. Various "equivalent" sweep sine tests have been proposed but since the sweep sine test cannot produce the same distribution of acceleration and stress amplitudes within the test specimen no general equivalence between the

two types of test is ever likely to be found. However, in 1957 M. W. Olesen of the Naval Research Laboratory (USA) proposed a sweeping narrow band random vibration test, a test which actually constitutes a compromise between a wideband random vibration test and a sweep sine test. It operates on the principle of replacing the wideband, low acceleration density excitation with an intense, narrow-band random excitation sweeping slowly over the frequency range of the test. When properly adjusted it will produce the same number of important stresses and acceleration, at each level, as the wide band test.
For a long time the equipment necessary to perform this kind of testing was not commercially available, and very little progress was thus made in the use of the method. In 1960 G. B. Booth (U. S. A.) published the paper "Sweep Random Vibration" where the mathematics of the test were reviewed for the case of linear single degree-of-freedom resonant systems, and an example of the "sweep equivalence" of a prototype wide band test was given. Since then

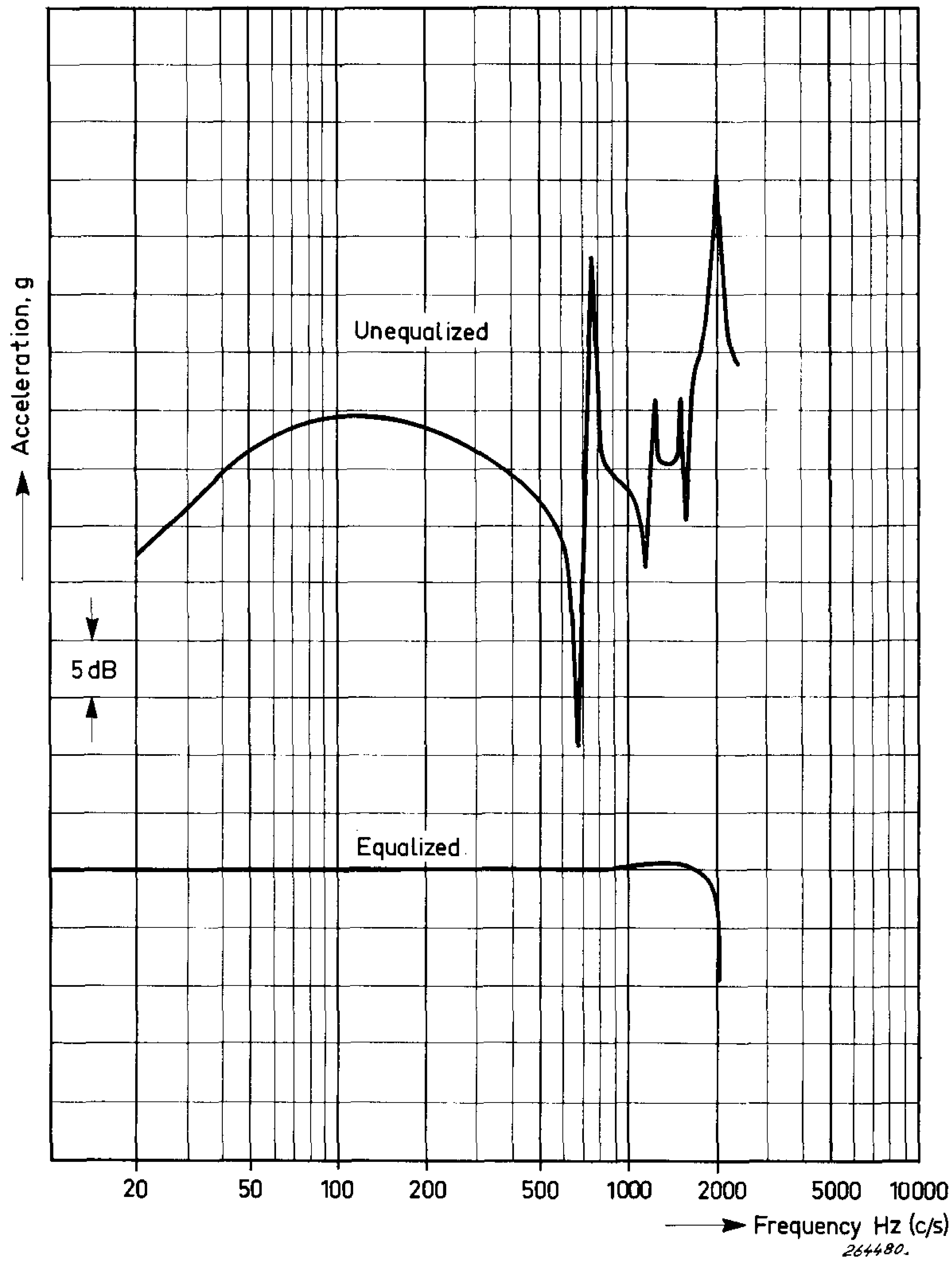

Fig. 4. Effect of proper equalization of the vibration exciter response during a wide-band random vibration test.

the complete control equipment required for sweep random vibration testing has been developed in the form of two units: The B & K Type 1040 Sine-Random Generator, and Type 2501 Vibration Meter.*) Also considerable efforts

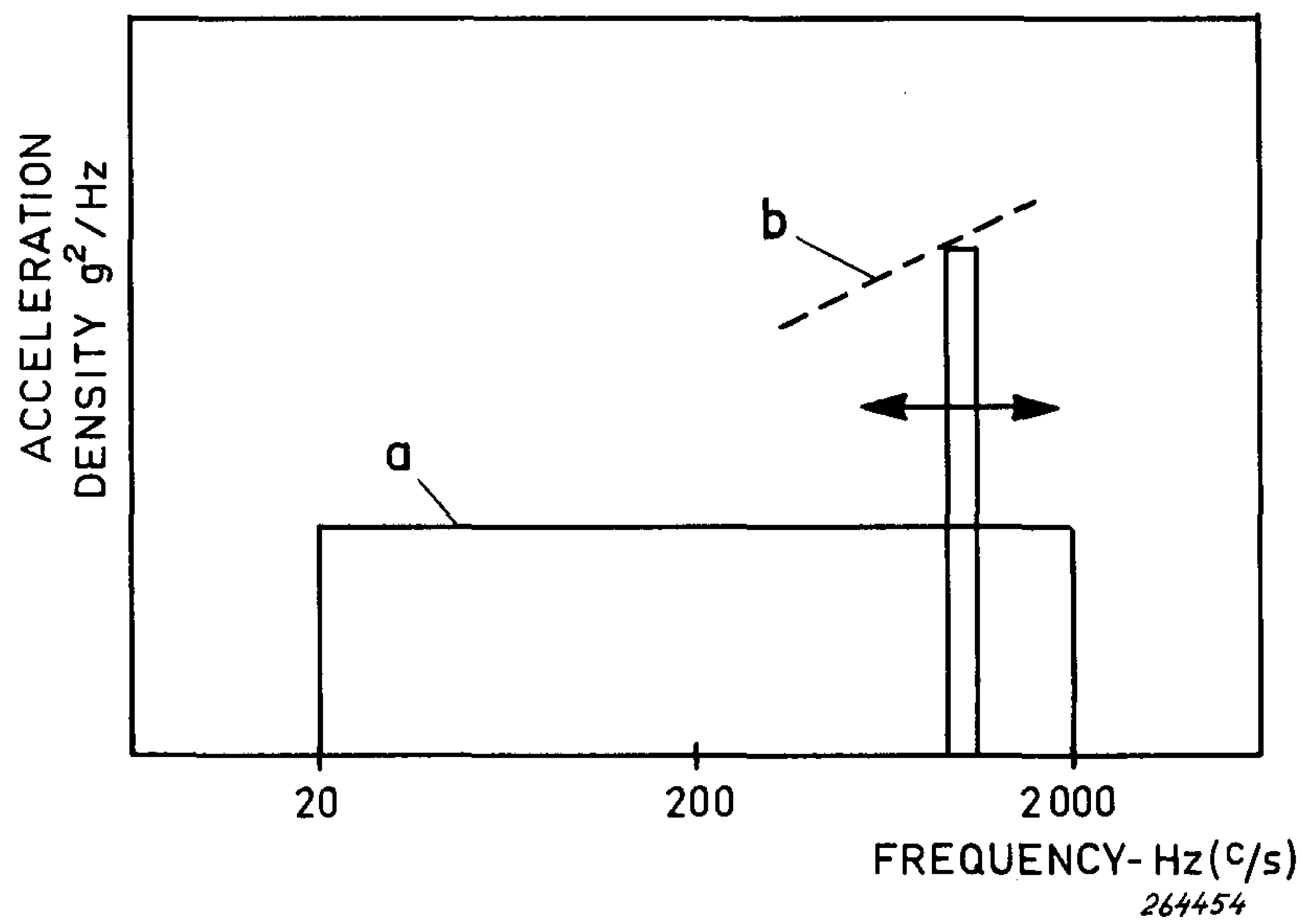

Fig. 5. Variation in excitation spectrum density:
a) Wideband random excitation.
b) Sweep random excitation.

have been, and are being made to evaluate and extend the test. This will be discussed further in articles to follow.

Now, how can, basically, the characteristics of a sweep random vibration test be adjusted to equate those of a wide-band test?

Since damage is normally caused when the test specimen resonates it is important that the response of a specimen resonance is the same whether the specimen is subjected to a sweep random test or to a wide band random test. The adjustment of the sweep random vibration characteristics should thus be made so that they produce the same response at the resonance as would the wide-band test *no matter where in the test frequency range the resonant frequency of the specimen lies.*

As the bandwidth of a resonance having a specific Q-value increases with increasing frequency, it is necessary to increase the sweep speed of the constant narrow band test-noise with frequency in order to obtain the same number of stress reversals inside the resonance as would result from wide band random excitation. A logarithmic sweep rate satisfies this condition, and is therefore used for the test.

The next problem to consider is that of obtaining an equal number of stress reversals *in any increment of stress level* for the two types of test. Again resonances of equal Q but different center frequencies are considered. The

*) See also "News from the Factory", p. 32.

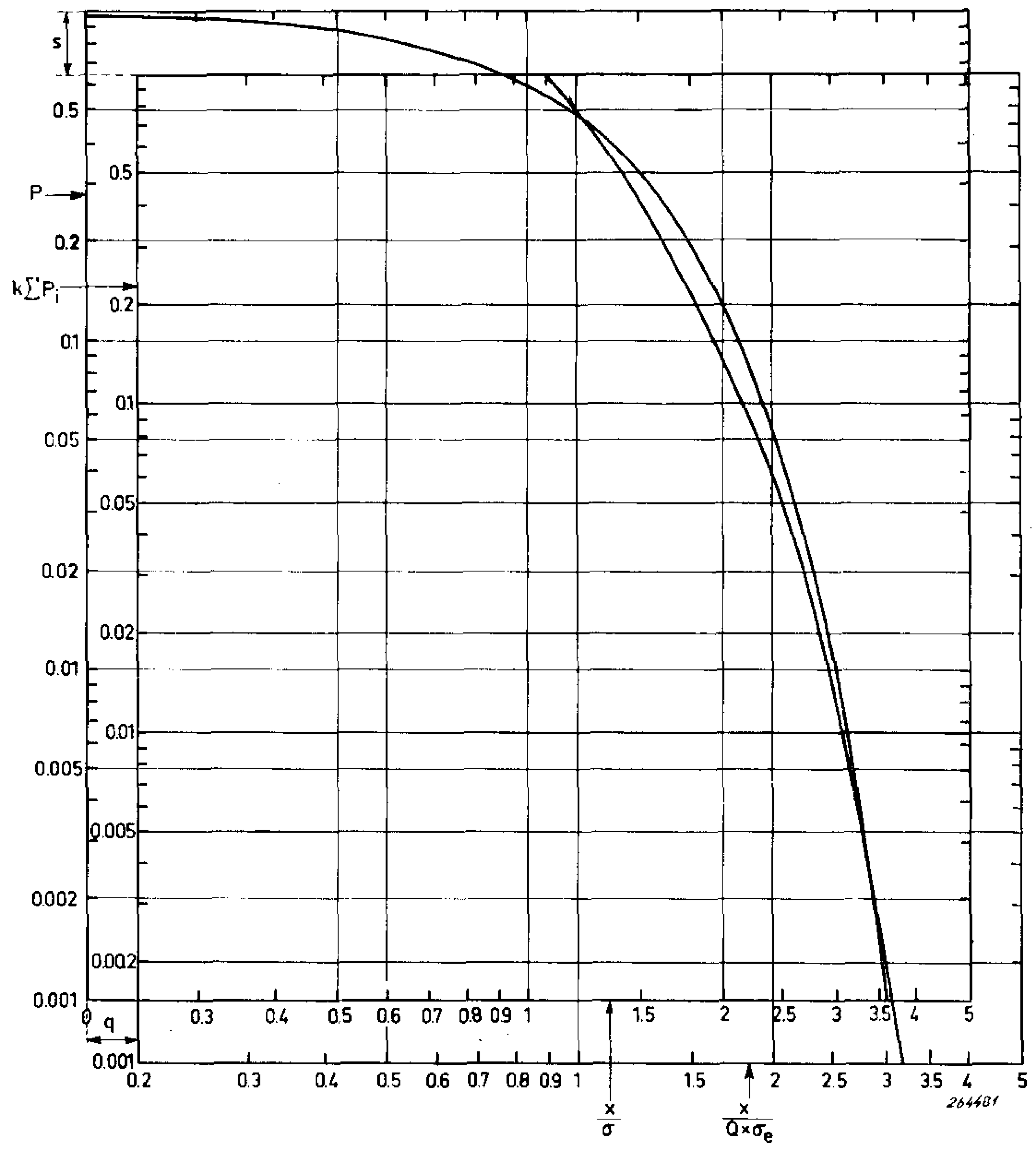

Fig. 6. Example of accumulated peak distribution matching.

r.m.s. response of such resonances increases with the square-root of frequency (3 dB/octave).

It is thus necessary somehow to increase the r.m.s. value of the test band with frequency. As the bandwidth of the test band in the practical sweep random test is kept constant throughout the sweep, the amplitude values of the signal must be increased according to a 3 dB/octave law, see Fig. 5.

The increase in magnitude with frequency is taken care of automatically by circuits built into the Sine-Random Generator. It has therefore been found convenient to introduce the term "acceleration gradient", the gradient here referring to "frequency space". Instead of specifying the test in the form of a varying power spectral density it can then be conveniently specified in terms of a "constant acceleration gradient" ($g \times \sqrt{\text{sec}}$).

So far the total number of stress reversals as well as the r.m.s. test level have been equated for the sweep random and the wide band random tests. However, it is required that the number of stress reversals *in any interval of stress levels* should be the same for the two tests.

This means that also the probability distribution of the peaks "around" the r.m.s. test level should be the same in both cases. Normally the bandwidth of the test band is considerably smaller than the bandwidth of the resonance being tested, and the determination of the "accumulated peak distribution" from a sweep through the resonance is a fairly complicated matter. On the other hand, by the use of analogue models the distribution for various test

conditions have been determined and compared to the "ideal" Rayleigh-distribution.
An example of the "matching" of an accumulated peak distribution in the sweep random test to the integrated Rayleigh distribution density curve is shown in Fig. 6. From such a matching it is possible to determine the excitation level and the actual sweep time for practical sweep random tests.

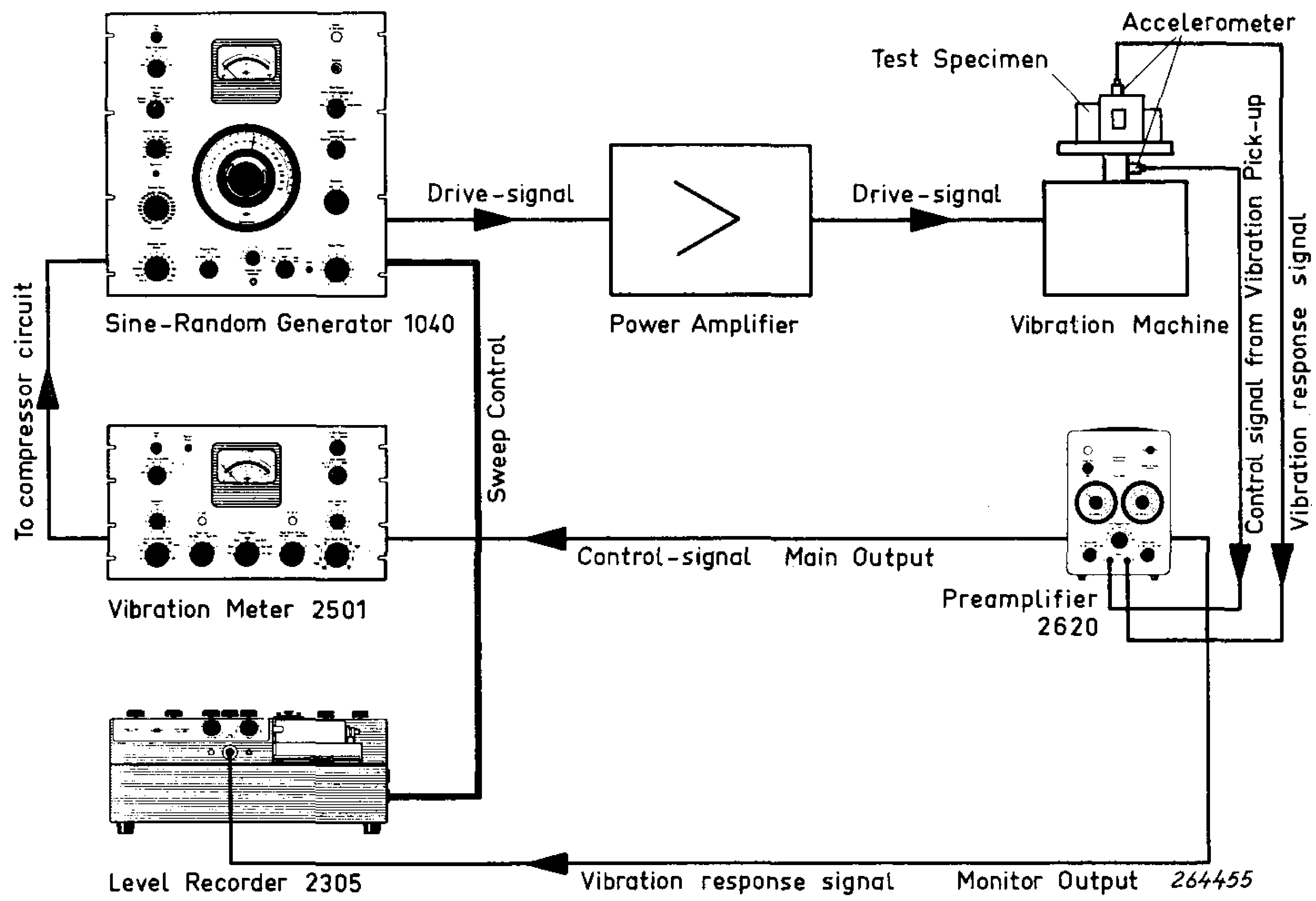

Fig. 7. Principle of operation of the servo controlled sweep random vibration test.

A very important feature of the sweep random vibration test technique is the possibility it offers for "simple" automatic level regulation. The use of a narrow band of noise as test signal makes it possible to utilize a servo regulation technique which is similar to that used in the sweep sine test, Fig. 7. This means a considerable reduction in setting up time, as compared to manually operated wide band systems, and very often also a much better "peak-notch" equalization is obtained. A disadvantage is, however, that the test itself is more time consuming than the wide band test.

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Appendix

Setting up a Sweep Random Vibration Test.

The test parameters involved in a sweep random vibration test are the acceleration gradient, the frequency sweep limits, the sweep random test time, the band width of the random test signal, and the compressor speed. The maximum r.m.s. excitation level is also of interest since this determines the maximum rating of the required test equipment. A determination of the five preceding parameters may be made either from measured environmental data or from test specification requirements, and the values of the parameters may be given either directly as sweep random test specifications or they may be derived from wide band data. The derivations of many of the formulae given in the following are based on wide band data and can be found in G. B. Booth: "Sweep Random Vibration". To illustrate the practical use of the formulae a numerical example is also outlined.

If the sweep random test is used to test the reliability of a specimen to a wide band vibration environment having a constant acceleration density of G g^2/cps, the equipment should be adjusted to maintain an acceleration gradient, γ, at the base of the test specimen of:

$$\gamma = q\sqrt{\frac{G}{4\,Q}}$$

where q is a factor determined from the distribution matching illustrated in Fig. 6 and Q is a median magnification factor of the many specimen resonances. In practice, the actual magnification factors are unknown, and a value for Q of 20 is used, which keeps the resonant responses within $\pm$ 3 dB for the expected range of magnification factors from 10 to 40, and within $\pm$ 7 dB for the extreme range of 4 to 100.

The low and high frequency sweep limits, f_H and f_L, are the same as the upper and lower frequency limits of the acceleration density spectrum.

The maximum r.m.s. acceleration excitation demanded from the test system will be

$$a_e = \gamma\sqrt{2\,\pi\,f_H}$$

The total sweep random test time is derived from the wide band test time, t_w, using a factor, s, also determined from the distribution matching illustrated in Fig. 6:

$$t_n = Q\,t_w\,s\,\ln\left(\frac{f_H}{f_L}\right)$$

By observation of the frequency dial of the sine random generator the angular travel required for a complete scan from f_L to f_H to f_L is determined. The angular sweep rate, r, for the case where the test is to be carried out in one complete angular scan of the frequency spectrum in both directions will then be:

$$r = \frac{\text{angular travel}}{t_n}$$

The scanning speed control on the sine random generator is set to the closest available scanning rate.
The band width of the random test signal Δf is normally made narrow, typical 3 Hz (c/s), which provides the most accurate compensation available for variations in table motion with frequency due to resonances of the specimen.
For sweep random tests of maximum precision the compressor speed in dB/sec must not be greater than 10 times the band width of the sweep random test signal in cps. Although accelerated testing is not discussed here, it is possible to reduce the sweep random test time by appropriate use of the higher compressor speeds and slightly increased test levels.

Numerical Example.

Wide Band Test Requirements:

Acceleration density: $G = 0.2$ g^2/cps, uniform over the frequency spectrum from 20 Hz (c/s) to 2000 Hz (c/s).
Test time $t_w = 2$ minutes
(Total excitation 20 g r.m.s.)

Equivalent Sweep Random Test calculations:
(Assume $q = 1.15$ and $s = 0.85$)

$$\gamma = 1.15 \sqrt{\frac{0.2}{4 \times 20}} = 0.058 \text{ g} \sqrt{\text{sec}}$$

$$t_n = 0.85 \times 20 \times 2 \times \ln\left(\frac{2000}{20}\right) = 156 \text{ minutes}$$

$\Delta f = 3$ Hz (c/s)
Compressor Speed = 30 dB/sec

$$r = \frac{288°}{156 \text{ min.}} = 1.85°/\text{min. (use nearest value of } 1.8°/\text{min.)}$$

The maximum r.m.s. acceleration excitation is:

$$a_e = 0.058 \sqrt{2\,\pi\, 2000} = 6.5 \text{ g r.m.s.}$$

which occurs at 2000 cycles/sec.

Summary.

A suitable adjustment of the sweep random equipment to simulate a wide band random test time of 2 minutes and a uniform acceleration density of 0.2 g^2/cps over the frequency spectrum from 20 Hz (c/s) to 2000 Hz (c/s) is therefore:

Acceleration Gradient $\gamma = 0.058$ g $\sqrt{\text{sec}}$
Sweep Rate: $r = 1.8°$/min.
Sweep Limits: $f_L = 20$ Hz (c/s) $f_H = 2000$ Hz (c/s)
Test Noise Bandwidth: $\Delta f = 3$ Hz (c/s)
Compressor Speed: 30 dB/sec.

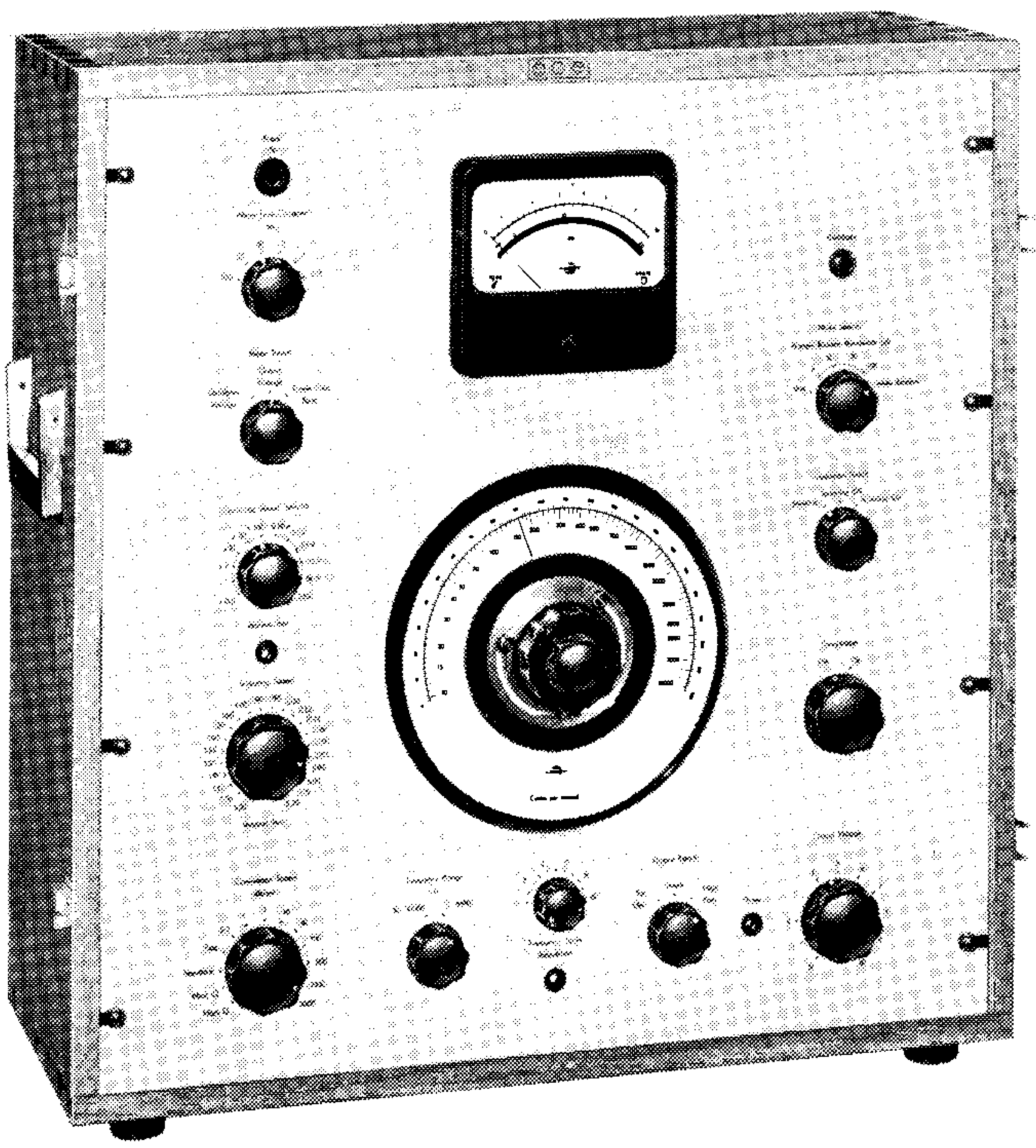
News from the Factory

New Sine-Random Vibration Control Equipment.

The Sine-Random Vibration Control Equipment has been designed for use in integrated vibration test systems to control the movement of electrodynamic vibration machines. It consists of two separate units namely:

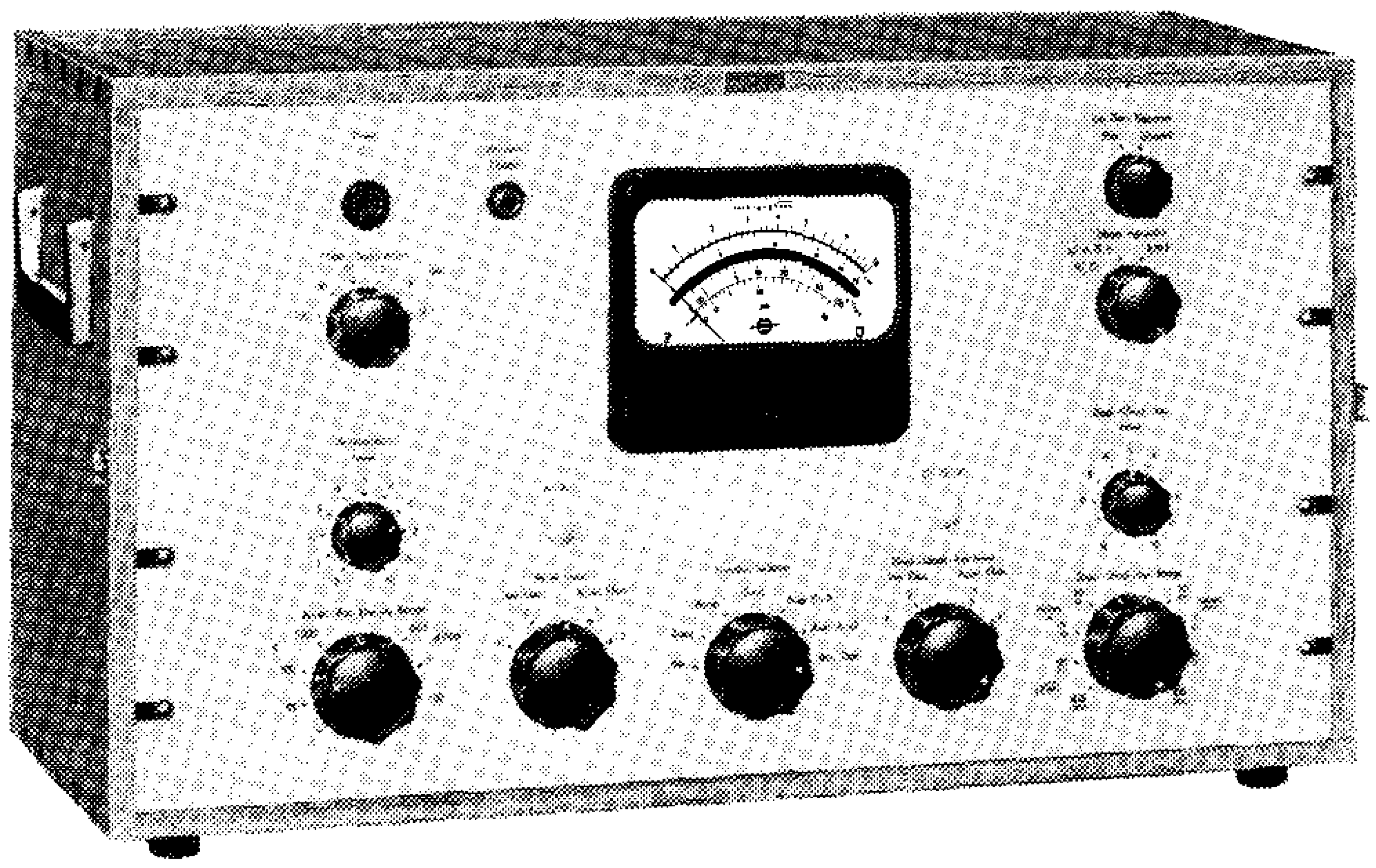
1. *The Sine-Random Generator Type 1040* which can supply sine-wave signals, narrow band noise signals or wide-band noise in the frequency range 5—10ooo c/s and
2. *The Vibration Meter Type 2501* which can be used to monitor the vibration level and to feed the regulator circuit of the Generator Type 1040 with the desired control signal.

Normally, the two units operate in a closed loop servo control system during vibration testing of components or structures.



Type 1040.

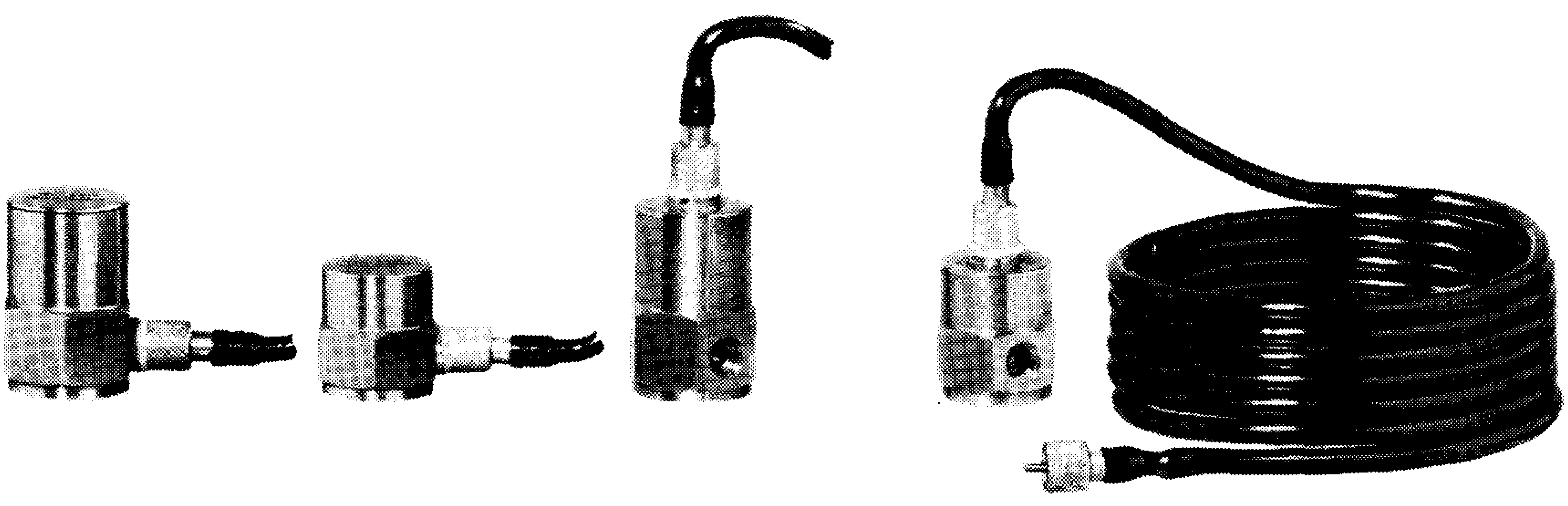
The equipment is equally well suited for complicated laboratory investigations as it is for production vibration testing, and has a wide field of practical applications. Not only will it fulfil all the requirements for controlling



Type 2501.

common sinusoidal vibration tests but may also be used as signal source and vibration meter in complicated wide-band random vibration systems.
It includes, furthermore, the necessary prerequisites to conduct a completely new type of vibration test—the sweep random test—see also p. 19.
Wide band random noise and *narrow band* noise (or sine) can also be supplied *simultaneously from different outputs,* thus allowing *a wide range of new vibration test applications.*
When operated in the sweep random or sweep sine condition up to 4 Generators and Vibration Meters can be connected together in a "Master-Slave" arrangement with individual servo controls and phase adjustments. It is thus possible to excite large complex test specimens by means of more than one vibration machine.

New Accelerometers.



The new accelerometers.

Four new types of accelerometers are now available either as *Accelerometer Sets Type 4312-13-14-15,* or as *Accelerometer Packages Type 4352-53-54-55.*
The Accelerometer Sets contain one accelerometer with all the accessories necessary for various methods of electrically isolated mounting*) or probe-

*) Electrically isolated mounting is often essential to avoid troublesome groundloops.

operation with interchangeable sharp and rounded probe-tips, as well as a special low noise, low capacity cable and plugs for electrical connection.
The Accelerometer Packages contain 5 accelerometers with connection cable only.

Accelerometer Set

Accelerometer Package

Each Accelerometer is individually calibrated up to 260°C (500°F) and all the calibration data are supplied with the instrument upon delivery. Transverse sensitivity is lower than 5 % and the units are humidity sealed and tested under water for leaks.
The accelerometers have a strong stainless steel or titanium base and provisions are made for watercooling of the types 4314 (4354) and 4315 (4355), see also table below.

	Accelerometer types			
Sets with Accessories: **Packages of 5:**	**4312** **4352**	**4313** **4353**	**4314** **4354**	**4315** **4355**
Sensitivity range mV/g	35—70	6—12	35—70	6—12
Frequency range c/s	2—8000	2—14000	2—8000	2—14000
Natural resonance Frequency	35 kc/s	60 kc/s	35 kc/s	60 kc/s
Weight	30 gr.	13 gr.	30 gr.	13 gr.
Mounting of cable	side	side	top	top
Base Material	st. steel	titanium	st. steel	titanium
Provisions for water cooling	—	—	+	+

New Noise Control Equipment.

The new noise control instruments are:

The Noise Limit Indicator Type 2212 and
The Outdoor Microphone System Type 4920.

Although these instruments can very well be used separately, one main field of application for the combination 2212 + 4920 is in *airport and traffic noise control systems.*

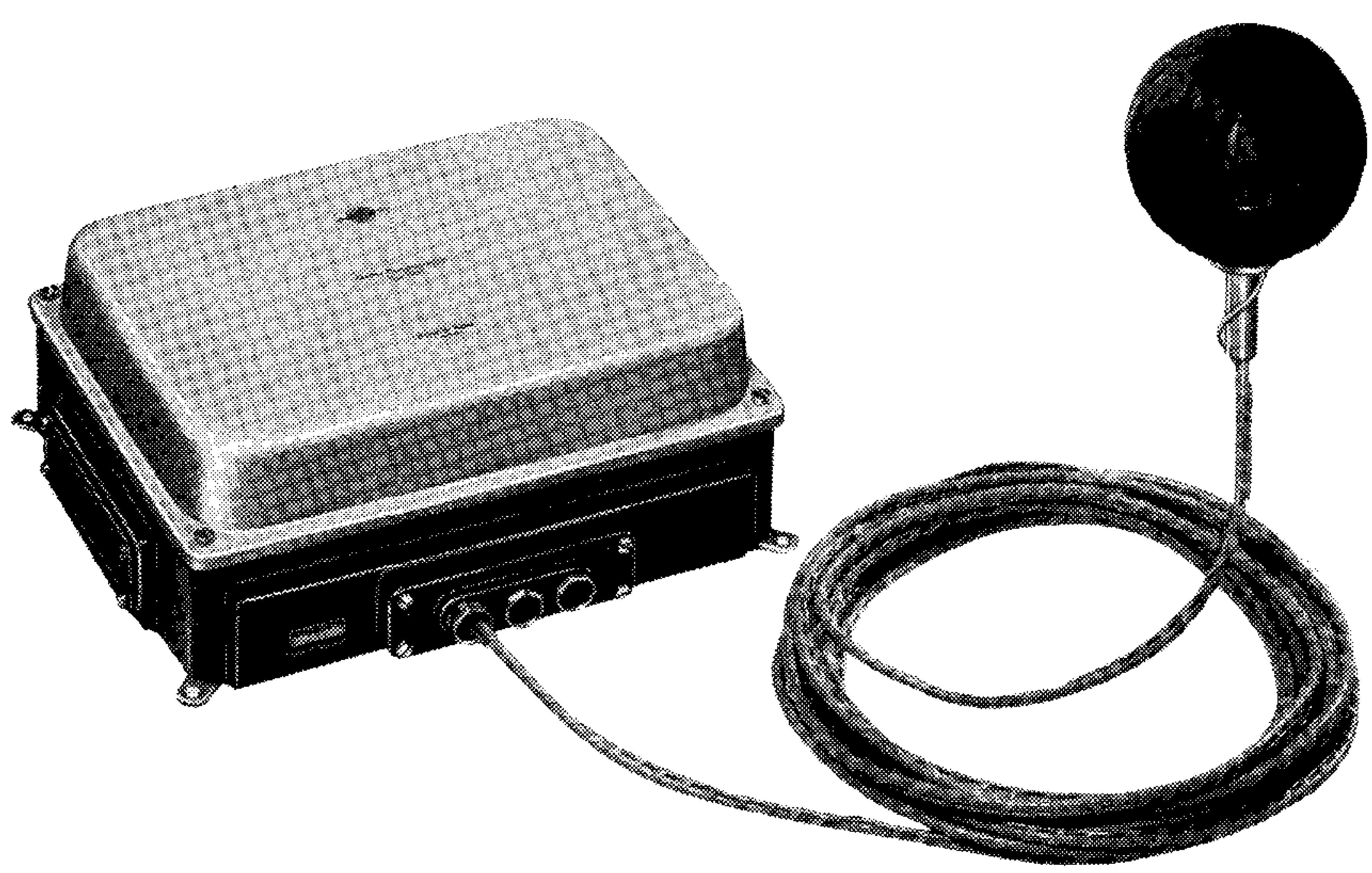
The Noise Limit Indicator Type 2212 is a modified version of the well-known Noise Limit Indicator Type 2211. It contains six identical, separate input amplifiers and six output amplifiers. Furthermore, two "sets" of six microphones each (or six vibration pick-ups) can be successively switched to the input amplifiers by means of a remotely controlled relay circuit. It is thus possible to quickly check 12 measuring positions—and continuously monitor six.

The input circuit of the input amplifiers contains a transformer which allows connection to a symmetrical transmission system, and a calibrated attenuator with a range of 60 dB, adjustable in 10 dB steps.

The input transformer has been included not only to allow connection to a symmetrical transmission system, but also to facilitate the remote control of the calibration oscillator in a connected Outdoor Microphone System Type 4920 over a two-wire system.

In the output amplifiers provision is made for the insertion of filters, and the amplifiers contain a calibrated twin attenuator of 48 dB, variable in 1 dB steps.

The "sensitivity increase" of Type 2211 is maintained in Type 2212.



Type 4920.

The Outdoor Microphone System Type 4920 has been designed, as the name implies, for outdoor acoustical measurements. It is especially well suited for long-term outdoor operation at fixed measuring positions and consists of a

sealed, waterproof amplifier with microphone power supply and calibration generator and a 1/2″ condenser microphone Type 4133 with cathode follower Type 2615, rain cover UA 0056, and wind screen.
The amplifier of Type 4920 is a two stage, RC-coupled, transistor amplifier with a maximum gain of 30 dB (adjustable by means of a screwdriver) and the output impedance can be set to "match" load impedances of 200 ohms, 200 ohms symmetrical or 50 ohms.
Without any alterations being made in the measuring set-up it is possible to calibrate and check the installation by means of the built-in calibration generator. The start and stop of the generator can be remotely controlled, and the calibration is based on the use of a carefully adjusted electrostatic actuator in the microphone rain cover.

New Carrying Case for the Sound Level Meter Type 2203.

This is a convenient carrying case for Type 2203 holding not only the instrument with Filter Set 1613 but also all the accessories necessary to make the Sound Level Meter a really versatile and accurate sound and vibration measuring instrument.
With these accessories the Precision Sound Level Meter is capable of measuring sound pressure levels with an absolute accuracy better than 0.3 dB, and to frequency analyse sound and vibration with octave filters. Acceleration or velocity may be chosen for vibration measurements.
The carrying case has compartments for the following items:

The new carrying case.

Precision Sound Level Meter Type 2203
Octave Filter Type 1613
Pistonphone Type 4220
Barometer UZ 0001
Connector UA 0039
Condenser Microphone Type 4131
Extra Microphone (Type 4133)
Accelerometer Type 4308-11
Extension Cable AO 0033
Artificial Ear Type 4152 or Windscreen UA 0082
Random Incidence Corrector UA 0055
1″ Nose Cone UA 0051
1/2″ Nose Cone UA 0051
Intgerator
Screwdrivers
Spare Batteries
Tripod Adaptor UA 0028

As the individual requirements to the various accessories may differ considerably, the case is not necessarily ordered as a set, but can be ordered with the accessories necessary for any particular investigation.

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