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To Advance Techniques in Acoustical, Electrical, and Mechanical Measurement

# FM Tape Recording

No. 1

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| | |
|---|---|
| 1-1962 | Artificial Ears for the Calibration of Earphones of the External Type, part 2. |
| 2-1962 | Loudness Evaluation. |
| 3-1962 | Testing of Stereophonic Pick-ups by means of Gliding Frequency Records. |
| 4-1962 | On the Use of Warble Tone and Random Noise for Acoustic Measurement Purposes.<br>Problems in Feedback Control of Narrow Band Random Noise. |
| 1-1963 | Miniature Pressure Microphones.<br>Methods of Checking the RMS Properties of RMS Instruments. |
| 2-1963 | Quality Control by Noise Analysis.<br>A. F. Nonlinear Distortion Measurement by Wide Band Noise. |
| 3-1963 | Effects of Spectrum Non-linearities upon the Peak Distribution of Random Signals. |
| 4-1963 | Non-linear Amplitude Distortion in Vibrating Systems |
| 1-1964 | Statistical Analysis of Sound Levels. |
| 2-1964 | Design and Use of a small Noise Test Chamber.<br>Sweep Random Vibration. |
| 3-1964 | Random Vibration of some Non-Linear Systems. |
| 4-1964 | The Accuracy of Condenser Michrophone Calibration Methods. Part I. |
| 1-1965 | The Accuracy of Condenser Microphone Calibration Methods. Part II. |
| 2-1965 | Direct Digital Computing of Acoustical Data.<br>The Use of Comparison Bridges in Coil Testing. |
| 3-1965 | Analog Experiments Compare Improved Sweep Random Tests with Wide Band Random and Sweep Sine Tests<br>The Frequency Response Tracer Type 4709. |
| 4-1965 | Aircraft Noise Measurement, Evaluation and Control. |
| 1-1966 | Windscreening of Outdoor Microphones.<br>A New Artificial Mouth. |
| 2-1966 | Some Experimental Tests with Sweep Random Vibration |
| 3-1966 | Measurement and Description of Shock. |
| 4-1966 | Measurement of Reverberation. |

# TECHNICAL REVIEW

No. 1 – 1967

# Contents

K. LARSEN & SØN - LYNGBY

# FM Magnetic Tape Recording

By

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## ABSTRACT

The main advantages of FM magnetic tape recording for analog measurement purposes are briefly outlined whereafter some basic design factors are discussed. It is shown that for a given magnetic head very close connections exist between the tape speed, the carrier frequency and the maximum useful frequency range. Certain restrictions also have to be imposed upon the maximum allowable frequency deviation (frequency swing) which determines the upper limit of the recorder's dynamic range.

The lower limit of the dynamic range is set by wow, flutter and inherent noise effects, and various methods of measuring and interpreting this level are described. Finally, some frequency and timing effects between channels in a two-channel recording system are considered with special regard to the new Brüel & Kjær Tape Recorder Type 7001.

## SOMMAIRE

Dans cet article, on fait brièvement ressortir les avantages principaux de l'enregistrement magnétique en FM utilisé aux fins de mesures analogiques, après quoi l'on discute de certains facteurs fondamentaux de la conception d'un enregistreur. Il est montré que pour une tête magnétique donnée existent des liens très étroits entre la vitesse du ruban, la fréquence porteuse et le domaine de fréquence maximum utile. Certaines restrictions aussi ont à être imposées à l'excursion maximum de fréquence à admettre, qui détermine la limite supérieure du domaine dynamique de l'enregistreur.

La limite inférieure de la gamme dynamique est donnée par le pleurage, le scintillement et le bruit propre, et diverses méthodes de mesure et d'interprétation du niveau correspondant sont décrites. Pour terminer on considère certaines effets intercanaux d'un dispositif d'enregistrement bi-canal, eu égard spécialement au nouvel enregistreur Brüel & Kjær type 7001.

## ZUSAMMENFASSUNG

Die wesentlichen Vorteile der Frequenzmodulation bei Magnetbandgeräten für analoge Datenspeicherung werden kurz aufgezeigt, worauf einige grundsätzliche konstruktive Gesichtspunkte diskutiert werden. Es wird gezeigt, daß zwischen der Bandgeschwindigkeit, der Trägerfrequenz und dem maximal nutzbaren Frequenzbereich bei einem gegebenen Spulenkopf ein sehr enger Zusammenhang besteht. Gewisse Beschränkungen müssen auch dem maximal zulässigen Frequenzhub auferlegt werden, der die obere Dynamikgrenze des Geräts bestimmt.

Die untere Grenze des Dynamikbereichs ist durch Schwankungen der Bandgeschwindigkeit (»Wow and Flutter«) sowie durch des Eigenrauschen gegeben, und es werden verschiedene Methoden beschrieben, um diesen Pegel zu messen und zu interpretieren. Schließlich werden einige Frequenz- und Zeiteffekte zwischen den Kanälen eines Zweikanal-Bandgeräts betrachtet — besonders im Hinblick auf das neue Brüel & Kjær-Bandgerät Typ 7001.

### Introduction.

Magnetic tape recording has proved to be of immense value in modern society. From its early beginning in 1898, when the Danish scientist and inventor Valdemar Poulsen demonstrated his first "telegraphone", and up to modern instrumentation tape devices a tremendous amount of scientific effort and ingenuity has been laid down in modifying and improving the magnetic recording and reproducing technique.

Even though there are many limiting factors in modern tape recording the ability of such systems to store information for later analysis, to expand and compress time scales, and, by multichannel recording techniques, to preserve time coincidence between events has made the magnetic tape recorder a key instrument in today's instrumentation systems.

The continuous improvement of magnetic recording techniques over the last decades has resulted in the development of various recording principles, such as direct recording, frequency modulation, pulse coding, pulse width modulation, amplitude modulation etc.

All of these types of recording techniques have their advantages and disadvantages, but the most widespread recording principles used for general purposes and analog measurements today seem to be the direct recording (with high frequency bias) and the frequency modulation techniques.

If the recorded (analog) data are to be stored for later ordinary spectrum analysis of single samples the direct recording technique is the simplest and most economical type of data preservation. On the other hand, if the stored data are very low frequency vibrations or contain necessary DC (static) information, the frequency modulation (FM) technique is far superior to direct recording.

The versatility of FM tape recording in analog measurement systems has made this kind of data preservation highly desirable and a number of FM magnetic tape recorders are at present commercially available. The new Brüel & Kjær Tape Recorder Type 7001 also utilizes the FM technique and great care has been taken in the development of the Recorder to achieve optimum performance and reliability of its various components.

Because many of the advantages and limitations inherent in FM magnetic tape recording may be unfamiliar to a number of noise and vibration engineers, it is intended, with this article, to describe briefly the basic principles involved with special references to the new B & K Recorder.

## The Basic Design Factors.

In most practical wideband FM*) magnetic recording systems the input signal frequency modulates a carrier frequency oscillator of frequency $f_o$ to a maximum frequency deviation, $\Delta f$, (frequency "swing") of ±40 % of the carrier, see Fig. 1.

In the figure the values $f_o \pm 2\Delta f$ have been indicated instead of $f_o \pm \Delta f$. The reason for this is that all the important sidebands of the modulation necessary for a faithful reproduction of the input signal are found within the frequency band $f_o + 2\Delta f$ to $f_o - 2\Delta f$ as explained in Appendix A.

Similarly, the highest modulating frequency $f_1$ max, is normally chosen to be approximately 1/2 of the maximum frequency deviation (i.e. 20 % of the

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*) For a brief explanation of the concept of frequency modulation the reader is referred to Appendix A.

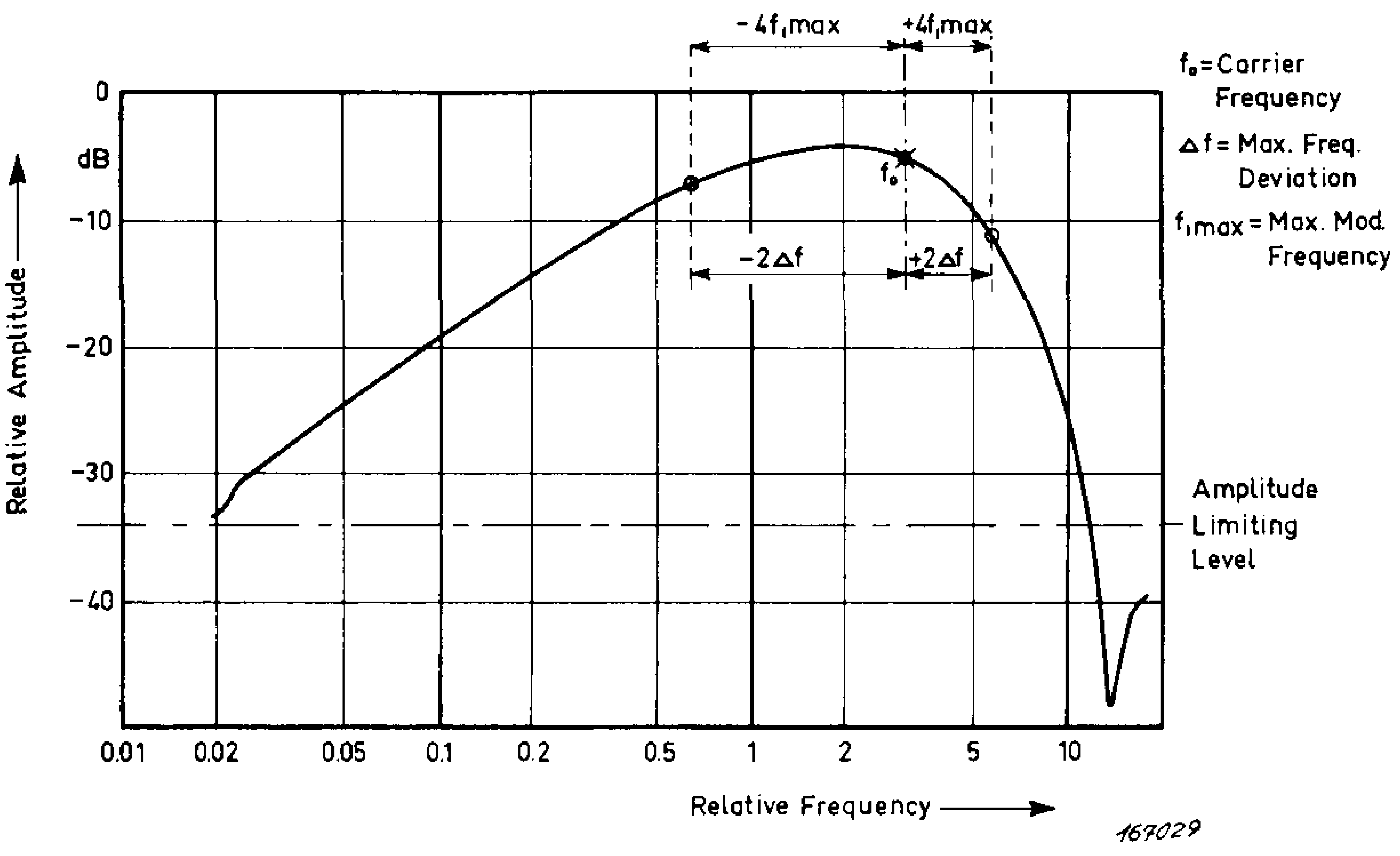

*Fig. 1. Typical frequency response characteristic of the playback head in a magnetic tape recorder.*
*With constant, frequency independent magnetization of the tape and constant tape speed the output voltage from the head will, at low frequencies, increase with frequency because* $e_{out} \sim \frac{d\Phi}{dt}$*. At higher frequencies, where the wavelength of the signal present on the tape becomes of the order of magnitude of the head gap width averaging effects take place which cause the output signal,* $e_{out}$*, to decrease with increasing frequency. When the signal wavelength equals the effective gap width of the head* $e_{out}$ *should theoretically become zero. At still higher frequencies the averaging effects become predominant, and this part of the frequency response curve is not normally used in magnetic tape systems.*

carrier. This also ensures that a reasonably large dynamic range is obtained even at the high frequency end of the overall frequency response.

The actual carrier frequency used depends basically upon the tape speed and the characteristics of the magnetic heads. In the Tape Recorder Type 7001 the highest carrier frequency is 108 kHz and consequently the highest input signal frequency component that can be recorded with full dynamic range is approximately 20 kHz. A maximum tape speed of 1.524 m/sec. (60 inches per second) is used.

The choice of carrier frequency, tape speed and input signal frequency range might be regarded as the basic factors in the design of an FM magnetic tape recorder. From these factors, and a careful development of the tape transport mechanism as well as the circuitry used in the record and reproduce electronics then follows the optimum achieveable dynamic range. The upper limit of this range is set by the so-called deviation ratio*) and the phase nonlinearity in the circuitry while the lower limit is normally determined by the wow and flutter of the tape transport as well as spurious (random) noises in the recorder. As can be seen from Fig. 1 the characteristics of the reproducing

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*) Deviation Ratio = Maximum Frequency Deviation/Modulating Frequency see also Appendix A.

process cause the amplitude to vary considerably with frequency. This variation, which in direct recording/reproducing systems is of great importance, is in the case of frequency modulation systems, of practically no importance at all because the amplitude is limited (clipped) anyway before detection of the modulating signal takes place, and the magnetic tape is always magnetically saturated. Also the amplitude vs. frequency nonlinearity produced by the tape itself due to demagnetizing effects of neighbouring magnetic areas is unimportant in FM systems for the same reason. As stated above, however, phase nonlinearities are very important and great care must be taken to minimize and/or compensate for their existence.

## Some Dynamic Range Considerations.

The lower limit of the dynamic range is, in single track recording systems normally determined by wow, flutter and spurious noises. In multi track recording systems on the other hand, crosstalk between channels also enters the picture.

Wow and flutter are affected by many factors: Possible small eccentricities in the capstan or pinch rollers, tension variations in the tape, variations in power supply frequency, mechanical vibrations in the recorder and finally friction effects and tape roughness.

Some of these factors cause periodic flutter components while others are of a more random nature. If the flutter was of a completely random nature and no resonance effects were present in the tape system a more or less white inherent noise would be expected. The output voltage caused by such a noise would increase with the square root of the measurement bandwidth as indicated by the dashed curve in Fig. 2. In the figure the frequency scale indicates the measurement bandwidth. Actually at low frequencies periodic flutter components and tape system resonances cause the noise voltage and thus the lower limit of the dynamic range, to vary with measurement bandwidth

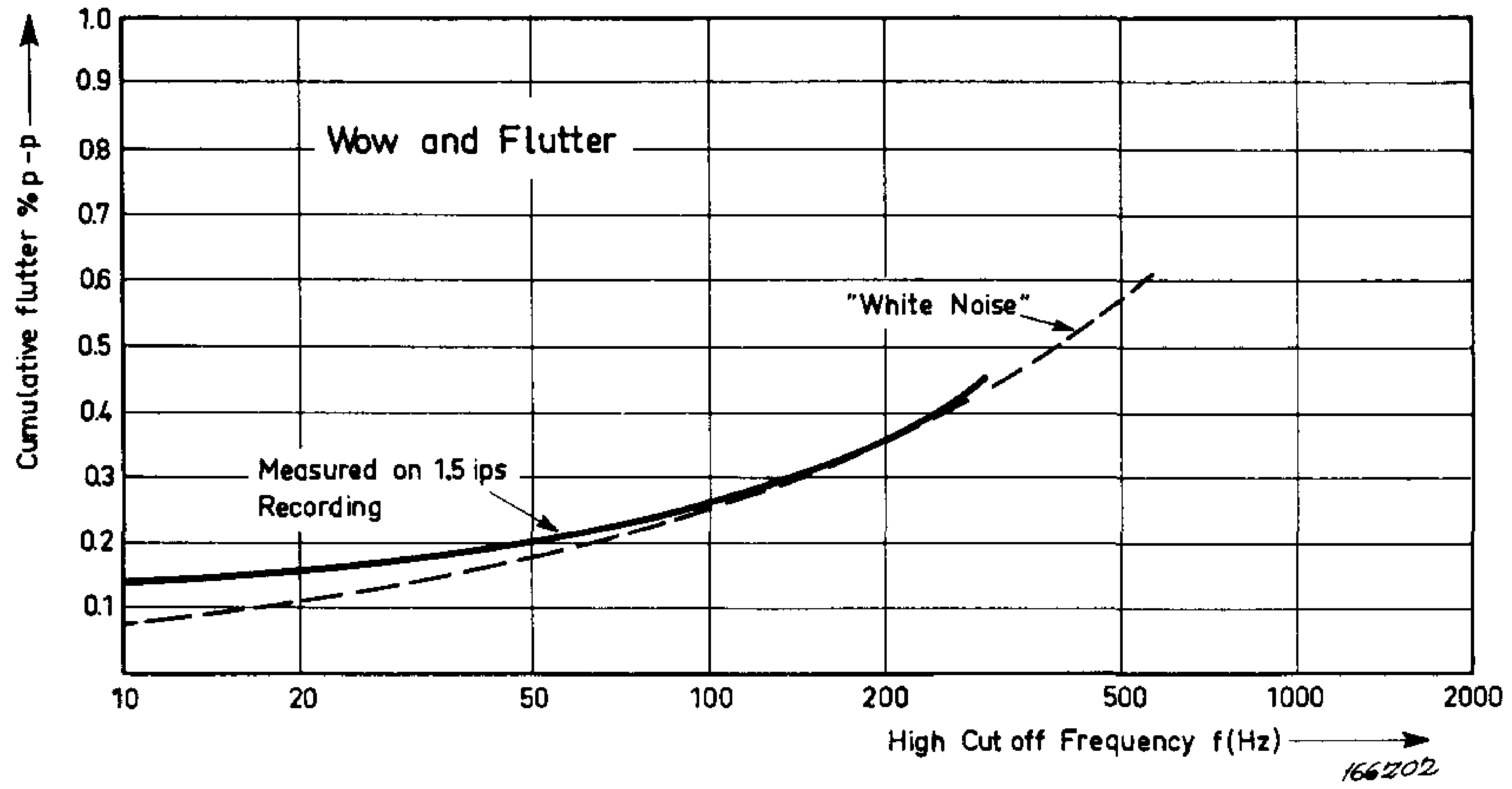


*Fig. 2. Typical cumulative noise and flutter characteristic measured at low tape speeds and indicating the dependency of the noise level upon recording bandwidth.*

as shown by the curve drawn in full, indicating that the noise is here not completely "white".

Because the Y-axis in Fig. 2 is marked "Cumulative Flutter (% peak-to-peak)" a few remarks should be made with respect to the meaning of this statement. It has become common practice in FM recording systems to use the peak-to-peak value of the modulating signal as a characteristic quantity because it determines the maximum frequency deviation produced in the system.

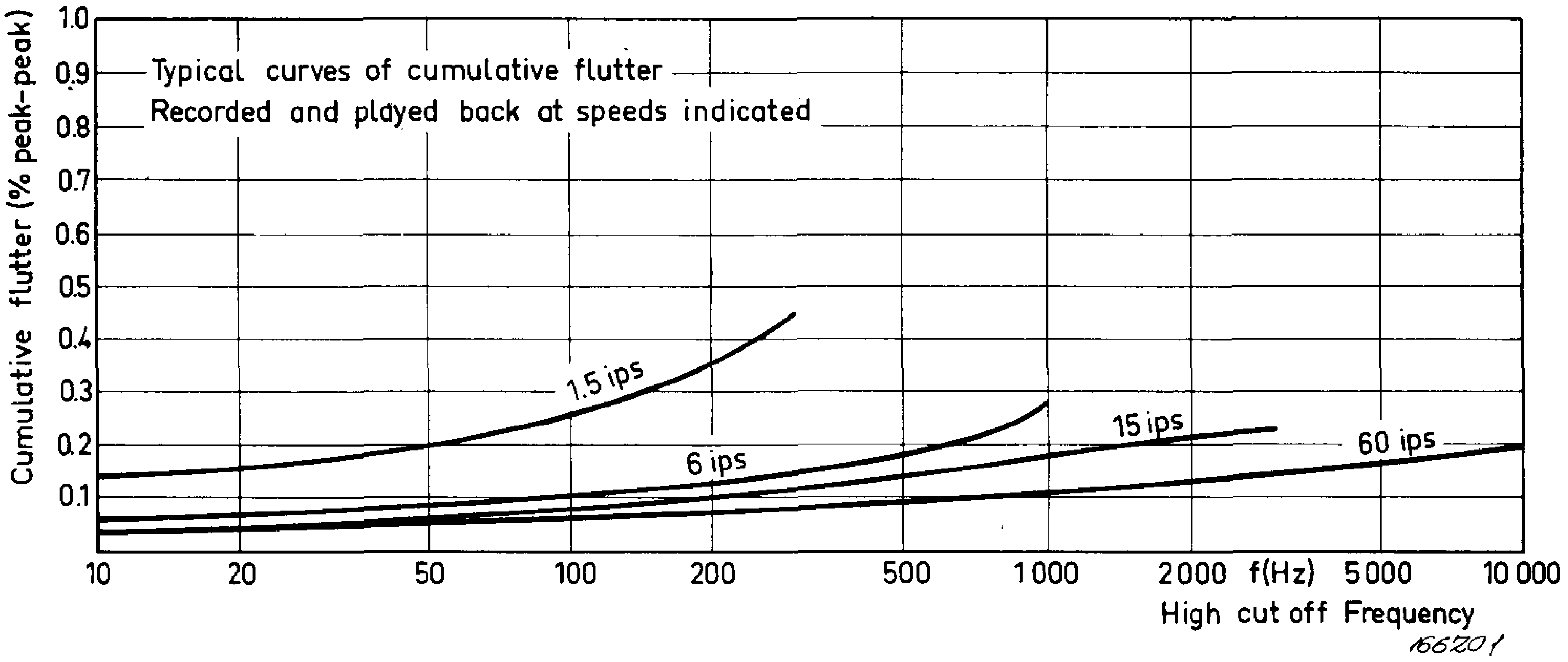


*Fig. 3. Examples of cumulative noise and flutter curves measured on the Tape Recorder Type 7001 at various tape speeds.*

In the case of random noise signals the absolute peak value has no real meaning because theoretically it is infinite, and this "terminology" is therefore rather inappropriate as the actual peak-to-peak value stated depends upon the measurement instrumentation used and the judgement of the person carrying out the measurements.

The curve shown in Fig. 2 has been obtained by recording an unmodulated carrier frequency of 3 kHz on magnetic tape at a tape speed of 3.81 cm/sec (1.5 ips), playing the tape back at the same speed and measuring the demodulated frequency deviations introduced to the signal by the recording and play back processes. As indicating instrument a calibrated cathode ray oscilloscope was used and the "peak-to-peak"-value was estimated by an experienced experimenter.

To determine the bandwidth dependency of the wow and flutter effects the demodulated signal was filtered through a low pass filter with variable high frequency cut-off before it was displayed on the oscilloscope.

The tape speed 3.81 cm/sec (1.5 ips) is the lowest speed available on the Tape Recorder Type 7001. As the wow and flutter effects are greatest at low speeds Fig. 2 may be taken to represent a "worst case". This is clearly seen by comparing this curve with similar curves measured for other tape speeds, Fig. 3. Even though a determination of wow and flutter in the form given above may after all be a useful measure for the quality of the tape transport system a more meaningful quantity with regard to the practical utilization of an instrumentation tape recorder is the wideband RMS value of the inherent noise voltage (including wow and flutter effects). This is obtained by again recording the unmodulated carrier frequency and then by means of a wideband electronic voltmeter, measuring the overall RMS noise voltage produced during playback.

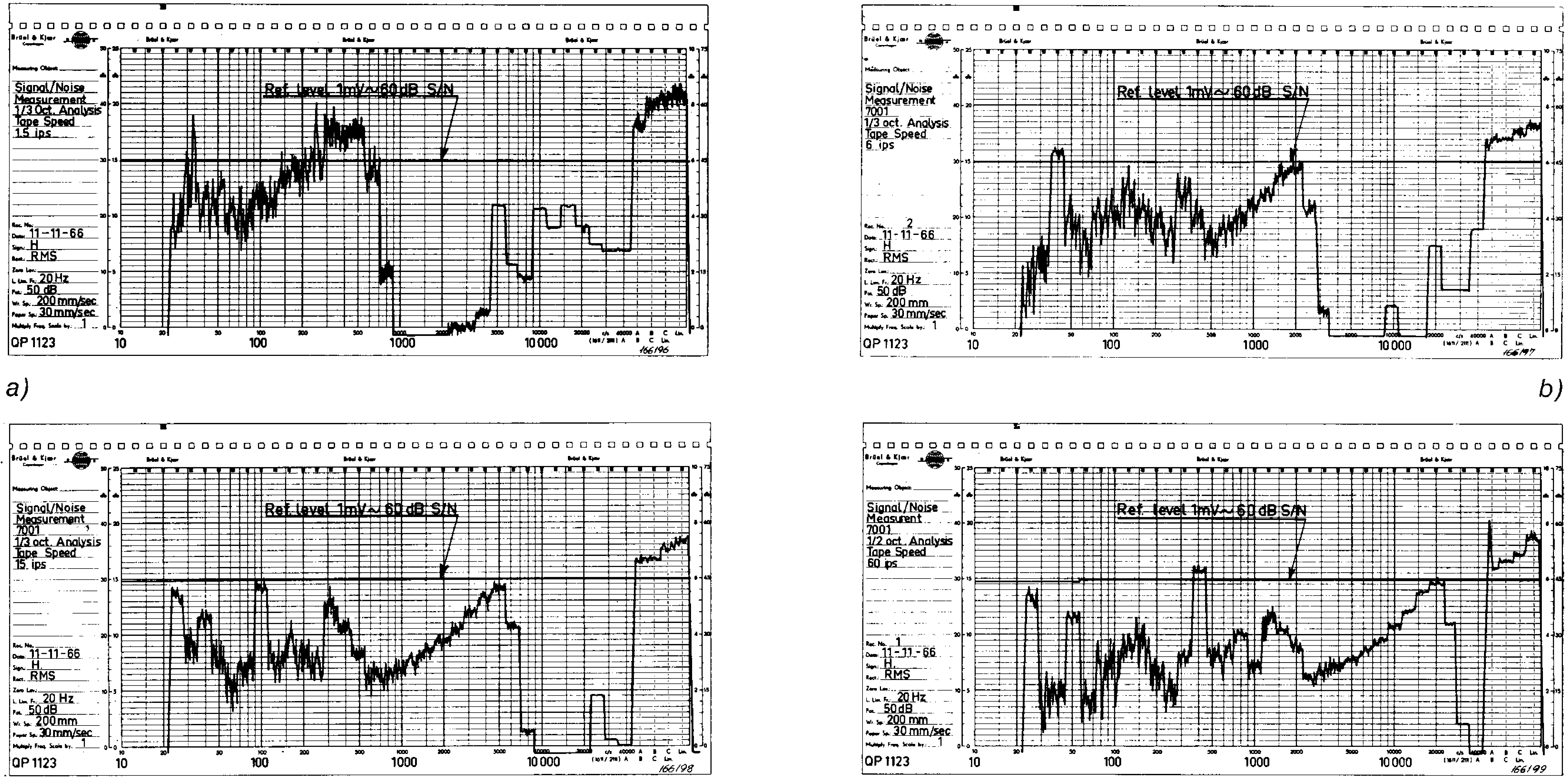
If the upper limit of the dynamic range is chosen to be the 1 % harmonic distortion level for a sinusoidal modulation signal a very useful figure in terms of the maximum wideband signal-to-noise ratio can be defined. For the Brüel & Kjær Tape Recorder this is of the order of 45 to 50 dB, somewhat dependent upon the tape speed chosen.

As the inherent noise level depends upon the measurement bandwidth the maximum signal-to-noise ratio can be greatly improved by the use of frequency selective recording and reproduction technique. To demonstrate this the results of a 1/3 octave frequency analysis of the inherent noise in an experimental model of the Tape Recorder are shown in Fig. 4 with indication of a reference line which is 60 dB below the 1 % distortion level. The considerable increase in maximum dynamic range is clearly noticed.

It was mentioned an p. 6 that in multi track recording systems crosstalk between the tracks might in some cases influence the maximum dynamic range. Crosstalk effects are mainly determined by the shielding between the magnetic heads belonging to different tracks as well as the separation distance. As the crosstalk process is basically different for FM and direct recording systems the two FM channels in the Tape Recorder Type 7001 have been separated on the tape by a direct recording channel. (The direct recording channel is, however, only meant as a voice channel for marking and indentification of special parts of the tape when desired, and is not intended to be used for measurement purposes). This together with careful shielding of the heads ensures that the crosstalk between the two FM channels is negligible (below the overall inherent noise level) even when one channel is modulated by DC producing maximum frequency deviation.

### Frequency and Timing Effects Between Channels.

There are other between-channel-effects, besides crosstalk, that are of importance in multi track recording systems. When multi track recording is used it is normally desired to preserve the original time coincidence between the recorded signals so that a thorough analysis of their possible interdependency can be made whenever convenient. It is then necessary that *both* the frequency characteristic *and* the phase characteristic of the channels are as equal as possible. Deviations between the characteristics will cause dispersion in the original time interdependency and upset the results of an analysis. Fig. 5 shows typical frequency responses of a single FM-channel while Fig. 6 indicates the responses of the two channels to a square-shaped pulse of 1 millisecond duration recorded simultaneously on both tracks. The photograph



a) b) c) d)

Fig. 4. Spectrograms showing the results of 1/3 octave frequency analysis of the inherent noise and flutter in the Tape Recorder. The level is here measured in terms of RMS values re. maximum input signal (1 % distortion level) and level lines of − 60 dB are indicated.

a) Tape speed 3.81 cm/sec (1.5 ips). c) Tape speed 38.1 cm/sec (15 ips).
b) Tape speed 15.24 cm/sec (6 ips). d) Tape speed 152.4 cm/sec (60 ips).

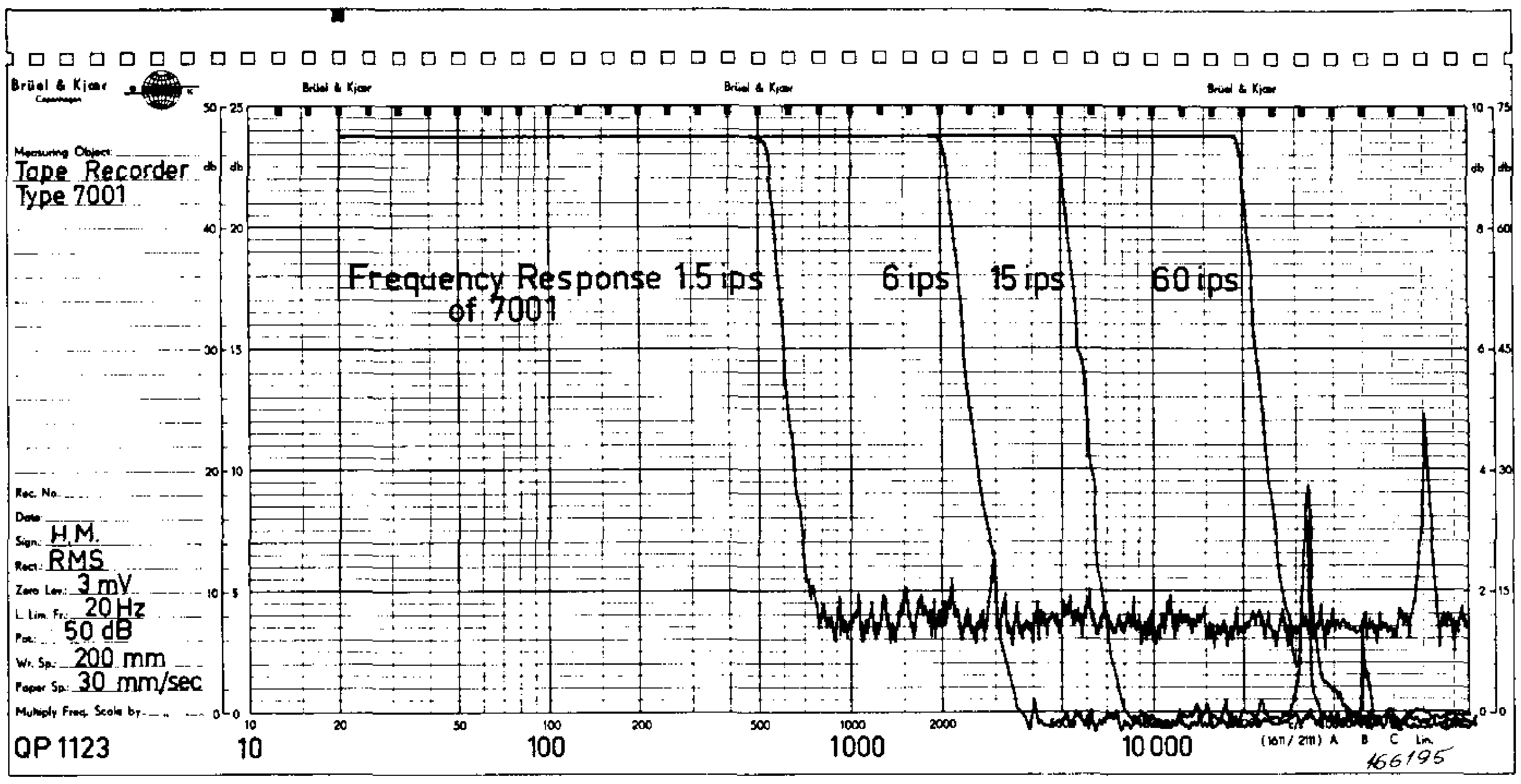


*Fig. 5. Typical frequency characteristics of the Tape Recorder Type 7001 valid for various tape speeds.*

shown was taken off the screen of a double beamed cathode ray oscilloscope.

By studying the photograph Fig. 6 a little closer it is found that the pulse responses are remarkably equal, and that an "apparent" phase difference is present. The word "apparent" is used here, because the phase difference has been introduced on purpose so that the two pulse responses could be more easily compared. By "tipping" the magnetic heads slightly it is possible to reduce the phase difference to zero. A mechanical adjustment of this kind is made on all the 7001 Tape Recorders before they leave the factory whereby no significant phase difference exists between the two channels.

As the adjustment is made both on the record and on the playback heads (using a standard tape) *the phase relationship between two signals recorded on one Recorder Type 7001 retain their correct relationship even when the*

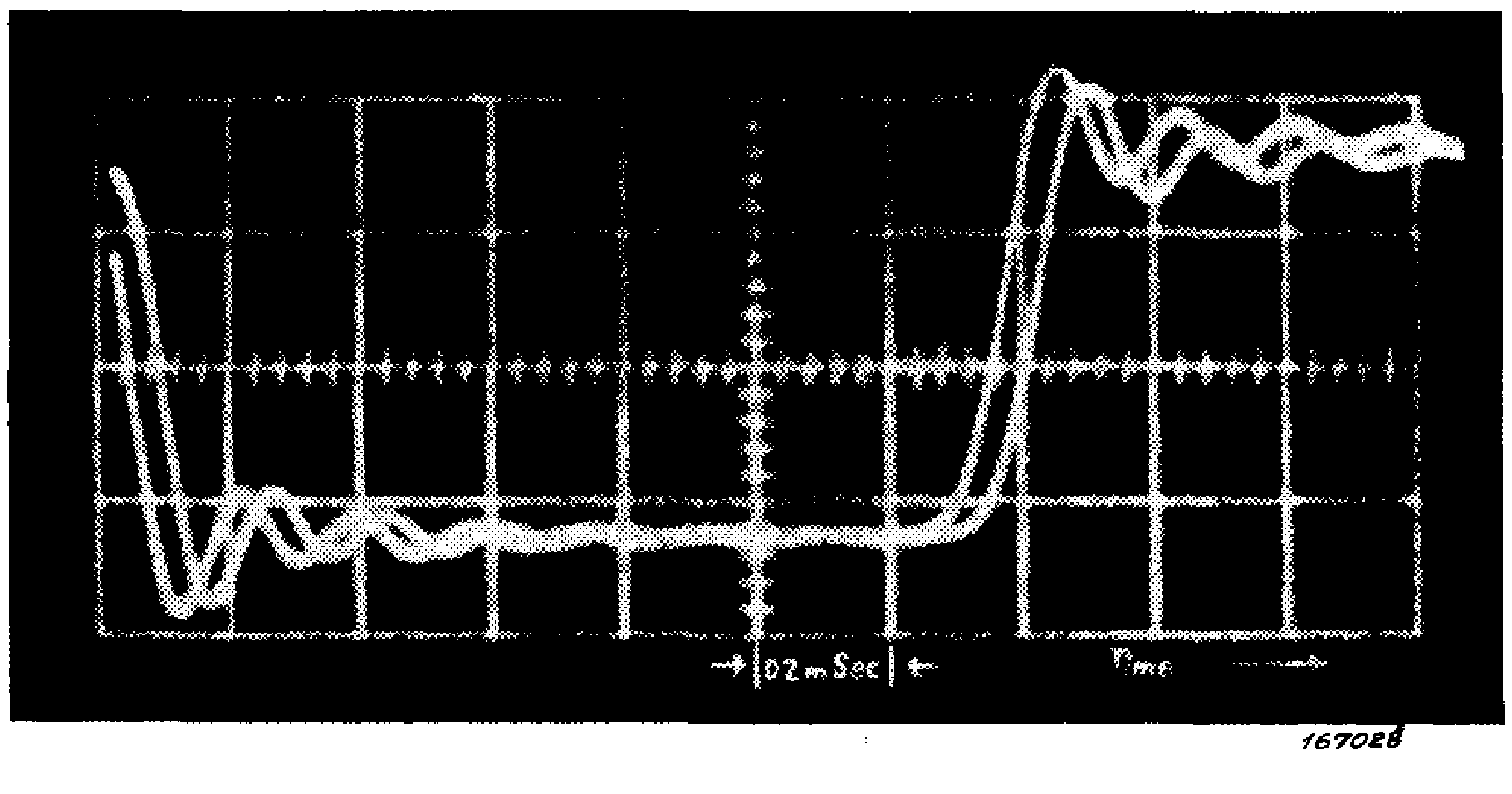


*Fig. 6. Response of the two measurement channels to pulses of 1.3 milliseconds duration. Tape speed 15 ips. (frequency response flat from 0–5000 Hz, see also Fig. 5).*

*tape is played back on a second Type 7001 Recorder.* This is of considerable importance for instance when one Tape Recorder is used to record signals in the field and another is used to analyze the tape in the laboratory.

**Conclusion.**

In the preceeding text an attempt has been made to discuss some of the basic considerations involved in the design and use of an FM magnetic tape recorder, as well as the advantages of utilizing FM principles in the recording technique. It was furthermore stated that one of the greatest advantages of FM recording and reproduction is the ability to record very low frequency signals down to DC, still maintaining a wide dynamic range. On the other hand, the "price" paid for this advantage is, from the user's point of view, mainly the less efficient utilization of the tape (due to the higher tape speed necessary to accomodate the carrier frequency and the modulation sidebands). Also the electronic circuitry used in FM recording is normally more complex than that used in direct recording, and the requirements to precision in the engineering and production of the tape transport are rather stringent.

For analog measurement purposes, however, it seems that the advantage offered by the FM technique is well worth the "price".

# Appendix A

**Frequency Modulation.**

There are many excellent and thorough textbooks describing the principles of frequency modulation in great details*). On the following few pages only a brief recapitulation of the most basic facts pertinent to the use of FM technique in magnetic tape recording is thus made.

Almost any practical AC signal can be interpreted as a sum of simple sinusoidal and cosinusoidal "waves". For a basic understanding of for instance a modulation process it is thus often sufficient to just consider one cosinusoidal signal

$$a = A_0 \cos \varphi \qquad (1)$$

where $A_0$ is the maximum amplitude of the signal and $\varphi$ is a continuously varying, generalized angle. For a constant frequency signal of frequency f, $\varphi$ can be written

$$\varphi = \int 2\pi f \, dt = 2\pi f t + \Phi = \omega t + \Phi$$

where $\omega = 2\pi f$ = angular frequency.

If the signal frequency is *not* constant it is useful to define an *instantaneous angular frequency*

$$\frac{d\varphi}{dt} = 2\pi f = \omega \qquad (2)$$

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*) See for instance A. Hund: "Frequency Modulation". Mc.Graw-Hill Book Company, Inc. New York 1942.

In frequency modulated systems the amplitude factor $A_o$ in equation (1) is kept constant while the instantaneous frequency is varied according to some function determined by the modulating signal.

Using a simple cosine representation of the *modulating* signal the instantaneous frequency is given by

$$f = f_o + \Delta f \cos(\omega_1 t) \tag{3}$$

Here $f_o$ is the carrier frequency around which the modulating signal varies with a frequency $f_1 = \frac{\omega_1}{2\pi}$ and a maximum *frequency deviation* of $\Delta$ f.

Multiplying equation (3) by $2\pi$ and utilizing equation (2) the angle $\varphi$ in equation (1) can be determined:

$$\begin{aligned}\varphi &= \int [2\pi f_o + 2\pi \Delta f \cos(\omega_1 t)]\, dt = \\ &= \omega_o t + \frac{\Delta \omega}{\omega_1} \sin(\omega_1 t) + \Phi_o\end{aligned} \tag{4}$$

where $\Phi_o$ is a constant, time independent angle (phase angle).

An expression for the complete frequency modulated signal is thus:

$$a = A_o \times \cos(\omega_o t + \frac{\Delta f}{f_1} \sin(\omega_1 t) + \Phi_o) \tag{5}$$

It can be shown that if $\Phi_o$ is assumed to be 0 the expression given by equation (5) can be mathematically transformed into the following formula:

$$\begin{aligned}a = A_o [&J_o(\beta) \cos(\omega_o t) + \\ &+ J_1(\beta) \cos(\omega_o + \omega_1) t - J_1(\beta) \cos(\omega_o - \omega_1) t + \\ &+ J_2(\beta) \cos(\omega_o + 2\omega_1) t + J_2(\beta) \cos(\omega_o - 2\omega_1) t + \\ &+ J_3(\beta) \cos(\omega_o + 3\omega_1) t - J_3(\beta) \cos(\omega_o - 3\omega_1) t + \\ &+ - - - - - - - - - - ]\end{aligned} \tag{6}$$

where $J_n(\beta)$ is the Bessel function of the first kind with argument $\beta$ and order n, n being and integer. $\beta = \frac{\Delta f}{f_1}$ is a kind of modulation "index" and depends, as can be seen, not only upon the maximum frequency deviation frequency "swing"), $\Delta$ f, but also upon the frequency of the modulating signal itself, $f_1$. This is due to the dependency of the actual modulating "phase" angle upon the *instantaneous* frequency see equation (2).

The ratio $\Delta f/f_1$ max. is commonly called *deviation ratio* and is in wide-band FM magnetic recording in the order of 1 to 2 or greater.

Equation (6) describes the frequency modulated signal in terms of *sidebands* with frequencies $\omega_o \pm \omega_1$; $\omega_o \pm 2\omega_1$; $\omega_o \pm 3\omega_1$ etc. Now, how many sidebands must be correctly handled by the measurement system to be able to reproduce the original modulating signal with negligibly small errors?

To be able to answer this question it is necessary to consider Fig. A.1. Here modulation spectra of a frequency modulated signal of the kind discussed above are shown for various values of the modulation "index". It is

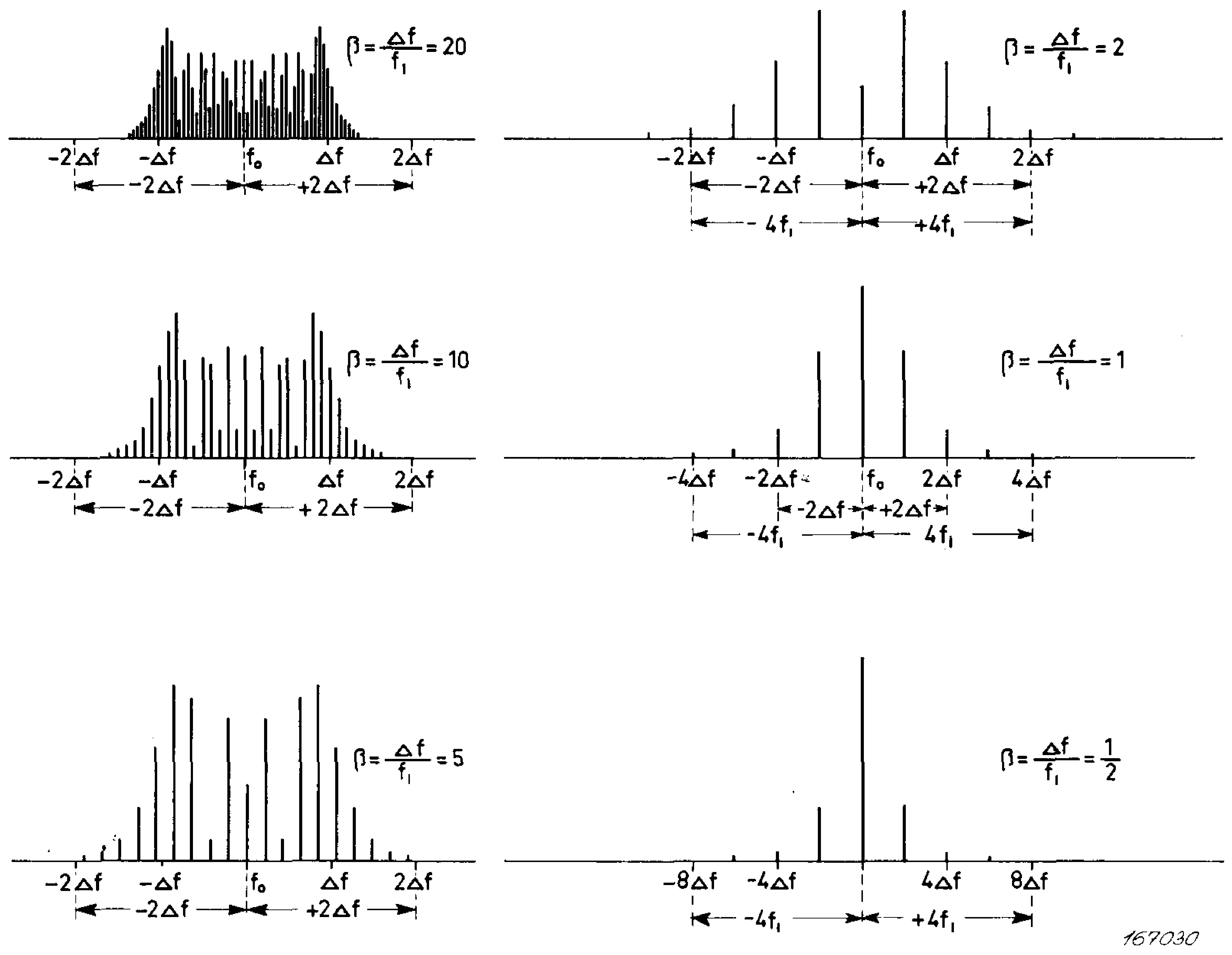
Frequency Modulation Spectra

*Fig. A.1.*

seen that as long as $\Delta f/f_1$ is great then a great number of sidebands are necessary for a complete description. However, most of the important sidebands are found within the limits ± 2 $\Delta$ f the spacing between the sidebands being $f_1$.

On the other hand if $\Delta f/f_1$ is small only one (or two) sidebands are present and a general bandwidth requirement for FM-systems would thus be 4 $\Delta$ f or 8 $f_1$ which ever is the greater, a requirement which is practically always fulfilled in FM magnetic tape recording.

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# Vibration Measurements in the Laboratory of Applied Physics at the Technical University of Denmark

By

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## ABSTRACT

This article describes some building vibration measurements carried out at the Technical University of Denmark. These vibrations were of a very low level and low frequencies, making it necessary to construct a special high sensitivity transducer and to employ frequency transformation in order to carry out frequency analysis. The frequency transformation was obtained with the B & K Tape Recorder Type 7001.

It was found that the measures taken to obtain a position with a vibration velocity level less than $3 \times 10^{-5}$ m/sec had been successful and that the isolation between this point and the rest of the building was adequate.

## SOMMAIRE

Cet article décrit comment furent effectuées à l'École des Hautes Études Techniques du Danemark, certaines mesures de vibrations d'immeubles. Le niveau des vibrations était très bas de même que les fréquences entrant en jeu, ce qui rendit nécessaire la construction d'un capteur spécial à grande sensibilité et le recours à une multiplication de fréquence en vue de permettre l'analyse des signaux. La multiplication de fréquence fut effectuée à l'aide d'un enregistreur sur bande B & K du type 7001.

On arriva à la conclusion que les moyens utilisés pour obtenir une position ayant une immobilité suffisante, le mouvement résiduel devant avoir une vitesse inférieure à $3 \times 10^{-5}$ m/sec, étaient efficases et que l'isolation entre le point considéré et le reste de la construction était appropriée.

## ZUSAMMENFASSUNG

In diesem Artikel sind einige Schwingungsmessungen an Gebäuden beschrieben, die an der Dänischen Technischen Hochschule ausgeführt wurden. Da diese Schwingungen mit einem niedrigen Pegel und bei niedrigen Frequenzen erfolgen, war es erforderlich, einen speziellen hochempfindlichen Aufnehmer zu konstruieren und zum Zwecke der Frequenzanalyse eine Frequenztransformation durchzuführen. Die Frequenztransformation wurde mit dem Brüel & Kjær-Bandgerät Typ 7001 bewerkstelligt.

Mand fand, daß die Messungen, die zum Auffinden eines Standortes mit einem Schwinggeschwindigkeitspegel von weniger als $3 \times 10^{-5}$ m/s dienten, erfolgreich waren und daß die Isolation zwischen diesem Punkt und dem übrigen Gebäude ausreichend war.

### Purpose.

Vibration measurements have been carried out in the Laboratory of Applied Physics at the Technical University of Denmark, in order to determine the efficiency of certain floor constructions with regard to vibration damping, and to find a suitable location for conducting experiments with some extremely vibration sensitive instrumentation. It was desirable to find a position where the background vibration velocity was smaller than $3 \times 10^{-5}$ m/sec, preferably down to $3 \times 10^{-7}$ m/sec.

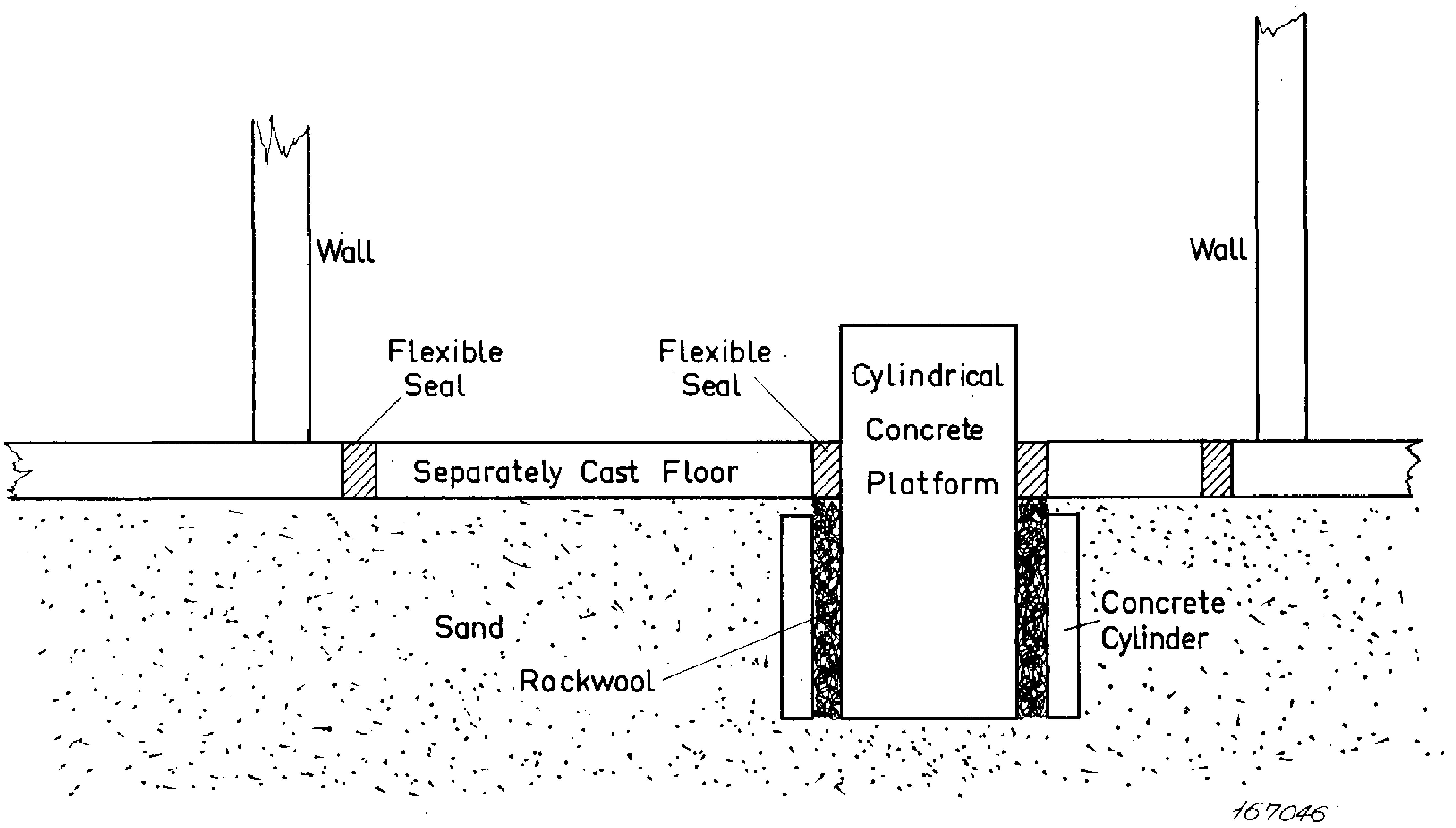

*Fig. 1. Schematic drawing of floor construction.*

The floor construction in some of the rooms in the cellar was as indicated in Fig. 1. In order to obtain isolation from the rest of the building structure these floors had been cast separately, but no damping material was used beneath the floor, apart from the ordinary layer of sand. A heavy concrete platform, also cast separately, was intended for vibration sensitive instruments or experimental set-ups where it was desirable to isolate from the vibrations caused by people moving about in the room.

The purpose of the measurements was to measure the background vibration on the floor and on the platform and to compare with measurements taken at other positions in the building. An indication of the isolation between the free floor and the concrete platform, and of the isolation between these two points and the rest of the building was also desired.

**Preliminary.**

A sinusoidal vibration may be specified in terms of RMS acceleration, velocity or displacement. These quantities are simply connected through the frequency of the vibration in the following way:

$$a = 2\pi f v = (2\pi f)^2 d$$

where $f$ = frequency in cycles per second (Hz).
$a$ = acceleration in meter per second per second (m/sec$^2$).
$v$ = velocity in meter per second (m/sec).
$d$ = displacement in meter (m).

The kind of vibrations found in buildings are usually of a random nature, irregular in amplitude and often intermittent in time. Thus several frequencies are present, and each frequency component must be treated separately if conversion from one vibration quantity to another is to be carried out. A separation of the vibration time function into its various frequency components is therefore desirable. This also gives a more qualitative picture of the vibration and helps to predict its effect on any structure which is influenced by the vibration.

A mechanical vibration time function is fairly easily converted into a proportional electrical signal by means of a piezoelectric transducer. The most common type is the accelerometer, which gives as output an electrical signal proportional to the acceleration amplitude of the vibration. A separation into frequency components is then simply achieved with the aid of electrical band-pass filters. Usually the separation of components into frequency bands of 1/3 octave is considered satisfactory. (22 % relative bandwidth).

Random vibration consists of a continuous distribution of frequency components with random phase. Phase information is not included in frequency spectra, and amplitudes are given on a root mean square basis, (RMS). An acceleration amplitude versus frequency spectrum therefore expresses the square root of the power distribution and it is not possible to obtain peak amplitudes from such a plot. Addition of the RMS amplitudes in each frequency band gives the total RMS amplitude. The peak amplitudes can not be determined. Generally, however, one can expect the peak amplitudes to be below three times the RMS value (for 99 % of the time).

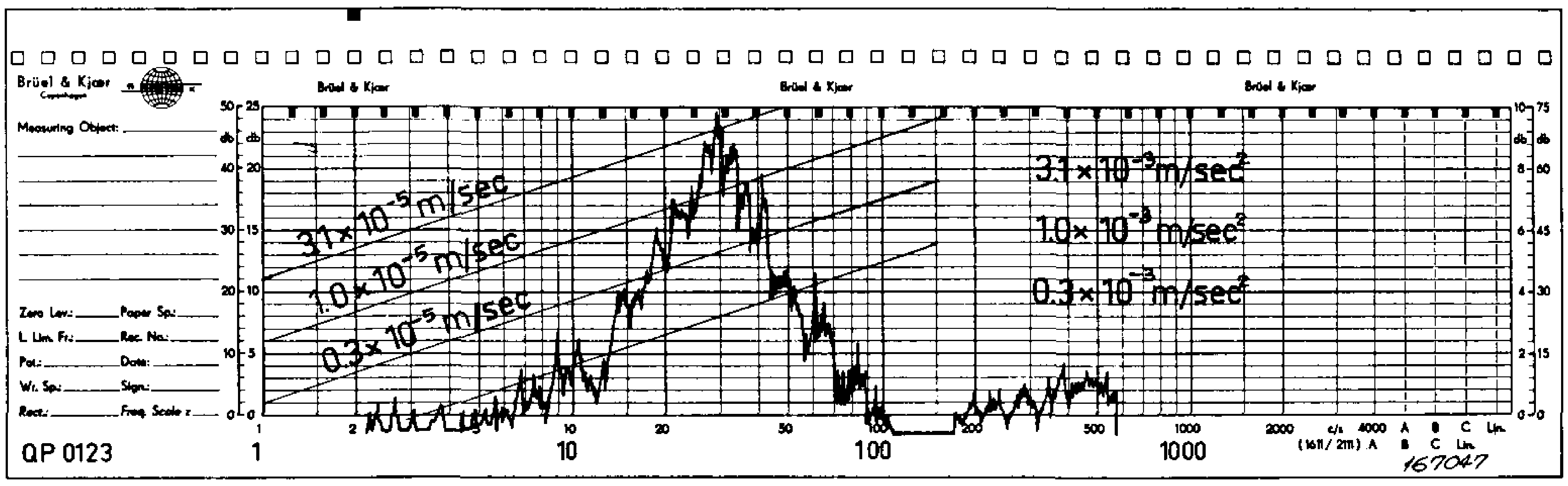

*Fig. 2. Construction of velocity spectrum from an acceleration spectrum.*

In order to obtain a velocity spectrum from an acceleration spectrum, it is necessary to divide the RMS value in each 1/3 octave band by $2\pi$ times the average frequency (centre frequency) of the pass band. When the acceleration spectrum is plotted on double logarithmic paper a scale for velocity is easily constructed by drawing in lines with a positive slope of 20 dB per decade as shown in Fig. 2. The plot is thereby automatically converted into a velocity spectrum when these lines are used for reading amplitude values. The frequency scale is unchanged.

Amplitude values must be added logarithmically when the amplitudes from several frequency bands are combined. The instrumentation used in this

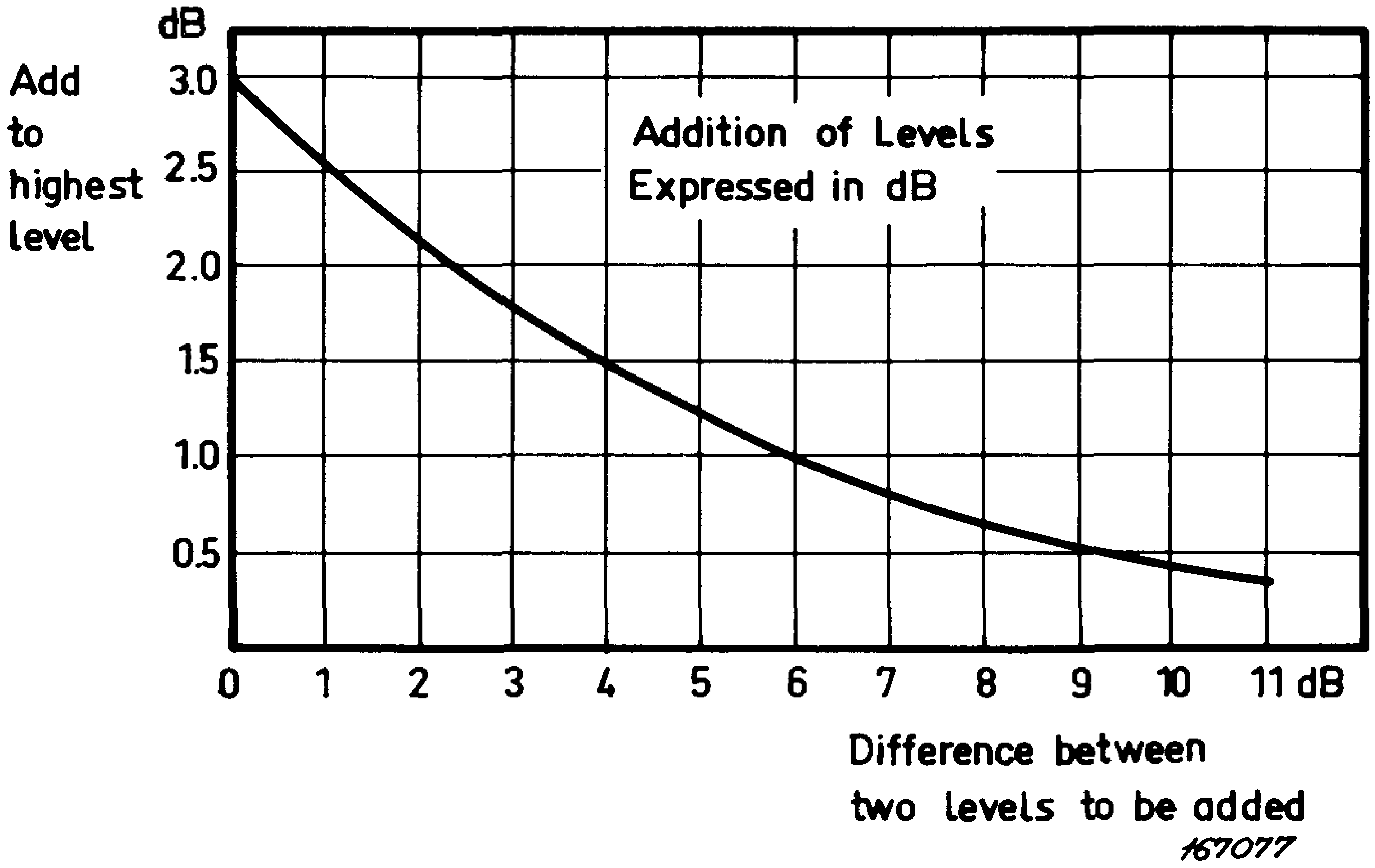

*Fig. 3. Curve used for logarithmic addition of amplitude values expressed in decibels.*

investigation gives amplitude values in decibel, and a curve for logarithmic addition with decibels is given in Fig. 3. (In the results given in this report addition of the amplitude values into a total RMS value has already been carried out).

**Frequency Transformation.**

When a signal is analysed it is sometimes necessary to employ a frequency transformation method, in order to bring the frequency components of the signal into the frequency range of the available analyzer. An easy way of doing this is to employ a variable speed tape recorder. If a signal is recorded at one speed and played back at some other speed the frequency components are shifted in frequency in the same ratio as the speed ratio. Thus a doubling of the tape speed multiplies all the frequencies by a factor two. The amplitude of the components remain unchanged, within the linear frequency range of the amplifiers etc.

The B & K Instrumentation Tape Recorder Type 7001 has tape speeds of 1.5, 6, 15 and 60 in/sec so that frequency transformation ratios up to 1 : 40 are available. In the present measurements it was found that important frequency components existed down to a few cycles per second, and since the standard B & K Audio Frequency Spectrometer can analyse down to some 22 Hz, it was convenient to use a 1 : 10 frequency transformation, whereby analysis was possible down to some 2.2 Hz.

**Initial Measurements.**

Preliminary measurements were carried out in order to determine the range of vibration amplitudes encountered, and to decide if the standard Brüel & Kjær accelerometers were suitable as transducers for this special application.

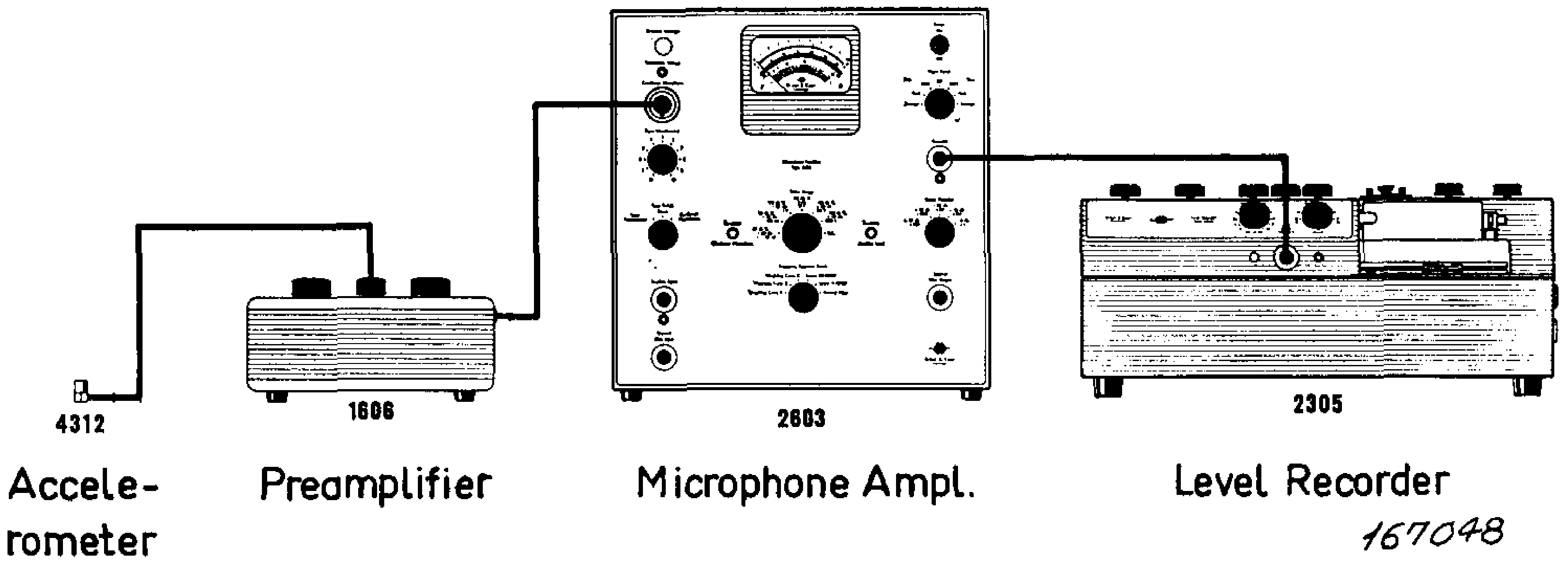

*Fig. 4. Instrumentation used for the preliminary measurements.*

The instrumentation consisted of the following parts:

| | |
|---|---|
| Accelerometer | Type 4312 |
| Preamplifier | Type 1606 |
| Amplifier | Type 2603 |
| Level Recorder | Type 2305 |

A sketch of the set-up is shown in Fig. 4. The sensitivity of the accelerometer was 51.3 mV/g and the noise level of the instrumentation was 8 $\mu$V, making acceleration measurements possible down to about $3 \times 10^{-3}$ m/sec$^2$ in the frequency range 2 Hz to 10,000 Hz.

The preliminary measurements were taken in room 932 in the cellar, which was intended for "Fundamental Measurements". In order to determine the effect of nearby air conditioning machinery, the measurements were carried out with and without this machinery running. Measurement positions and results were as follows:

| Position | Aircond. on | | Aircond. off | |
|---|---|---|---|---|
| | $\mu$V | m/sec$^2$ | $\mu$V | m/sec$^2$ |
| Concrete platform | 8 | – | 8 | – |
| Floor | 8 | – | 8 | – |
| Wall | 15 | 0.003 | 10–15 | 0.002–0.003 |
| Corridor outside | 10–70 | 0.002–0.014 | 10–30 | 0.002–0.006 |

Some recordings of the acceleration level as a function of time are given in Fig. 5.

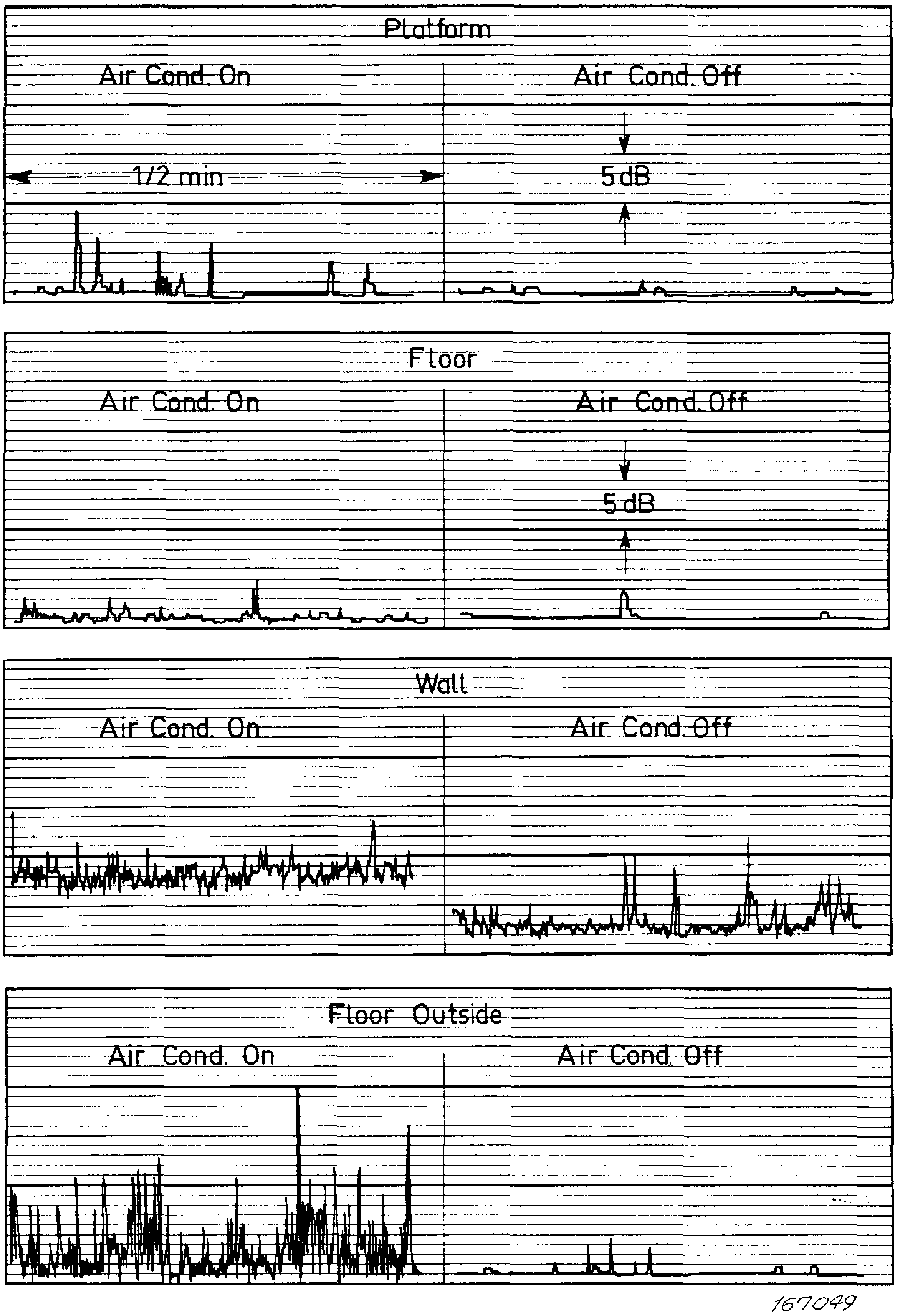

*Fig. 5. Recordings of variation of acceleration level with time.*

From the results obtained can be seen that the vibration level is lower than the dynamic limit of the instrumentation, i.e. the transducer is not sensitive enough to measure the vibration on the concrete platform and on the isolated floor. The recordings show that the vibration level is very irregular and that even at the positions where the vibration level is too low to be measured, occasional peaks come through, indicating that the vibration level is not far below the lower dynamic limit of the instrumentation.

It is also seen that the air conditioning system has some slight influence on the vibration level.

**Construction of new Transducer.**

In order to obtain the required sensitivity it was necessary to construct a transducer especially for the purpose. Since building vibrations consist mainly of low frequency components, it was possible to sacrifice some of the high frequency response for a higher sensitivity.

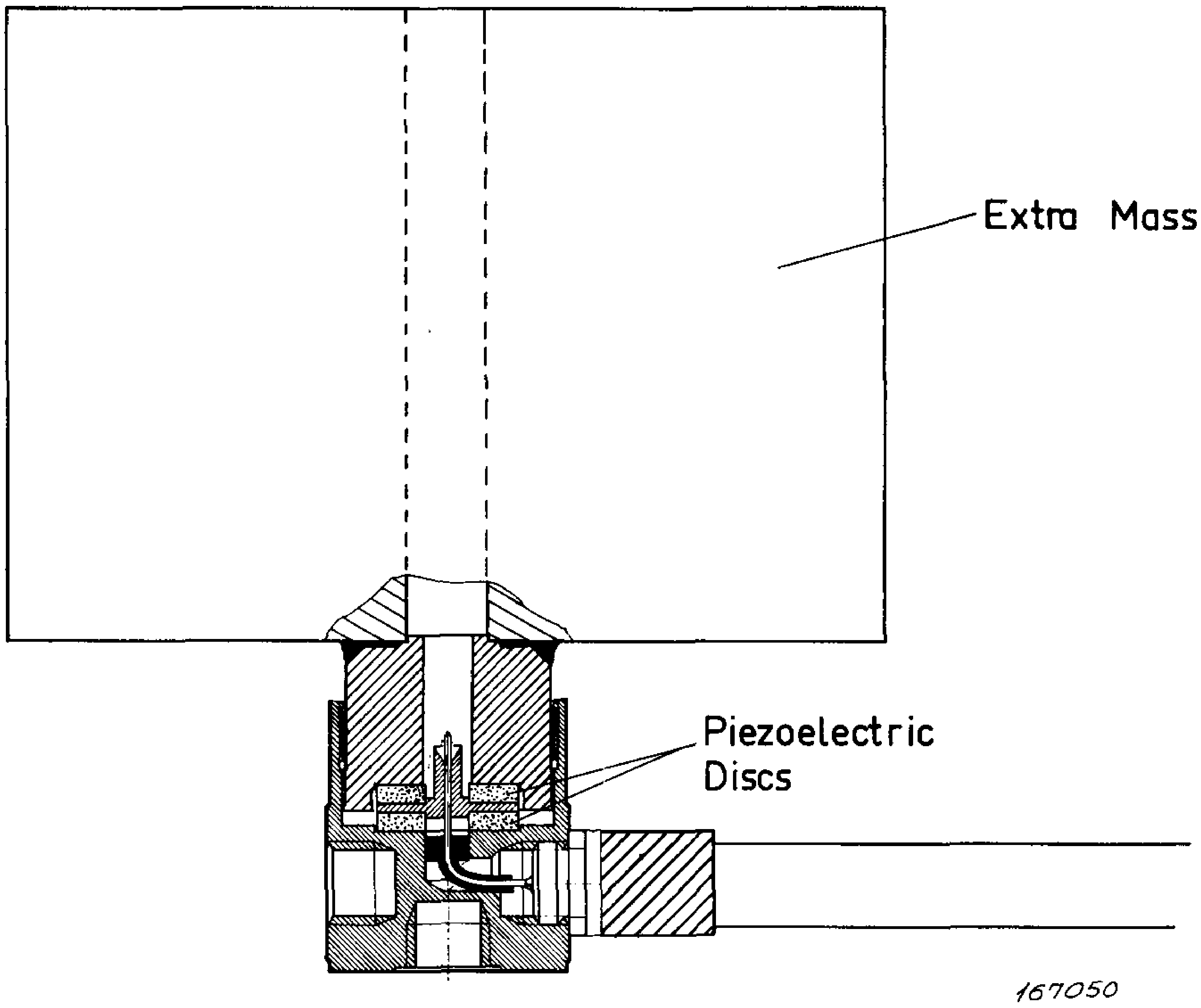

*Fig. 6. Modified accelerometer with extra mass added.*

After trying three different approaches the best solution seemed to be an ordinary accelerometer construction with extra mass added to increase sensitivity. The modified accelerometer is shown in Fig. 6. It consists of an ordinary accelerometer base and piezoelectric discs. A large mass was placed on top of the discs, thereby increasing the sensitivity from the normal 15 mV/g to some 3000 mV/g.

Because of the special application of vibration measurements in dry rooms, on horizontal, plane surfaces with vibration levels only a fraction of 1 g, the transducer could be made very simple. It was thus not considered necessary to clamp the mass, nor to seal the construction against moisture. Also the accuracy of measurement was not critical, so that calibration procedures were greatly simplified.

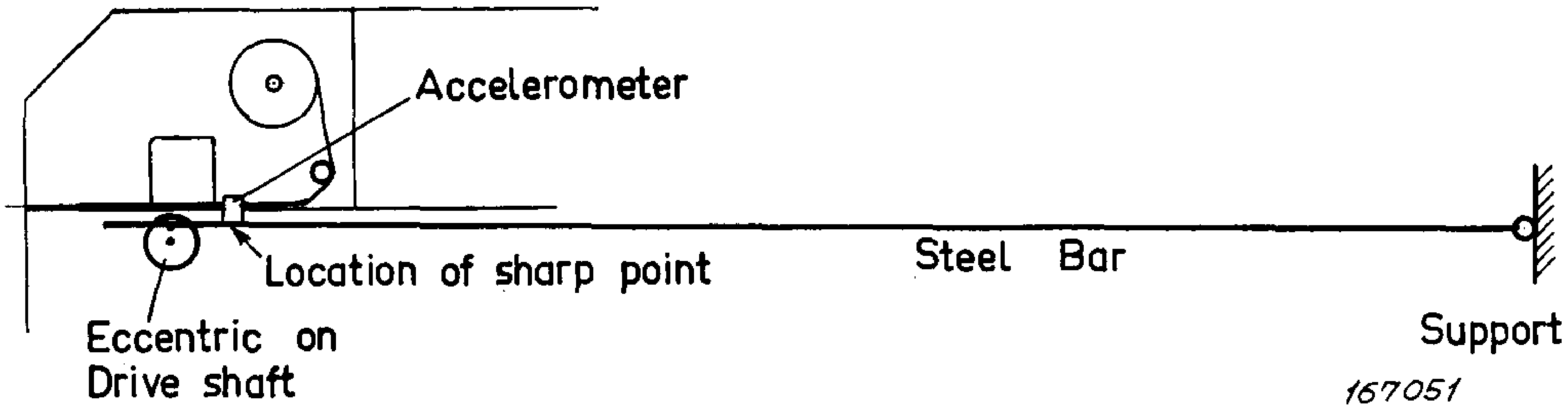

*Fig. 7. Set-up for accelerometer calibration at 2 Hz.*

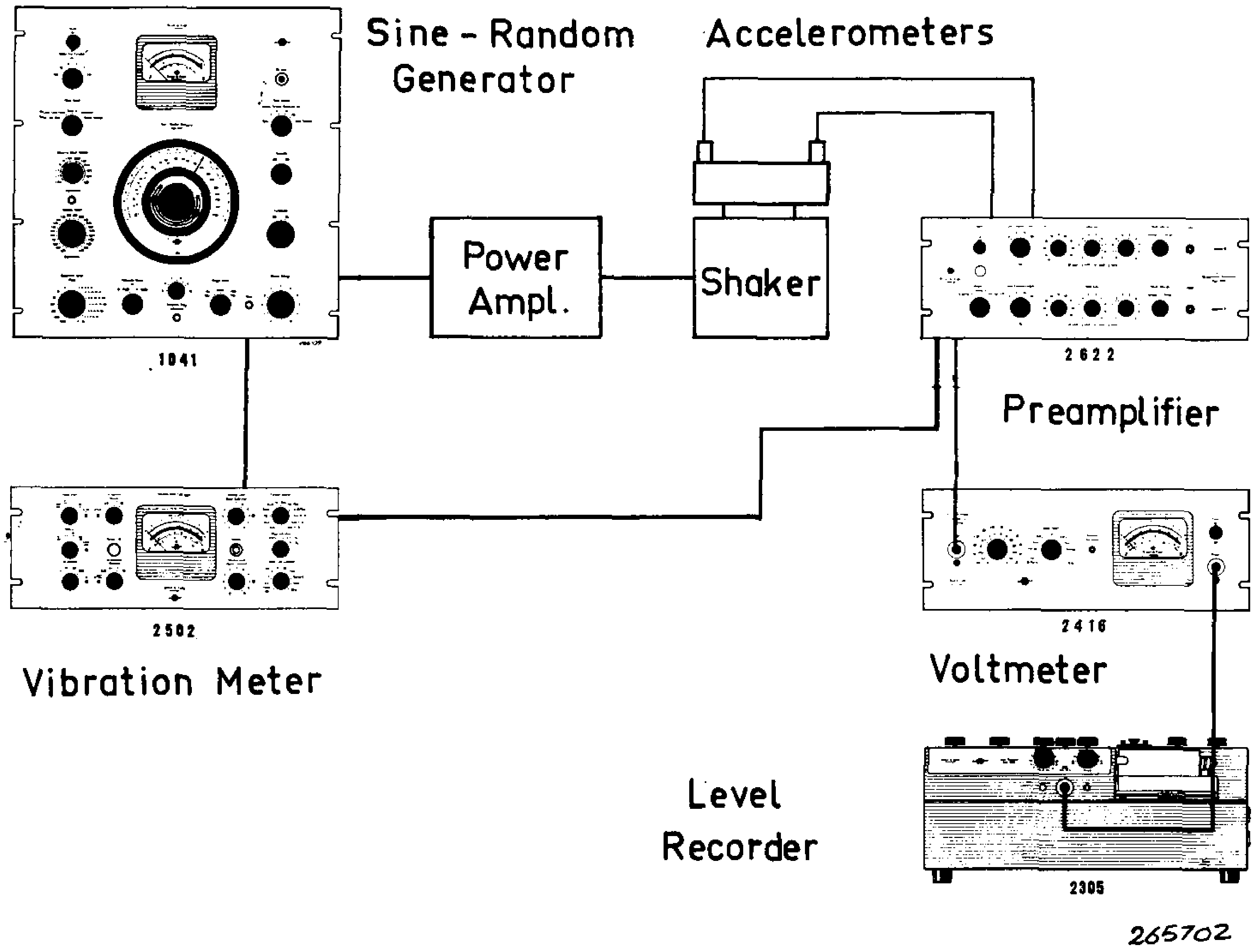

*Fig. 8. Set-up for frequency response test.*

**Calibration.**

Building vibrations are usually of a low frequency nature, and contain frequency components down to 2 Hz or lower. As the Brüel & Kjær measuring amplifiers have a flat frequency response down to 2 Hz, it was considered desirable to calibrate the transducer down to this frequency, in order to extract the maximum amount of information from the measurements.

Calibration at 2 Hz was achieved by placing the accelerometer on a long steel bar which was pin supported at one end and driven by an eccentric at the other end. The eccentric was fixed to the drive shaft of the Brüel & Kjær Level Recorder running at exactly 2 Hz (120 RPM). The peak-to-peak amplitude was measured with a sharp point fixed to the steel bar and making a trace on a piece of paper. See Fig. 7. In order to check the accuracy of the method, a standard B & K accelerometer was also calibrated in the same way.

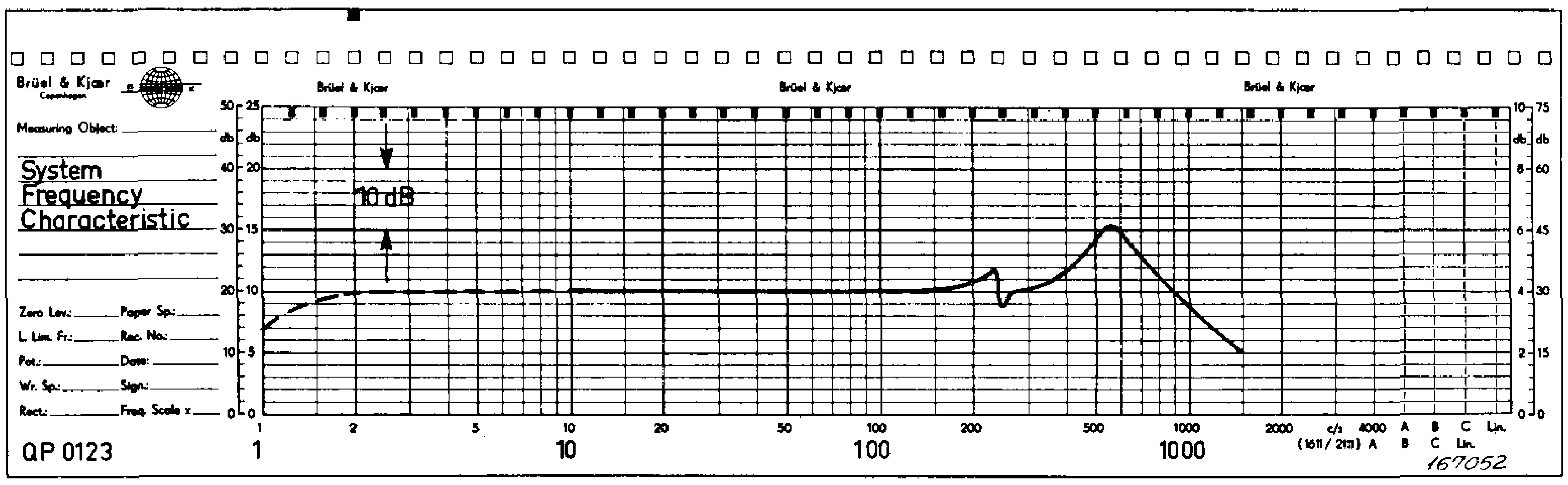

*Fig. 9. Total frequency response of the measuring system.*

At 2 Hz the sensitivity of the transducer was found to be 3100 mV/g. The standard accelerometer showed a sensitivity of 14.0 mV/g which is in good agreement with the 14.7 mV/g given as its factory calibration at 50 Hz. The transducer sensitivity may therefore be taken as accurate to within ±1 dB which is adequate for this application.

As the heavy mass on the accelerometer must give a fairly low resonance frequency, it was decided to find the relative frequency response curve for the new transducer. This was done on an electrodynamic shaker utilizing the Brüel & Kjær vibration test instrumentation as shown in Fig. 8. This gives the frequency characteristic of the transducer from about 10 Hz upwards, and with the former calibration at 2 Hz the total frequency response of the instrumentation system can be drawn as in Fig. 9. It is seen that the system may be used without correction up to some 400 Hz within the accuracy required by this investigation.

## Measurements.

Two types of measurement were carried out, viz. ordinary background vibration measurements, and measurements of vibration isolation using the B & K Tapping Machine Type 3204. This machine has been designed as an artificial "footstep" generator for building research work.

### *Background Vibration.*

The instrumentation used for the measurements is shown in Fig. 10. The signal from the transducer is taken via a Preamplifier Type 1606 to a Spectrometer Type 2112 giving 1/3 octave and octave analysis. Since the Spectrometer can only analyze frequency components down to 22 Hz and since important vibration components exist at much lower frequencies a Tape Recorder Type 7001 was employed for frequency transformation. The signals were recorded with a tape speed of 1.5 in/sec with the Spectrometer used as a linear amplifier in the range 2 Hz to 40,000 Hz, and later played back into the spectrometer for analysis at 15 in/sec, whereby it was possible to analyse down to about 2.2 Hz.

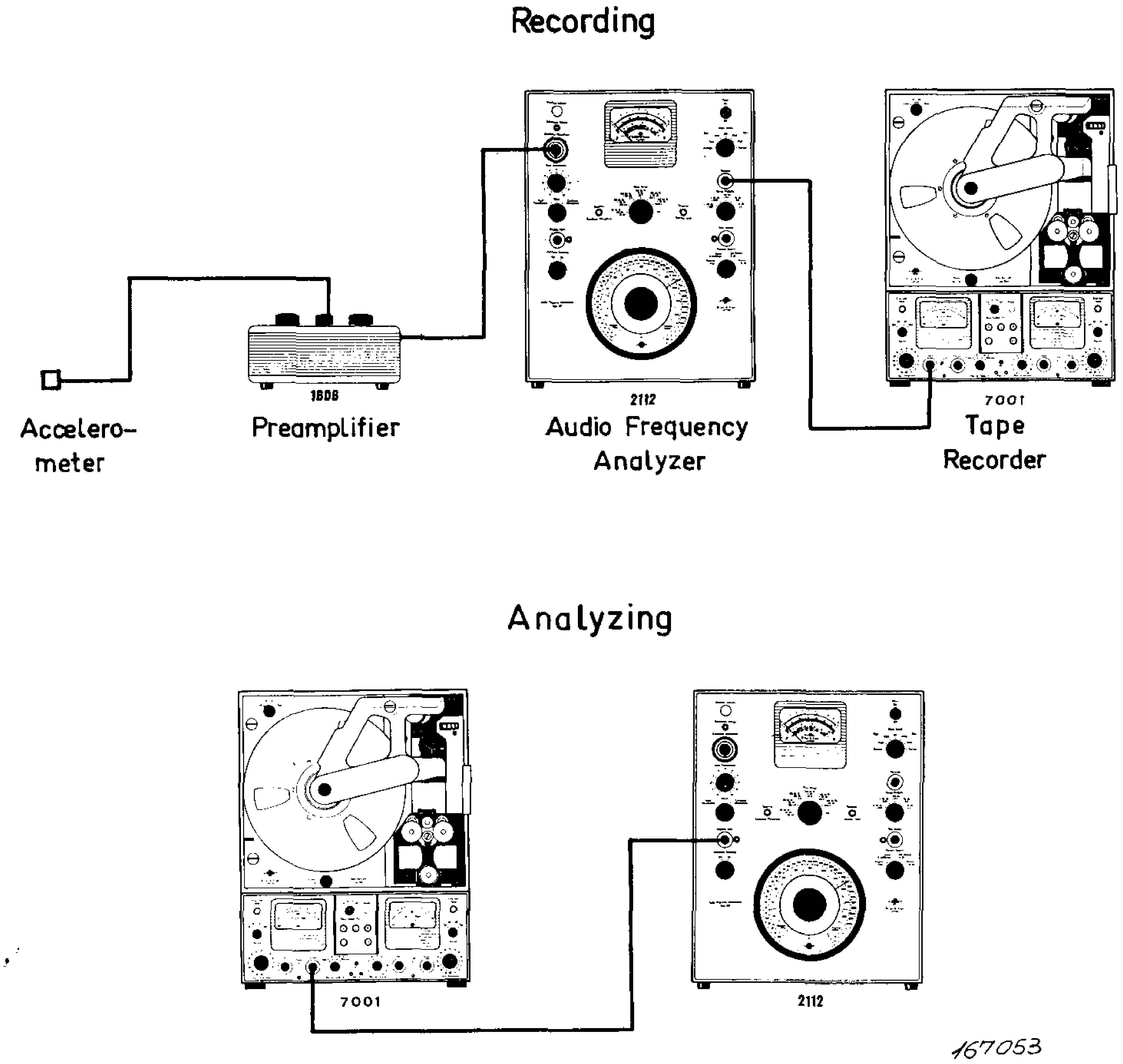

*Fig. 10. Set-up used for background vibration measurements.*

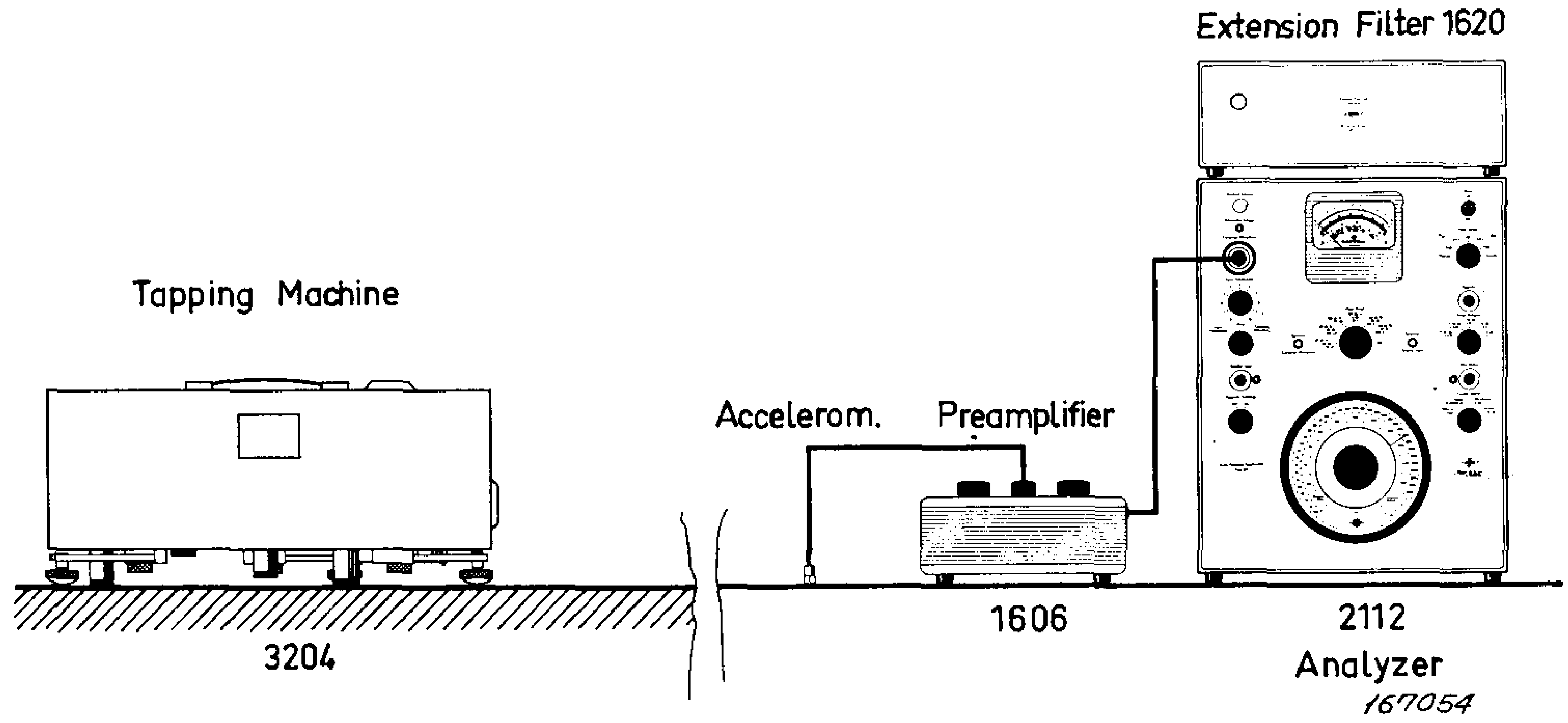

*Fig. 11. Set-up used for vibration isolation measurements.*

*Vibration Isolation.*

The Vibration isolation between various points was investigated with the Brüel & Kjær Tapping Machine, as shown in Fig. 11. The acceleration signal was fed directly via a preamplifier to the Spectrometer for immediate 1/3 octave analysis. (With the Extension Filter Set Type 1620 the Spectrometer can analyse frequency components down to about 11 Hz).

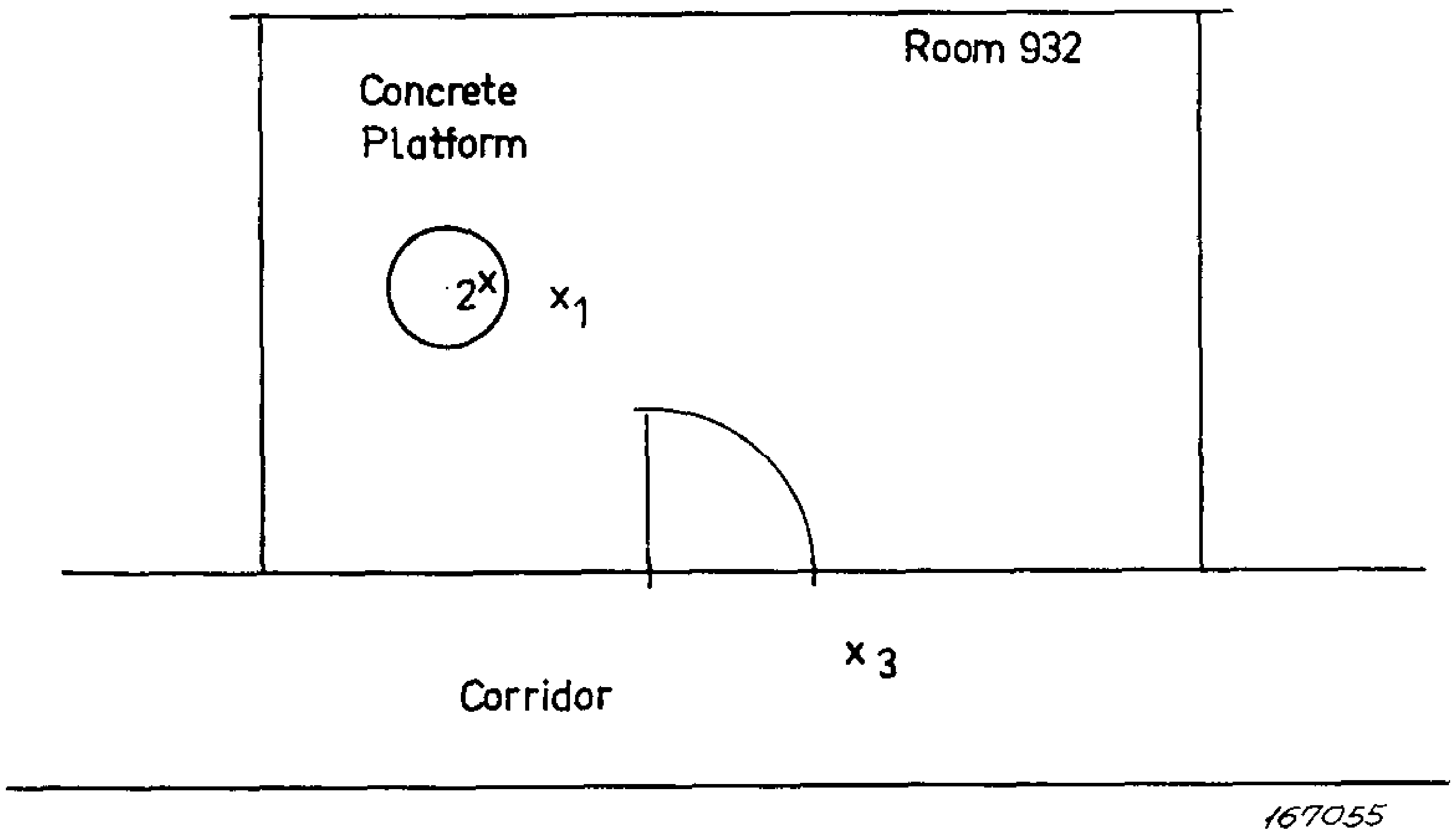

Fig. 12. Room 932 with measurement positions.

*Measurements.*

The first room in which measurements were taken was Room 932, sketched in Fig. 12. Measurement points were

1. On the floor.
2. On the concrete platform.
3. On the floor just outside the room.

In all three positions background vibration measurements were taken, with and without the air conditioning system working. Results are given in Fig. 13, showing the background vibration spectra down to about 2.2 Hz.

Measurements with the Tapping Machine were as follows:

1. Tapping Machine on the floor, accelerometer beside.
2. Tapping Machine on the floor, accelerometer on the concrete platform.
3. Tapping Machine outside the room, accelerometer on the concrete platform.
4. Tapping Machine outside the room, accelerometer on the floor inside.

It was found that the main part of the vibrations caused by the tapping machine consisted of frequencies higher than 10 Hz, so that direct analysis, without frequency transformation, was used. The frequency spectra obtained are shown in Fig. 14.

Similar measurements were carried out in Room 922, which is of the same basic construction as Room 932. The vibration on the concrete platform and on the floor was analyzed with and without the Tapping Machine operating in the corridor outside. Results are given in Fig. 15.

The next room in which measurements were taken was No. 938. A special arrangement with an inflatable rubber ring (tractor inner tubing) and lead weights was set up in order to try to obtain a very low background vibration, in order to be able to conduct some extremely vibration sensitive experiments with the Mössbauer Effect. See Fig. 16. The following measurements were taken:

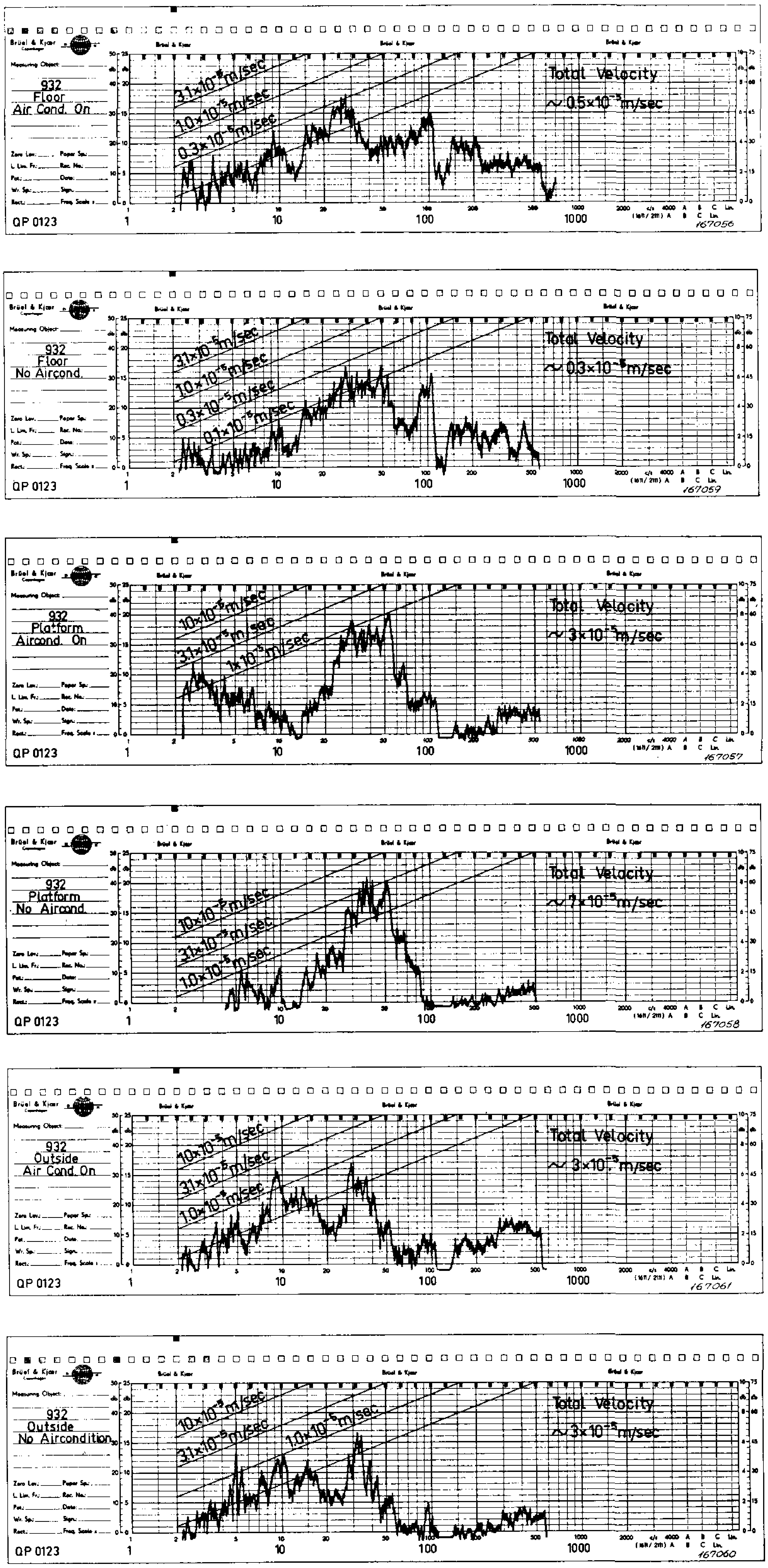

*Fig. 13. Results from measurements in Room 932. (Background vibration).*

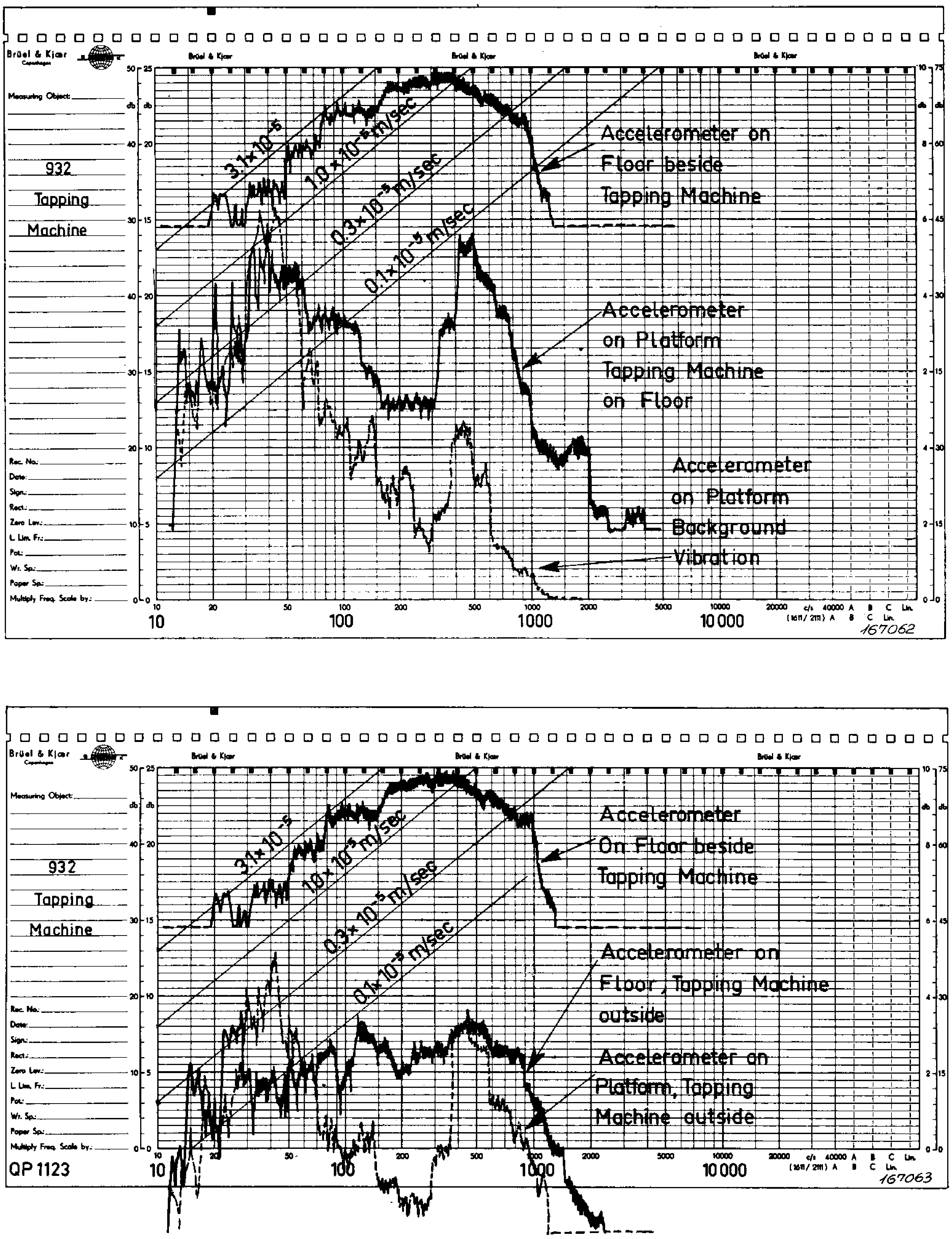

Fig. 14. Results from measurements in Room 932. (Vibration isolation).

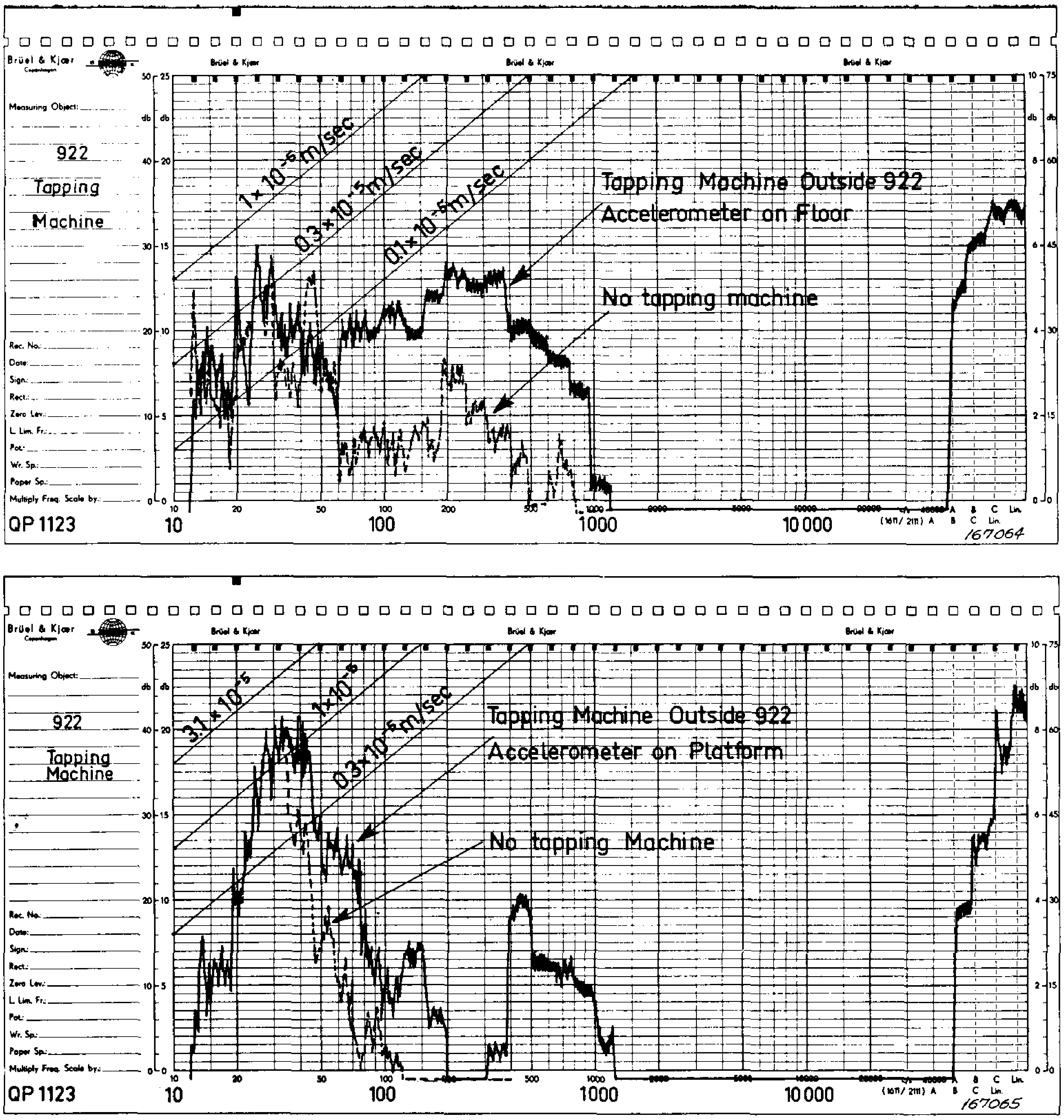

*Fig. 15. Results from measurements in Room 922.*

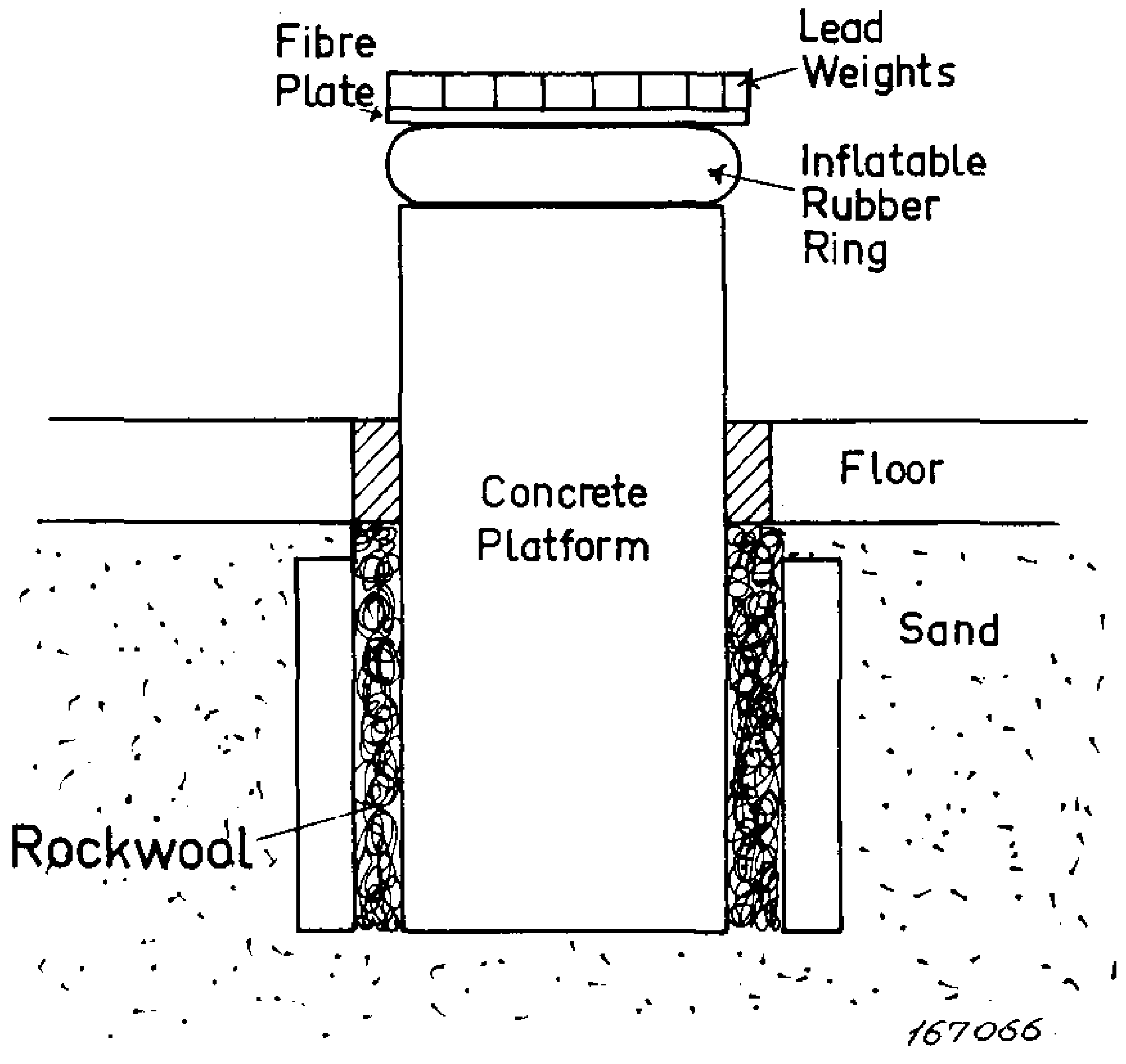

*Fig. 16. Arrangement with tractor inner tubing and lead weights.*

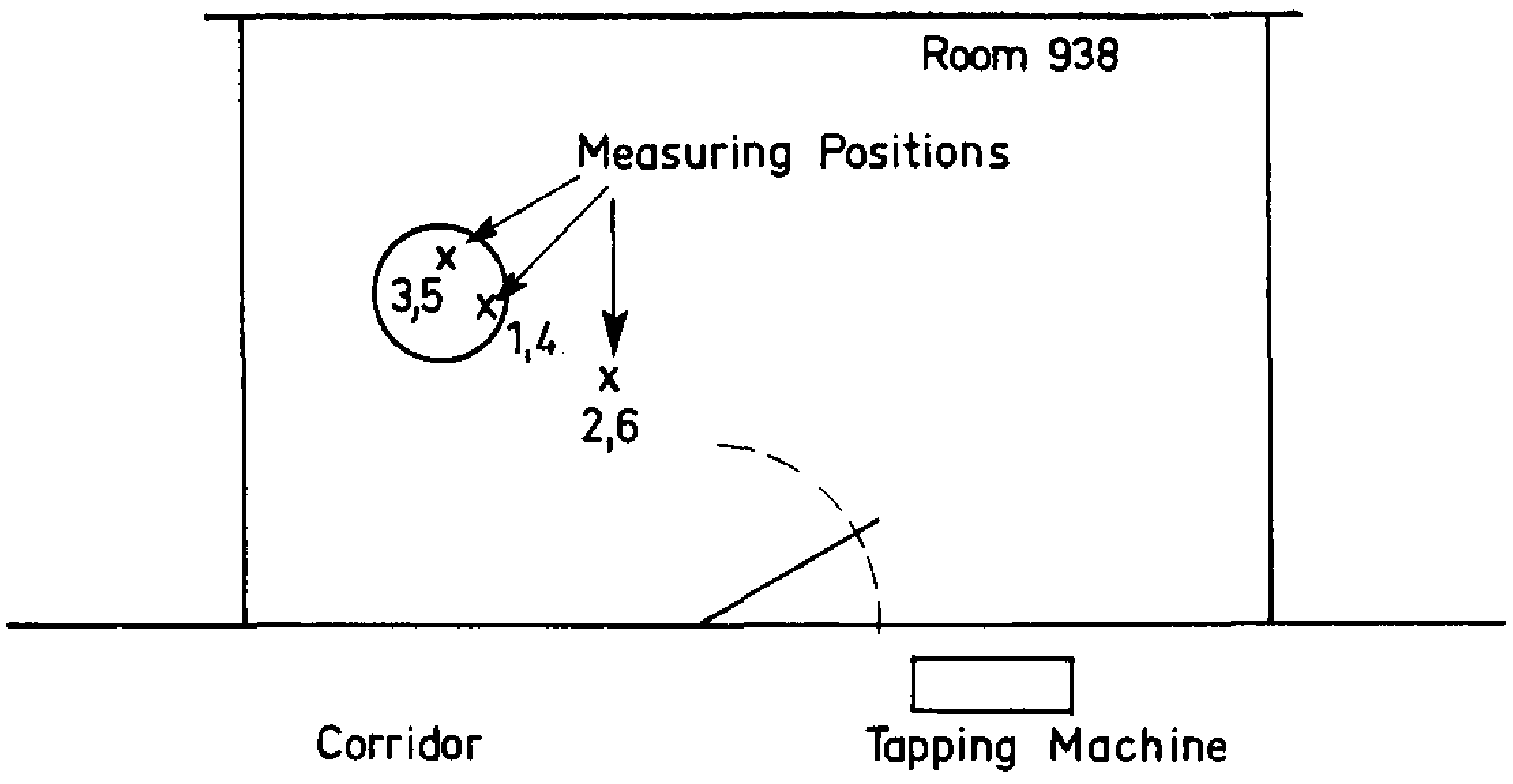

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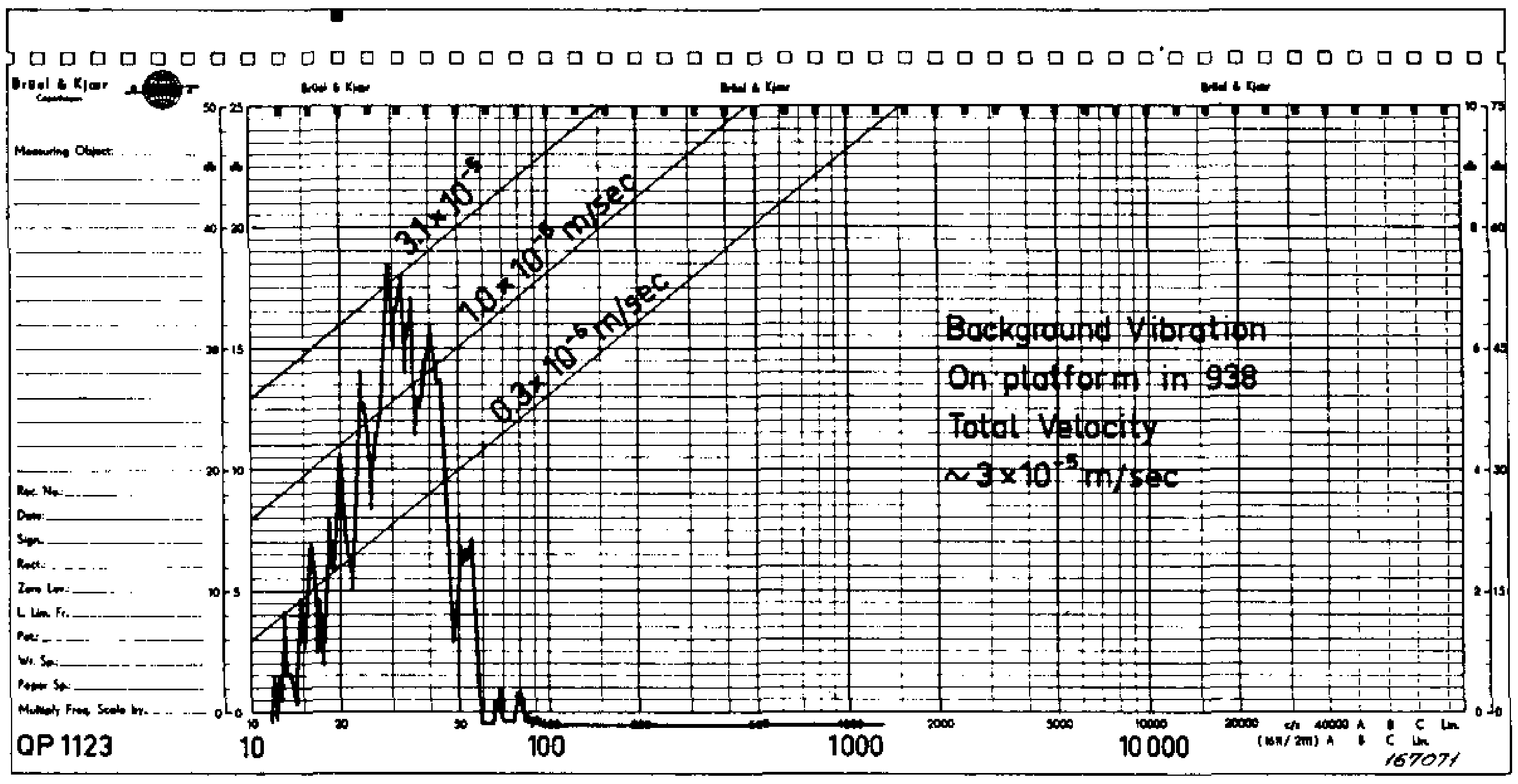
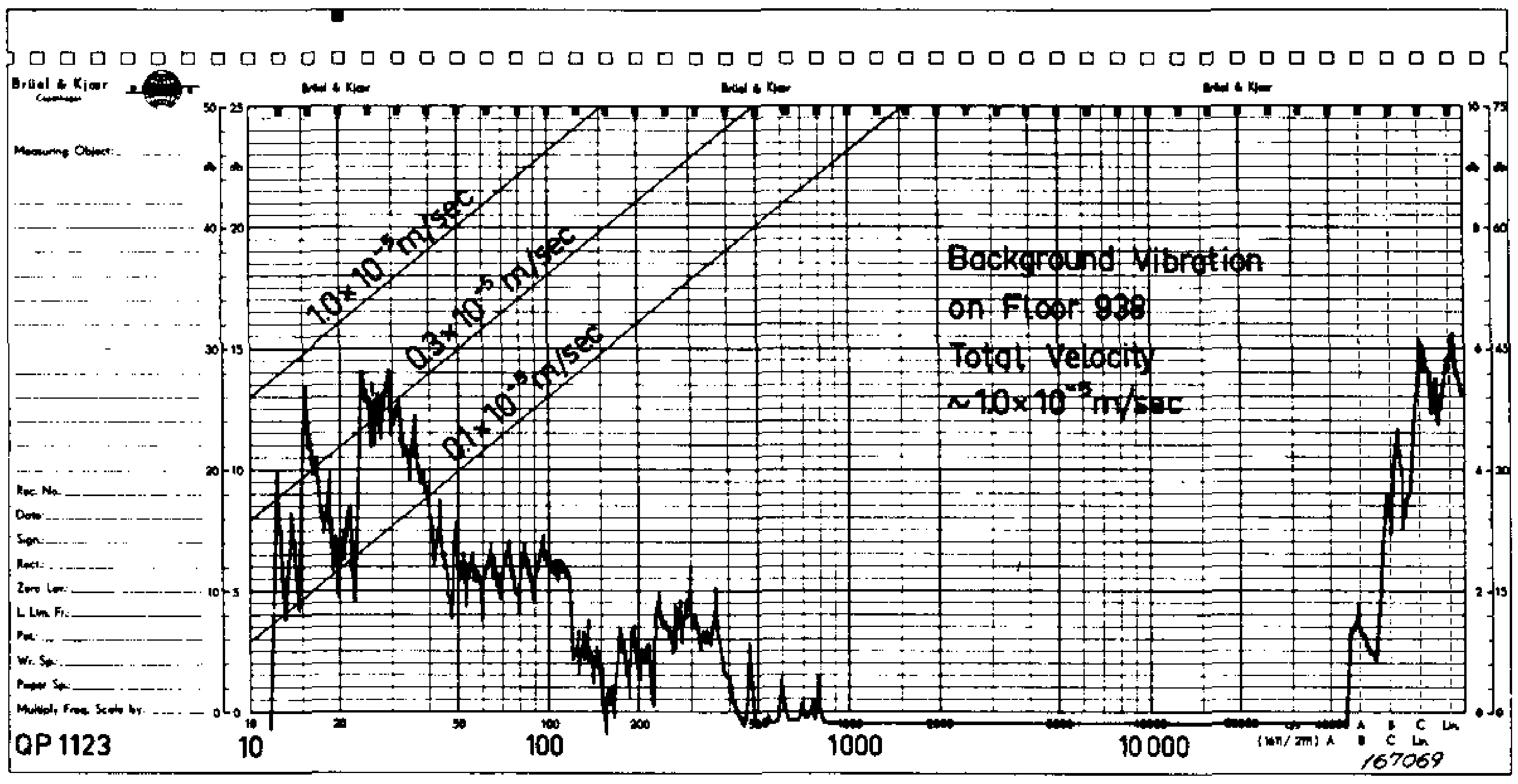
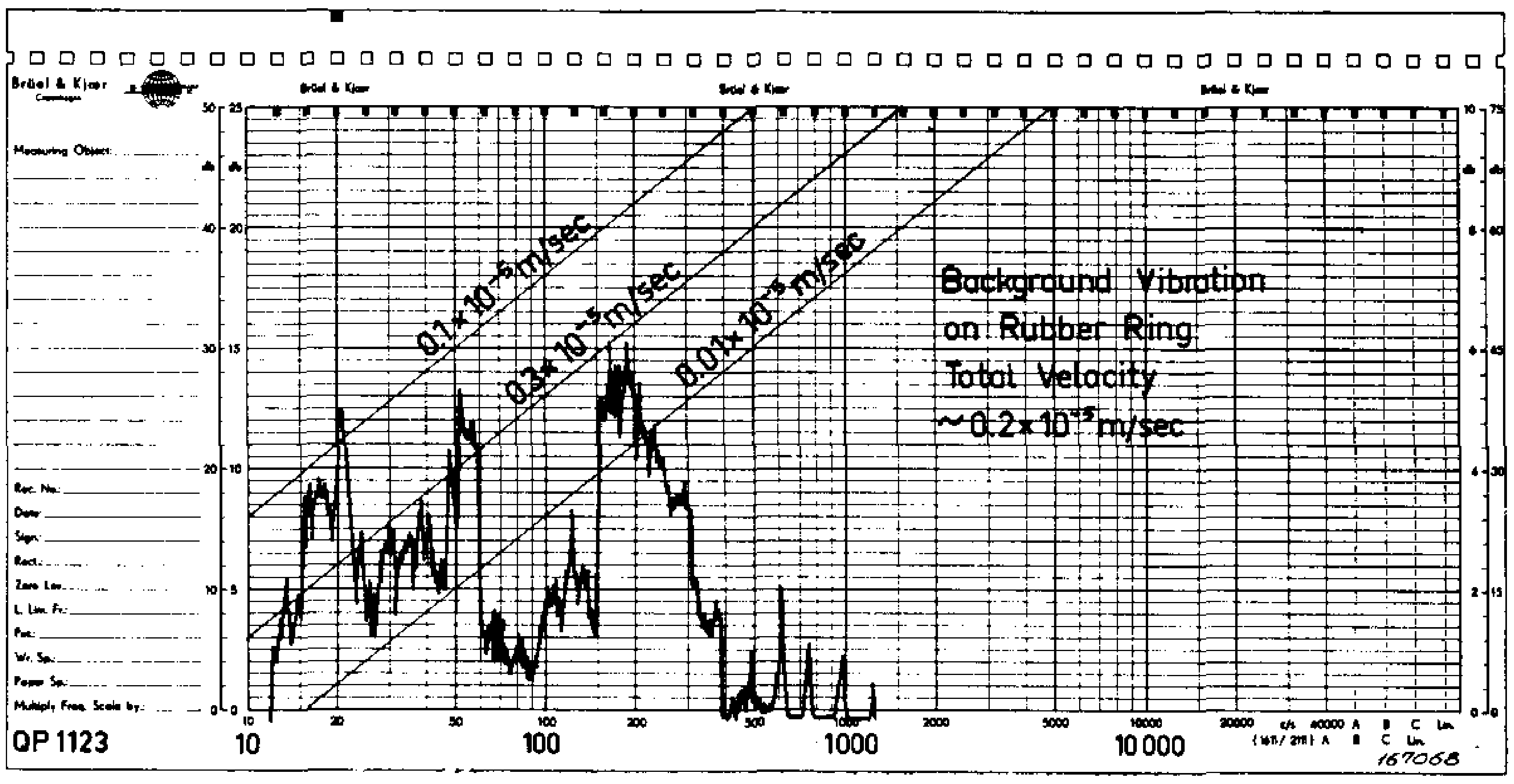
Fig. 17. Measuring positions in Room 938.







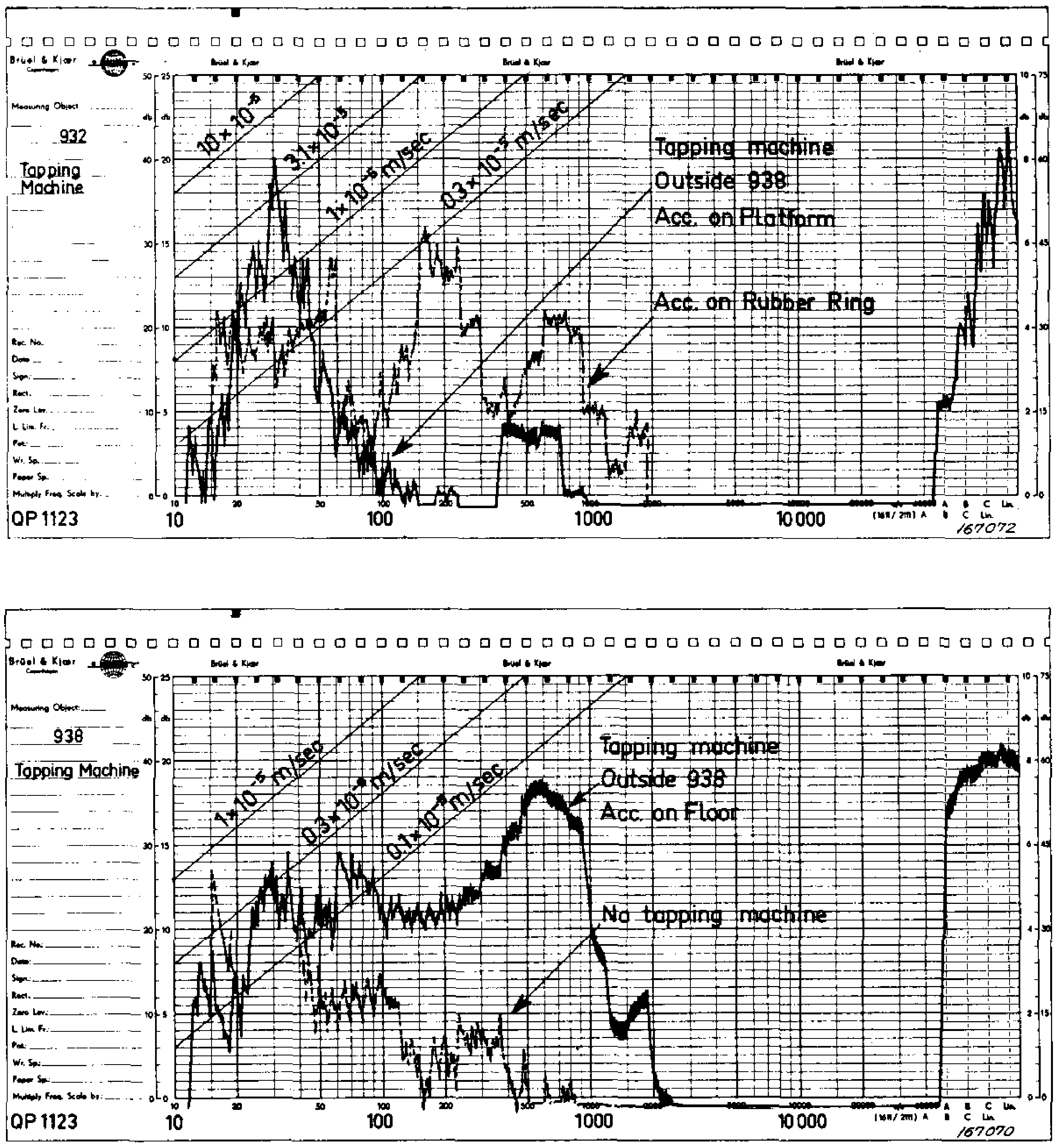


Fig. 18. Results from measurements in Room 938.

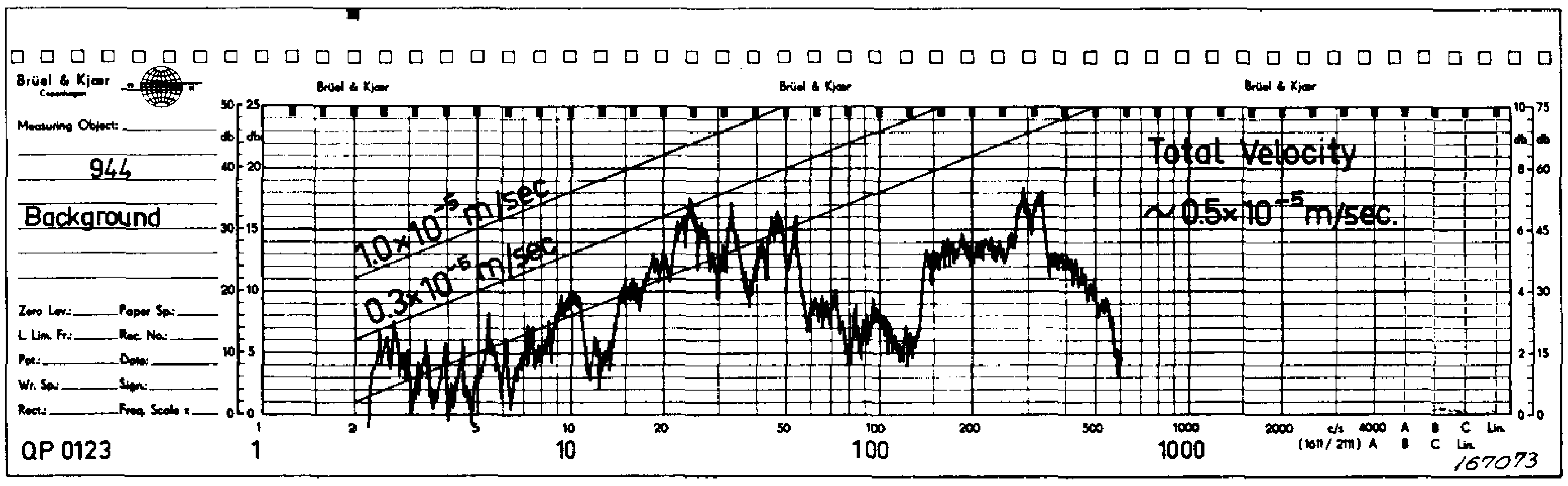


Fig. 19. Spectrum of the background vibration in Room 944.

1. Background vibration on the concrete platform.
2. Background vibration on the floor.
3. Background vibration on the rubber ring.
4. Vibration on the concrete platform with the Tapping Machine outside.
5. Vibration on the rubber ring with the Tapping Machine outside.
6. Vibration on the floor with the Tapping Machine outside.

The measuring positions are given in Fig. 17 and the spectra obtained are reproduced in Fig. 18.

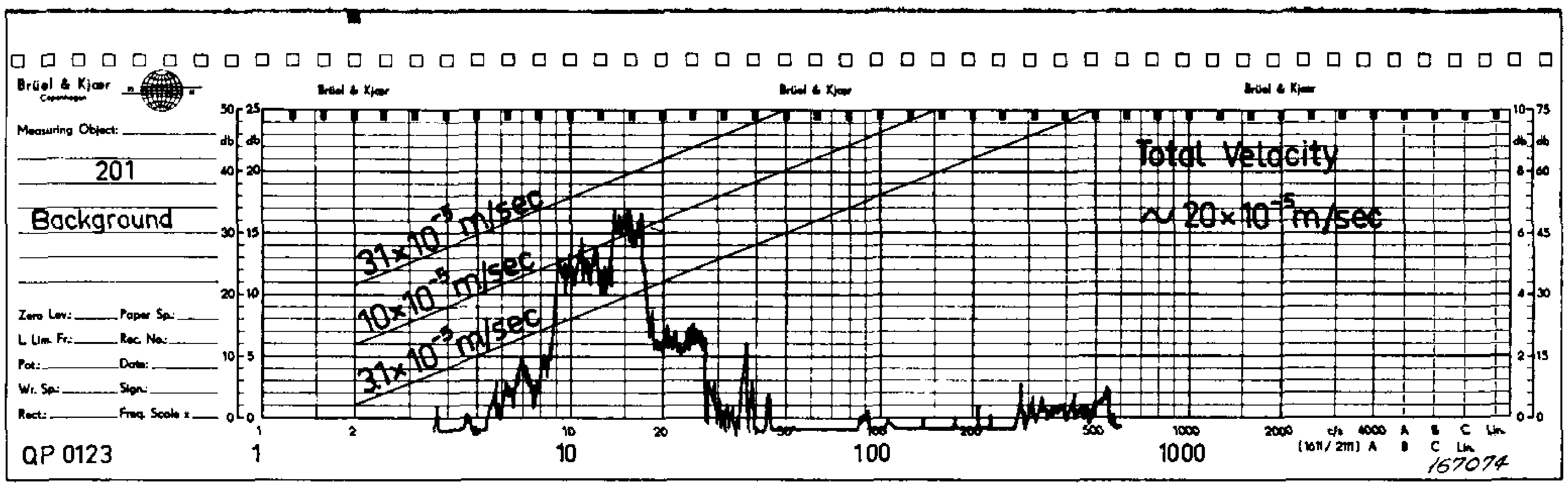


Fig. 20. Spectrum of the background vibration in Room 201.

For comparison purposes the background vibration was measured on the floor in Room 944. This floor is not isolated from the rest of the building. The resulting spectrum is shown in Fig. 19.

Measurements were also carried out in Room 201 on the second floor, where the Mössbauer experiment was set up, and where the background vibration had been found excessive. The spectrum obtained is shown in Fig. 20.

## Traffic Induced Vibration.

During the preliminary measurements it was noticed that periodically some very strong, low frequency vibrations were induced in the building. The frequency range extended upwards into the audible range, perhaps to some 50 Hz. An examination of the activity in the building and in its vicinity revealed only one possible source. This was a bulldozer working some 100 meters away from the building.

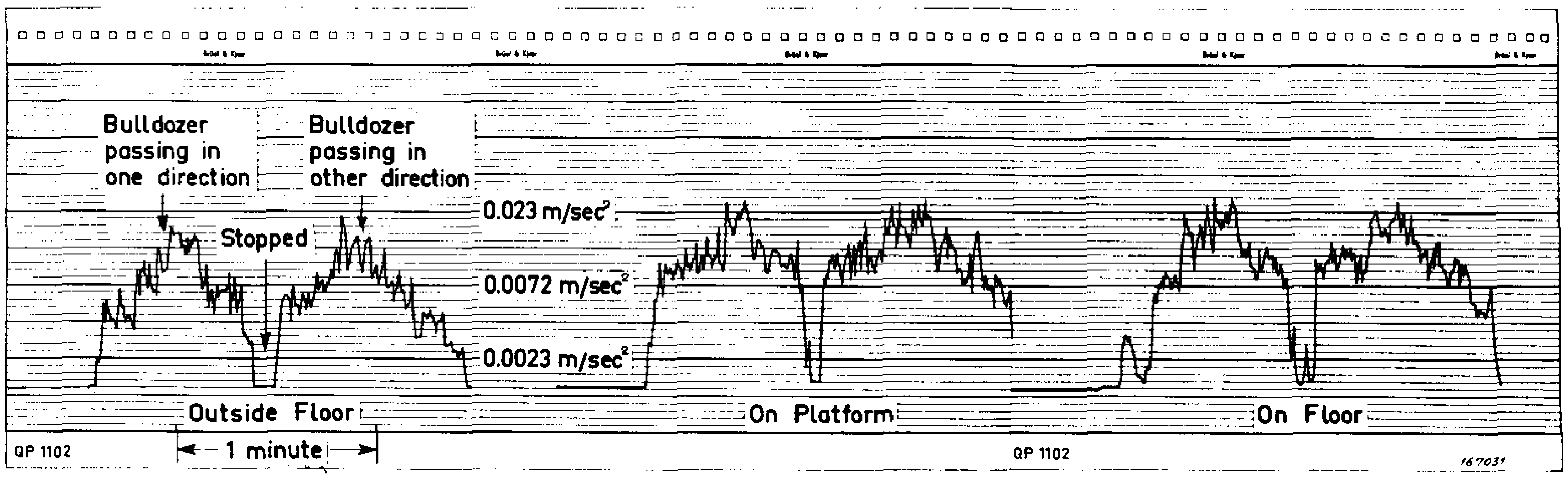


Fig. 21. Vibration levels resulting from road traffic.

It was then decided to measure the effect of moving vehicles on the road just outside the building, and the operator of the bulldozer was persuaded to drive back and forth on the road a couple of times, while vibration measurements were taken down in the cellar.

The B & K accelerometer was placed on the isolated floor, on the concrete platform and on the floor outside, with results as shown in Fig. 21.

## Discussion of Results.

*Nearby traffic.*

It is obvious from the results shown in Fig. 21 that motorized traffic in the immediate vicinity of the building will induce considerable vibrations in the building. It is also seen that these vibrations are transmitted equally well to the isolated floors and the concrete platforms as to the rest of the building structure.

Estimating the frequency of the vibrations recorded to be in the order of 30 Hz, the vibration velocity resulting from the bulldozer passing by was approximately $10^{-4}$ m/sec, RMS.

It should be noticed that distant traffic, such as railway trains and heavy road vehicles, may also cause vibration in the building. Low frequency seismic waves can travel considerable distances through the ground without appreciable attenuation, depending very much upon the ground structure. Generally, of course, the attenuation increases with distance.

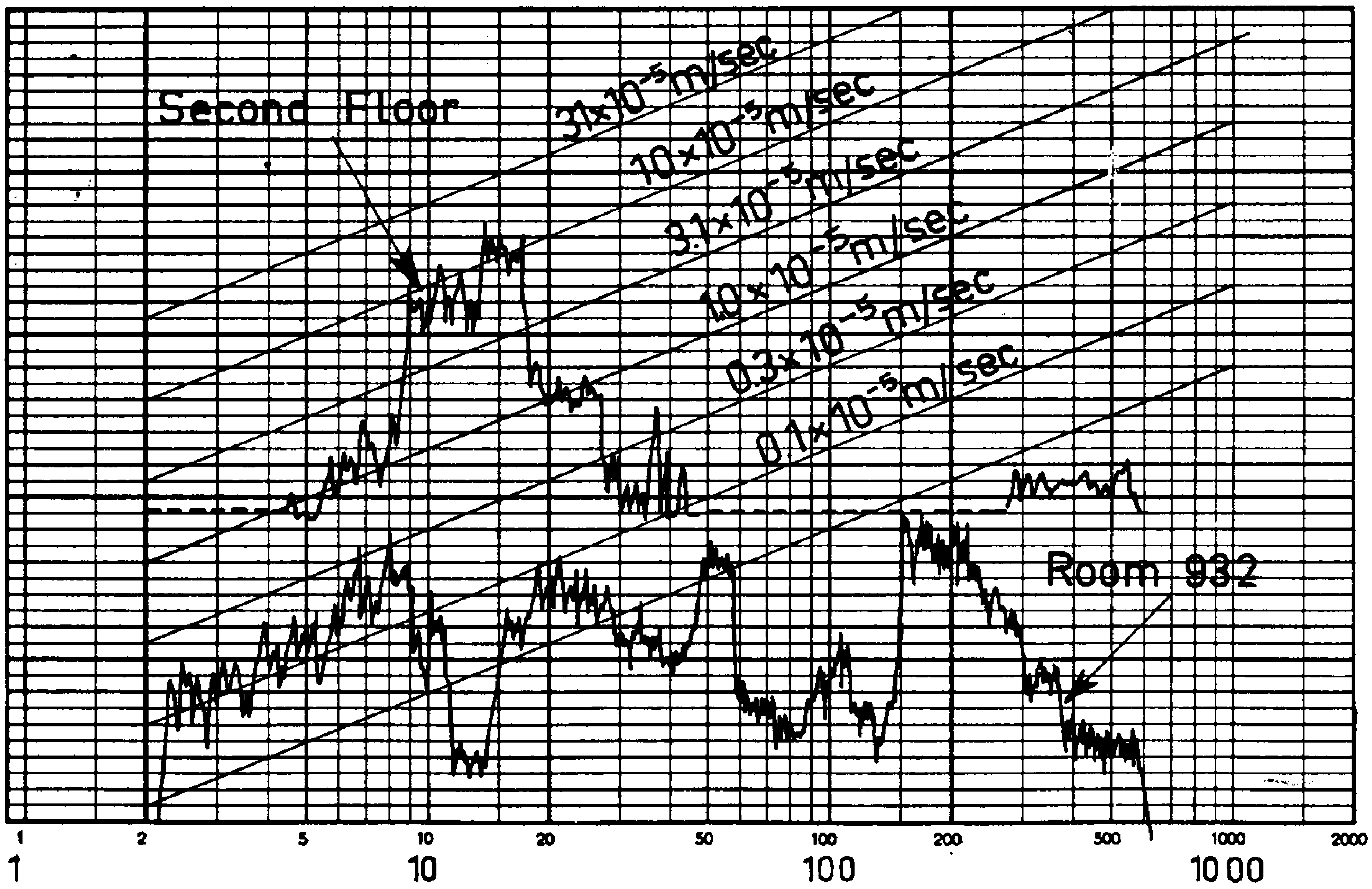


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*Fig. 22. Comparison of spectra obtained in Room 201 and room 932.*

*Background Vibration.*

The background vibration spectra indicate that the RMS velocity on the separately cast floors and concrete platforms is low enough ($\angle 0.3 \times 10^{-5}$ m/sec) for the Mössbauer experiments to be conducted. A difference of some 35 dB (55 times) exists in the vibration velocity level between the present position on the second floor and the proposed positions in the cellar. See Fig. 22.

*Vibration Isolation.*

An indication of the vibration isolation between the various measuring points in the cellar is obtained from Fig. 23. It is seen that the vibration amplitude is reduced considerably from the isolated floor to the concrete platform, and even more from the floor outside. It therefore seems that vibration sensitive experiments carried out on for example the concrete platform will not be unduly disturbed by people moving about in the room or in the corridor outside.

The rubber ring gives an additional velocity reduction of some 10–12 dB (3–4 times).

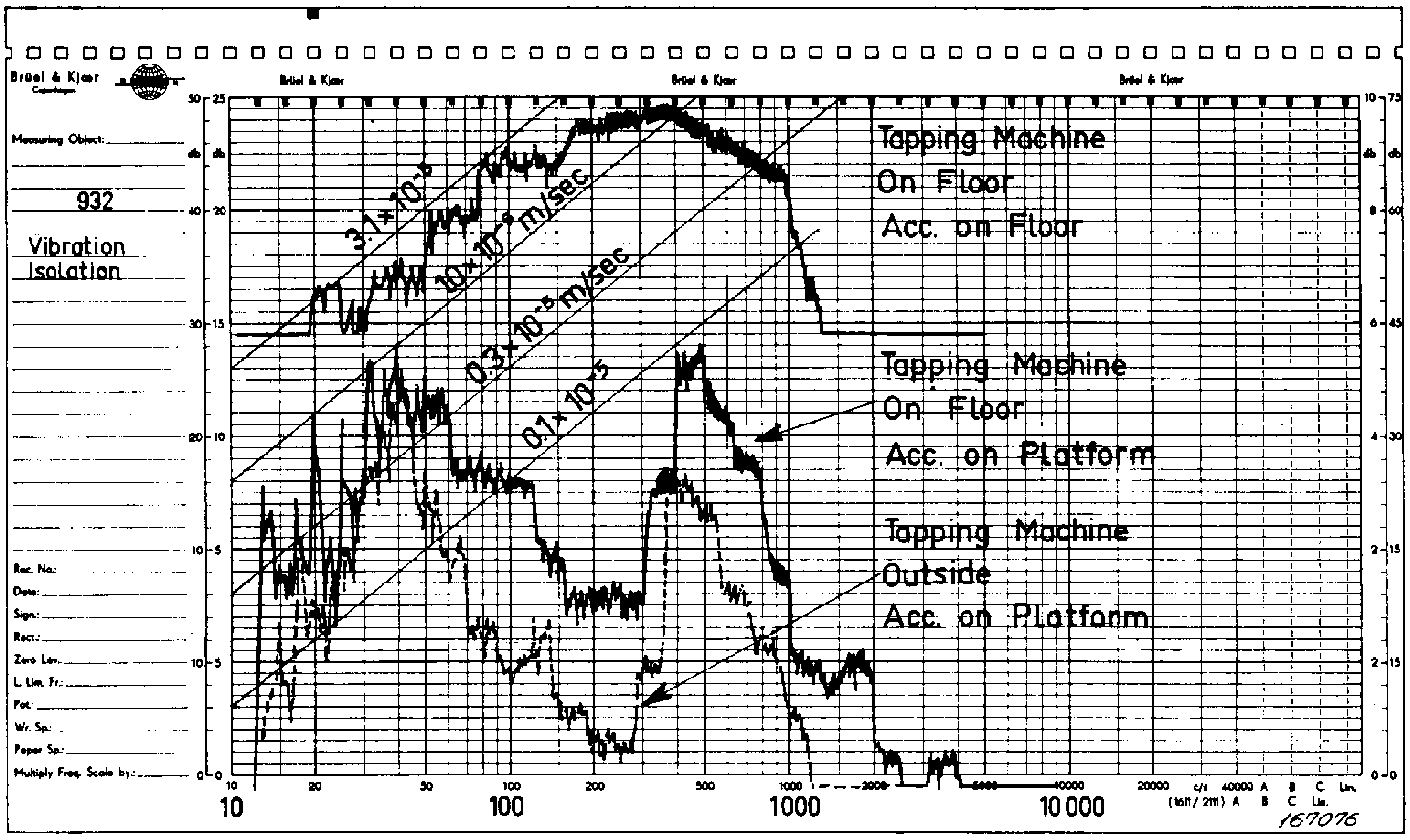
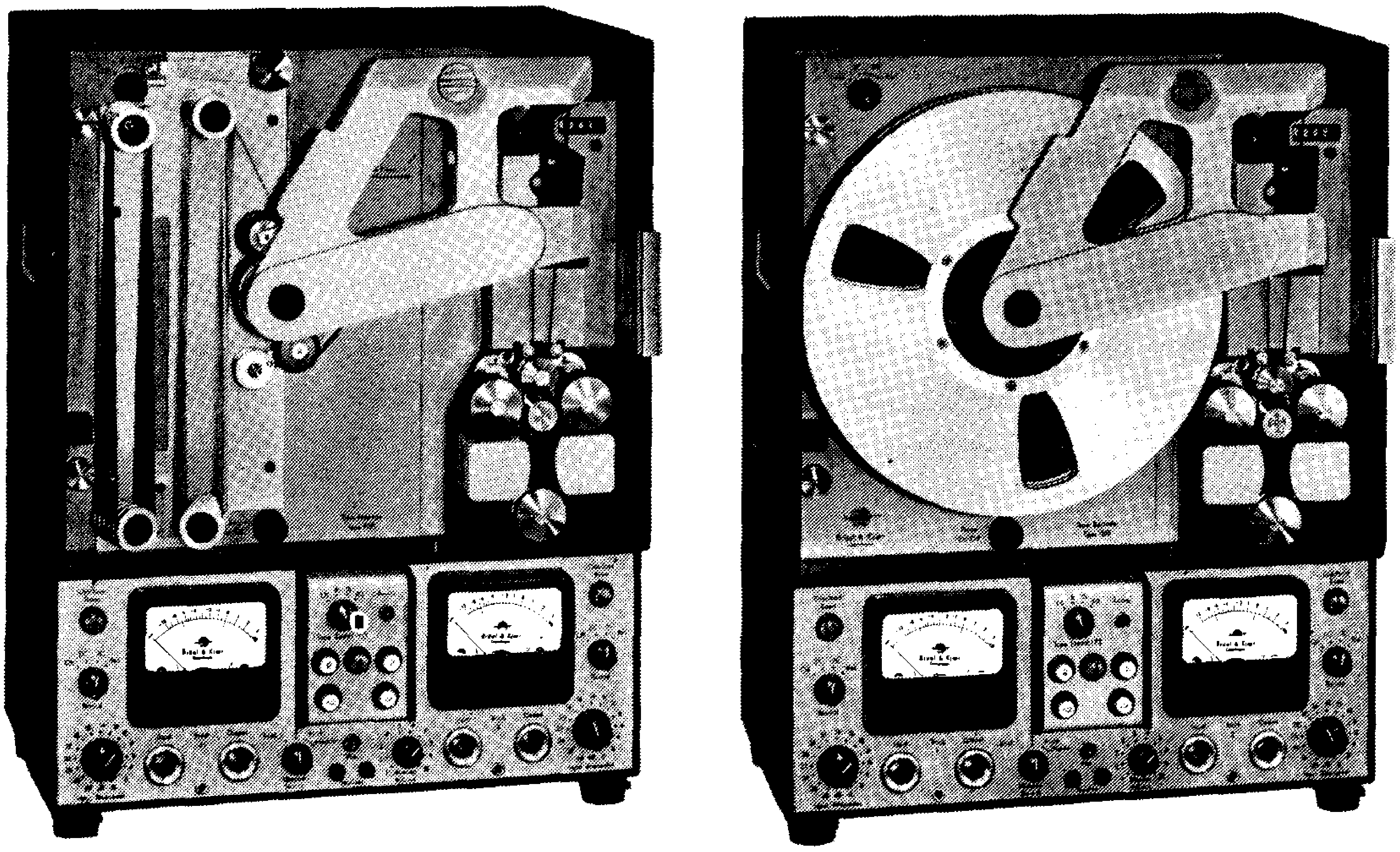


*Fig. 23. Vibration spectra obtained with the Tapping Machine.*

# News from the Factory



**New Magnetic Tape Recorder Type 7001.**

The Tape Recorder Type 7001 is designed as a two-channel laboratory recorder for frequency transformation purposes. The recording principles utilized in the two measurement channels is based on frequency modulation (FM) technique while an extra voice channel, which is included for marking and tape identification purposes, employs ordinary direct recording. Solid state electronics have been incorporated throughout.

A loop adaptor allows detailed analysis of special parts of a recording and four different speeds make it possible either to bring very low frequency signals up into the analysis range of modern analog frequency analyzers, or to bring more high frequency signals down to the range of direct graphic pen recording.

Typical fields of application are shock, vibration and noise measurements as well as room acoustic model experiments. Also the recording, storing and analysis of two time-interdependent phenomena are possible due to the two identical measurement channels.

To avoid overloading, both of the main channels are equipped with peak responding meters for signal level control, and special overload indicators are triggered if the maximum recording level has been exceeded. Accurate input attenuators allow the tape to be calibrated at any desired signal level.

The tape transport system consists of a capstan motor, a take-up spool drive motor, a rewind motor and control and safeguarding circuits which control the operation of the three motors. To ensure low flutter not only the design of the electronic circuits but also the mechanical layout of the tape transport system is of the greatest importance. Therefore all the mechanical parts are produced to very close tolerances and to keep the unsupported section of the tape as small as possible a closed loop drive has been used. Outside the closed loop the tape tension is controlled by an electromechanical servo system.

A special feature of the Recorder is the possibility offered for separate external drive of the capstan motor.

To allow convenient operation of the tape transport controls, Record-Playback Stop-Rewind-Forward and Speed Changes they are all located in a small control box which can either be inserted into the front of the instrument, or can be taken out for remote control of the Recorder.

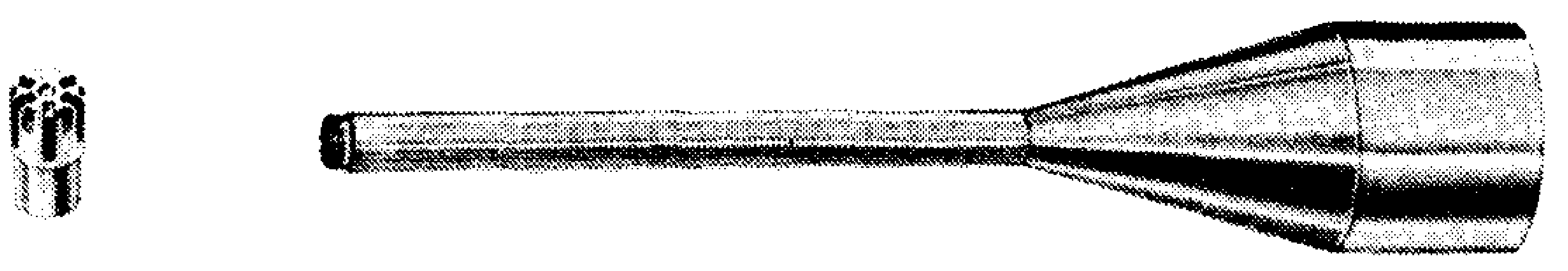
"Drop-outs" and noise due to dust particles electrostatically attached to the tape are reduced to a minimum as the Recorder is supplied with a hinged dust cover which should be closed during operation. A coaxial arrangement of the tape reels has been used to minimize the physical dimensions of the Recorder while emphasis has been placed on the accessibility of all the essential parts.

**Main Specifications.**

*Input Level:* ±1.4 volts peak with attenuator in most sensitive position.
*Input Attenuator:* 0–28 dB in 2 dB steps.
*Input Impedance:* 20 kΩ parallel to 100 pF.
*Output Level:* ± 1.4 volts peak with no load.
*Output Impedance:* Less than 150 Ω
*Load Impedance:* Min. 200 Ω.

*Linearity:* Better than 1 % of full scale deviation from best straight line through zero center.

| Tape Speeds | 38.1<br>1.5 | 152.4<br>6 | 381<br>15 | 1524<br>60 | mm/sec<br>ips. |
|---|---|---|---|---|---|
| Frequency Ranges (± 0.5 dB) | 0–0.5 | 0–2 | 0–5 | 0–20 | kHz |
| S/N Ratio | > 44 | > 48 | > 48 | > 48 | dB |
| Carrier Frequency | 2.7 | 10.8 | 27 | 108 | kHz |
| Rise Times | < 1200 | < 300 | < 120 | < 30 | µsec |

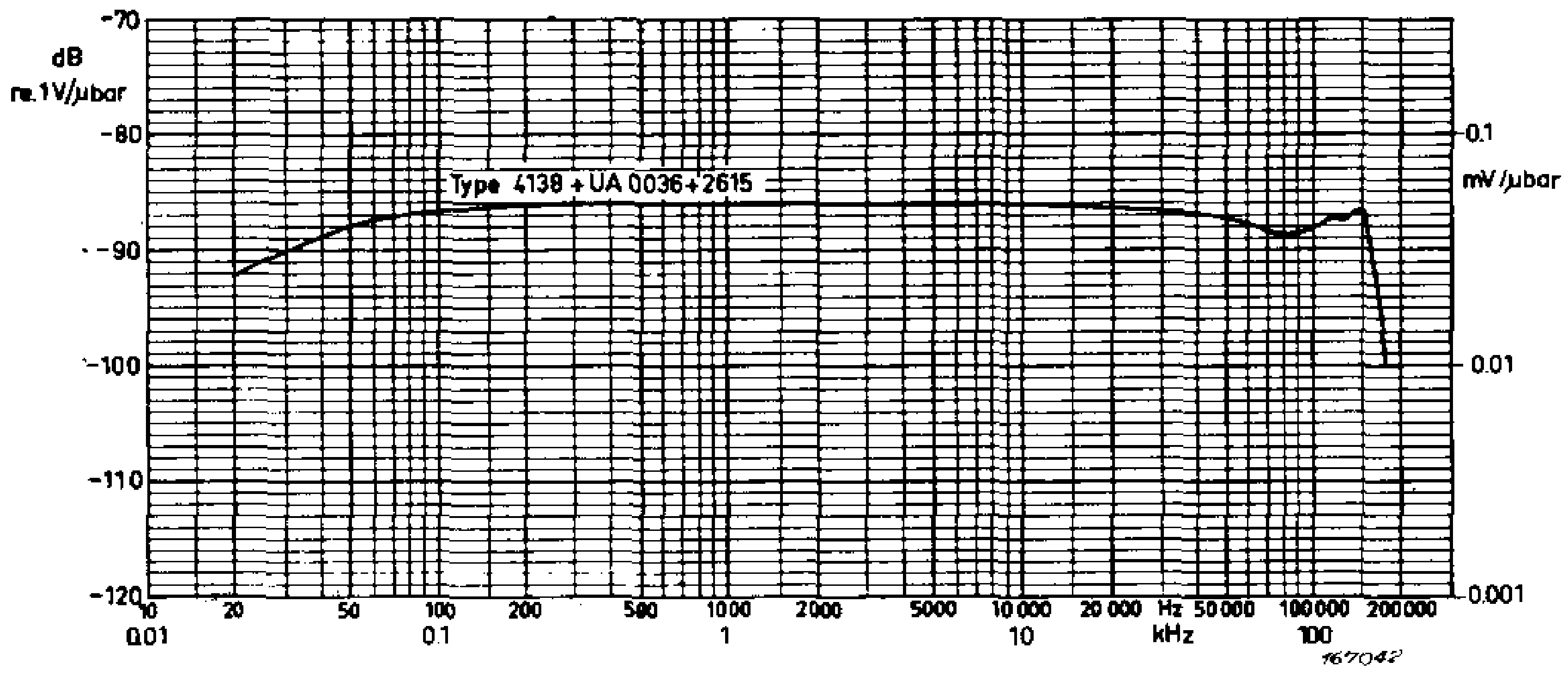


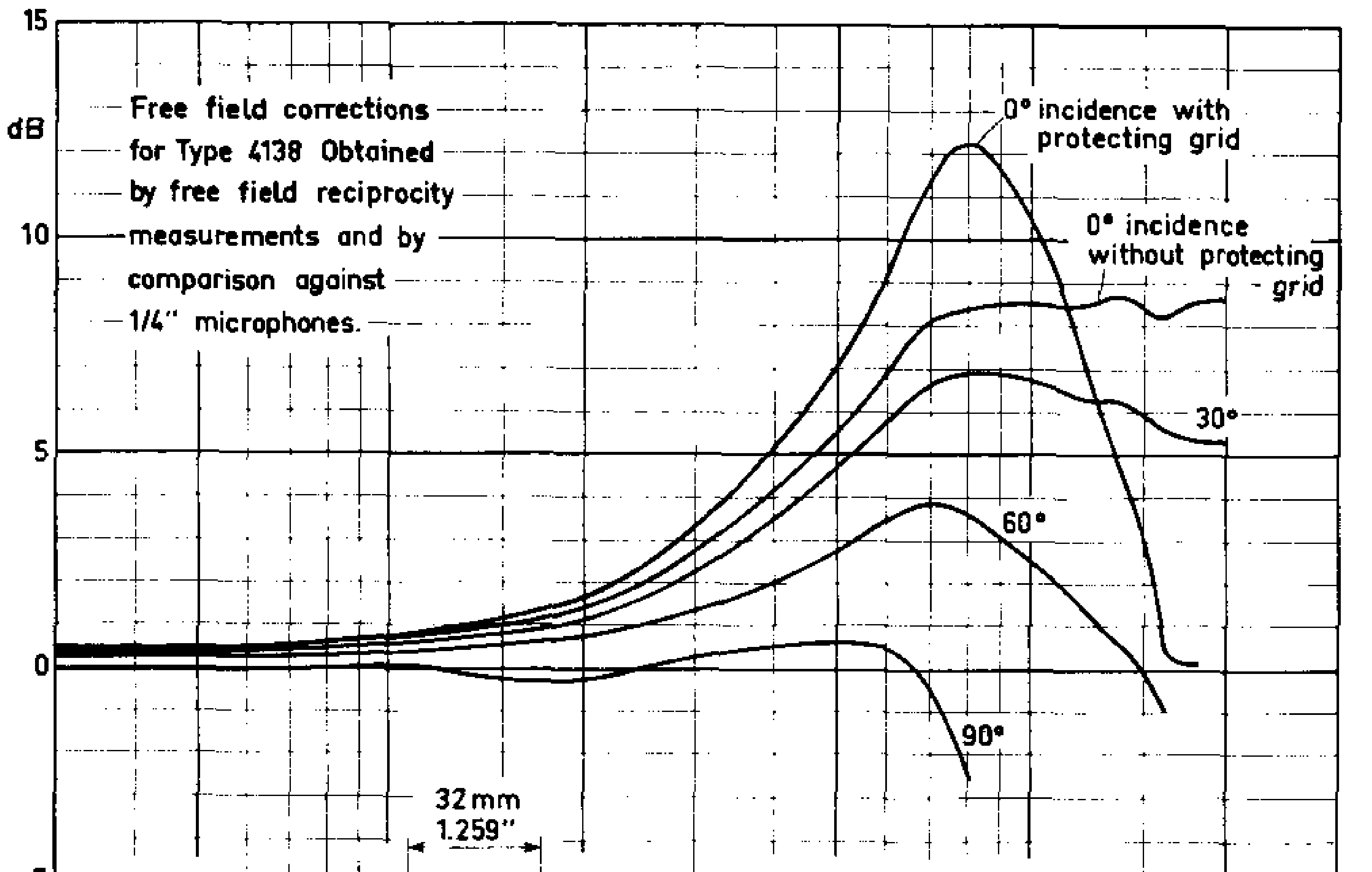
**New 1/8" Condenser Microphone Cartridge Type 4138.**

This Condenser Microphone Cartridge, which is only 1/8" in diameter, is one of *the smallest condenser microphones ever built.* It is especially well suited for wide band and high frequency measurements as point receiver and point source. The extreme care taken in the manufacturing and testing of this miniature microphone ensures the same outstanding quality as the rest of the B & K Microphone family, and a typical frequency response curve as well as free-field correction curves are shown below. It is seen from the curves that its effectively flat frequency response extends from 30 Hz to above 140 kHz. The dynamic range is 76 to 184 dB re. 0,0002 μbar, approximately.

Due to these characteristic data its most typical fields of application are: Very high frequency and high intensity sound measurements, measurements of turbulent boundary layer pressure fluctuations, as well as measurements of very sharp acoustic pulses, and scale model work.

The cartridge can be mounted on the 1/2" cathode followers Type 2614 or 2615, by means of the Adaptor UA 0036.





## Amendment to B & K Technical Review No. 4/1966

(On the Measurement of Reverberation)

In the tables Figs. 14 through 17 we regret that during the printing and proof-handling process a systematic error has been introduced: The columns marked "Full decay" read

| Full decay | |
|---|---|
| T/sec | T/sec |

They should read:

| Full decay | |
|---|---|
| T/sec | $\sigma$/sec |

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