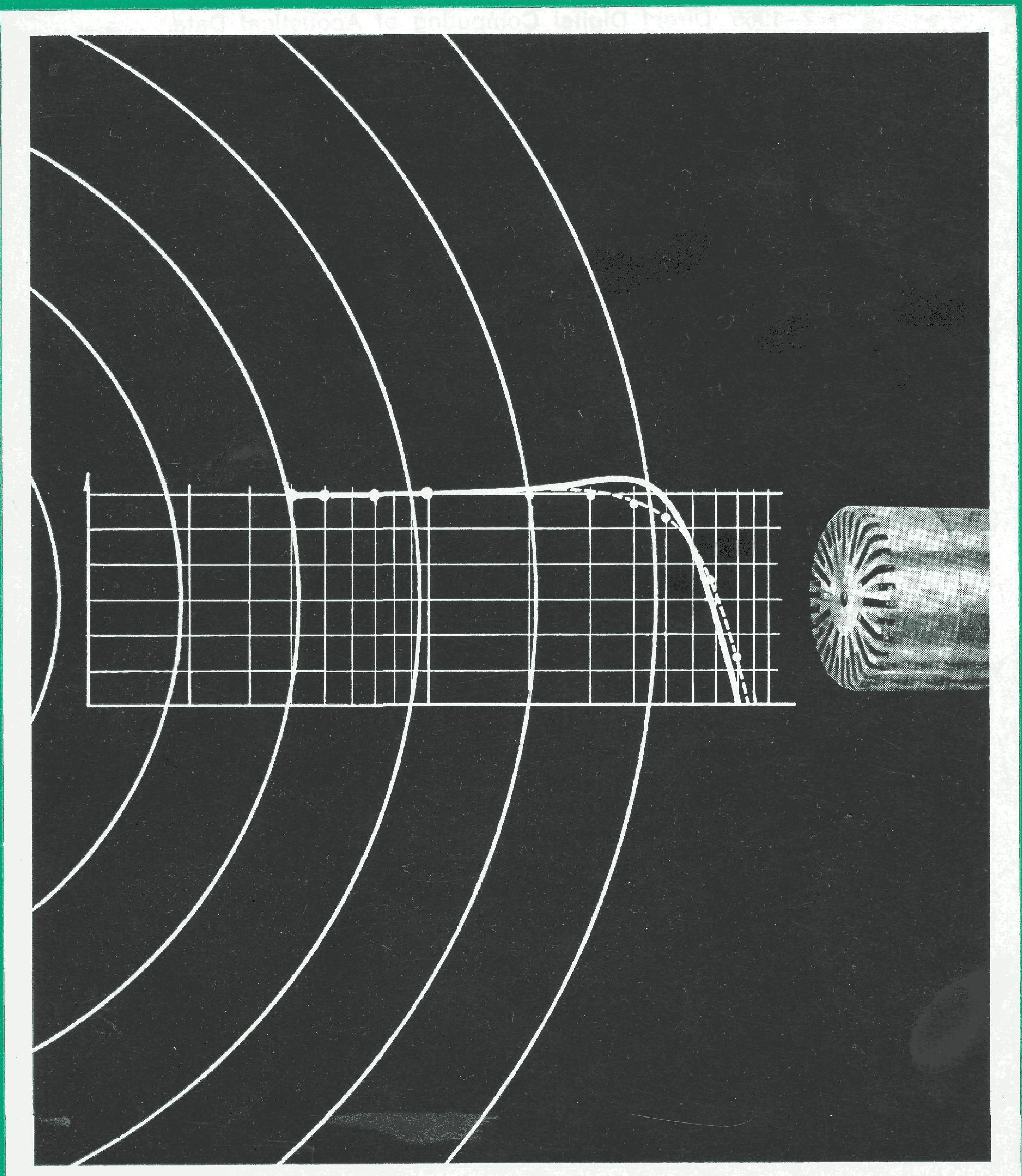
Brüel & Kjær

Technical Review

To Advance Techniques in Acoustical, Electrical, and Mechanical Measurement



No. 2

1969

PREVIOUSLY ISSUED NUMBERS OF BRÜEL & KJÆR TECHNICAL REVIEW

1–1964	Statistical Analysis of Sound Levels.
2–1964	Design and Use of a small Noise Test Chamber. Sweep Random Vibration.
3–1964	Random Vibration of some Non-Linear Systems.
4–1964	The Accuracy of Condenser Microphone Calibration Methods. Part I.
1–1965	The Accuracy of Condenser Microphone Calibration Methods. Part II.
2–1965	Direct Digital Computing of Acoustical Data. 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 The Frequency Response Tracer Type 4709.
4–1965	Aircraft Noise Measurement, Evaluation and Control.
1–1966	Windscreening of Outdoor Microphones. 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.
1–1967	FM Tape Recording. Vibration Measurements at the Technical University of Denmark.
2–1967	Mechanical Failure Forecast by Vibration Analysis. Tapping Maschines for Measuring Impact Sound Transmission.
3–1967	Vibration Testing – The Reasons and the Means.
4–1967	Changing the Noise Spectrum of Pulse Jet Engines. On the Averaging Time of Level Recorders.
1–1968	Peak Distribution Effects in Random Load Fatigue.
2–1968	The Anechoic Chambers at the Technical University of Denmark.
3–1968	On the Measurement and Interpretation of Cross-Power-Spectra. Cross Power Spectral Density Measurements with Brüel & Kjær Instruments (Part 1).
4–1968	On the Damaging Effects of Vibration. Cross Spectral Density Measurements with Brüel & Kjær Instruments. (Part II).
1–1969	The Use of Digital in Acoustical Measurements. Impulse Noise Measurements. Low Frequency Measurements Using Capacitive Transducers. Details in the Construction of a Piezo-electric Microphone. A New Method in Stroboscopy.

TECHNICAL REVIEW

No. 2 – 1969

Contents

The Free Field and Pressure Calibration of Condenser Microphones using Electrostatic Actuator*)

by

Gunnar Rasmussen

ABSTRACT

Absolute calibration of microphones in a free field at high frequency is a tedious and time consuming job. If a high degree of accuracy is required it is also difficult and expensive to establish. The electrostatic actuator method of calibration offers advantages, which will be discussed along with some of the problems involved.

RESUME

L'étalonnage en valeur absolue des microphones en champ libre est un travail lent et fastidieux. Si, en outre, une degré de précision élevé est exigé, il devient difficile et coûteur. La méthode de l'excitateur électrostatique offre des avantages, qui sont discutés dans l'article, de même que quelques problèmes rencontrés.

ZUSAMMENFASSUNG

Die absolute Kalibrierung von Mikrofonen im Freifeld bei hohen Frequenzen ist eine zeitaufwendige Arbeit. Wenn ein hoher Genauigkeitsgrad gefordert wird, ist zudem die Durchführung schwierig und verursacht hohe Kosten. Die Kalibriermethode mit dem elektrostatischen Eichgitter bietet Vorteile, die zusammen mit auftretenden Problemen erläutert werden.

Free field reciprocity calibration of condenser microphones is a very time consuming and demanding task. It is therefore common practice to make pressure calibrations and add corrections for the diffraction thereby obtaining the free field response of the microphone.

An important factor and one often overlooked in this procedure is that the microphone diaphragm when used in a free field will look into another acoustical impedance than the impedance of the coupler volume used for the closed chamber reciprocity calibration technique**). If therefore a free field calibration of a microphone and a closed coupler calibration of the same microphone are carried out and the pressure response $\frac{e_p}{p}$ is subtracted from the free field calibration $\frac{e_f}{p_1}$, this correction $\frac{e_f}{p_1} - \frac{e_p}{p}$ can only be transferred to another microphone if the impedance of this microphone diaphragm is the same as the impedance of the microphone used for the original calibration.

---

*) Paper presented at the 6th International Congress on Acoustics, Tokyo, Japan 21 – 28 August 1968.

**) Discussed in a paper presented to WG 13 T.C. No. 29 under I.E.C. by Professor F. Ingerslev.

It is shown in this paper that this problem is only significant around and above the diaphragm resonance. Unfortunately, this is also the range where the closed coupler reciprocity calibration has severe limitations, and calibration in this range is by some people considered more or less an art. The electrostatic actuator offers great advantages for frequency response calibration under those circumstances.

The electrostatic actuator makes it possible to apply a fictive pressure to the diaphragm. This may be done while the diaphragm is looking into its normal free field radiation impedance. It is also possible to use the electrostatic actuator in a closed coupler volume, thereby getting the difference between the closed coupler volume pressure response $\frac{e_{op}}{p}$ and the pressure response under free field load conditions $\frac{e_{42p}}{p}$.

It was the purpose of this work to investigate the correlation between the two methods under closed coupler conditions, to check possible influence of the electrostatic actuator on the calibration, to present typical data for some microphones and give a typical curve, which may be used either way deducting the closed coupler response $\frac{e_{op}}{p}$ from the actuator response $\frac{e_{42p}}{p}$ or vice versa.

The force F applied by the electrostatic actuator is inversely proportional to the square of the distance between the diaphragm and the actuator d and proportional to the polarization voltage E_o and the variation imposed on the polarization voltage e. $F = \frac{E_o e}{d^2} K$.

It is important that the actuator is acoustically transparent so the diaphragm is loaded in the same way as without actuator. This is most easily obtained for microphones with no cavity surrounding the diaphragm. The actuator should cause no change in the microphone response. Typical values of E_o and d are 800 V and 0.5 mm. The force attracting the diaphragm to the back plate inside the microphone is 200 V over 0.02 mm. That means less than 0.65 % change in diaphragm position due to the actuator.

This may be counteracted by raising the polarizing voltage of 200 V to 201.28 V and referring the calibration to 200 V polarizing voltage.

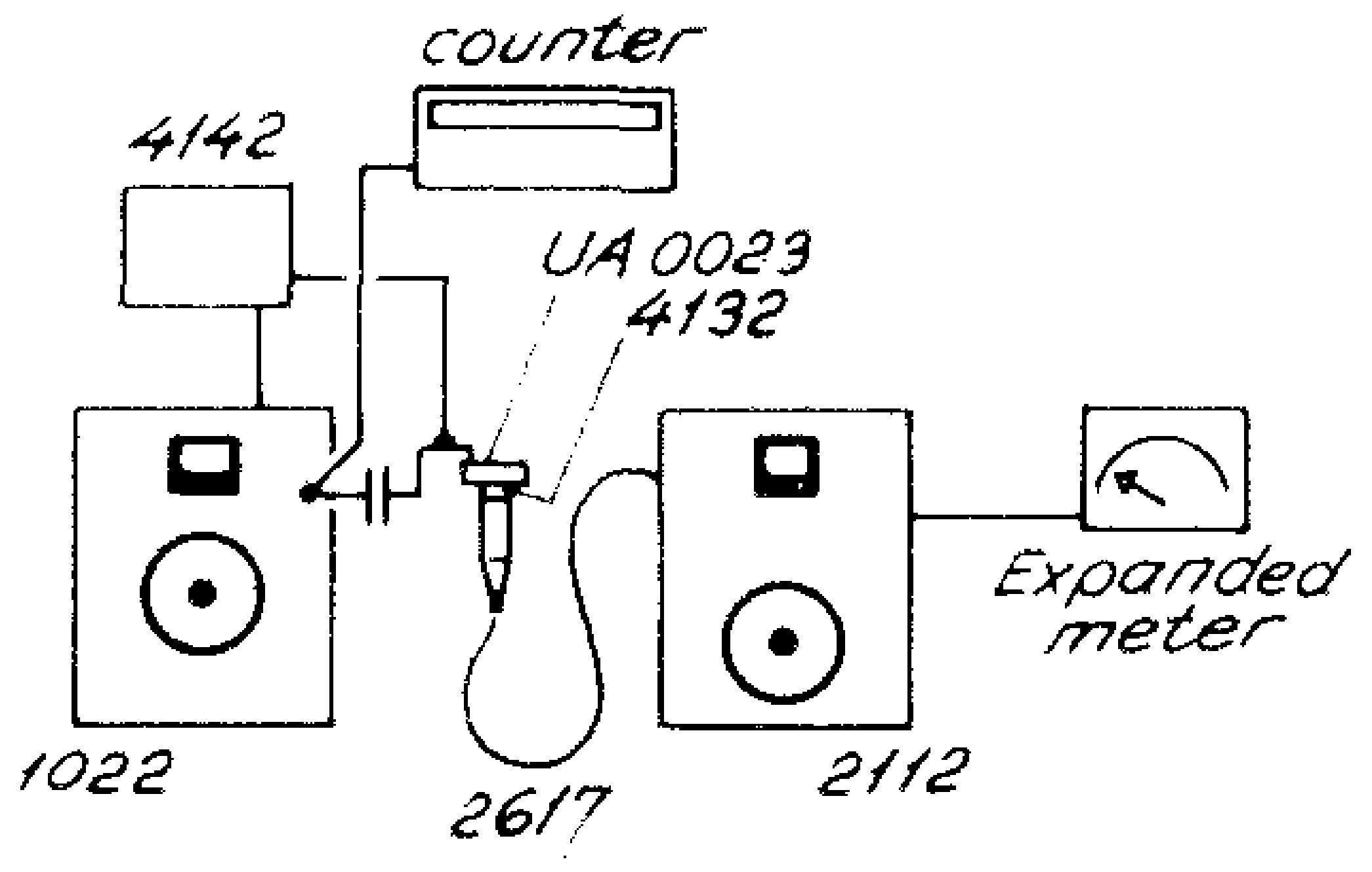


Fig. 1. Measuring set-up.

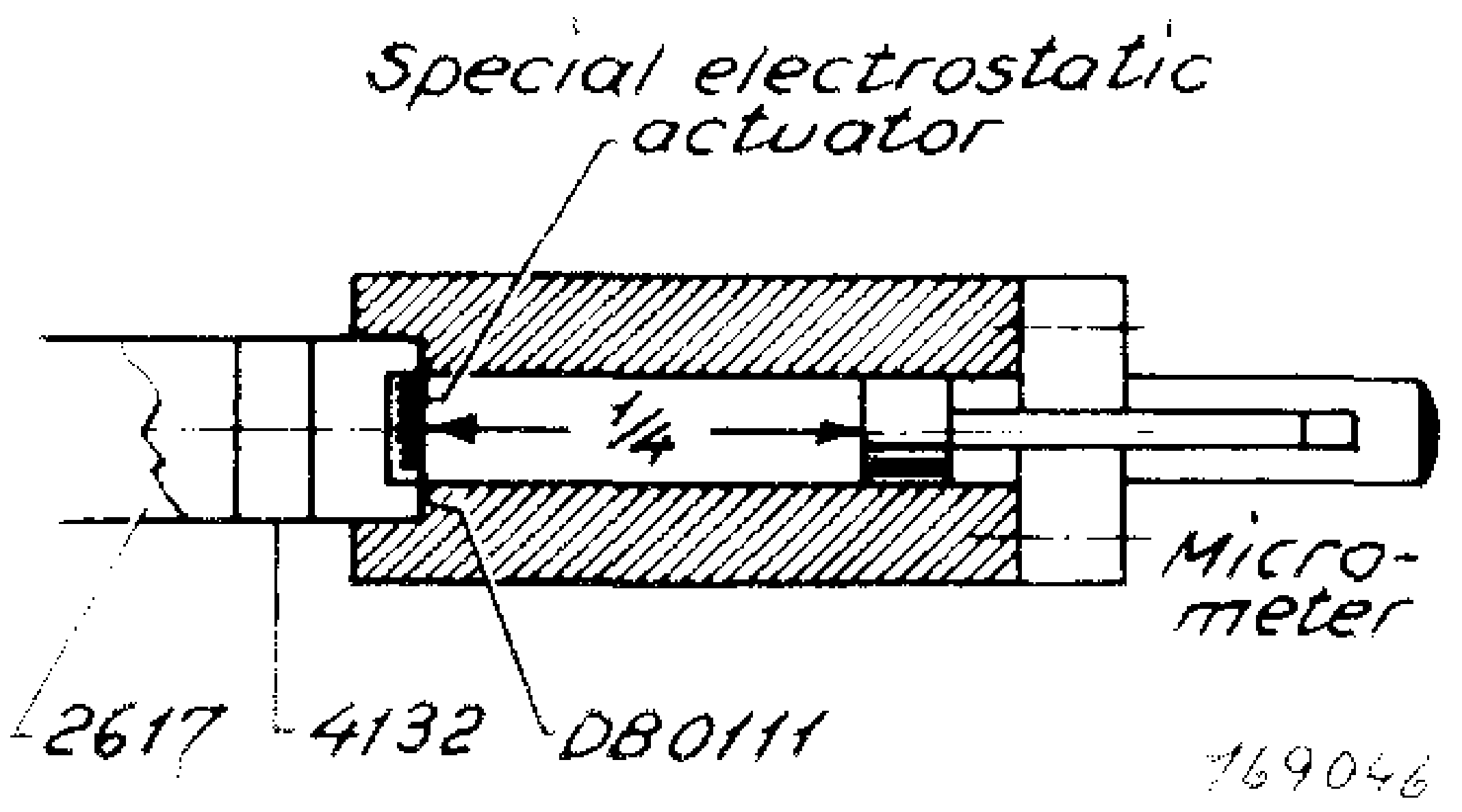


Fig. 2. 1/4 wave length tube.

The pressure response was measured under different load conditions by the set-up shown in Fig. 1. The load on the microphone diaphragm is changed by plotting the frequency response while radiating into a free field and then placing a 1/4 wave length tube over the microphone with actuator as shown in Fig. 2. For a 1/4 wave length between the diaphragm and the rigid end surface of the tube will the pressure at the diaphragm approach zero hence presenting a very low radiation impedance to the diaphragm, which is allowed to swing freely with maximum volume displacement.

The frequencies used was accurately adjusted using an electronic counter and the 1/4 wave length tube tuned to proper length by a micrometer moving a piston as the end surface of the tube. The output signal was filtered and could be read on an expanded precision meter scale. There is good agreement between the closed coupler reciprocity method and the 1/4 wave length actuator tube as also reported earlier privately by Mr. K. Rasmussen, The Acoustical Laboratory of the Technical University in Copenhagen. See Fig. 3. It is worth noting that the calibration in closed couplers is very tedious and time consuming if carried out at higher frequencies due to wave motions in the coupler volumes.

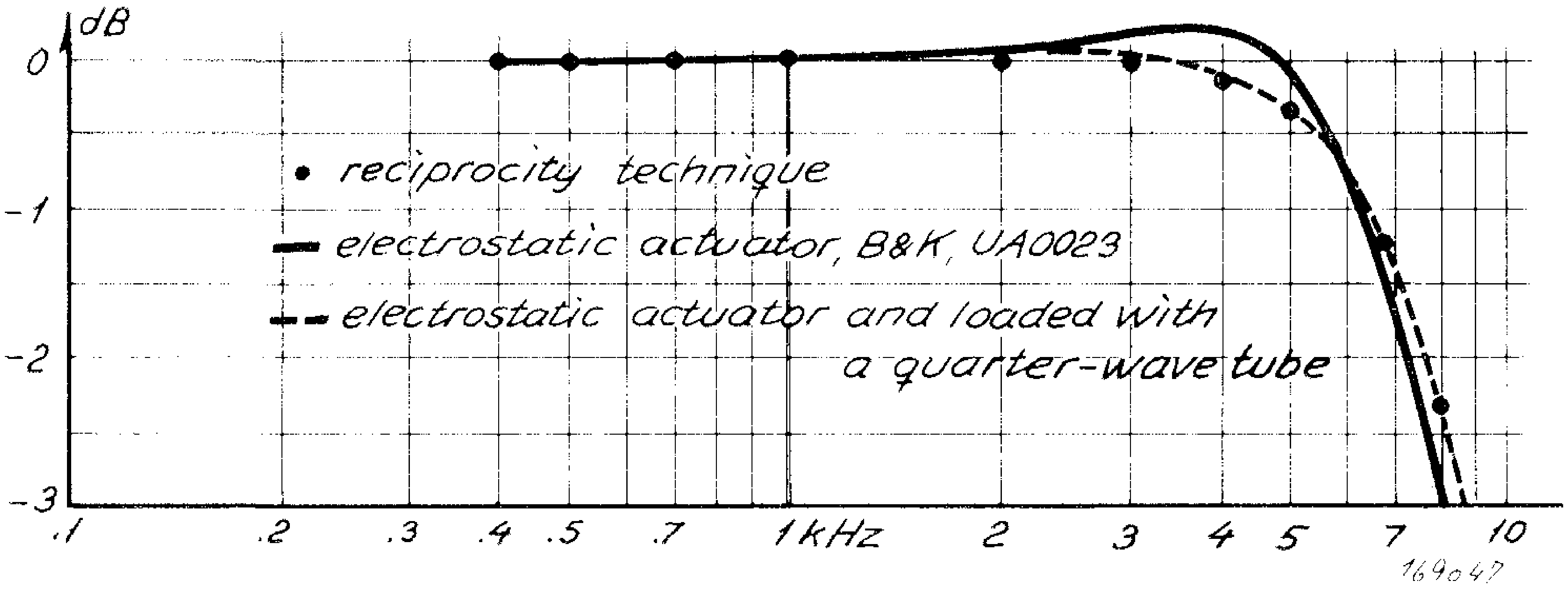


Fig. 3. Frequency response curve, measured by the electrostatic actuator terminated by a 1/4 wavelength tube. Measured by closed coupler reciprocity and by electrostatic actuator radiating into a free field.

The impedance Z_r of Fig. 4 through which the force creating the diaphragm motions looks into the microphone may be deducted from the curves, see Fig. 3. By assuming that it is mainly a mass reactance m_r and then calculate

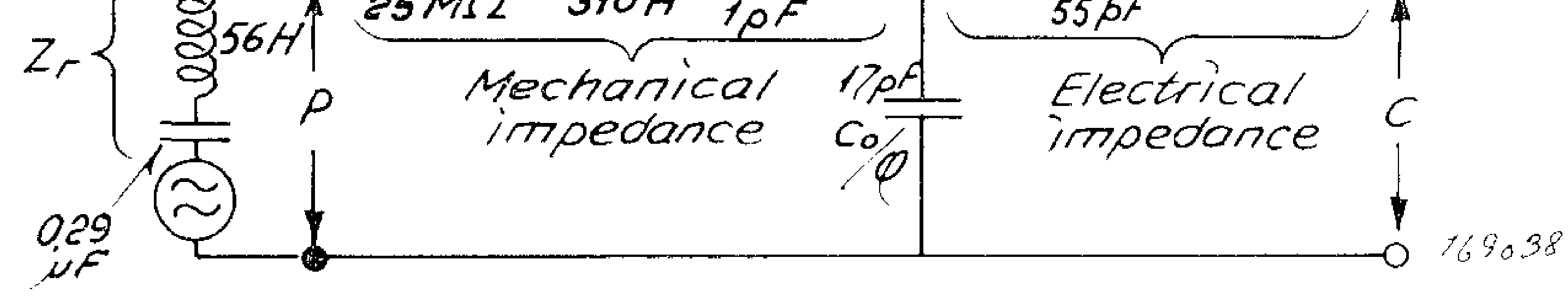


Fig. 4. Electromechanical equivalent circuit for a typical condenser microphone.

m_r from the change in resonance frequency of the diaphragm we get for $f_o = \frac{1}{2\pi\sqrt{m_a c_a}}$ the change in m_a in % to be $\frac{(f_{o1} - f_{o2})\,2}{f_{o1}}\, m_a \sim 56$ kg/m^4 where f_o is the diaphragm resonance looking into essential zero rayls, f_{o2} the resonance for 42 rayls load and m_a a typical value for the diaphragm mass of a B & K 4132 Microphone.

This may also be calculated from the impedance in a plane progressive wave Z_s which for a shallow column of air of depth equivalent to d is $Z_s = -j\varrho c \cot \frac{\omega}{c} d$ where ϱc is 42 rayls and ω angular frequency, c the speed of sound in air. For small values of $\frac{\omega}{c} d$ we have

$$Z_\varrho = -\frac{\varrho c}{j\omega \frac{d}{c}} + j\omega \frac{d\varrho}{3}$$

Here is the mass reactance $Z_r = j\omega \frac{d\varrho}{3}$ and the actual mass m_r added to the diaphragm under free field conditions is

$$m_r = \frac{Z_r}{j\omega} = \frac{d\varrho j}{3} = \frac{8 \times 18 \times 0.27 \times 1.29 \times 10^3 \times 10^4}{3\pi} \sim 55.6\ \text{kg/m}^4$$

for a diaphragm of 18 mm in diameter and a reduction factor of 0.27 for the diaphragm movement.

The compliant reactance C_r is large compared to C_a that means the stiffness of the air is small compared to that of the diaphragm.

$$C_r \frac{1}{j\omega Z_r} = \frac{d}{\varrho c^2} = \frac{8 \times 18 \times 0.27}{3\pi \times 1.29 \times 10^3 \times 10^4 \times 340^2} \sim 0.29 \times 10^{-6}\ \text{m}^5/\text{N}\ \ 0.29\ \mu\text{F}$$

The mass reactance cannot be ignored and the order of magnitude is large enough to require consideration in transferring diffraction corrections from one microphone to another. One may hope that future standardization efforts will take also the unique calibration possibilities offered by the electrostatic actuator into consideration. The typical correction curve obtained for B & K 4132 and 4131 is shown in Fig. 5.

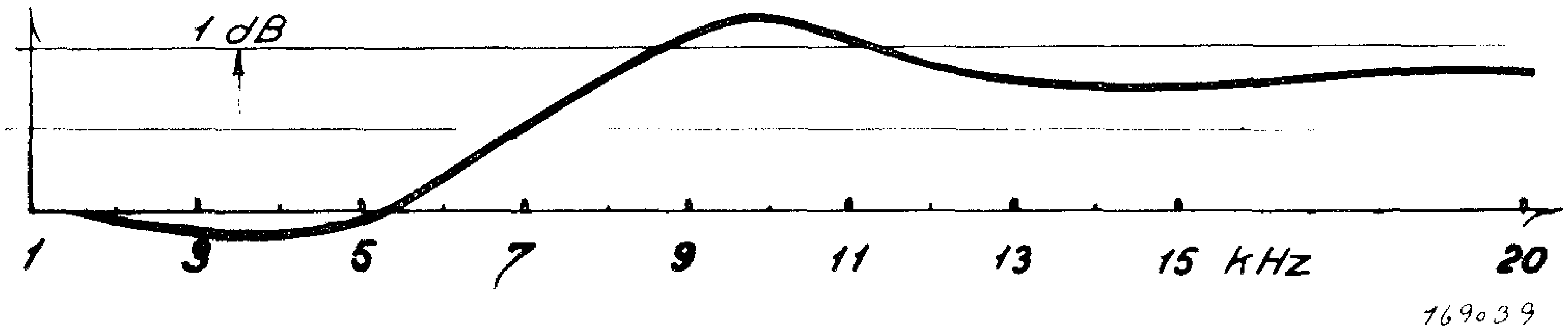


Fig. 5. Correction curve. The given correction should be added to the electrostatic actuator response in order to obtain the closed coupler reciprocity calibration.

It is obvious that no problem exist in the use of a microphone when the correction for the acoustical load is known. Under normal circumstances would the pressure response for the microphone looking into a free space be most valuable allowing correction for free field diffraction to be added with no correction for the mechanical impedance of the microphone needed.
With the miniature condenser microphones available to-day it seems reasonable to choose a small microphone for the measurement of sound pressure levels in confined spaces at high frequencies, where the only applications may be found, in which the pressure response under zero impedance load conditions seems of any practical relevance.

Long Term Stability of Condenser Microphones*)

by

Erling Frederiksen

ABSTRACT

After a brief discussion of the main design parameters in the construction of condenser microphones an electrical analog circuit for the Microphone Type 4144 is given. It is shown that the most critical parameter with regard to long-term stability of the Microphone is the mechanical tension in the microphone diaphragm, and a new artificial ageing procedure is described which, for any practical purpose, eliminates long term stability problems at room temperature.

RESUME

Après une brève discussion des principaux paramètres intervenant dans la construction des microphones à condensateur, on donne le circuit analogue électrique du microphone type 4144. On montre que le paramètre le plus critique, en ce qui concerne la stabilité à long terme du microphone, est la tension mécanique de son diaphragme. Une nouvelle procédure de vieilissement est alors décrite qui, pour n'importe quelle application pratique, élimine les problèmes de stabilité à long terme à la température du local.

ZUSAMMENFASSUNG

Nach einer kurzen Darlegung des wesentlichen mechanischen Parameter in der Konstruktion des Kondensatormikrofons wird für den Mikrofontyp 4144 ein elektrisches Analogschaltbild entworfen. Es wird gezeigt, daß der kritischste Parameter hinsichtlich der Langzeitstabilität des Mikrofons die mechanische Spannung in der Mikrofonmembrane ist. Ein neuer künstlicher Alterungsprozeß wird beschrieben, welcher für jeden praktischen Zweck die Langzeitprobleme bei Raumtemperatur eliminiert.

Introduction

As the number of applications for Condenser Microphones at high temperatures is increasing and as the newly revised U.S.A. Standard for Laboratory Standard Microphones (S1. 12-1967) defines certain requirements as to long term stability Brüel & Kjær decided to reexamine this problem carefully in order to be able to specify the long term stability of their condenser microphones at any temperature, and if possible improve the microphones in this special direction.

Several experiments were carried out using the different types of Brüel & Kjær microphones. However, in the following the description will concentrate on the Type 4144 which is a further development of the wellknown Brüel & Kjær microphone Type 4132. This microphone has, together with the Western Electric Microphone Type 640 AA, through several years been the most commonly used Standard Microphone.

It can be shown that the voltage produced by an idealized, unloaded condenser microphone is:

---

*) Based on a paper presented before the Scandinavian Acoustical Society in Trondheim, Norway, 14-16 May 1968.

$$e = \frac{d}{D} E$$

where:

D = distance between the diaphragm and the back electrode with the polarization voltage supplied but with zero sound pressure on the diaphragm

d = deflection of the diaphragm caused by the sound pressure

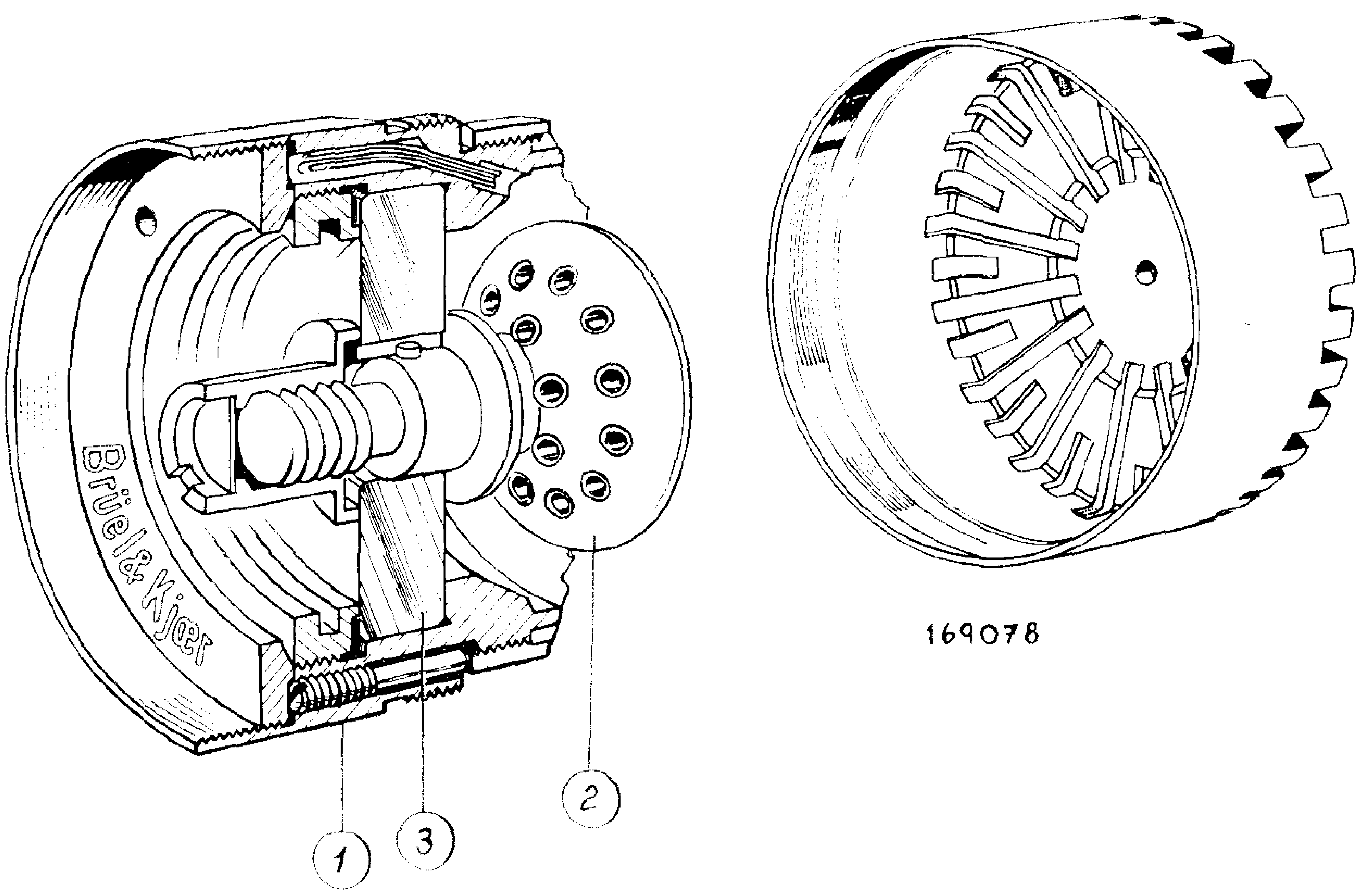
E = polarization voltage

By dividing both sides of the equation with the sound pressure (p) the sensitivity of the microphone is obtained

$$S = \frac{e}{p} = \frac{\frac{d}{p}}{D} E$$

The sensitivity thus depends on two mechanical dimensions D and $\frac{d}{p}$ ($\frac{d}{p}$ = diaphragm deflection for a given sound pressure). If a stable microphone is to be manufactured the effect of time on these parameters has to be reduced to a minimum.

The distance, D, between the electrodes actually is the original mechanical distance between the electrodes, D_0, minus the decrease, ΔD_0, in this distance caused by the electrostatic attraction due to the polarizing voltage. ΔD_0 is, in the Microphone Type 4144, approximately 1.5 μm while D_0 is 22 μm. D_0 is thus by far the most important part of this distance.



1. *Microphone housing.*
2. *Back electrode.*
3. *Quartz insulator.*

Fig. 1.

Stability in the electrode-distance, D_0, can be obtained by a suitable construction and suitable choice of construction materials, see Fig. 1. Note how the microphone housing and the back electrode refer to the same side of the flat and formstable quartz insulator. Considering the materials and forces involved there is no theoretical reason to expect changes in the geometry of the housing.

Even though the distance, D_0, in Type 4144 is only 22 μm, and variations of 0.2 μm thus alter the sensitivity with approximately 1 %, many years of experience have shown that variations in D_0 can be kept insignificant. ΔD_0 has relative little influence and is a function of D_0 and the diaphragm compliance, which will be discussed later.

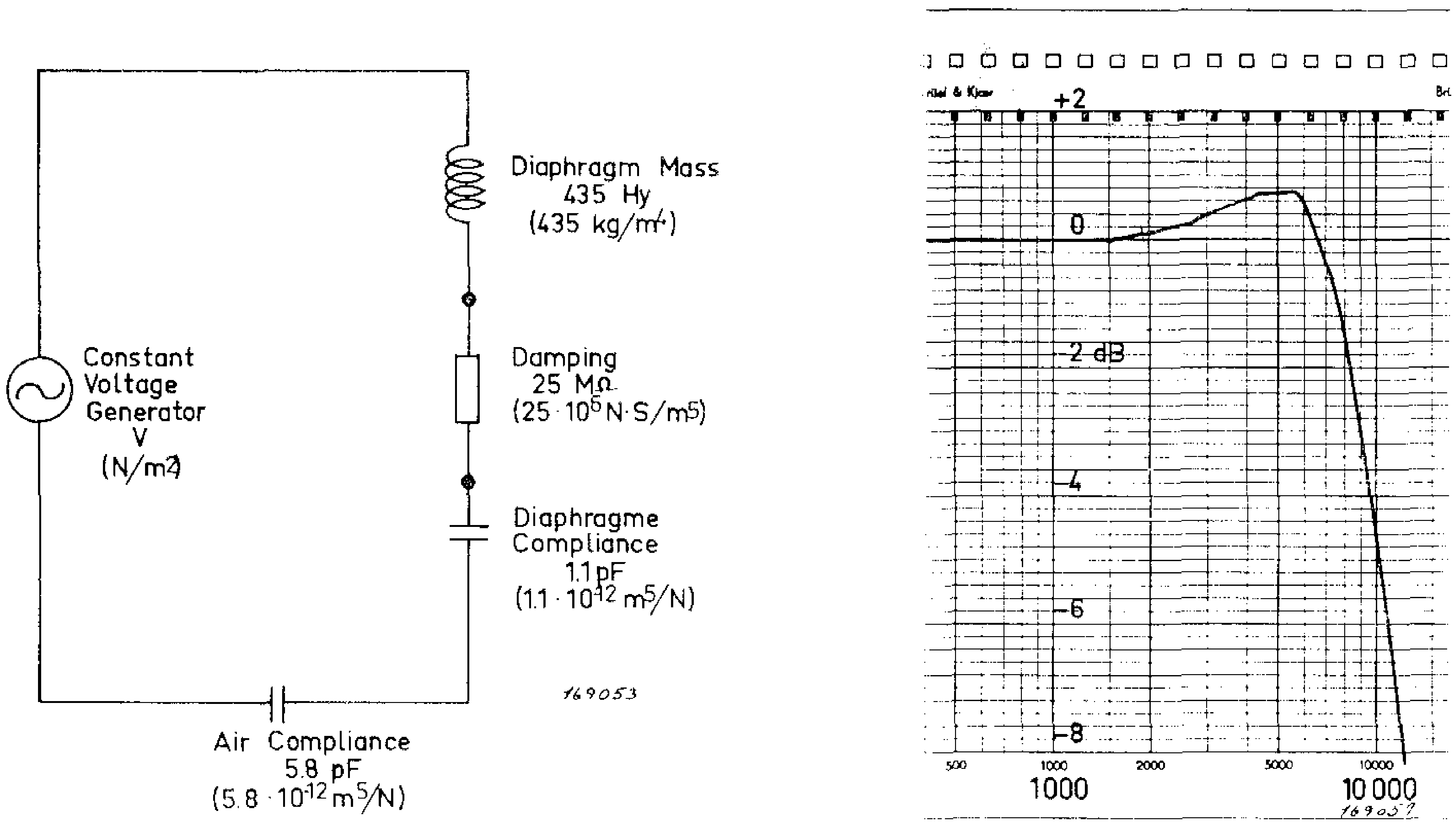


Fig. 2.

The displacement amplitude of the diaphragm for a given sound pressure, $\frac{d}{p}$, is a quantity depending on frequency because it is determined by the following significant acoustical parameters:

1. The compliance of the diaphragm
2. The compliance of the internal volume
3. The resistivity of the spacing between the diaphragm and the back electrode
4. The mass of the diaphragm

It is possible to construct electrical analogs to these four elements and combine them into an electrical equivalent diagram of a microphone. For a typical Type 4144 microphone this diagram will be as shown in Fig. 2. Here the compliance of the diaphragm is represented by a 1.1 pF capacitor, the compliance of the internal volume by a 5.8 pF capacitor, the acoustical resitivity by a 25 MΩ resistor and the last element, the mass of the diaphragm, by an inductor of 435 Hy. When a constant voltage generator is connected to the input, the charge on the 1.1 pF capacitor will be proportional to the output voltage from the microphone. The charge as a function of frequency is also shown in Fig. 2.

The equivalent circuit makes it possible, in an easy way, to examine how changes in the elements will change the frequency response. Examples of this are shown in Fig. 3 A, B and C. Fig. 3 D shows how changes in the distance, D_0, will affect the frequency response.

Possibilities for Changes in the Elements as a Function of Time

The MASS-ELEMENT is determined by the mass of the diaphragm material

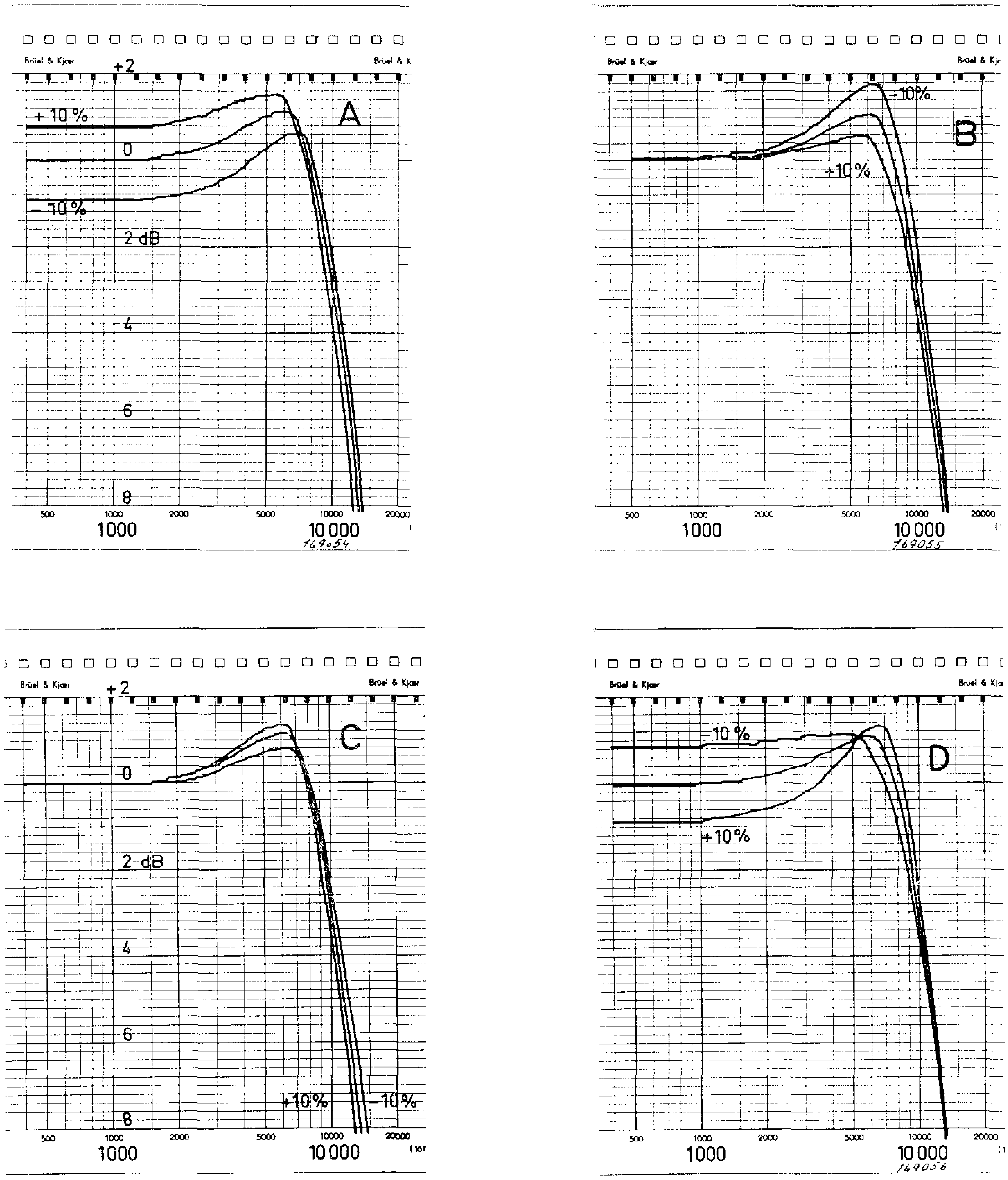


Fig. 3.

A. Influence of changes in the compliance element.
B. Influence of changes in the mass element.
C. Influence of changes in the resistive element.
D. Influence of changes in the electrode distance, D.

and from the mode of deflection. Significant changes with time are not to be expected.

The RESISTIVE ELEMENT is determined by the geometry of the fixed electrode and from D_0. The resistivity is inversely proportional to the square of D_0. Again significant changes with time are not to be expected because of the good stability of D_0 mentioned earlier.

The AIR COMPLIANCE ELEMENT is at a certain static pressure dependent only on the internal volume of the microphone. Changes in this element will be ignored.

The DIAPHRAGM COMPLIANCE ELEMENT must be regarded as the only element where a systematic variation with time can be expected. As the diaphragm is very close to being an ideal membrane, its compliance is determined purely by the tension by which it is stretched. Compared to most mechanical constructions this tension is very large. This is necessary, however, to obtain the desired microphone properties. The tension is about 2.1 Kp/cm, but as the thickness of the diaphragm is only 5 μm the stress becomes 42 Kp/mm^2 and even though the diaphragm is made of very strong, fine grain nickel, the material permanently floats. The floating of the material results in a reduction in the diaphragm tension, which again causes the compliance to increase.

The only major changes that could take place with time are thus, according to the above disussion, those shown in Fig. 3 A. Such changes will result in an increased sensitivity of the microphone over most of its important frequency range, an increase which for Type 4132 microphones is of the order 0.05 dB per year at room temperature. Here therefore is the place where improvements may be made.

An Improved Artificial Ageing Procedure

General improvements in the techniques used for the production of condenser microphones at Brüel & Kjær have made it possible to introduce a new

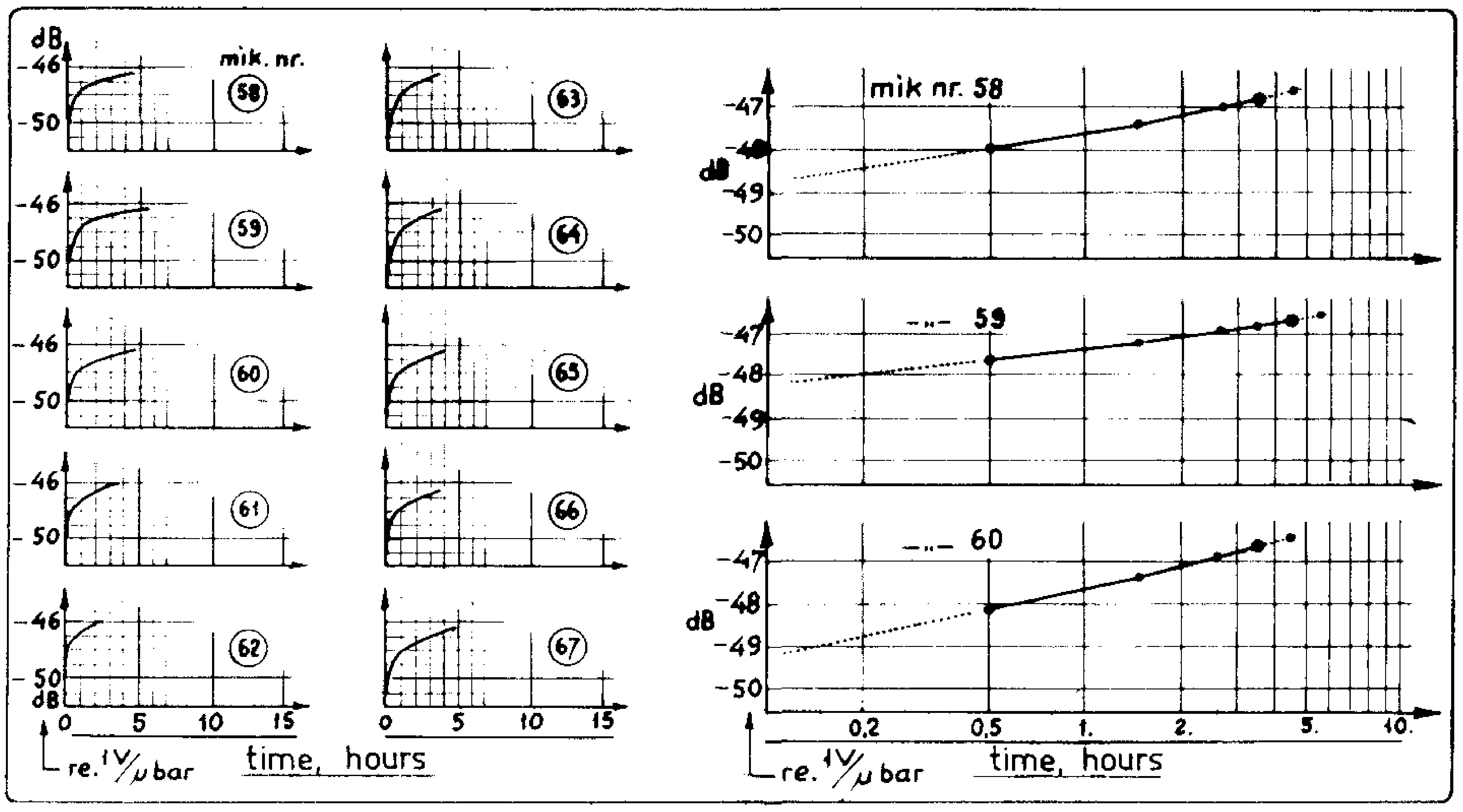


Fig. 4.

169058

artificial ageing procedure, which is considerably more efficient than the one previously used. This new method is utilized in the production of the Type 4144 microphones. After a certain pre-aging, the new method requires the diaphragm to be mechanically tensioned to a value which is greater than that desired for the finished microphone. By then exposing the microphone to a temperature of 150°C for a certain period of time the tension decreases until the required microphone sensitivity is obtained. The curves, Fig. 4, shows the sensitivity of a number of microphones as a function time during temperature exposure. The curves at the left hand side of the figure are plotted to linear time scales while those to the right have logarithmic time scales. If the slope of the curves is measured at the point where the artificial ageing is stopped (marked in the figure by a heavy dot) it is seen that this slope is of the order of 0.2 dB/hour. The rate at which the sensitivity increases at room temperature is so many times smaller than this value that it is not possible, from direct measurements, to determine its value, even when the measurements are carried out over a number of years and the calibration reproducibility now obtainable is better than 0.02 dB.

Determination of the Long Term Stability as a Function of Temperature

The relationship between time, t_T, and temperature, T, for a material process is, in general, of the form

$$t_T = k \times \exp\left(\frac{Q}{RT}\right)$$

where k is a constant, Q is the process activation energy, R is the universal gas constant and T is the temperature in degress Kelvin.

Assuming this general relationship between time and temperature to be valid also in this case one obtains:

$$\log t_T = K_1 + K_2 \times \frac{1}{T}$$

$$\frac{d(\log t_T)}{d\left(\frac{1}{T}\right)} = K_2$$

K_1 and K_2 are constants. By plotting ($\log t_T$) linearly as a function of $\left(\frac{1}{T}\right)$ this function should be a straight line.

The time required to produce a certain increase in sensitivity has been measured on several microphones at four different temperatures. The results are shown in Fig. 5 and seem to be in satisfactory agrement with the above assumption. It is therefore, by the use of this assumption, and the measured results, possible to extrapolate (or interpolate) on the curves *whereby the stability of the microphone can be estimated for any given temperature.* If the stability at room temperature (25°C) is estimated it turns out to be approximately 4×10^6 times better than the stability at 150°C, i.e. of the order of

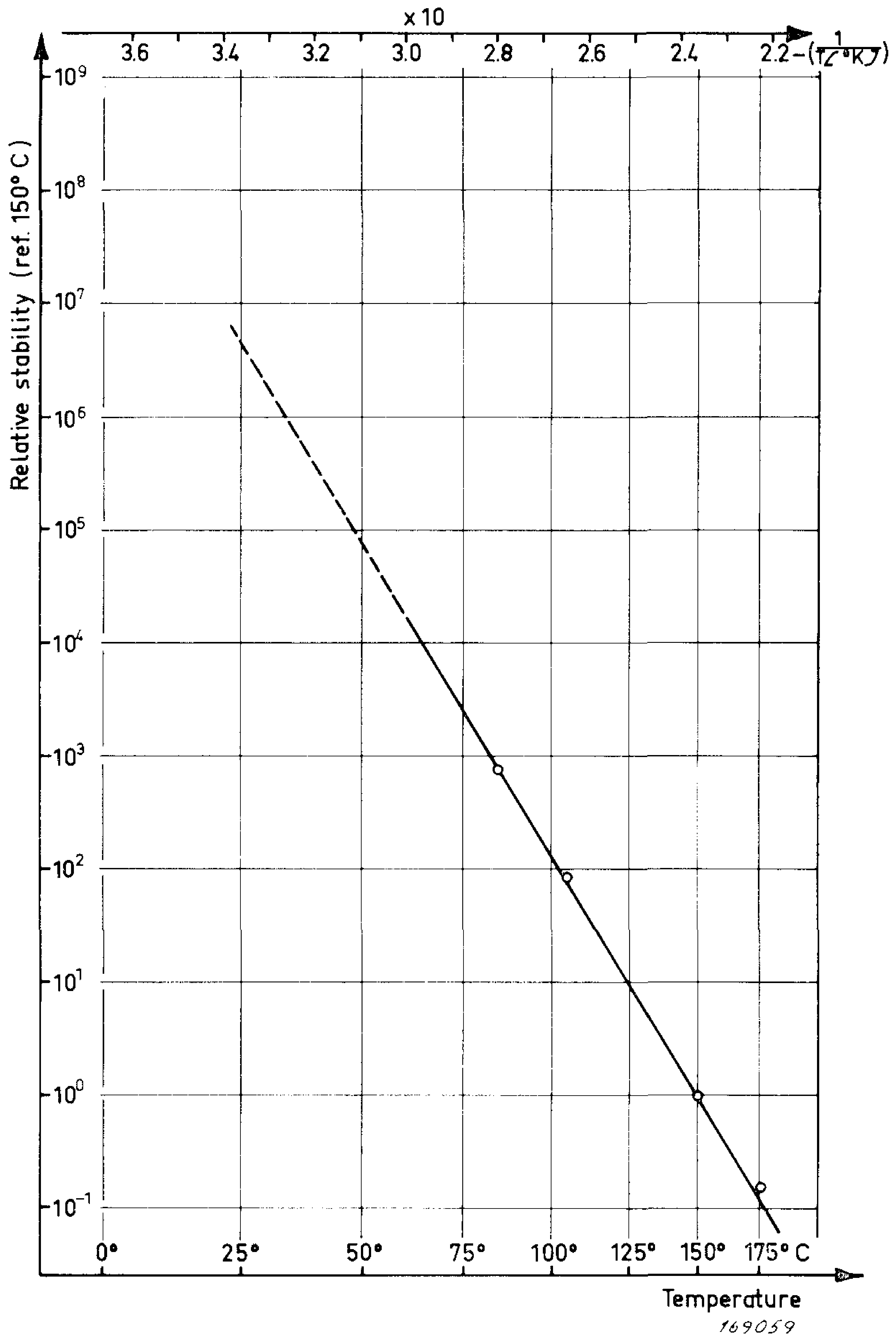


Fig. 5.

0.1 dB per 200 years! This result is roughly *1000 times better than the stability required by the U.S. standard for Laboratory Standard Microphones.*

It may be concluded that the new artificial ageing procedure, described in this paper, has made it possible to stabilize the most critical element in the condenser microphone to such an extent that long term stability problems at room temperature have been completely eliminated for any practical purpose. The time intervals between the time-consuming and elaborate precision calibration of standard microphones in high quality acoustics laboratories can therefore be increased, and highly skilled labour saved for other important work.

The Free Field Calibration of a Sound Level Meter*)

by

Peter Hedegaard

ABSTRACT

Inaccuracies in sound level measurements caused by diffraction around the sound level meter are discussed for various shapes and configurations of the sound level meter body.

RESUME

Les inexactitudes dans les mesures de niveau sonores causées par la diffraction autour du sonomètre sont étudiées pour diverses formes et configurations du corps du sonomètre.

ZUSAMMENFASSUNG

Ungenauigkeiten bei Schallpegelmessungen aufgrund der Beugung am Schallpegelmesser werden für verschiedene Gehäuseformen und -gestaltungen des Schallpegelmessers diskutiert.

If a microphone is placed in a sound field the diffractions of the sound waves on the microphone produce an appreciable change in the resulting sound pressure acting on the microphone diaphragm. The ratio of the RMS output voltage from the microphone to the RMS sound pressure existing in the free field at the microphone location with the microphone removed from the sound field is called the Free-field correction. The Free-field correction depends on the orientation of the microphone with respect to the direction of propagation of the sound and on the external dimensions of the microphone (in particular those of the front and of fitted protective grids). The Free-field corrections of the microphone used in the following measurements are shown in Figs. 1, 2 and 3.

With hand held sound level meters where the microphone is mounted in solid connection with the rest of the instrument, not only the microphone, but the entire apparatus, whose dimensions compared with those of the microphone are large, is placed in the sound field and, because of its size, will have some influence on the measuring results. In the following are shown some results of measurements carried out on sound level meters with different sizes and shapes.

---

*) Paper presented at the 6th International Congress on Acoustics, Tokyo, Japan 21–28 August 1968.

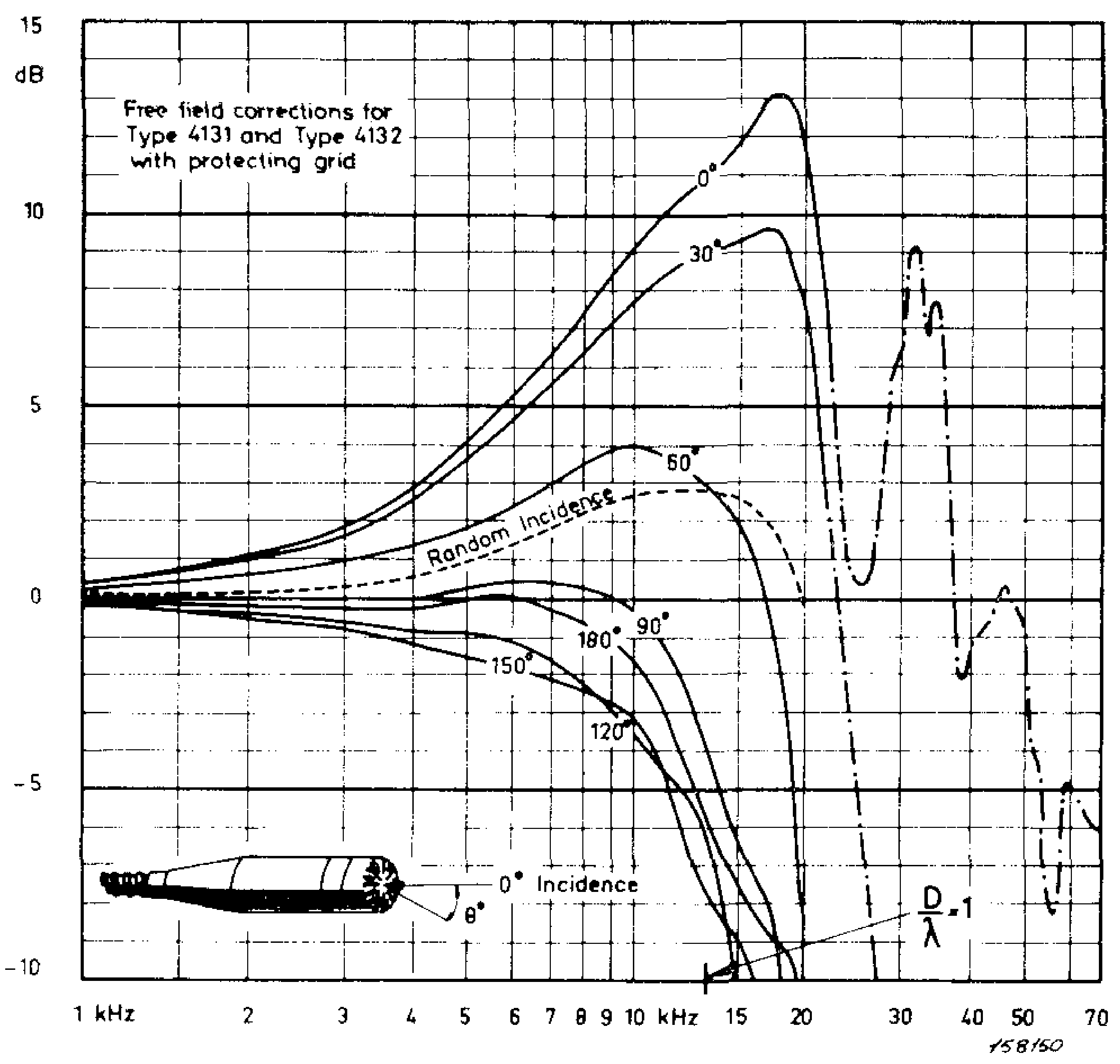


Fig. 1. Free field corrections for the Microphones Type 4131 and Type 4132 fitted with protection grid.

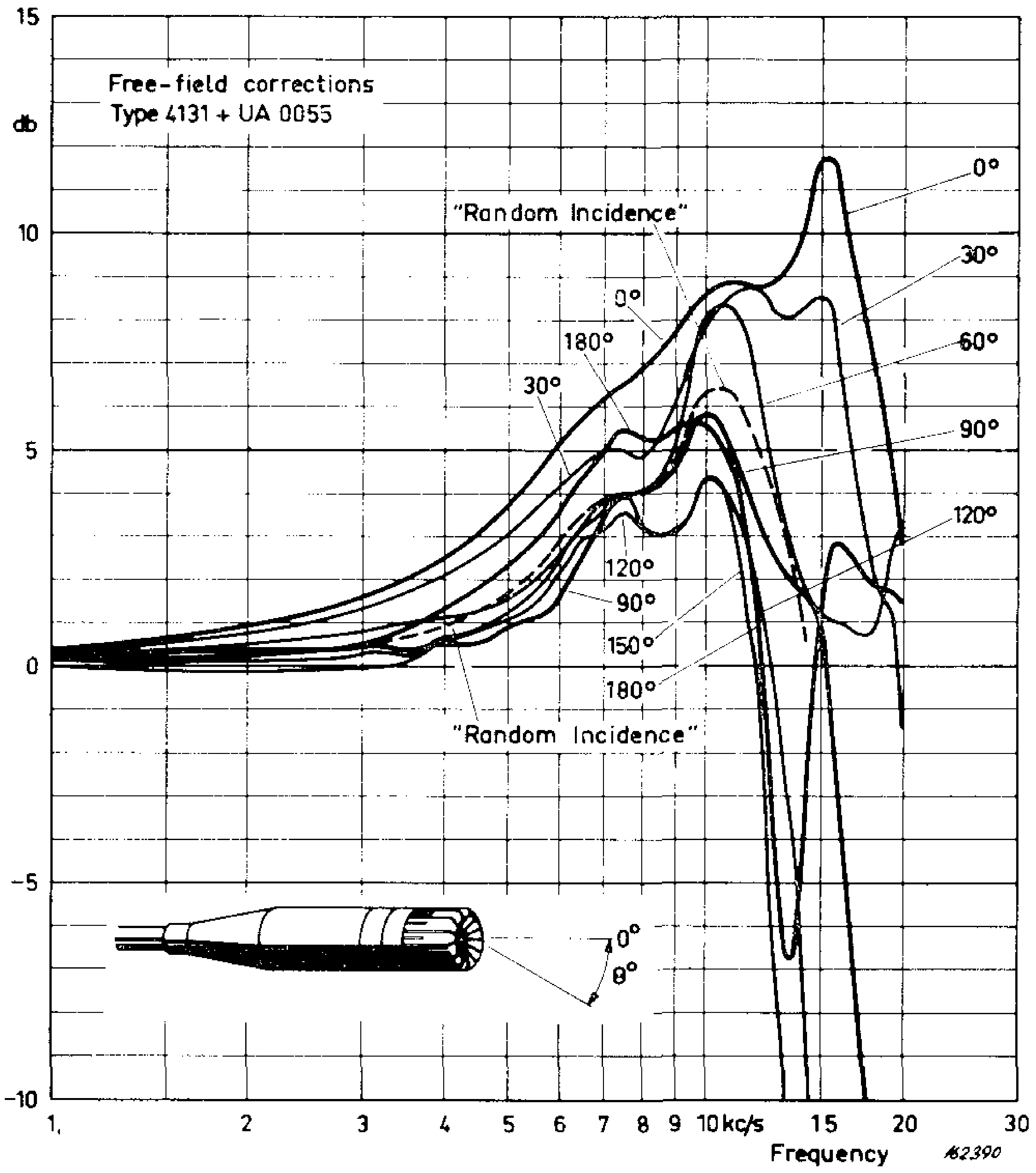


Fig. 2. Free field corrections for the Microphone Type 4131 supplied with the Random Incidence Corrector UA 0055.

Description of the Measuring Set-up

The measuring set-up is illustrated in Fig. 4. The measurements were carried out on wooden dummies on which the microphone could be placed. Each of the curves given in Fig. 6 show difference (in dB) of the RMS output voltage from the microphone when placed on the dummy and the corresponding volt-

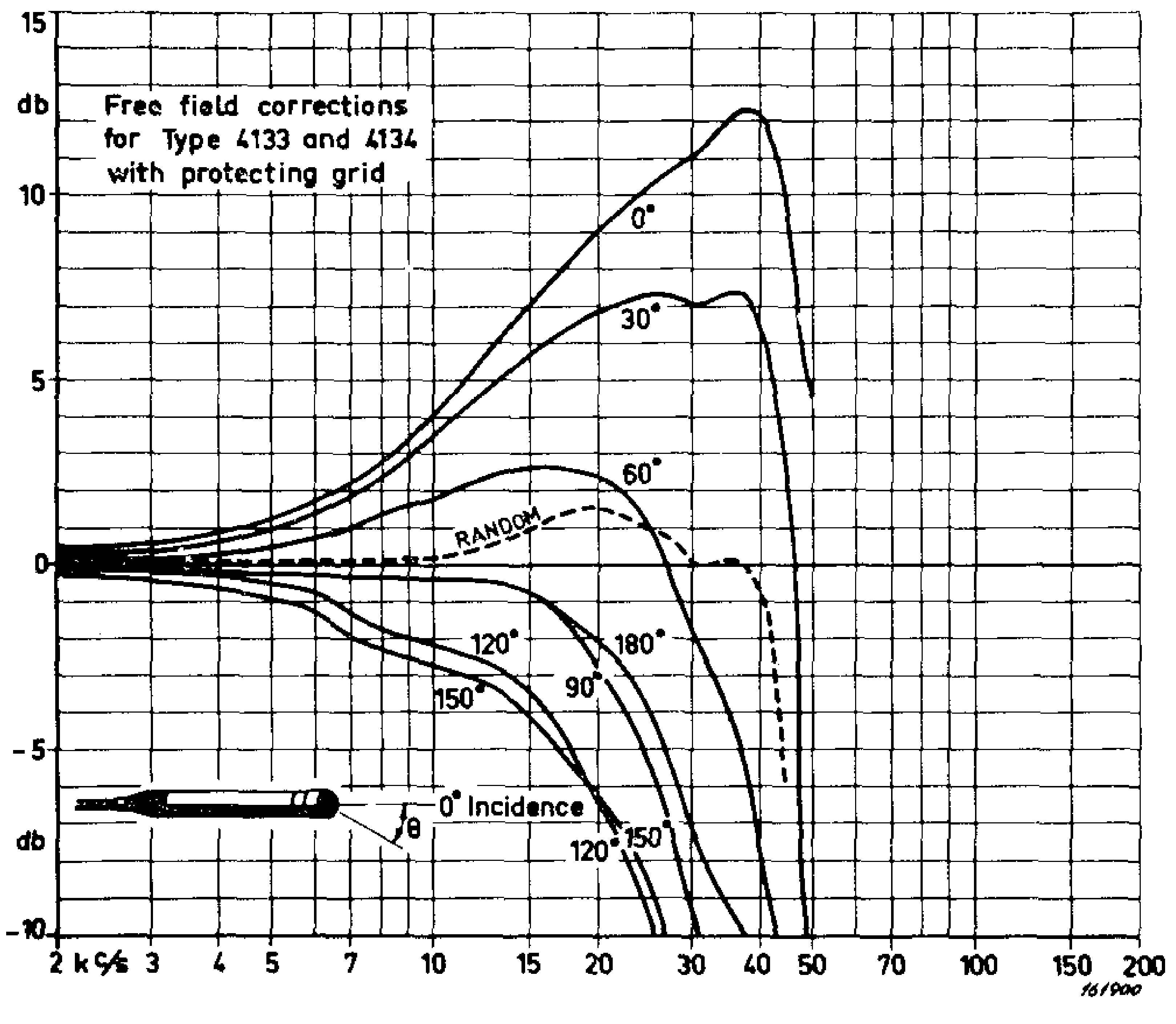
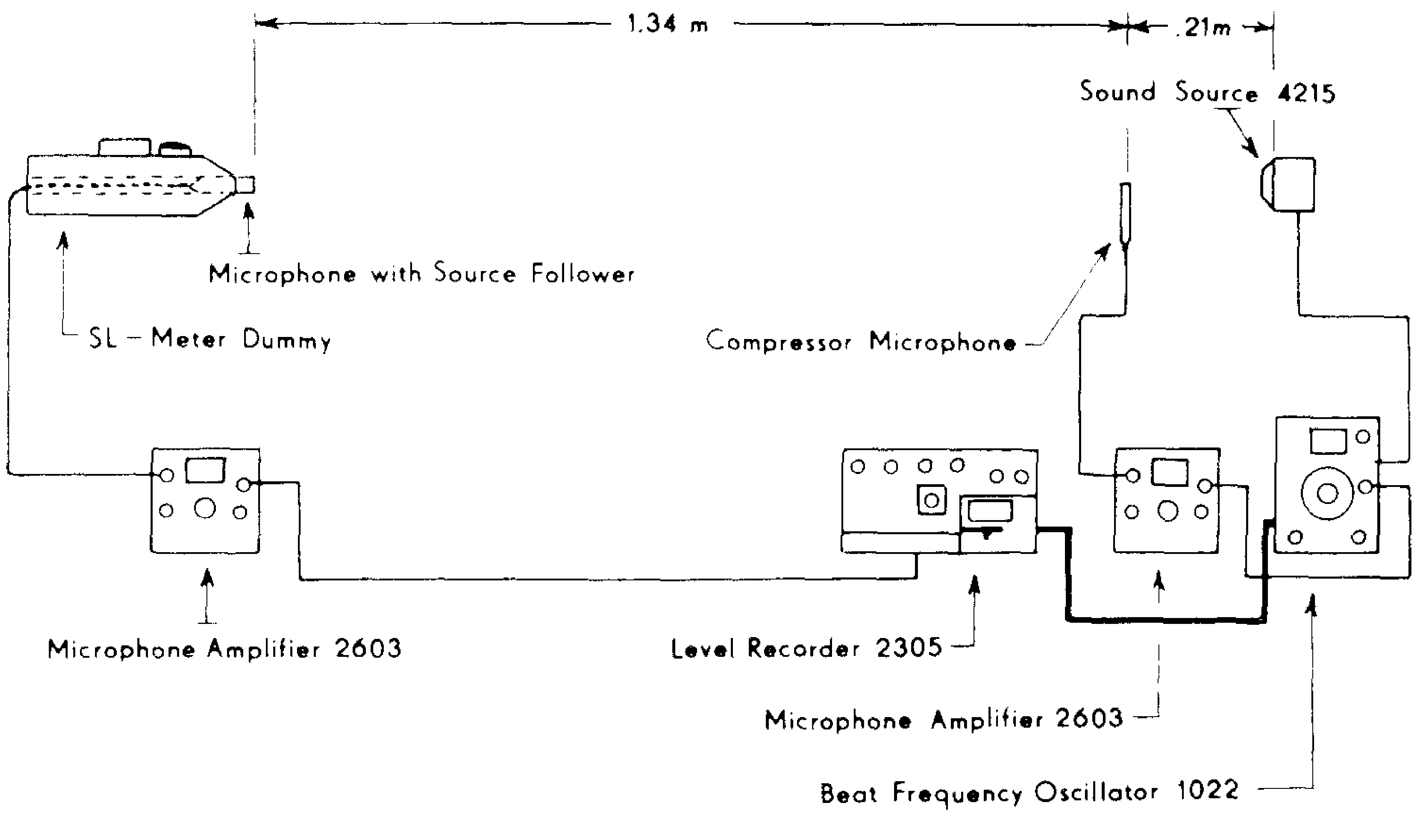


Fig. 3. Free field corrections for the Microphones Type 4133 and Type 4134 fitted wih protection grid.

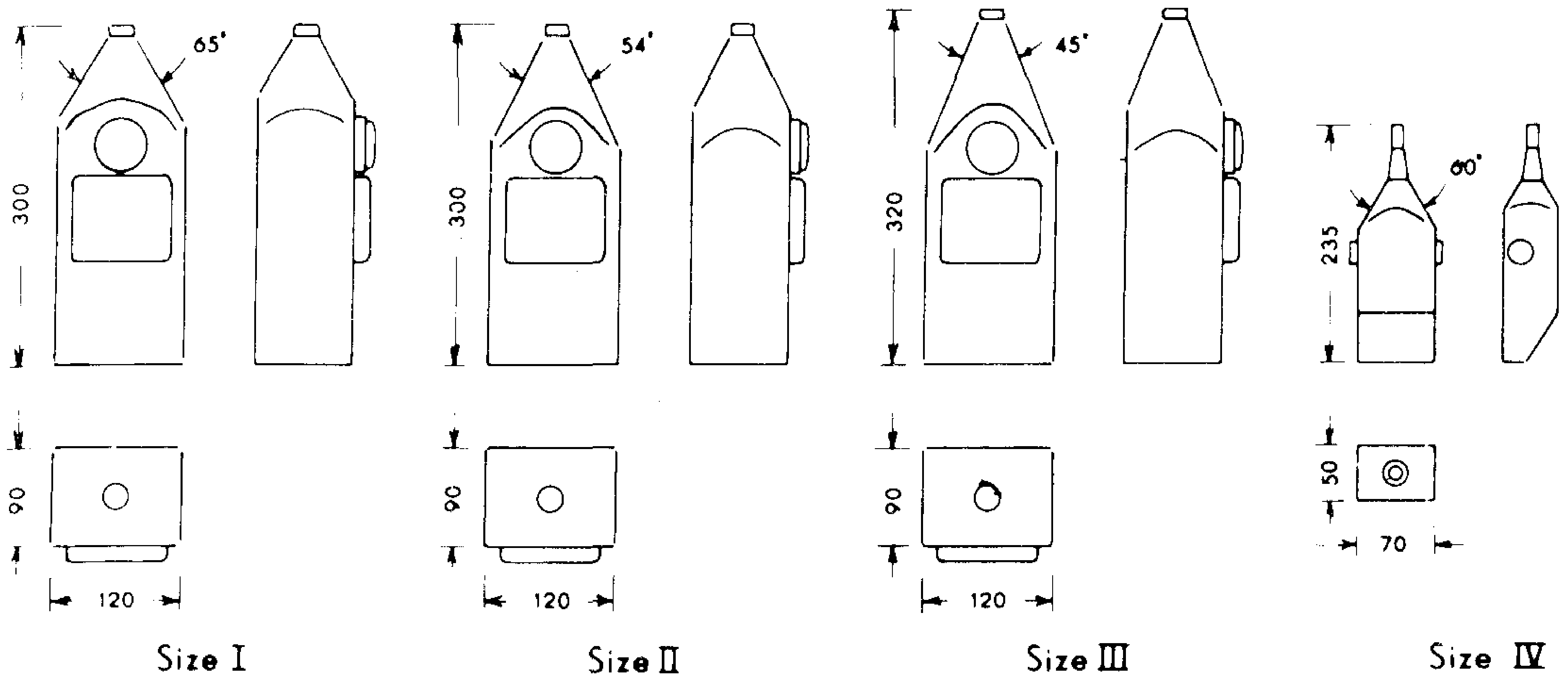
age measured with the microphone alone, placed in the same position in the sound field and the same angle of incidence. The curves therefore show the influence of the sound level meter body. The measurements were carried out in an anechoic room (8 × 10 × 12 meters) with the inside covered by 1.5 meter rock-wool wedges. The wooden dummies used are shown in Fig. 5 and are referred to in the following text by the numbers I, II, III, and IV.

The measurements were carried out at 0°, 30° and 90° angle of incidence. On account of the fact that none of the used sound level meter dummies have rotational symmetry the measurements at 30° and 90° of incidence were carried out with the dummy in 3 positions, 1 with the side, 2 with the front



16901o

Fig. 4. Measuring arrangement.



76 9011

Fig. 5. Sizes and shapes of the sound level meters (dimension in mm).

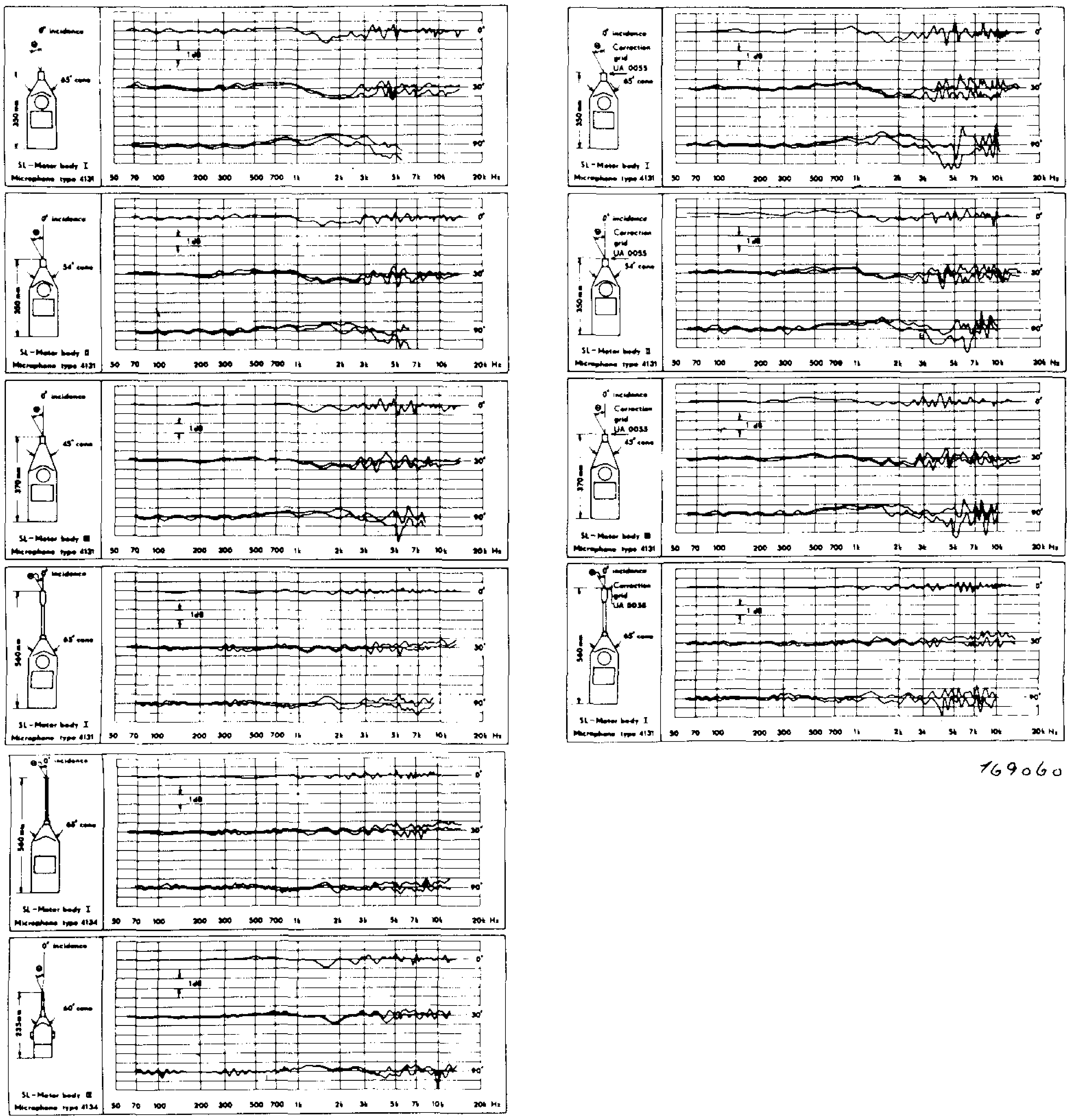
(side of the indicating instrument) and 3 with the back toward the sound source. The curves therefore also show the spread of the influence from the sound level meter body if it is turned 360° around its own axis.
For the measurements a 1" microphone, Type 4131, was used, partly mounted with normal protecting grid and partly mounted with a correction grid (Random Incidence Corrector, UA 0055) which gives the microphone a better omnidirectional sensitivity (Fig. 2). In addition a 1/2" microphone, Type 4134, was used (Fig. 3).

Results and Discussion

From Fig. 6 it is seen that the diffraction caused by the cone-shaped sound level meter is relatively small in view of dimensions but too great to be overlooked for free field measurements. By comparing the curves from the sound level meter sizes I, II and III it is seen that the cone-shape with the smallest angle naturally is the best one, but that the improvement does not justify the, in other respect, unpractical shape. A real improvement is obtained when the microphone is placed at a certain distance in front of the sound level meter. The spread that arises when the sound level meter is turned around its own axis will in this case also be minimum.

A Man's Influence on the Sound Field

By examination of the diffraction on hand held sound level meters it will be innatural not to examine the disturbance of the sound field that will be produced by a man holding the instrument in his hands. By comparing the curves Fig. 7 it is easily seen that the disturbance produced by the observer is much greater than that produced by the sound level meter. It is seen that the disturbance is greatest in the range 300–700 Hz. In Fig. 8 is shown the disturbance that an average man will produce in a free sound field measured

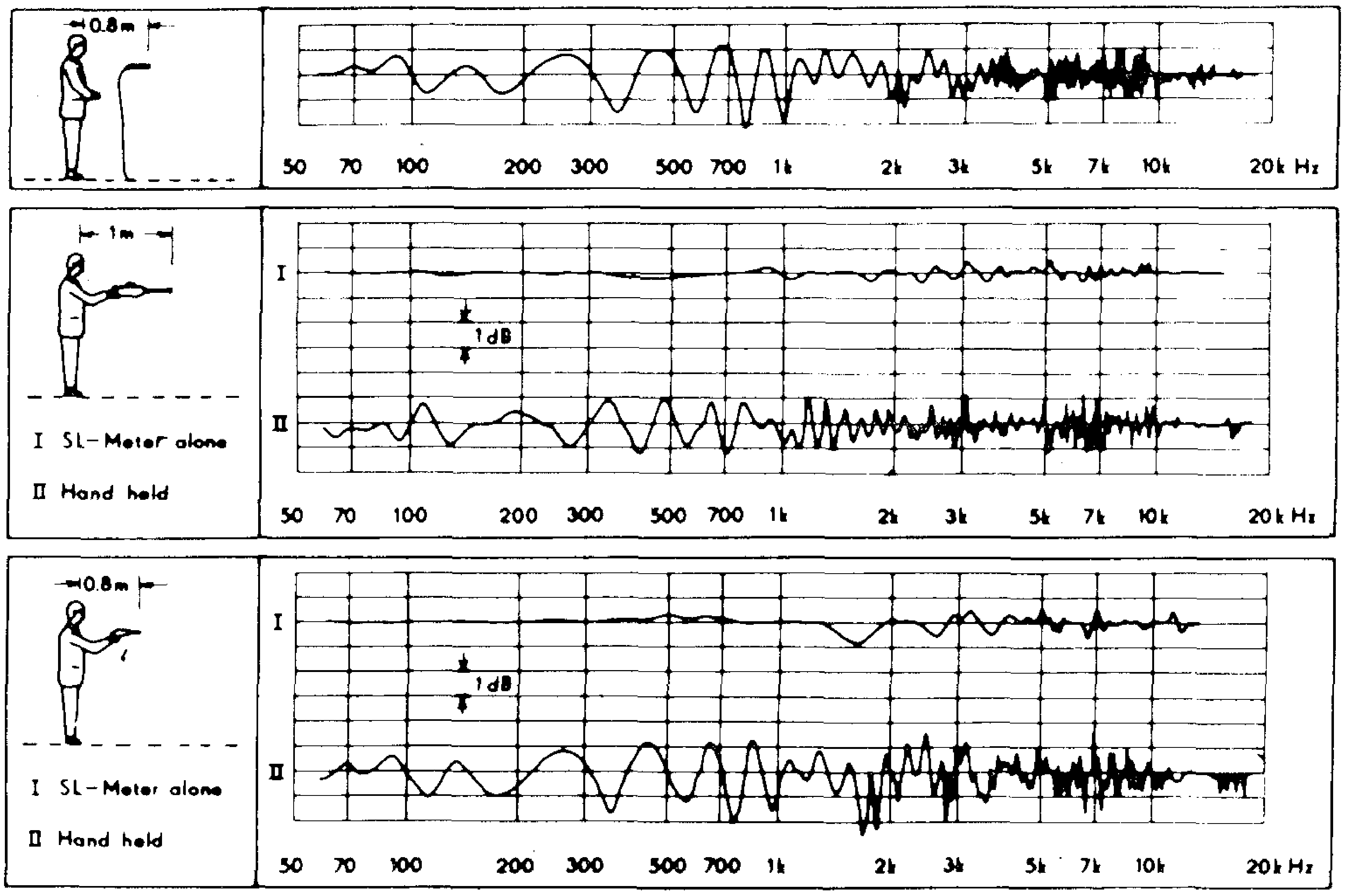


169060

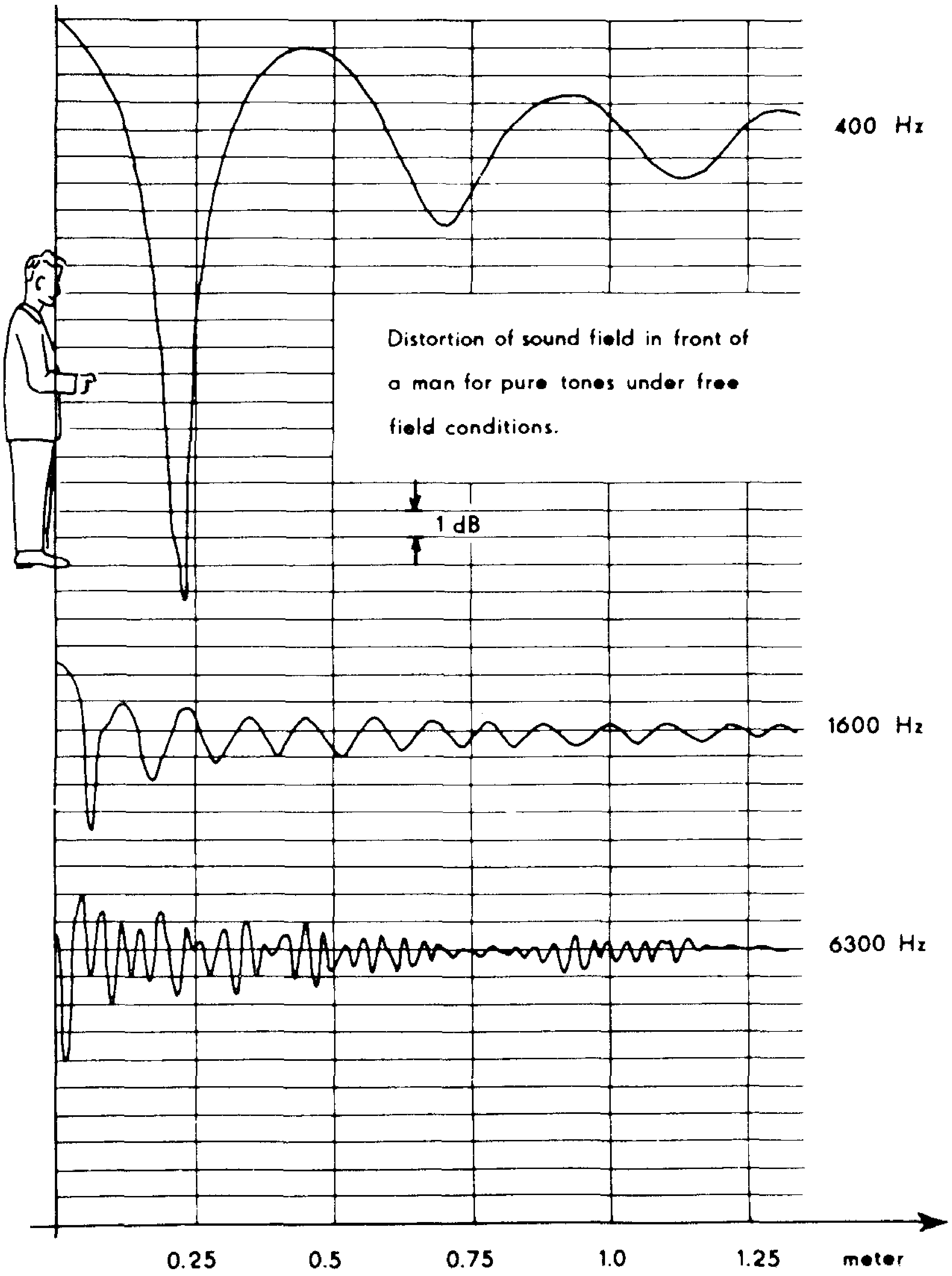
Fig. 6. *Influence of the sound level meter body.*

at 400 Hz, 1600 Hz and 6300 Hz. It is seen that the distance between the microphone and the observer must be approx. 1 meter or more if the disturbance shall be less than ± 1 dB.

The shown set-up with the sound level meter with the observer behind, in a free sound field will hardly occur in practical measurements, but can be looked upon as a worst case. With measurements in a diffuse sound field or with measurements of noise with a certain bandwidth the influence from the observer will be small and the accuracy of measurements will therefore be considerably better than indicated by the curves Figs. 6, 7 and 8.



▲
Fig. 7. Man's influence on the sound field.



◀
Fig. 8. Distortion of sound field of an average size man.

Accelerometer Configurations*)

by

Gunnar Rasmussen and *Jens August Jensen*

ABSTRACT

A discussion of various configurations used in accelerometer design. Advantages and disadvantages of different mechanical designs and different piezoelectric materials. A rating is proposed, taking into consideration the electrical impedance, sensitivity, frequency range and mass. Also the influence of base bending, temperature and other environmental effects is discussed.

RESUME

Discussion des diverses conformations utilisées pour la réalisation des accéléromètres. Avantages et inconvénients des différents modèles mécaniques et différents matériaux piézo-électriques. Un classement est proposé en prenant en considération l'impédance électrique, la sensibilité, la couverture de fréquence et la masse. On discute également l'influence d'une flexion de la base, des effets d'environnement, en particulier de la température.

ZUSAMMENFASSUNG

Verschiedene Anordnungen werden erörtert, die bei der Auslegung von Beschleunigungsaufnehmern benutzt werden. Vor- und Nachteile der unterschiedlichen mechanischen Konzepte und piezoelektrischen Materialien werden aufgezeigt. Ein Bewertungsfaktor wird vorgeschlagen, der die elektrische Impedanz, den Übertragungsfaktor, den Frequenzbereich und die Masse berücksichtigt. Auch die Biegefestligkeit der Basis, sowie die Einflüsse von Temperatur und anderen Umgebungsbedingungen werden besprochen.

Recent years the piezoelectric type of accelerometer has become the preferred type of transducer for measurement of shock and vibration. The piezoelectric accelerometer has several advantages over other types of transducers, such as for instance velocity and strain gage type pick-ups. Some of the most obvious advantages are small weight and size, they are self generating and have high reliability.

There are, however, various ways to design these accelerometers. Some of them present good frequency response, some have high sensitivity and others are practically uninfluenced by extraneous effects such as temperature, magnetic fields etc.

Most accelerometers are made as a compromise trying to fulfil a specific requirement compromising on some of the other.

---

*) Paper presented at the 6th International Congress on Acoustics, Tokyo, Japan 21–28 August 1968.

The purpose of this paper is to give a survey of the most normally used accelerometer designs showing their main advantages, and to try to give a method of rating an accelerometer in order to evaluate its quality as a general purpose accelerometer.

If we list the desirable criteria for accelerometers they would appear as follows:

Table I.

1. *High electromechanical conversion efficiency.*
2. *Wide frequency range.*
3. *Large dynamic range.*
4. *High stability.*
5. *Low weight.*
6. *Low cross sensitivity.*

and low sensitivity to extraneous environmental effects such as:

Temperature – humidity – magnetic and acoustic fields – torque – base strain.

If we now look at the most often used designs, these can be classified in the following major classes:

Table II.

1. *Twister design (early type).*
2. *Cantilever beam.*
3. *Mushroom design.*
4. *Shear design.*
5. *Basic compression type.*
6. *Isolated compression type.*
7. *Single ended compression type.*
8. *Inverted single ended compression.*

All the above types can be made from various types of ceramics.

Some of the characteristics of an accelerometer do not only depend on the design, but also to a large degree on the piezoelectric material used. This we shall revert to at a later time.

First we shall look at the characteristics that can be obtained by the various basic designs.

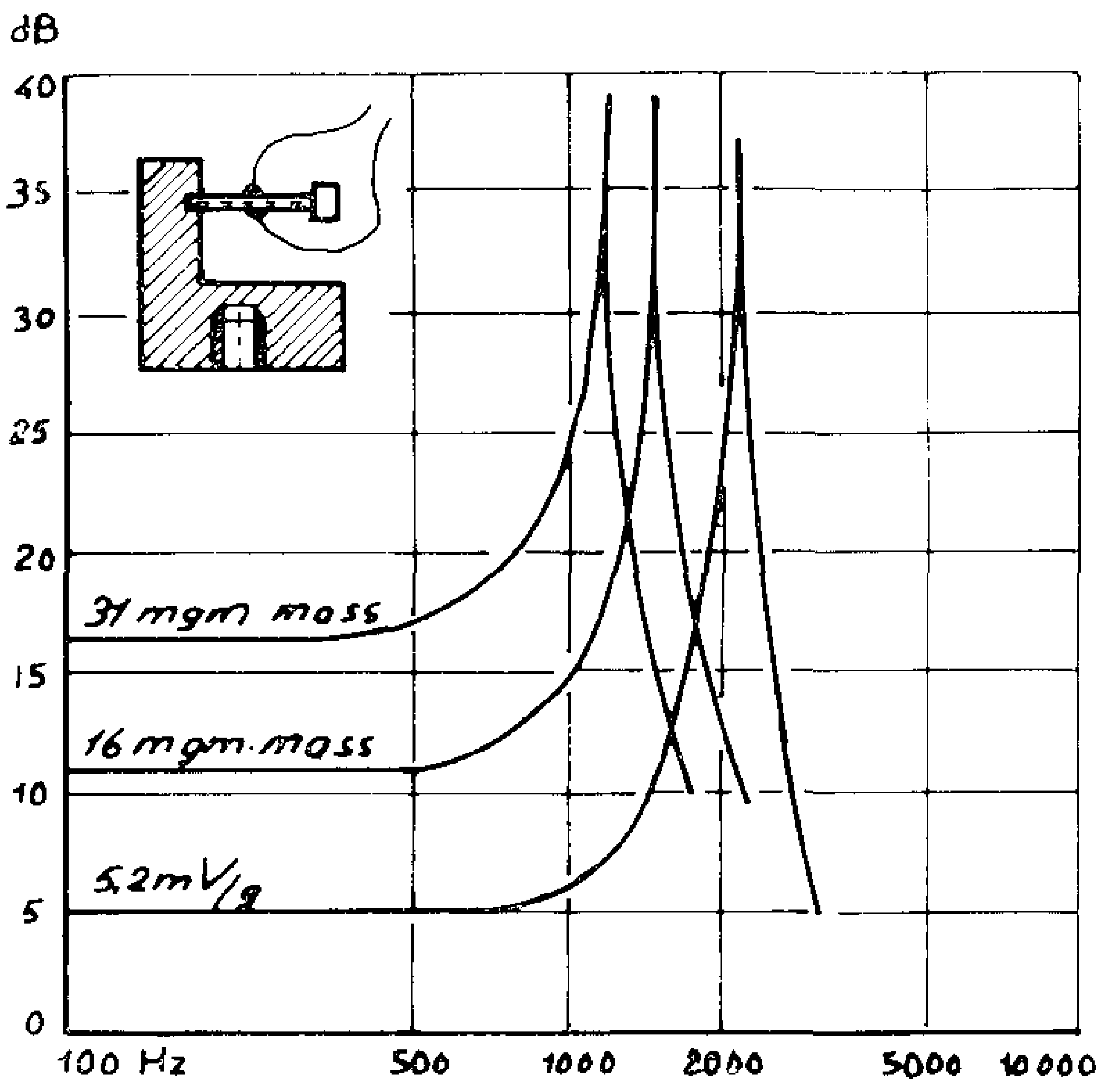
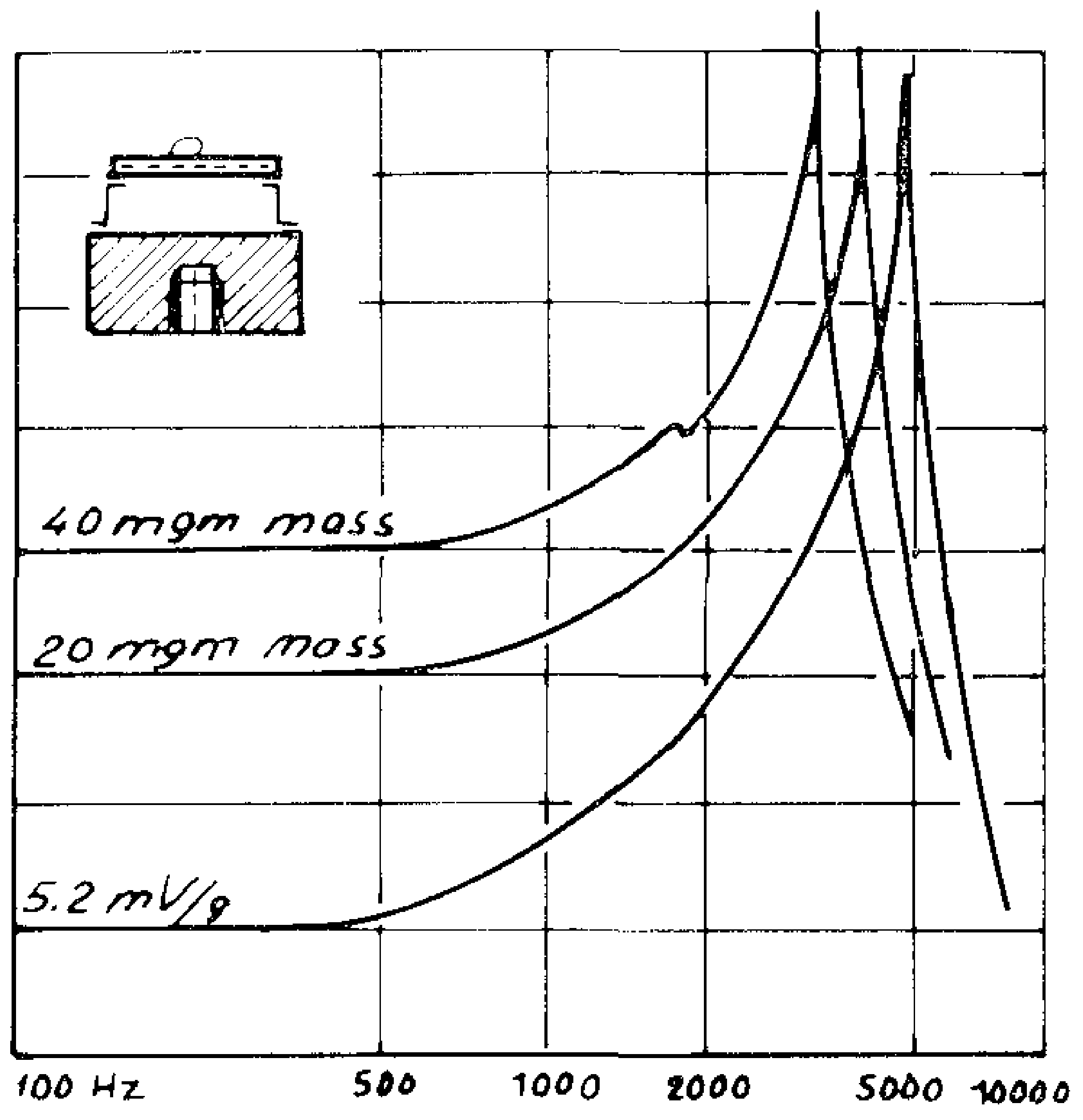


Fig. 1.



769050

Fig. 2.

The output voutage V from a piezoelectric bender is proportional to the deflection it is forced into. Depending on the configuration used we have $V = K\frac{M\,a\,L^4}{E\,I}$ where K is a constant depending on the material used, the clamping Fixed-Free; Fixed-Fixed etc. M is mass of element and possible applied extra mass, a acceleration, L free length, E modulus of elasticity and I moment of inertia of the beam. In Fig. 1 typical curves and sensitivity for a Fixed-Free design is shown, and in Fig. 2 typical data for a Hinged-Hinged design. As seen the sensitivity of these designs are rather low for the available frequency range.

The mushroom design may perform better than the cantilever beam types in respect to transverse sensitivity, but it is in general not very effective. The shear design is very good when low transverse sensitivity is an important goal. Only very few good designs exist for use at higher temperatures. The shear

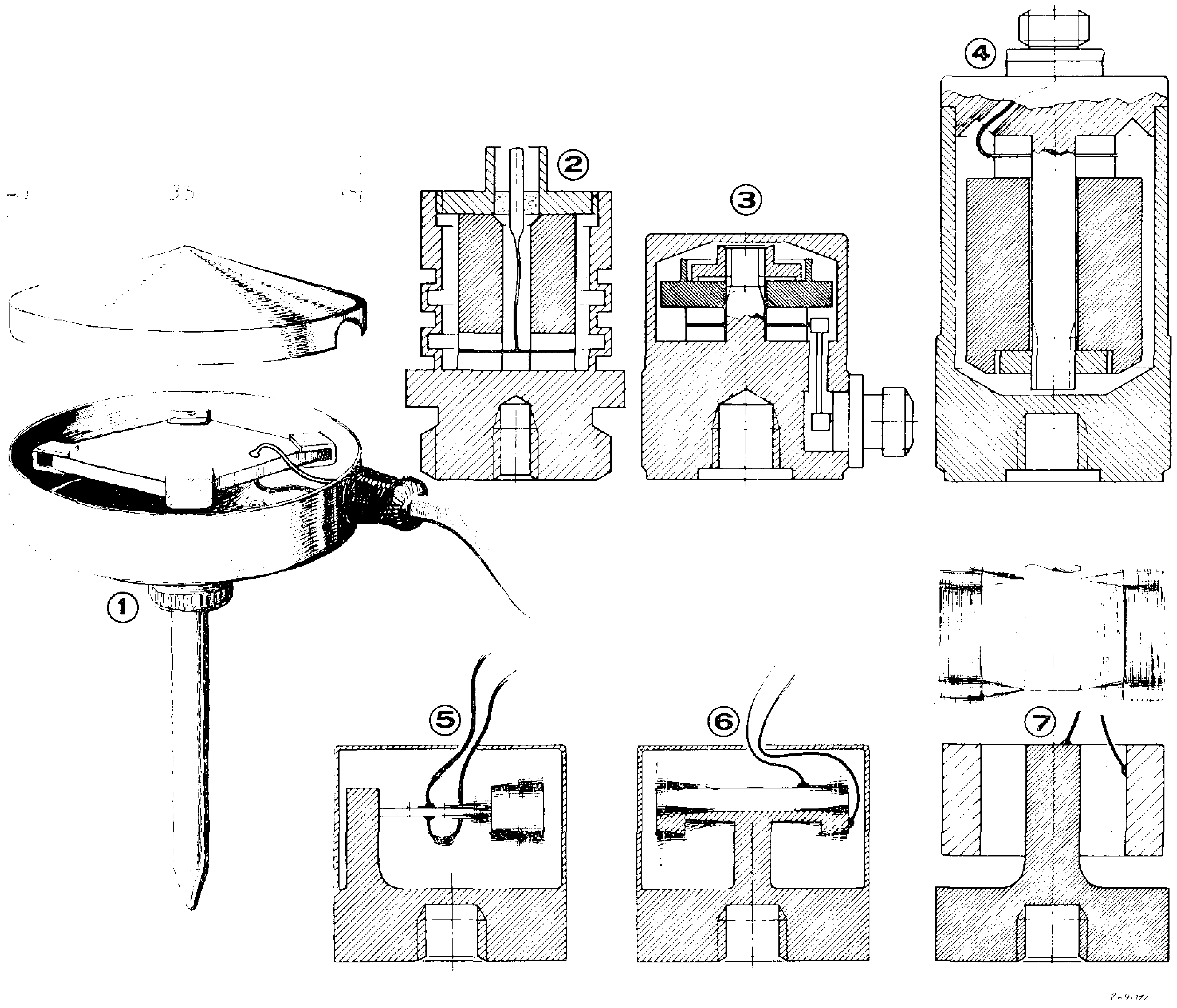


Fig. 3.

1. *Bender design.*
2. *Basic Compression.*
3. *Single ended compression.*
4. *Inverted single ended compression.*
5. *Cantilever beam.*
6. *Mushroom design.*
7. *Shear design.*

design is utilizing the piezoelectric material in shear deformation. The limitation in these types is in weight or in high temperature performance.

The most effective design is the compression. The output voltage in compression is $V = K \frac{M a t}{E A}$ where t is the thickness of the piezoelectric material and A the area in compression. A more representative figure is the charge sensitivity which in general should be used when comparing the effectiveness of different designs $q = K \frac{M a}{E}$.

In the basic design of the compression type the outside housing was effectively used as a spring, see Fig. 3. This was later improved by using a spring and obtaining the isolated compression. In order to reduce the sensitivity to external acoustic pressure variations and temperature shock it has thus been further developed into compliant rod types, single ended compression types and inverted single ended compression types. See Fig. 3.

It is obvious from the foregoing that it is difficult to judge about the quality of an accelerometer.

For a certain application one may of course look only on the qualification needed for this particular application, but if one wish to select the best type to its price it is difficult. Therefore an attempt is made to propose a formulae which takes the most important factors influencing the general use into consideration, and try to rate different designs accordingly. This is may be so much more important as also several different piezoelectric materials are available. A table comparing some of the materials available is given in Fig. 4.

Table IV	Efficiency	Diel. constant	Max. Pressure Kg/cm^2	Max. Temp. °C
Rochelle Salt	80	350	70	55
ADP	10	15	210	130
Barium-Titonate	20	1000	350	120
PZT	40	1500	700	300
Pb $Nb_2 O_6$	18	250	350	450
Quartz	1	4	3500	300
Li $N_6 O_3$ Y-cut	6	84	~	1250

161186

Fig. 4.

We should also like to include a stability factor in this scheme. It is, however, not possible to give exact figures for several of the materials. Typical figures for P. Z. T. as used by B & K are less than 0.2 % drift per decade of time at room temperature, first decade being one year after artificial aging. For quartz the figures are much lower as the quartz in itself is a very old material. The stability for quartz transducers is determined by the mechanical stability and the ability to use the very low efficiency resulting in very high impedance levels.

Considering the number of factors involved in judging a general purpose accelerometer it is rather difficult to compare different designs. If, however, we look at the different design variables, we may judge about the efficiency by using following reasoning in trying to establish a "quality factor". The sensitivity *S in* pCb/g is proportional to the mass acting on the sensitive element. The resonance frequency *f.res.* is inversely proportional to the root of the mass. We may thus set up a quality factor: *Q*

$$Q = \frac{s\sqrt{f.res.}\,.\,D}{W}$$

where

W = Accelerometer weight in grammes
D = Useful dynamic range in decades
$f.res.$ = Resonance frequency mounted on a 180 g steel block

Using this formulae*) on different designs we will find high quality modern accelerometers with a *Q* of 500–1000 and spreading out for less good designs or special types down to 10.

Other factors are also important. The base strain sensitivity should in general be below 0.002 g/μin/in. A typical example of very low base strain sensitivity is Brüel & Kjær 4338 with a *Q* of 600 and base strain sensitivity of less than 0.00002 g's/μin/in.

Also a response to thermal shock which is equivalent to less than 0.05 g for a step function temperature change of 10°C measured across 1000 MΩ resistance is typical for high quality accelerometers. Cable movements of 5 mm from side to side right outside the cable plug may be used for evaluating cable sensitivity. A good design will respond with an output which is equivalent to less than 0.02 g and figures as low as 0.007 may be obtained.

Although these factors count in the selection of a proper accelerometer for a particular situation the formula for *Q* given above may be looked upon as "basic" for general purpose accelerometers.

---

*) Actually, the formula suggested here for *Q* is of purely empirical origin, based on transducer design experience, and it expresses an attempt to estimate the relative importance of the various accelerometer design factors. In the author's opinion it should, furthermore, be possible to extend the expression to also include the importance of the transducer transverse sensitivity and long term stability. A reasonable extension seems to be:

$$Q^{1} = Q\left(1 - \frac{t}{100} - \frac{V^{2}}{100}\right)$$

where: t = Transverse sensitivity in % and
v = Long term stability in % change of S (sensitivity) per year.

Vibration Monitoring and Warning Systems*)

by

Peter Wilhjelm, M.Sc.

ABSTRACT

The criteria of detecting defects in rotating machinery with accelerometers used as vibration detectors is discussed.

The paper is mainly based on equipment designed to monitor unwanted signals on water and gas turbines and to give alarm when a preset level is exceeded.

RESUME

On étudie les critères pour la détection des défauts de machines tournantes par des accéléromètres comme détecteurs de vibrations. L'article a principalement en vue de l'équipement conçu pour surveiller des signaux non désirables, sur turbines hydrauliques ou à gaz, et pour donner l'alarme au cas où un niveau prédéterminé serait dépassé.

ZUSAMMENFASSUNG

Das Kriterium der Aufspürung von Schäden in umlaufenden Maschinen mit Hilfe von Beschleunigungsaufnehmern als Schwingungswandler wird dargelegt.

Der Aufsatz stützt sich auf ein Gerät, das zur Überwachung unerwünschter Schwingungen an Wasser- und Gasturbinen entwickelt wurde und welches das Überschreiten voreingestellter Grenzwerte signalisiert.

Introduction

The purpose of this paper is to give some practical points of view with respect to measurement (detection) of defects in machinery before severe troubles take place. On machinery in continuous operation it is of great importance that no interruption in the normal operation period occurs, otherwise great economic loss would result. This is relevant to power stations, machinery in all transportation vehicles, pumps and large machinery in automatic production factories.

Detection of Defects

If we can detect the beginning of all defects at a very early time where no severe trouble takes place, it is possible to maintain the machinery in a condition causing no trouble during normal operation and then repair, replace or reconstruct parts in periods where the machinery is otherwise out of operation.

---

*) Paper presented at the 6th International Congress on Acoustics, Tokyo, Japan 21–28 August 1968.

The determination of defects at the very beginning is the main and normally unsolved problem of this concept. A human detection of defects is always possible. We are all familiar with a sensing of structural vibration through the feet, fingers or the whole body, or we can hear airborne vibrations with the ear. This observation is usually at a level where the damage is severe and only gives us a short period of further operation before complete break-down. This generalisation is not correct, as very little energy has to be transferred to the ear before sensing takes place, but our "unwanted" signal may be masked by other signals of higher levels, naturally excited and without harm. More relevant is perhaps to observe that the man may not be there at all.

Nearly all machinery are of a such complex nature that it is impossible to calculate the complete dynamic behaviour of the mechanics and construction, even by using computers. Furthermore defects are often due to changes in parameters which have been determined as constant in the laws of calculation.

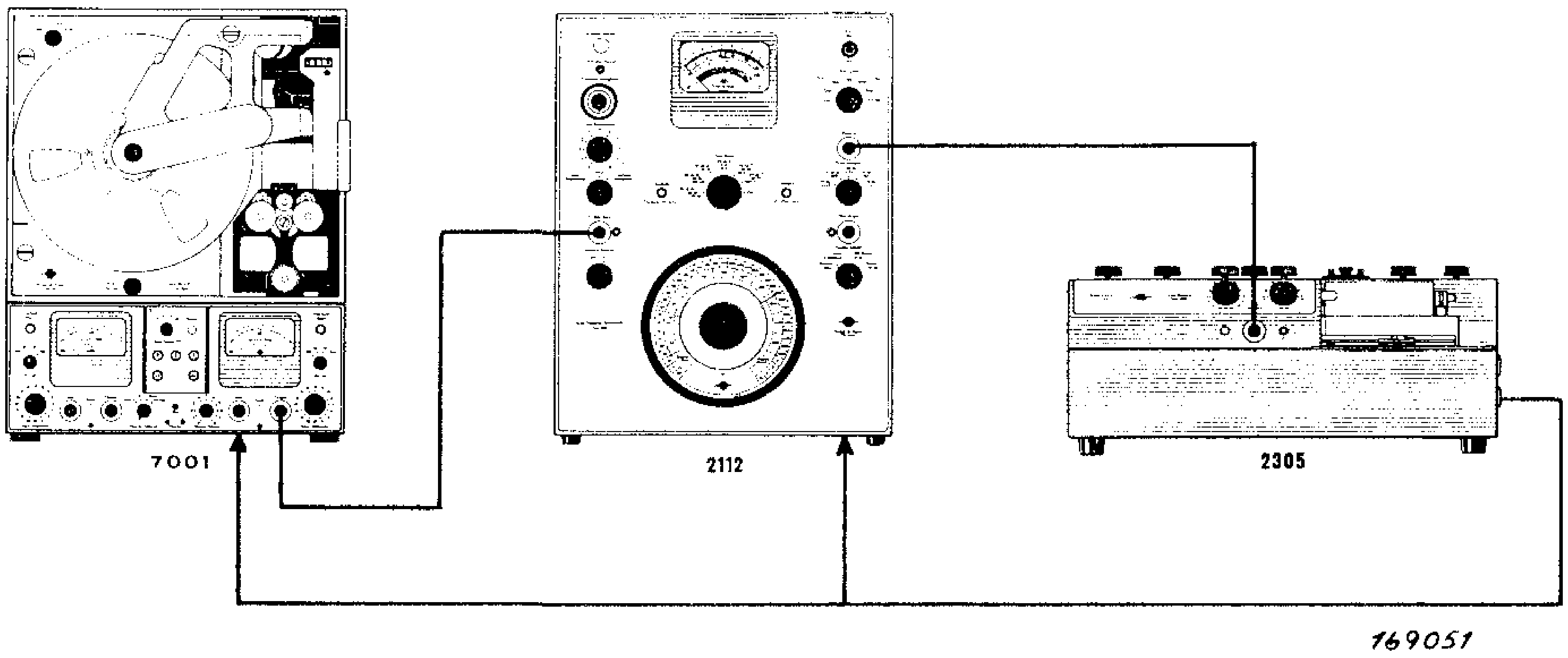
Realizing this we have to admit that it is very difficult to determine which parameter it is sensible to transduce to a monitoring and warning system, and which parameter will give us the earliest and best criterion of fault detection. A determination of defects has to be based on an analysis of what happens. We can mention a whole series of defects recognized by experience, but we do never know when a new one appears, one not taken into consideration previously.

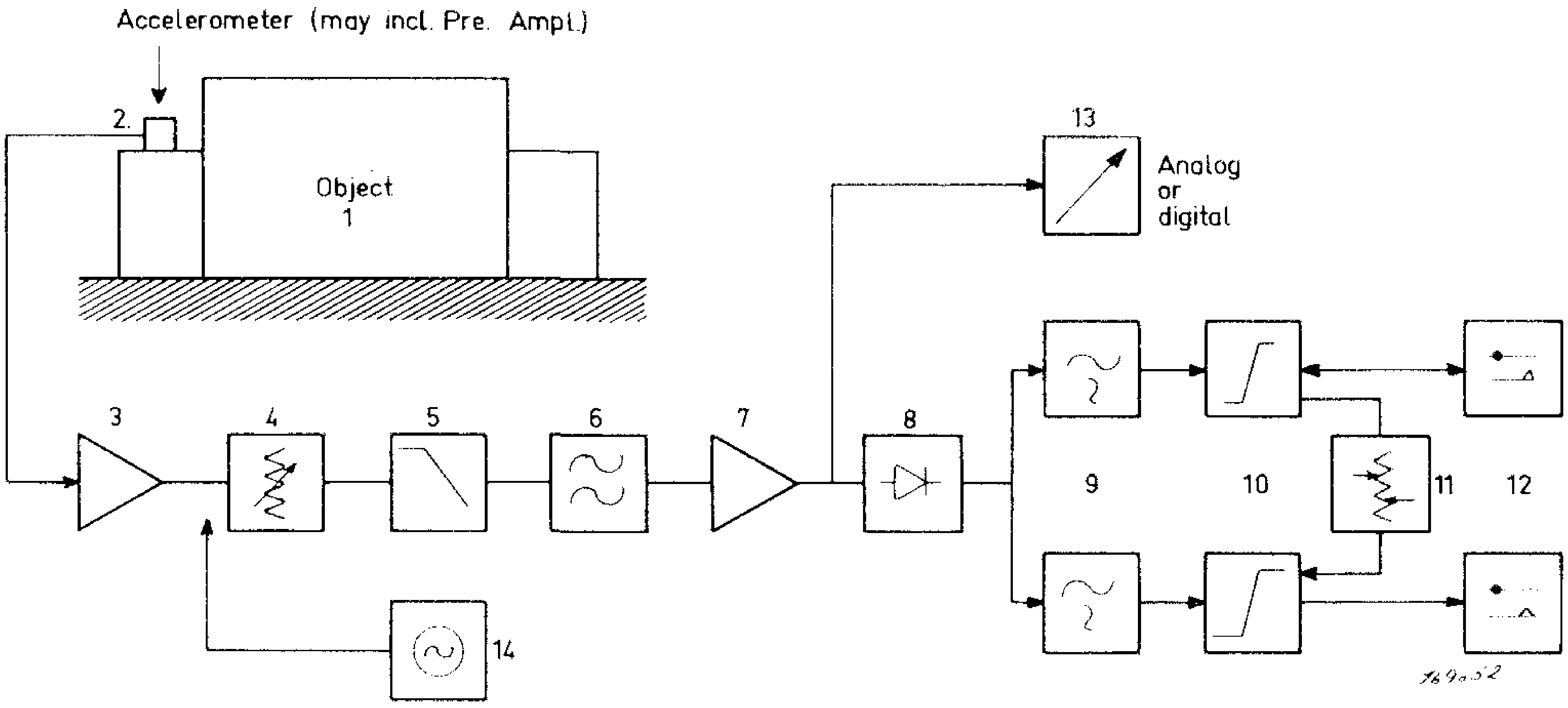
By experience it is possible to determine that a machinery is operating satisfactorily. During this normal operation we can make an analysis of the vibration spectrum excited by the machinery. This analysis could be based on displacement, velocity or acceleration parameters together with a frequency determination and perhaps even representated in the complex form, this would be a complicated approach to the problem. Each later analysis should then appear the same, if not, there must have been changes in the system, perhaps indicating the beginning of defects. This is in practice a too complicated way of detection, and even so we would only know that something has happened, we do not know what and we have not made a correlation with our problem.

Practice in Detection

It is normal practice that displacement is the most relevant parameter to observe at very low frequencies up to 50 Hz, corresponding to 3000 RPM. This is due to the law of elasticity and the fatigue of materials. Experience from static calculations may influence some engineers to consider displacement as most important. Going through the frequency range from low frequencies it is usually the velocity that is directly related to defects. This is valid up to perhaps 100 Hz

From the equation determining mechanical impedance Z, $Z = P/x$, P is the force and x the velocity in vectorial representation. It is seen that velocity is proportional to force if the mechanical impedance is constant, or inversely proportional to mechanical impedance if the force is constant. If we assume that the force produced by the machinery is constant it is most likely that defects will cause changes in the mechanical impedance and therefore a detection of velocity will be correct. Vibration may be represented by the equation $x = x_0 \cos \omega t$, where x_0 denotes the displacement amplitude of the motion. Velocity or acceleration may be derived by differentiation once or twice respectively with respect to time. Velocity $x = \omega x_0 \sin \omega t$, acceleration $x = -\omega^2 x_0 \cos \omega t$. As seen from these equations the frequency parameter gives more and more weight to the amplitude of expression. Assuming that rapidly repeating forces on the component of our object will cause defects, it is more likely correct to monitor on acceleration levels, fatigue in crystal structure is one example.





3. PREAMP. (CHARGE AMP.)
4. ATTENUATOR
5. INTEGRATION CONVERTING SIGNAL PROP. TO VEL. OR DISPL.
6. FREQUENCY LIMITATIONS
7. AMPLIFICATION
8. RECTIFICATION, RMS, AVERAGE, PEAK
9. TIME CONSTANT
10. COMPARATORS (LIMITS)
11. PRESETTING OF LIMITS
12. LOGIC OUTPUT
13. VISUAL DISPLAY UNIT
14. CALIBRATION UNIT

Fig. 1. Block schematic of typical vibration monitoring and warning systems.

Selective Detection

Detection of errors with a frequency selective equipment (assuming that the error will occur inside a narrow frequency band) it is irrationel to prefer a detection of displacement level for velocity or acceleration levels, as it is only a matter of pure calculation of the corresponding value.

System in Practice

We will now briefly go through some monitoring and warning systems. A block schematic shows the principles of the systems. The idea of these systems are to use highly reliable modular units for easy replacement and for great flexibility in custom designed systems. We have furthermore put emphasis on a rigid construction so that severe environmental conditions will not harm the operation of the system.

Conclusion

This type of work is only in the beginning, but we expect that the rapidly increasing automation will require more work to be done, especially with respect to analysis of vibration and its correlation with breakdown.

Brief Communications

A Note on "Impulse Noise Measurements"

In the paper D-2-2 (I.C.A.-1968, Brüel & Kjær Technical Review No. 1-1969) entitled "Impulse Noise Measurements" the author discussed the importance of having high crest factor capability in instruments for impulse noise measurements. It was also concluded that it seemed recommendable to check these instruments with tone bursts shorter than 5 msec. to ensure their proper performance. To demonstrate this some measurements have been made on the rise curve of the meter circuit in the Brüel & Kjær Impulse Precision Sound Level Meter Type 2204, see Fig. M.1.

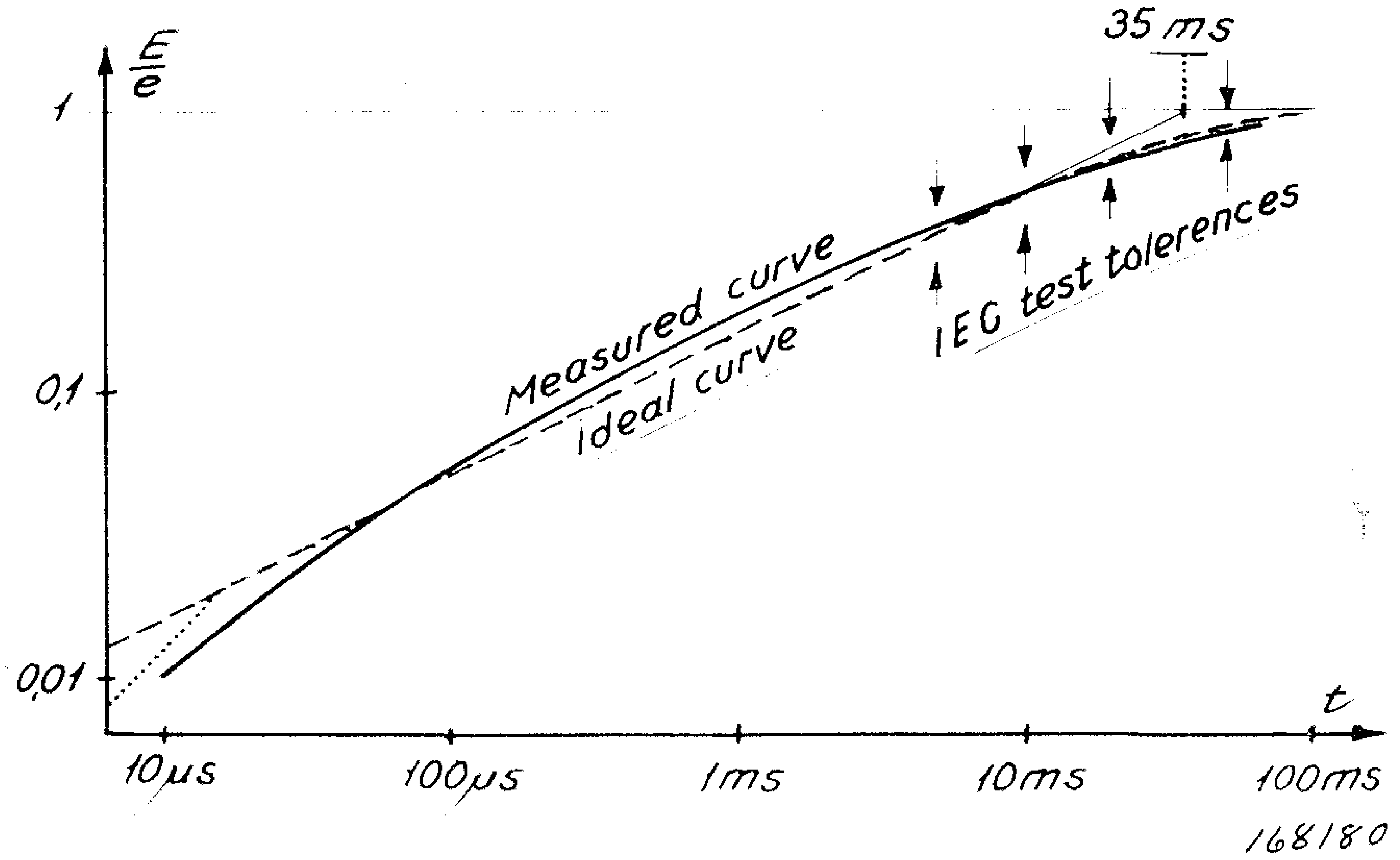


Fig. M.1.

It is seen that pulses down to 20–30 µsec. are evaluated reasonably near to the ideal. It should be mentioned, however, that the 2204 as a whole will not handle pulses down to 10 µsec. due to the limited frequency response of the microphone.

In Fig. M.1. are also shown the test tolerances for the rise curve. Only the upper part of the curve is thus specified, and it is probable that even a simple quasi RMS circuit can fit tolerances as well as the tolerances for repetitive pulses. This quasi RMS circuit will show much less than the ideal circuit for pulses shorter than 5 msec. for instance about 6 dB less at 1 msec (Note: the quasi RMS circuit will not fulfil the crest factor test specified by the German standard). *C. G. Wahrmann.*

Analysis of Speed Irregularities in Rotating Machinery

The introduction of low-frequency bandpass filters with center frequencies down to 2 Hz has made it possible to conveniently frequency analyze speed irregularities in rotating machinery (flutter). A suitable measuring arrangement is shown in Fig. 1 below. Here the speed of the machinery is measured by means of a specially designed tachometer, and the speed irregularities (frequency variations) are transformed into amplitude variations by utilizing the filter skirt of a B & K Type 2107 Frequency Analyzer. (If a flutter meter with AC output is available it may be an advantage to substitute Type 2107 by the flutter meter).

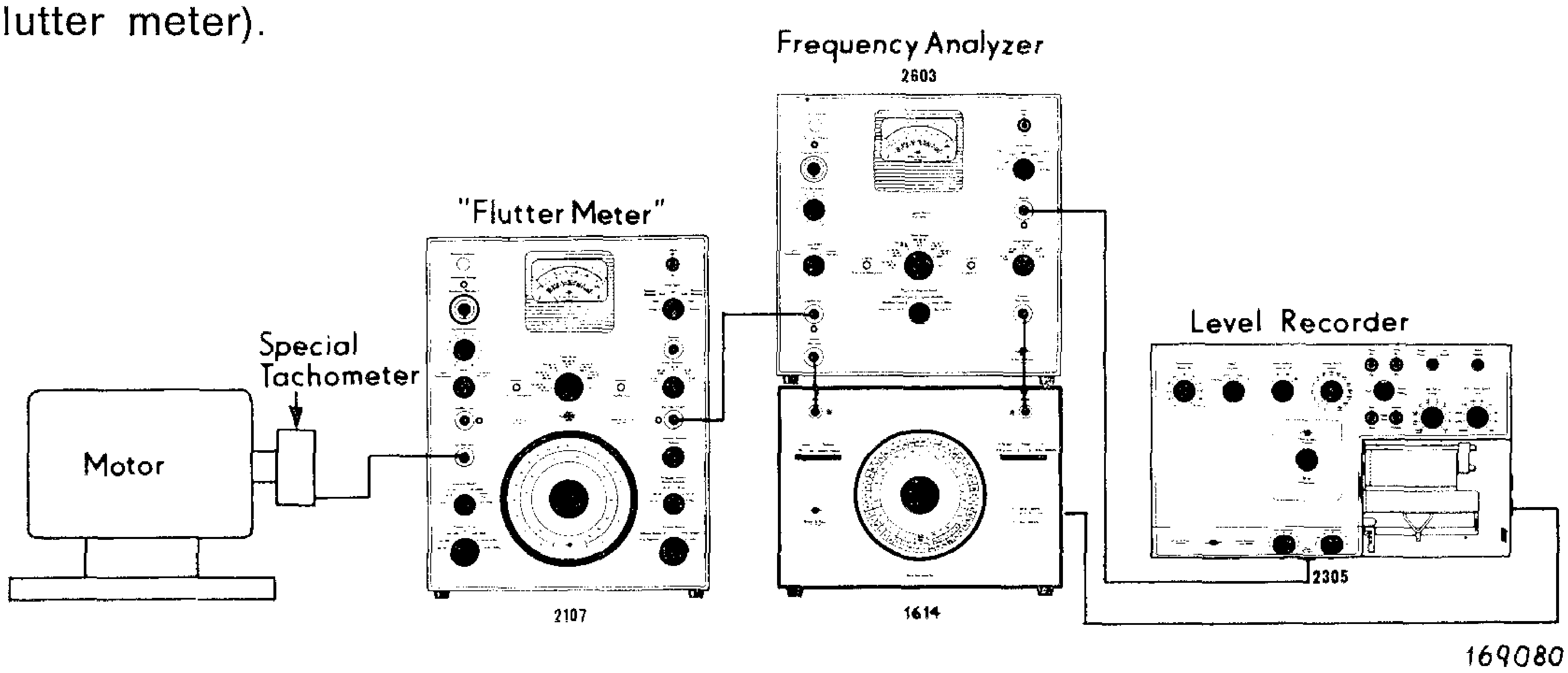
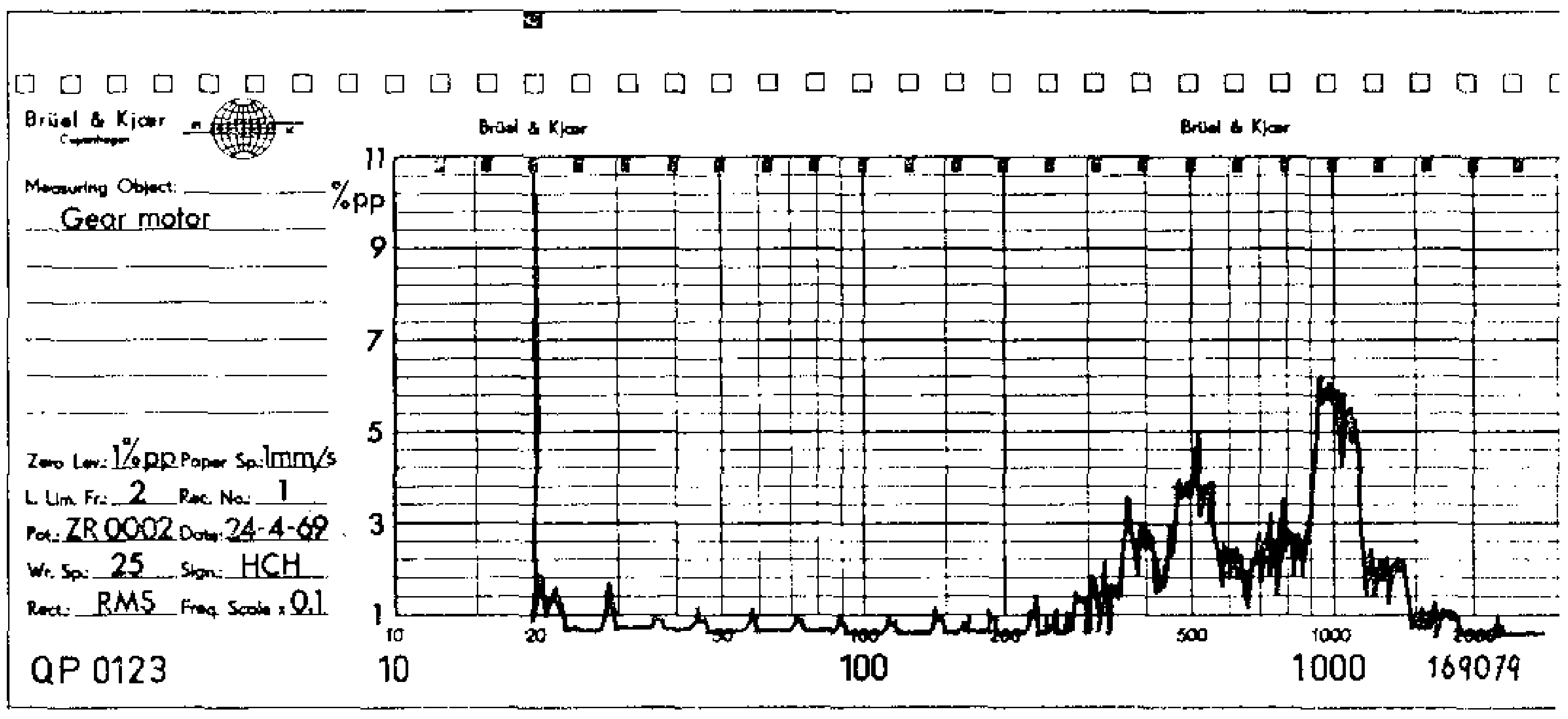


Fig. 1.

The tachometer consists of two cup-shaped toothed discs of a magnetic material facing each other. One of the discs is stationary while the other is driven by the rotating machinery. A coil and a permanent magnet is located in the center between the two discs. As the teeth along the circumference face alternately a tooth and a slot a variation in the magnetic flux results which again produces an output voltage from the coil. This voltage will vary in frequency when the speed of the rotating machinery varies, the frequency variations being transformed into amplitude variations as described above.


Brüel & Kjær Copenhagen

Measuring Object: Gear motor

Zero Lev.: 1%pp Paper Sp.: 1mm/s
L. Lim. Fr.: 2 Rec. No.: 1
Pot.: ZR 0002 Date: 24-4-69
Wr. Sp.: 25 Sign.: HCH
Rect.: RMS Freq. Scale x 0.1

QP 0123

Fig. 2.

The analysis itself is performed in terms of 1/3 octave frequency bands by means of a Filter Set Type 1614 and an Amplifier Type 2603. When a Level Recorder Type 2305 is added to the arrangement the resulting frequency spectrum can be recorded automatically on pre-printed recording paper, see Fig. 2.

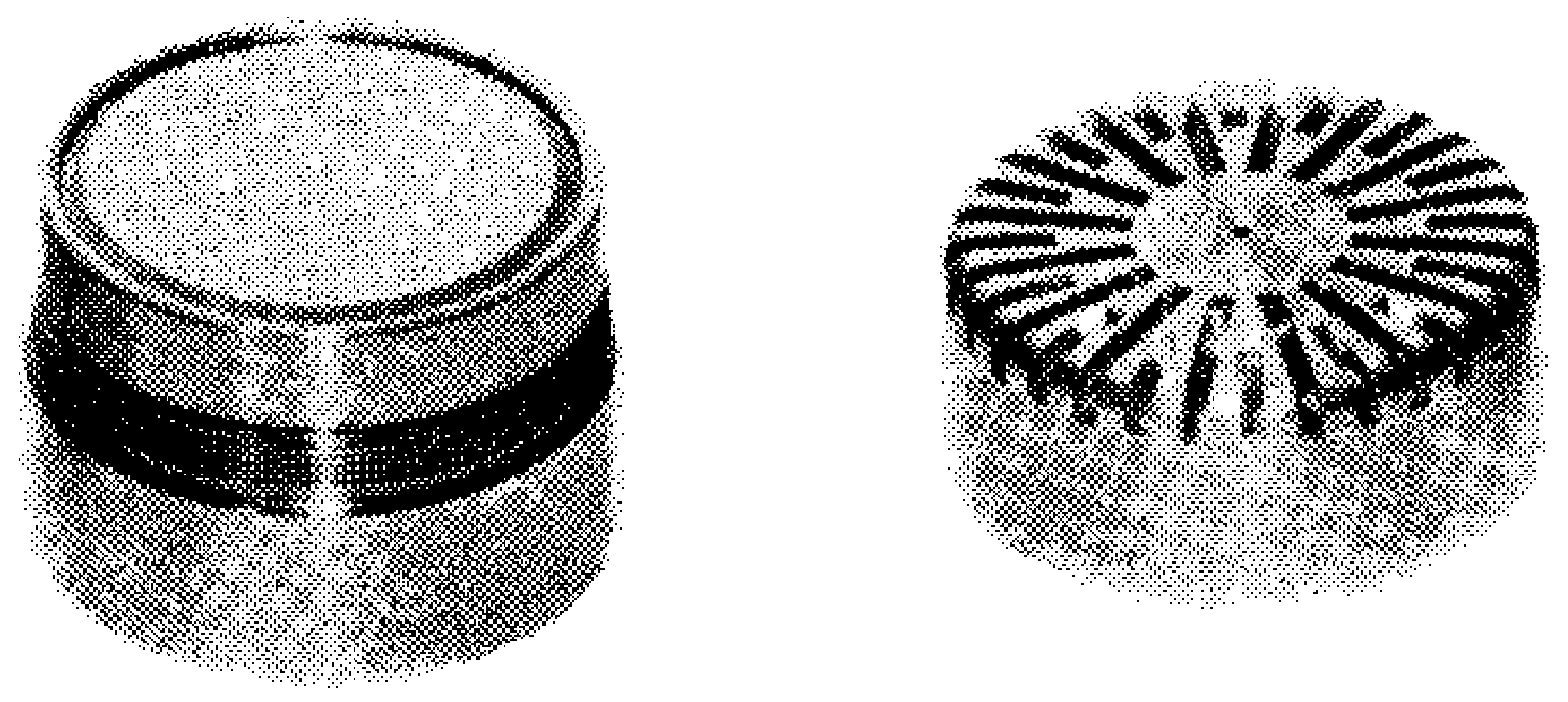
H. C. Hansen. *Magnus Christensen.*

News from the Factory

New 1 inch Condenser Microphones Type 4144/45

These two new 1″ condenser microphones are developments based on the previous 4131 and 4132 microphones which have come to be accepted throughout the world as measuring microphones and laboratory standards of the highest quality. The appearance and construction are basically similar to the earlier types but experience gained in over 10 years of manufacture has been gathered into significant design modifications and revised production technique. These have resulted in a *considerable improvement in long term stability, higher leakage resistance and closer tolerances in operating characteristics.*

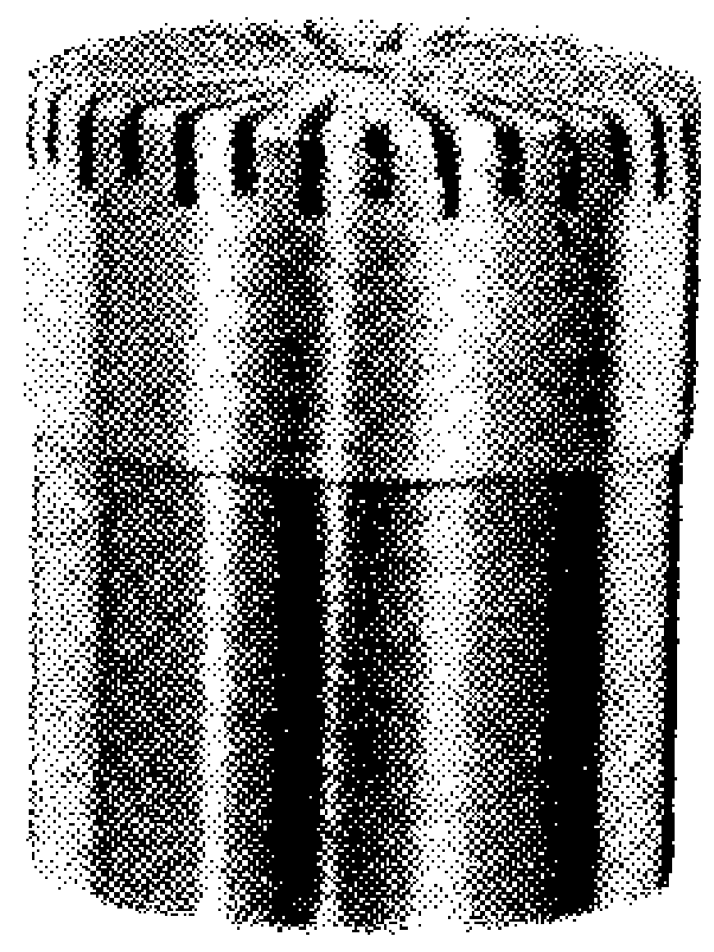
Type 4144 is intended for sound pressure *measurements in closed volumes* (couplers etc.) while *Type 4145* has a frequency response which is corrected for *free-field measurements,* so that it gives an output which represents the free-field sound pressure prior to the introduction of the microphone.



New 1/2 inch Condenser Microphone Type 4148

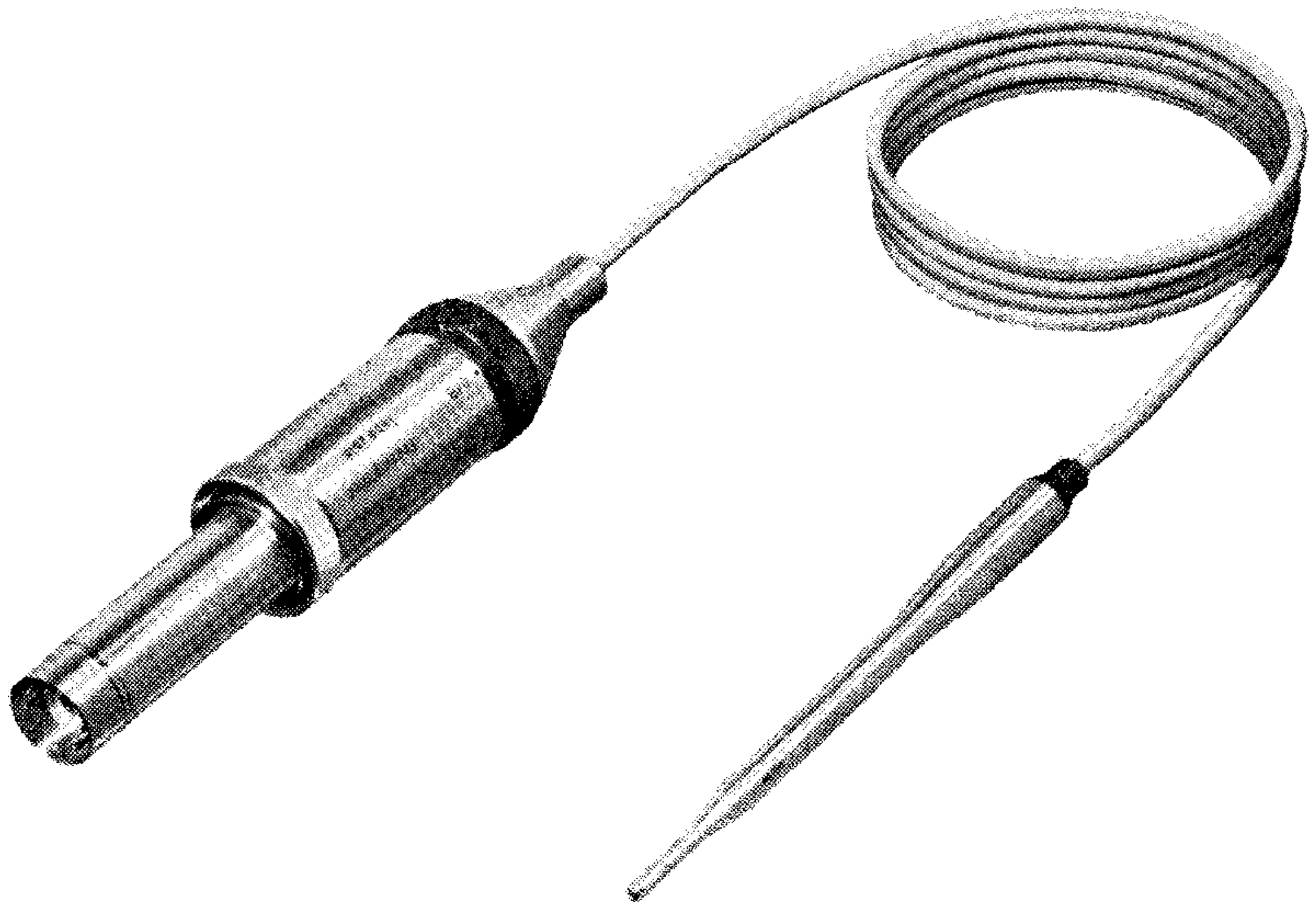
This further development of the well known B & K range of condenser microphones is designed for *operation from low voltage power supplies*. Sensitivity with the low polarization voltage (28 V) available from such supplies is maintained at high level, however, and is comparable with the sensitivity of similarly seized microphones with much higher polarization voltages.

An excellent precision battery driven microphone system is obtained in conjunction with the Type 2206 Precision Sound Level Meter or with the Type 2619 Microphone Preamplifier driven from a low voltage source. Sensitivity of the unit (1.4 mV/μbar) can be increased to 3.6 mV/μbar by increasing polarization voltage up to its maximum of 70 volts.



Quarter inch Preamplifier Type 2618 for Condenser Microphones

This preamplifier has been designed specifically for use with the B & K 1/4" or 1/8" condenser microphones.



The preamplifier has the same diameter as the B & K quarter inch microphone cartridges, with a screw thread for direct connection. An adaptor UA 0160 is available for use with 1/8" microphone cartridges.

Rugged construction and *small size* make the combined units (microphone + preamplifier) *ideal for high intensity, wide frequency range applications* in areas such as jet noise and boundary layer turbulence investigations. The preamplifier can be powered either directly from one of the B & K measuring amplifiers or analyzers, or from a B & K microphone power supply.

New 1/2 inch Microphone Preamplifier Type 2619

This microphone preamplifier is designed especially for use with the B & K condenser microphones, *featuring an extremely high input impedance and exceptionally low inherent noise level.* Allthough specifically designed to match the 1/2" microphone it may be used with all the B & K condenser microphones, ranging from 1" to 1/8" diameter.

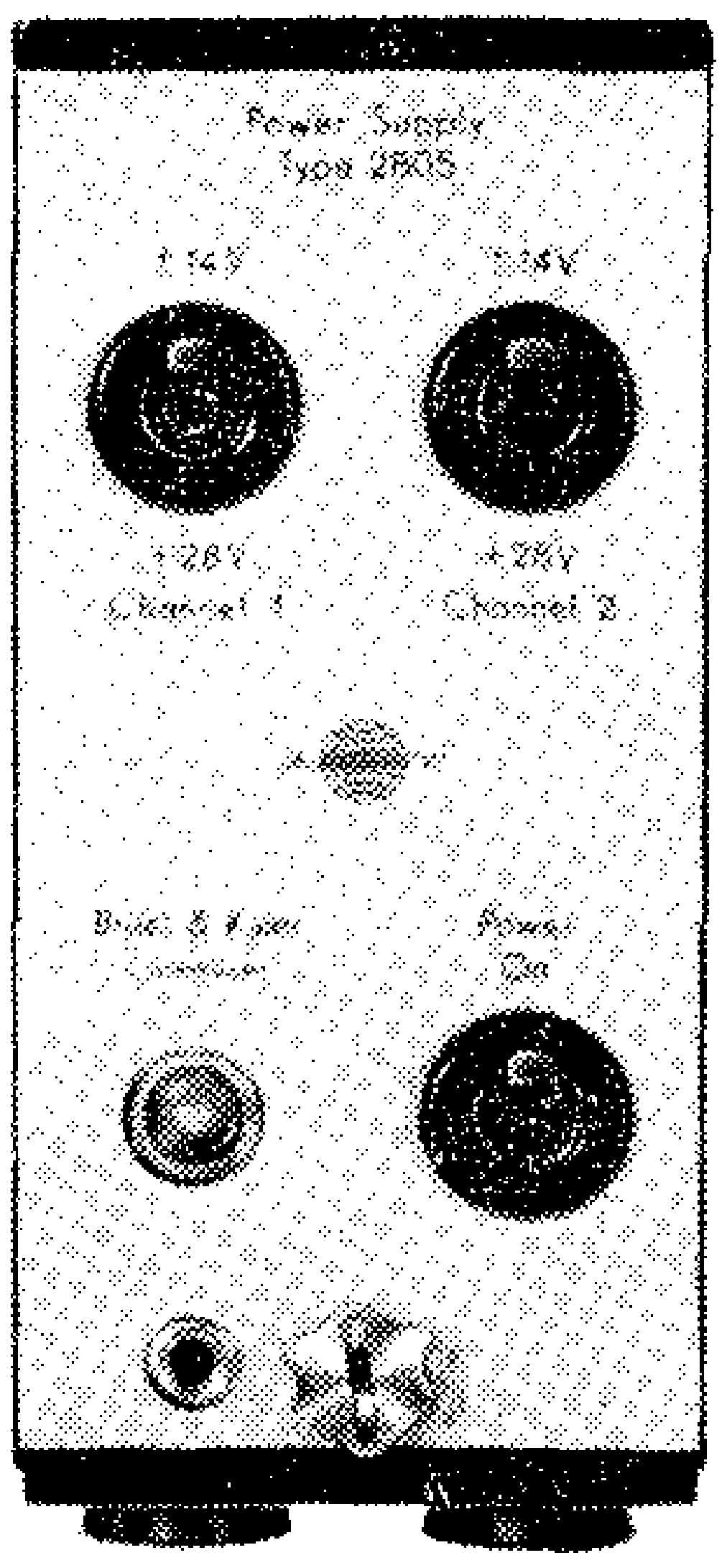
The preamplifier can be operated from 120 V DC supply such as the condenser microphone input of the B & K microphone amplifiers, or from a 28 V DC supply, with slightly different specifications.

A gooseneck UA 0196 is included to facilitate measurements in high temperatures (150°C) by taking the preamplifier away from the transducer, and for providing directional flexibility for the microphone.

Also included is an adaptor JJ 2615 for the connection of miniature cables, for example from an accelerometer. This adaptor contains a 50 pF capacitor for blocking the polarization voltage. With its wide frequency range and short rise and fall times, the preamplifier is ideal for measurements of transient signals and shocks.

DC Power Supply Module Type 2805

Designed for the B & K modular system, this unit is intended as a DC power supply for the types 2623 Accelerometer Preamplifier, 2624 Charge Amplifier and 2625 Vibration Pick-up Preamplifier. Operation is direct from the AC mains and the Power Supply is capable of supplying highly stable DC to up to 10 amplifier units.



Brüel & Kjær

ADR.: BRÜEL & KJÆR
NÆRUM - DENMARK

TELEPHONE: 800500
ϟ BRUKJA, Copenhagen

TELEX 5316

PRINTED IN DENMARK K. LARSEN & SØN – SØBORG