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Contents

Low Frequency Calibration of Acoustical Measurement Systems*

by

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ABSTRACT

The main parameters influencing the low frequency response of acoustical measurement systems in the infrasound range are outlined in this article. Depending on the measurement situation and the type of microphone used (side vented or back vented) different calibration methods are suggested. Advantages and drawbacks of the different methods are pointed out as well as precautions to be taken when carrying out measurements in this frequency range.

SOMMAIRE

Les principaux paramètres influençant la réponse basse fréquence des systèmes de mesures acoustiques dans la gamme des infrasons sont mis en valeur dans cet article. Suivant les conditions de mesure et le type de microphone utilisé (évent latéral ou arrière) différentes méthodes d'étalonnage sont suggérées. Les avantages et désavantages des différentes méthodes, ainsi que les précautions à prendre pour effectuer des mesures dans cette gamme de fréquence sont signalés.

ZUSAMMENFASSUNG

Die wesentlichen Parameter, die den Tieffrequenzgang von Schall-Meßsystemen im Infraschallbereich beeinflussen, sind in diesem Artikel beschrieben. Abhängig von der Meßsituation und des angewendeten Mikrofontyps (Druckausgleichsöffnung seitlich oder hinten) werden verschiedene Kalibriermethoden vorgeschlagen. Die Vor- und Nachteile der verschiedenen Methoden werden aufgeführt, ebenso die Vorsichtsmaßregeln, die bei der Durchführung von Messungen in diesem Frequenzbereich zu beachten sind.

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Introduction

Condenser microphones are used for practically all sound measurements today. Because of their operational principle and mechanical design they are generally considered to have a flat frequency response at lower frequencies, independent of the acoustical measuring conditions. This implies that the necessary calibration may be limited to a point calibration at one single frequency – 250 Hz is often used.

This consideration is, in practice, fully valid for modern measurement microphones down to 10 - 20 Hz; however, for measurements in the infrasound range, a number of parameters must be considered to influence the frequency response of the microphone and the subsequent instruments in the measuring chain. This fact increases the need for practical infrasound calibration methods.

Some parameters influencing the low frequency response

Compared with the slow variations in atmospheric pressure, the amplitude of the dynamic pressure to be measured is generally extremely small. Therefore, to avoid overload, the microphones must have a controlled vent which allows pressure equalization between the two sides of the diaphragm, i.e. between the internal cavity of the microphone and the space in front of the diaphragm. At low frequencies the vent causes a change in the microphone's sensitivity. The pressure equalization time constant should be chosen as a compromise between linearity of frequency response and ability to equalize.

The equalization time constant and the external region to which the equalization takes place are two of the dominant parameters determining the low frequency response. Before starting calibration for a specific measurement purpose, it is very important to know if the opening of the equalization vent is or is not facing the sound field in the measure-

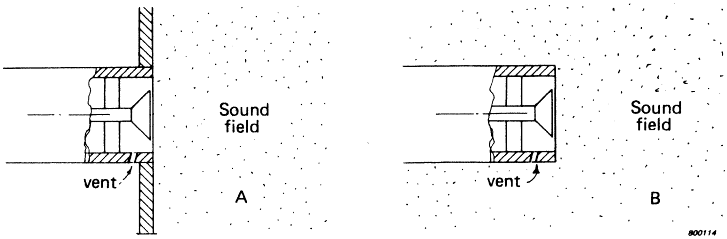

Fig. 1. Equalization vent outside (A) and inside (B) the sound field

ment situation. The frequency response of the same microphone is completely different for the two cases. Examples of the principle of the two different situations is shown in Fig.1 and the corresponding frequency responses in Fig.2 (A 1 and B 1). The calibration condition must correspond to the actual measurement situation.

For a specific transducer the lower limiting frequency may be altered by changing the resistance of the vent. By closing the vent channel and thus allowing leakage to occur only through stray leakage, a very low cut-off frequency is obtained; Fig.2 (A 2 and B 2) shows the two resulting responses.

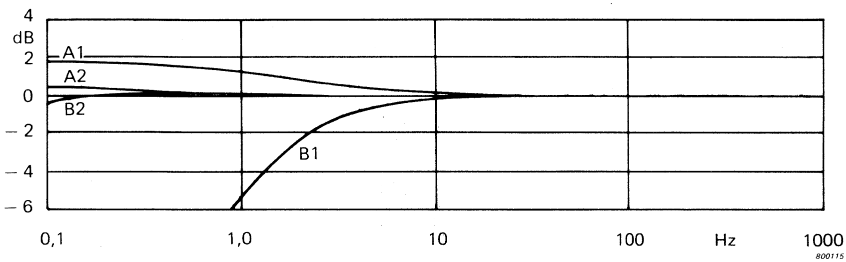

Fig. 2. Frequency responses of 1″ microphone. Vent outside (A 1 and A 2) and inside (B 1 and B 2) the sound field. Nominal vent resistance (A 1 and B 1). Partly sealed vent (A 2 and B 2)

The impedance of the cavity behind the diaphragm also influences the lower limiting frequency. The impedance varies proportionally to the ambient pressure; as most measuring microphones have relatively low air stiffness compared with the stiffness of the diaphragm, the lower

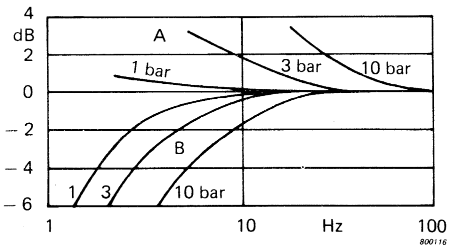

Fig. 3. Frequency response of a 1″ microphone at various ambient pressures. Vent outside (A) and inside (B) the sound field

limiting frequency varies proportionally to the ambient pressure variations. This fact is of less importance for measurements performed at ground level, but for special applications, such as sound measurements in spacecraft and aircraft as well as in diving tanks, the effect has to be taken into account. See examples of frequency responses, Fig.3.

A minor effect is due to the air compression process occurring in the internal cartridge cavity, which changes from adiabatic conditions at higher frequencies to isothermal conditions at lower frequencies. The change causes an increasing sensitivity at low frequencies which is most clearly observed with microphones having a relatively high proportion of air stiffness as well as a high equalization time constant, see Fig.4.

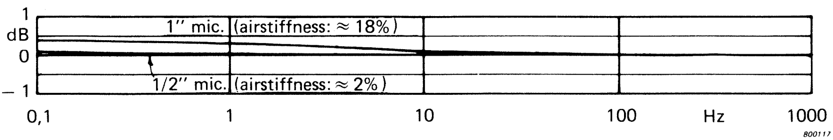

Fig. 4. Frequency responses of 1" and 1/2" microphones. The low frequency sensitivity increase is due to the change to an isothermal compression of the air in the internal cavity

A significant parameter is the combination of the microphone and the electronic system being connected. In the case of modern FET-preamplifiers having input impedances of 10 GΩ or more, very low cut-off frequencies are obtainable. If the transducer is shunted with a capacitor, even lower frequencies may be covered by the system, see curves in Fig.5. (In practice this is possible without limiting the lower part of the dynamic range, as sensitivity and noise are reduced equally. To obtain a flat response far below 1 Hz, a carrier frequency system must be used, see examples of frequency responses in Fig.5.

As can be seen, several parameters influence the low frequency (infrasound) response of a measuring system. For many applications, the specifications of the elements forming the measurement chain ensure the required measuring accuracy, but in cases where the environment differs significantly from normal conditions, and in cases where the system is going to be used to its very limits, a calibration which takes the actual measurement situation and the system into account is necessary.

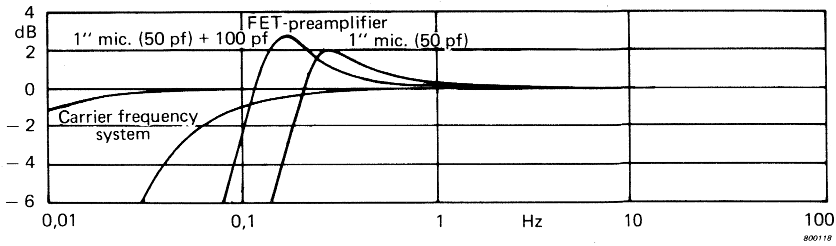

Fig. 5. Frequency responses of electronic systems valid for two different source impedances (FET - preamplifier Type 2627) and for two different settings of cut-off frequency (Carrier Frequency System Type 2631)

Calibration Methods

Different methods are available for calibration of infrasound measurement systems, some of which take only the response of the electrical system into account, while other methods allow calibration of the complete system, including the mechanical and acoustical parameters.

In some cases where well-defined acoustical transducers are used, the less complicated electrical calibration may be sufficient. Two methods, useable in connection with DC-polarized microphone systems and with Carrier Frequency Systems respectively, should be mentioned briefly.

Insert Voltage Calibration Technique

This method is used for determining the amplification of a preamplifier with a specific microphone cartridge as a source when Laboratory Standard Microphones are being calibrated. (It is described in ANSI and IEC-recommendations). Furthermore, the method is convenient for testing the frequency response of a system using the actual microphone impedance as source impedance. The principle is shown in Fig.6. The housing of the microphone cartridge, being the ground terminal of the source, is separated from the ground terminal of the preamplifier which allows series connection of an electrical source; the signal from that substitutes the open circuit signal delivered from the microphone when a sound pressure is present. The frequency responses of the FET - preamplifier shown in Fig.5 are obtained by use of this technique.

Additionally, the principle is practical for recording reference signals, for instance, on tapes during the actual measurement situation.

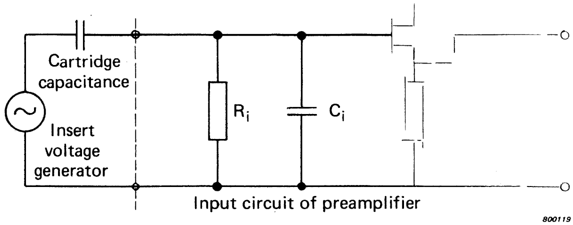

Fig. 6 Principle of Insert Voltage Calibration

Electrical calibration of Carrier Frequency Systems

Carrier systems do not respond directly to analog electrical signals. The signals have to be transformed to capacitance variations. Fig.7 shows a simple circuit which solves this problem. Variations in the DC - voltage across the so-called capacitance diode make its capacitance change. The series capacitance seen from the carrier system of the diode and the capacitors must correspond to the capacitance of the cartridge which is going to be used. The system shown can be used for frequency response calibration up to 100 Hz (determined by the RC time constant) but is not recommended for absolute calibration. See responses of a carrier system in Fig.5, they are obtained by use of this method.

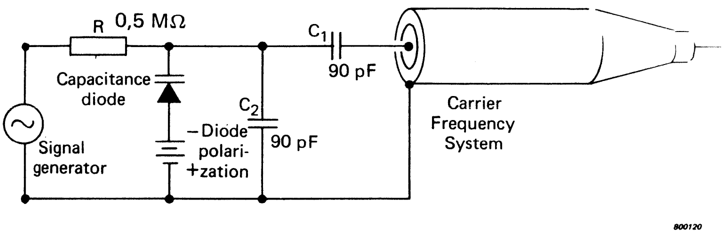

Fig. 7. Circuit producing capacitance variations for frequency response calibration of Carrier Frequency Systems

To calibrate the complete measurement system and thus to include the mechanical and acoustical parameters, other methods have to be used.

Electrostatic Actuator Calibration

Electrostatic actuators are practical tools for frequency response calibration in the case of microphones having a plane, accessible, metal surface diaphragm.

In principle, an actuator is a conducting plate placed in front of, and electrically isolated from, the diaphragm of the microphone in such a way that the actuator and the diaphragm form an electrical plate capacitor. If electrical voltage is applied to the actuator, the field in the gap will cause a force to act on the diaphragm. The force is independent of the frequency, which makes the system very practical for frequency response calibration. However, due to the edge effect of the plate capacitor (actuator), and problems in determining the plate distance precisely, the exact value of the force is difficult to determine. The method is of limited value for absolute calibration as accuracy is of the order of 1 - 2 dB. The equivalent sound pressure is given by:

$$p_e = \frac{\epsilon E^2(t)}{2 d^2}$$

ϵ = absolute dielectric constant for the gas in the plate gap ($\approx \epsilon_0 = 8{,}85 \cdot 10^{-12}$ F/m)

E(t) = actuator voltage as a function of time

d = effective distance

Proper choice of DC and AC voltage (800 V (DC) - 30 V (AC) - 0,5 mm distance) can give an equivalent sound pressure of approximately 1 Pascal.

It should be noted that no signal is applied to the vent, which reduces the number of application cases for the method, but in cases where the method can be used it offers great advantages, especially for the analysis of microphone behaviour in extreme environments, as the signal generated is practically independent of the ambient conditions. The actuator can be used for calibration in cases where the vent is outside the sound field (Fig.1 A) and thus the corresponding curves in Fig.2, 3 and 4 can be obtained that way.

Pistonphones as low frequency calibrators

As has earlier been described in B & K literature, the usual pistonphone type of calibrators suffer from several drawbacks when used for infrasound applications, and unless a complicated mechanical design is undertaken the use is limited to some single frequencies and high sound pressure levels. Furthermore, the piston(s) act as a Constant Volume Displacement Source, which means that the sound pressure generated is proportional to the impedance of the cavity. This impedance is a function of the volume (and thus of the microphone connected), the ambient pressure, leakage, the gas being compressed, and of the compression process, which in the infrasound range changes from adiabatic conditions to isothermal conditions, causing a change in the SPL, depending on the gas, of 2 – 4 dB.

Thus, the pistonphone is generally not practical for low frequency calibration, therefore other types of acoustical calibrators have been developed.

Constant Pressure Acoustic Calibrator

A Constant Pressure Calibrator is, ideally, an acoustical source producing a sound pressure which is independent of the loading microphone and the environmental conditions. (It is the acoustical equivalent of an electrical constant voltage source which maintains the voltage independent of the current flowing). In practice, such an ideal system can only be realized to a certain degree. The system should have a very

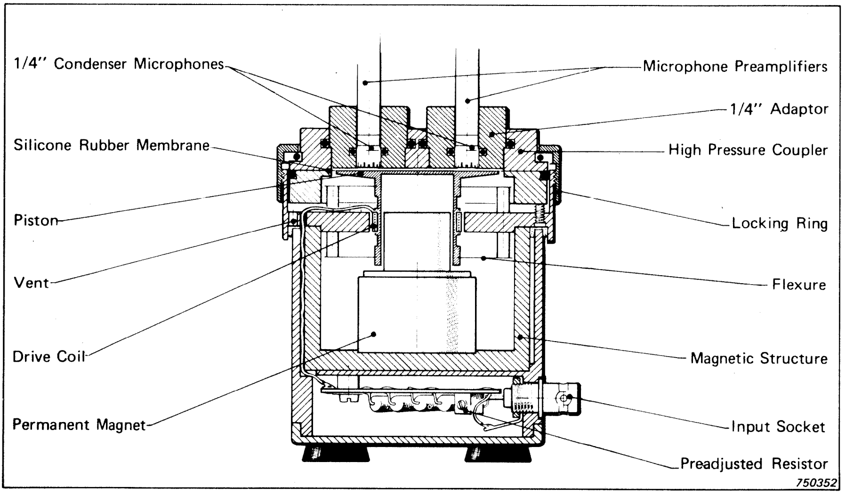

Fig. 8. Cross Sectional View of Constant Pressure Calibrator

low acoustical impedance compared with any actual loading impedances.

A physical realization of a Constant Pressure Calibrator* is shown in Fig.8. Basically, the source is an electrodynamic system coupled to a light weight, large area piston which is mounted with soft springs to obtain the required low acoustical impedance. The desired high load impedance is obtained by minimizing the volume of the couplers used for adapting the microphones being calibrated.

The corresponding electrical and acoustical circuit diagram of the system is shown in Fig.9.

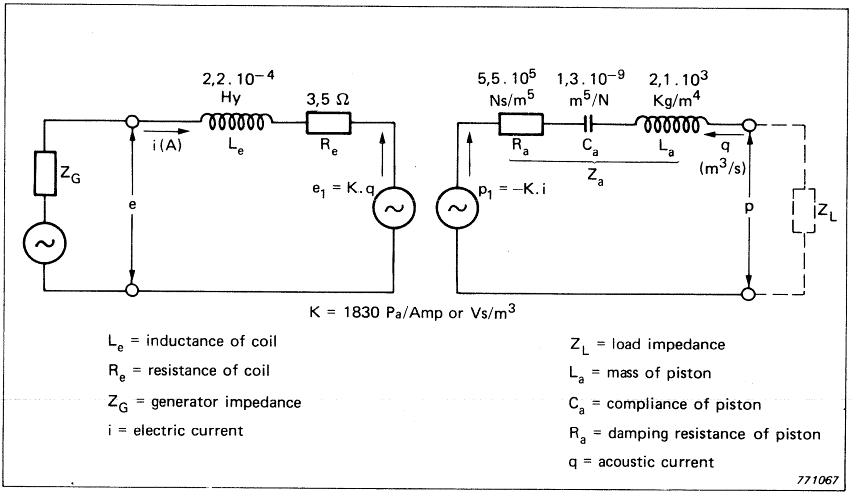

Fig. 9. Electrical and acoustical circuit diagram of Constant Pressure Calibrator

In principle, such a system may operate down to 0 Hz, but in practice is limited by leakage in the couplers. The system shown has a cut-off frequency (–3 dB) of less than 1 mHz at 1 bar. The upper limiting frequency is determined by the mass of the moving system, which at higher frequencies increases the acoustical source impedance. The upper 3 dB limit is at 500 Hz. Two couplers have been designed; one of which applies the sound pressure to the diaphragm only (Fig.1 A), while the other one surrounds the whole microphone with the sound pressure

* The system shown is the High Pressure Microphone Calibrator Type 4221.

(Fig.1 B). Using these couplers, the frequency response is flat within ± 2% from 5 mHz to 100 Hz. Generally most low frequency calibrations of condenser microphones and other pressure transducers can be performed using such a system. Figs.2, 3 and 4 illustrate some types of measurement which may be carried out using the Constant Pressure Calibrator described.

A calibrator of this type takes all the parameters of a measuring chain into account, and as it also allows absolute calibration it is a practical tool for many calibration purposes.

Conclusion

Calibration of microphones or measuring systems for use below 20 Hz is often necessary as many parameters may influence the frequency response.

No single method can solve all low frequency calibration problems occurring in the laboratory and in the field. The methods here and other methods* may be used as complements to extend the calibration range and to increase the reliability of the results obtained.

Although all the methods of calibration mentioned here may be used in the laboratory, the Insert Voltage Calibration Technique and the Constant Pressure Calibrator are the most practical methods for field use.

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* A method used by Brüel & Kjær for calibration of microphone type 4147 having a very high equalization time constant is described in the B & K Microphone Handbook.

APPENDIX

The low frequency response of a condenser microphone cartridge is determined by three parameters, the compliance of the diaphragm, the compliance of the air filled internal cavity and the acoustical resistance of the equalization vent. In addition it depends on the use of the microphone, whether the equalization vent is in or outside the sound field (see Fig.1 of the article).*

The frequency response for the two different conditions of use is determined by the pressure difference occurring between the two sides of the diaphragm, and is in principle given by

$$p = p_o \frac{C_2}{C_1 + C_2} \frac{1 + \dfrac{C_1 + C_2}{C_2} \dfrac{1}{j\omega R\,(C_1 + C_2)}}{1 + \dfrac{1}{j\omega R\,(C_1 + C_2)}} \qquad \text{(A)}$$

for vent outside the sound field and

$$p = p_o \frac{C_2}{C_1 + C_2} \frac{1}{1 + \dfrac{1}{j\omega R\,(C_1 + C_2)}} \qquad \text{(B)}$$

for vent inside the sound field,

where C_1 = diaphragm compliance (inverse stiffness)
C_2 = air cavity compliance (inverse stiffness)
R = resistance of equalization vent
p_o = pressure in the sound field.
ω = angular frequency

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* It should be noted that the vent opening can be in the sound field also for back vented microphones, as the preamplifiers used have sufficient leakage to transfer the sound pressure to the backside of the cartridge at the low cut-off frequencies normally used.

The formulae can be used only for an approximate evaluation of the response, as they do not take into account that the air compression process in the cavity may change from being mainly adiabatic to being isothermal at the lowest frequencies.

The above formulae can be rewritten as formulae (C) and (D) respectively in terms of specified parameters summarized in the table.

$$p = p_o K \frac{1 + \frac{1}{K}\frac{f_o^2}{f^2} - j\left(\frac{1}{K} - 1\right)\frac{f_o}{f}}{1 + \frac{f_o^2}{f^2}} \qquad \text{(C)}$$

$$p = p_o K \frac{1 + j\frac{f_o}{f}}{1 + \frac{f_o^2}{f^2}} \qquad \text{(D)}$$

where $K = \frac{C_2}{C_1 + C_2} = \frac{\frac{1}{C_1}}{\frac{1}{C_1} + \frac{1}{C_2}}$ = the ratio of the diaphragm stiffness to total stiffness (see Table).

f_o = lower limiting frequency (–3 dB) (see Table).
f = actual frequency.

Mic. Type No.	Frequency limits for f_o (– 3 dB)* Hz	Corresponding time constant limits s	Equalization vent position side/back	Stiffness Ratio K
4144	1 – 2	0,16 – 0,080	side	0,81
4145	1 – 2	0,16 – 0,080	side	0,83
4160	1 – 2	0,16 – 0,080	back	0,81
4155	1 – 3	0,16 – 0,053	back	0,88
4165	1 – 2	0,16 – 0,080	back	0,88
4166	1 – 2	0,16 – 0,080	back	0,88
4133	1 – 3	0,16 – 0,053	side	0,93
4134	1 – 3	0,16 – 0,053	side	0,93
4147	0,001 – 0,005	160 – 32	back	0,97
4148	1 – 3	0,16 – 0,053	back	0,83
4149	1 – 3	0,16 – 0,053	back	0,93
4135	0,3 – 3	0,53 – 0,053	side	0,93
4136	0,3 – 3	0,53 – 0,053	side	0,97
4138	0,05 – 5	3,20 – 0,032	side	0,88
4125	0,5 – 5	0,32 – 0,032	back	0,71
4175	0,5 – 5	0,32 – 0,032	back	0,71
4129	0,5 – 5	0,32 – 0,032	back	0,77
4130	0,5 – 5	0,32 – 0,032	back	0,77
4176	0,5 – 5	0,32 – 0,032	back	0,77

* Opening of equalization vent in sound field.

The values in the table are valid for air for ambient pressure of 1 bar.

Calibration and Standards
Vibration and Shock Measurements*

by

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and
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ABSTRACT

This article shows how a hierarchy of standard accelerometers is established, such that working transducers can be traced back to primary standards and fundamental units. A survey of absolute and comparison methods of calibration of accelerometers for vibration and shock measurements is presented and the accuracies achievable by these methods are given.

SOMMAIRE

Cet article montre comment est établie une hiérarchie avec des accéléromètres étalons, de façon à pouvoir remonter des accéléromètres en usage aux étalons et aux unités fondamentales. Les méthodes d'étalonnage absolues et par comparaison des accéléromètres pour mesures de chocs et de vibration, ainsi que la précision que l'on peut en obtenir y sont passées en revue.

ZUSAMMENFASSUNG

Dieser Artikel beschreibt, wie eine Rangordnung von Beschleunigungsaufnehmernormalen errichtet ist, so daß eingesetzte Beschleunigungsaufnehmer wieder auf ihre ursprünglichen technischen Daten zurückgeführt werden können. Ein Überblick über Absolut- und Vergleichsmethoden zur Kalibrierung von Beschleunigungsaufnehmern für Schwingungs- und Stoßmessungen wird gegeben.

* First published in Measurement and Control, Journal of the Institute of Measurement and Control, 20 Peel Street, London, W.8.

Introduction
Mechanical vibrations and shock are dynamic phenomena, – i.e. their intensity varies with time. Since the intensity of vibration can be determined in terms of displacement, velocity or acceleration, the fundamental units that have to be measured are basically length and time. The definitions of displacement, velocity and acceleration are given in ISO 2041 [1] and for linear harmonic motion, these quantities are related by the formulae:

$$x = X_{peak} \sin\left(2\pi \frac{t}{T}\right) = X_{peak} \sin(2\pi f t) = X_{peak} \sin(\omega t) \qquad (1)$$

$$v = \frac{dx}{dt} = \omega X_{peak} \cos(\omega t) = V_{peak} \cos(\omega t)$$

$$= V_{peak} \sin(\omega t + \pi/2) \qquad (2)$$

$$a = \frac{dv}{dt} = \frac{d^2x}{dt^2} = -\omega^2 X_{peak} \sin(\omega t) = -A_{peak} \sin(\omega t)$$

$$= A_{peak} \sin(\omega t + \pi) \qquad (3)$$

where

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

$X_{peak} =$ Maximum displacement from the reference position

$t =$ time

As the intensity of vibration and the rate of change of intensity vary over a wide measurement range, the transducers that have been developed for vibration and shock measurements have their electrical output proportional either to displacement, velocity or acceleration. The parameter of interest is then subsequently obtained using differentiating or integrating circuits. From the formulae it can be seen that as displacements are relatively large at low frequencies, displacement and velocity transducers would be more suitable for low frequency measurements, while accelerometers would be preferable for high frequencies. However, due to the inherent difficulties in the construction, calibration and mounting of displacement and velocity transducers, accelerometers are far more widely used, even at low frequencies.

Accelerometers are generally calibrated either in terms of their voltage sensitivity (volts/ms^{-2}) or charge sensitivity (pC/ms^{-2}). Thus using a common vibration source and a "standard" accelerometer, calibration can be conveniently carried out through direct comparison of associated preamplifier voltage outputs.

Traceability of Standard Transducers

To avoid the necessity of carrying out absolute calibrations of each individual accelerometer, a hierarchy of standard accelerometers is established.

Table 1 shows how the calibration of vibration transducers can be traced back to fundamental units via Working Reference, Transfer and Primary Standard Transducers.

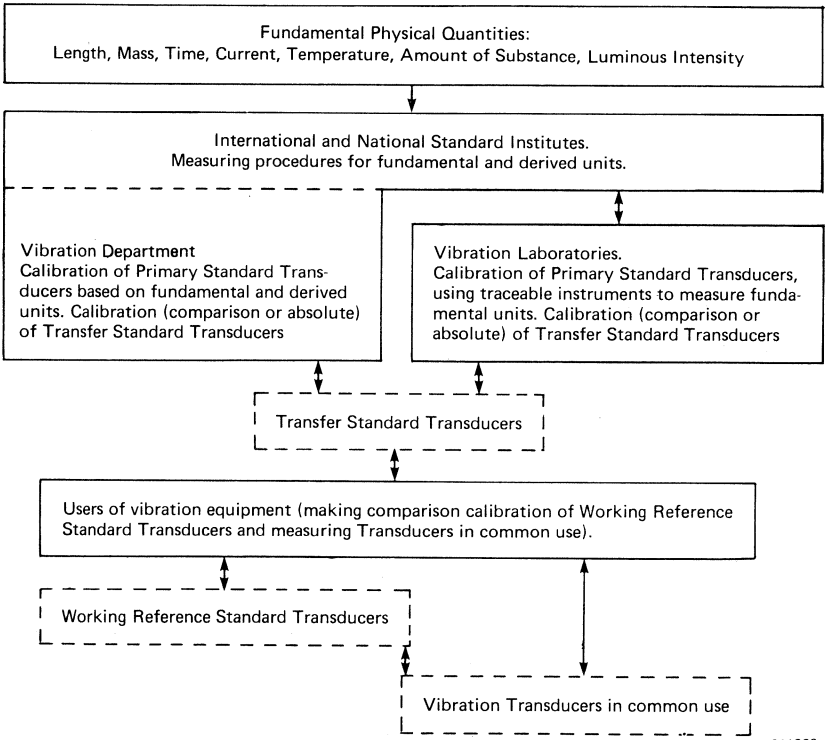

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Table 1

The Primary Standard Transducers are calibrated by absolute methods and kept at the laboratories where the calibration is carried out.

Calibration methods for Standard Transducers

Due to the high stability, wide frequency range and large dynamic range, the majority of standard transducers are of the piezoelectric accelerometer type. Most other vibration transducers without DC-response are calibrated by comparison to these standards, while relative displacement transducers are calibrated by normal length measuring systems. In the following, absolute and comparison methods of calibration are described and in Table 2 the estimated ranges and accuracies achievable are given.

Absolute Methods				
Method / Parameter	Laser Interferometer	Earth's Gravitation	Shock (Ballistic Pendulum or Steel Ball Drop)	Reciprocity
Input	Sinusoidal Vibration	Constant Acceleration	Transient Acceleration	Sinusoidal Vibration
Amplitude Range	10–1000 m/s^2 (freq. dependent)	$-g_L$ to $+g_L$ (−10 to +10 m/s^2)	50–10^5 m/s^2	up to 100 m/s^2 (25Hz–10kHz)
Frequency Range (Pulse duration)	20–5000Hz (1,5Hz–16kHz with special exciters)	0 Hz	0,1–40 ms	5Hz–10kHz
Estimated Error (Standard deviation)	±0,5% (20Hz–5kHz) ±1% (10Hz–10kHz)	± 0,05%	±3%	±0,5% at 100Hz ±1% (5–1000Hz) ±2% (1–10kHz)

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Comparison Methods using Primary Standard Accelerometers		
Excitation / Parameter	Electrodynamic Exciter	Shock Machine
Input	Sinusoidal vibration	Transient Acceleration
Amplitude Range	10–1000 m/s^2	50–10^5 m/s^2
Frequency Range (Pulse duration)	20Hz–5kHz (5Hz–10kHz with special precautions)	0,1–40 ms
Estimated Error (Standard deviation)	Accelerometers: 0,1–1kHz ±1% 10Hz–10kHz ±2% Displacem. and vel. pickups: 20–1000Hz ±4%	±5%

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Table 2

Absolute Methods

Laser Interferometer

The method most widely used today to calibrate standard transducers is the laser interferometric method. Set-ups similar to the one shown in Fig.1 are used. In the frequency range 20 – 500 Hz the so-called fringe counting method is used to determine the peak amplitude by the formula $X_{peak} = \lambda/8 \times R_f$ where R_f is the number of fringes counted per vibration period.

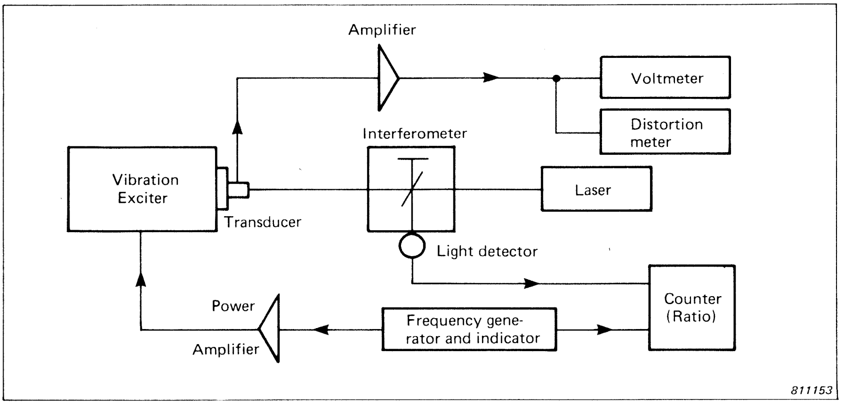

Fig. 1. Laser Interferometer Calibration system (fringe counting method)

The accuracy to which the amplitude of vibration can be determined by this method is 0,02%. However, the main errors are caused by tilting (0,2%), transverse vibration (0,25%), voltage measurements (0,2%) and distortion (0,2%). The total error is given by

$$\sqrt{(0,2)^2 + (0,25)^2 + (0,2)^2 + (0,2)^2} + \text{(minor errors)} \approx 0,5\%$$

as shown in Table 2.

At higher frequencies other methods are used. They are all based on the properties of the Bessel functions describing the light intensity [2, 7, 10].

Reciprocity Calibration

Reciprocity Calibration was used extensively before the advent of the laser. Since the method is time consuming and requires very careful measurements it is now rarely used. However, details of the method can be found in Ref. [2, 7, 10].

Earth's Gravitation Calibration

Earth's Gravitation Calibration [2, 7] is used to calibrate transducers having DC-response such as servo-accelerometers, inertial guidance systems and strain gauge accelerometers. Since the acceleration due to gravity g_L can be determined with a high degree of accuracy all over the world, an accurate and easy calibration can be performed by tilting the sensitive axis of the transducer 180° from the vertical, giving an output corresponding to $2 \times g_L$.

Shock Calibration

To test the linearity of the accelerometer different impulsive methods are normally used, since sinusoidal vibration without significant distortion is difficult to generate at levels higher than 1000 m/s^{-2} [2, 7].

The classic calibration method is shown in Fig.2. The accelerometer under calibration is mounted on a freely suspended anvil, which is subjected to an impact from a hammer. By measuring the resulting change in velocity, and integrating the acceleration record, the sensitivity of the accelerometer can be determined. The pulse length of the acceleration record should, however, be greater than $10/f_0$ where f_0 is the lowest resonant frequency of the system.

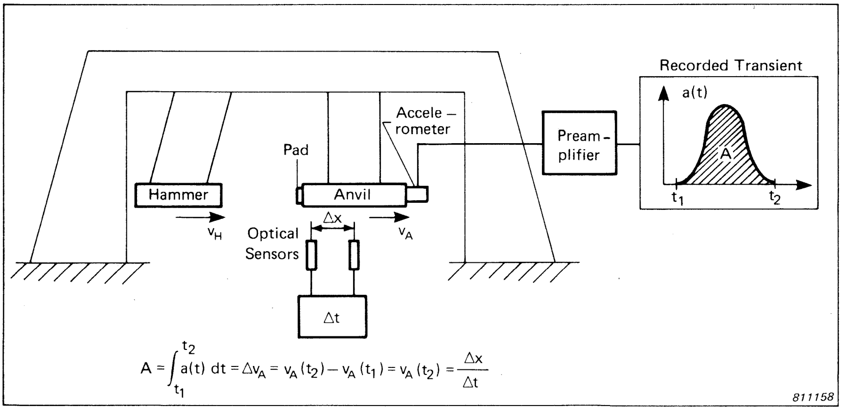

Fig.2. Shock Calibration system

Other methods and more details can be found in ref. [2], and its addendae (under preparation) or in ref. [3, 7].

Comparison Calibration Methods
Standard Transducers can be used to calibrate other transducers by comparison.

Vibration Calibration
Transducers used to calibrate other transducers are often accelerometers provided with a mounting surface for the transducers to be calibrated such as shown in Fig.3. If such a surface is not accessible, it must be guaranteed that the two transducers are subjected to the same motion within the frequency range used.

Fig.3. Standard Transducer and associated preamplifier

A set-up such as shown in Fig.4 can be used. The exciter must have a stable non-distorted output and a low transverse, bending and rocking motion at the frequencies of calibration.

The voltage ratio determined gives the sensitivity of the unknown transducer by simple multiplication if the two transducers respond to the same vibration parameter. If they respond to different parameters formulae (1), (2), (3) have to be used. As shown in the figure, the transducer-preamplifier combination is often considered an integral unit.

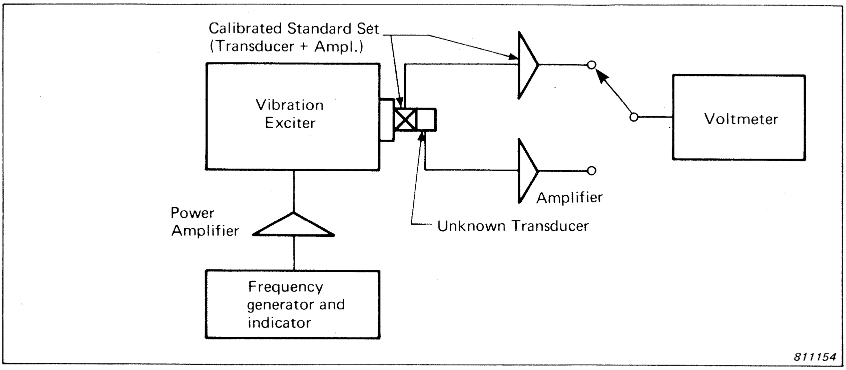

Fig.4. Comparison Calibration Set-up

Shock Calibration

In this method the transducer to be calibrated is mounted together with a reference standard accelerometer on the anvil of the shock machine shown in Fig.2. Records of the shock signals from the two transducers are captured on a transient recorder and compared.

Recalibration of Standard Transducers

It is recommended that standard transducers are checked every 12 months to ensure that their calibration is still valid.

The check can be performed by different certified laboratories. In the UK the only organisation with full UK certified approval is A.Q.D. Laboratories. Other important laboratories are NBS, PTB and CESTA.*

AQD:
Aeronautical Quality Assurance Directorate Laboratories; Harefield; Middlesex; U.K.

NBS:
National Bureau of Standards; Washington DC 20234; USA

PTB:
Physikalisch-Technische Bundesanstalt; Bundesallee 100; 33 Braunschweig; West Germany

CESTA:
Centre d'Études Scientifiques et Techniques d'Aquitaine; BP 2 Le Barp; 33830 Belin-Beliet; France

A number of UK companies and laboratories are able to make less demanding comparison calibrations, while a few offer absolute calibration.

Calibration in practice

A typical problem encountered in all measuring situations in practice, is the calibration of the whole measuring chain such as

Transducer – Preamplifier – Amplifier Analyzer – Recorder

Several methods can be used to achieve accurate results.

1. *Independent calibration*
   This is generally used to ensure a basic level of accuracy. All instruments are checked at fixed time intervals. The transducers are normally checked by comparison to a Working Reference Standard at one or more frequencies of vibration.

2. *Removal of working instruments to a test facility*
   This method is often used if distances and portability are not a problem. Here the measurement chain as a whole is calibrated and this provides the best possible calibration. The test will often be the same as performed when the equipment was originally installed.

3. *Test in-situ by bringing an accurate vibration source*
   In this method vibration generators with internal or external reference transducers are often used. They provide normally only a one level one frequency calibration with limited accuracy (2 – 5%), but they have the advantage that the whole measuring chain is calibrated together and in-situ.

Choice of best methods in practice

On account of the inherent differences between different measurement situations and test laboratories, the choice of method would depend on the individual requirements. For example for an organisation that has several transducers used mainly for vibration measurements, a typical method would be as described below.

Equipment Required

Traceable Working Reference Standard accelerometer, vibration exciter and associated electronics. Level and frequencies preferably covering expected measurement range.

One (or two) accurate measuring chain(s) as discussed above.

Electronic test laboratory to perform AC-voltage calibrations and frequency calibrations.

Portable vibration source (e.g. giving 10 m/s^2 at 80 or 160 Hz).

Procedure

1. The working reference transducer should be recalibrated at intervals of less than one year, and additionally after use at high levels or in extreme environments.

2. The transducers and electronics should be individually calibrated every year or before each measurement situation. An accurate calibration at one frequency together with a frequency response curve is often sufficient.

3. If the accuracy required is higher than can be expected from the combination of instruments, the chain should be calibrated as a unit before use.

4. A check/calibration is made in-situ by means of the portable vibration source.

Problems and pitfalls to be avoided

1. The transducer must be properly mounted to the structure to ensure a good frequency response (see ISO DP 5348, ref. 4). If voltage preamplifiers are made use of, the same cable that is used during calibration must also be used during measurements.

2. The cable between the transducer and the preamplifier must be fixed to the vibrating structure as close as possible to the transducer, and guided to a spot with minimum vibration before it leaves the structure to avoid generation of signals inside the cable.

3. Ground-loops must be avoided.

4. Errors encountered in practice are often due to erroneous manual settings on electronic instrumentation. Newer electronic systems with automatic or computer-controlled settings help to reduce such errors.

Accuracy
The accuracy which can be expected from the combination of transducer preamplifier and indicating instrument would be in the order of ± 5 – 10% in the mid-frequency range.

If the system is calibrated as a unit before the measurement an accuracy of about ± 3 – 5% can be obtained.

If the signals to be measured are within a limited range of levels and frequencies, a calibration of the system in the proper ranges can be made and corrections used to achieve accuracies in the range ± 2 – 3%.

Long and short term stability
Modern transducers and solid state electronics have short term stabilities that have negligible influence on the accuracies mentioned above. Since long term stability could be in the order of a percent per time decade or year, recalibration every year is recommended.

Recalibration cost
The price of a calibration of a reference standard accelerometer in the frequency range 20 Hz – 5 kHz would be approximately 30% of the cost of the accelerometer.

References
[1] ISO 2041 – 1975: Vibration and shock vocabulary.

[2] ISO/DIS 5347: Methods for the calibration of vibration and shock pickups.

[3] ASA S 2.2-1959: American Standard Methods for the Calibration of Shock and Vibration Pickups.

[4] ISO/DP 5348: Mechanical Mounting of Accelerometers (Seismic Pickups).

[5] ISO/DP 4865: Methods for analysis and presentation of vibration and shock data.

[6] ANSI S2.11-1969: American National Standard for the Selection of Calibrations and Tests for Electrical Transducers used for Measuring Shock and Vibration.

[7] HARRIS, C. M. & CREDE, C. E.: Shock and Vibration Handbook, McGraw-Hill 1976.

[8] Mechanical Vibration and Shock Measurements. Brüel & Kjær.

[9] Accelerometer Calibration. Brüel & Kjær.

[10] Brüel & Kjær Technical Review No. 1-1971.

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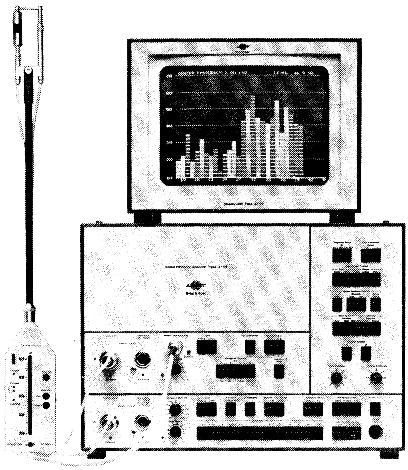
News from the Factory

Sound Intensity Analysing System Type 3360



The Sound Intensity Analysing System Type 3360 opens new horizons for acoustical measurements. In many applications there is a distinct advantage in measuring the vector quantity sound intensity rather than the scalar quantity sound pressure. For example, the sound power of a source (stationary or moving) can be determined by integrating the sound intensity vector over a surface enclosing the source. There is no need for a special anechoic chamber. Even high levels of background noise do not unduly affect the results because noise sources outside the enclosing surface do not contribute to the integrated sound intensity (Gauss' Theorem). Other uses include the location and identification of sources, mode studies, noise control, tracing of energy flow lines, for example, inside vehicles and the investigation of absorption as a function of the angle of incidence.

The 3360 is based on a two microphone technique. A finite difference approximation is used for the pressure gradient measurement, and hence for the calculation of particle velocity. The time averaged product of particle velocity and pressure gives the sound intensity.

The 3360 consists of the Sound Intensity Analyzer Type 2134, the Display Unit Type 4715 and the Sound Intensity Probe Type 3519. The 3360 can measure the vector quantity sound intensity level in real time in the 36 third-octave bands with centre frequencies from 3,2 Hz to 10 kHz and in the 12 octave bands with centre frequencies from 4 Hz to 8 kHz. The results are displayed on the separate, calibrated Display Unit Type 4715 where not only the sound intensity level can be measured but also the direction of the incident sound intensity can be inferred.

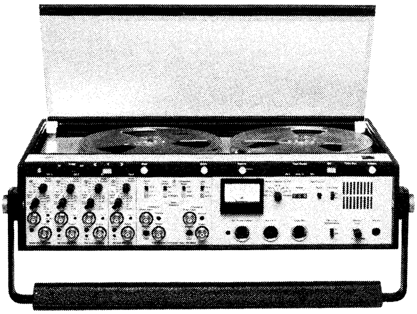
The Sound Intensity Probe Type 3519 consists of two matched (amplitude and phase) pairs of free-field microphones (1/2" Microphones Type 4165 and 1/4" Microphones Type 4135) and two 1/4"-diameter Microphone Preamplifiers Type 2633. The accessories include two 1/4"-diameter spacers (of approximately 6 mm and 12 mm long) and two 1/2"-diameter spacers (of approximately 12 mm and 50 mm long), an angle piece, contacts, stem and handle. The spacers are designed to give a spacing between the acoustic centres of the paired microphones of 6 mm, 12 mm and 50 mm.

The 2134, which is based on the B & K Digital Frequency Analyzer Type 2131 is a real time 2-channel digital frequency analyzer primarily designed for sound intensity measurements. However, it can also be used for sound pressure measurements as a 2131. In this mode of operation real time analysis can be achieved in 42 third-octave bands with centre frequencies from 1,6 Hz to 20 kHz and in 14 octave bands with centre frequencies from 2 Hz to 16 kHz. For both modes of operation the input signal may be A-weighted prior to analysis.

The 2134 is almost entirely digital in operation, giving the instrument many advantages, the main one being better controlled filter shape. Not only does the digital filter have greater freedom from drift and requires no special trimming to maintain its properties as components age, but also it greatly simplifies the use of a digital detector and a digital averager. The digital detector permits true RMS detection without crest factor limitations, while the digital averager permits both linear and exponential averaging. In both modes 13 different averaging times from 1/32 s to 128 s in a binary sequence can be selected. To obtain the same statistical accuracy in each channel for measurements on random signals, exponential averaging can be used with a fixed 68% confidence level for $\sigma<0{,}5$ dB, $\sigma<1$ dB or $\sigma<2$ dB.

The measurement results obtained from the 2134 can be read out to a variety of analogue and digital peripheral instruments. Besides, most of the 2134's functions can be sensed and controlled over the IEC interface by an IEC interface bus controller.

Portable Instrumentation Tape Recorders Types 7005 and 7006



Types 7005 and 7006 are two wide-band, instrumentation tape recorders for multichannel FM and Direct recording to IRIG standards. What makes them unique is that they are the only instrumentation tape recorders which are truly portable, i.e. they are easy to carry single handed and can be operated completely independently of external power sources. Moreover, both are designed to withstand the rigours of operating in a vibration environment and therefore are also particularly well suited for mobile use.

Type 7005 consists of a tape transport and monitor mainframe with 1 Direct and 3 FM Record-Reproduce Units plus a Two Channel Compander Unit, while Type 7006 is the mainframe only with the choice of ordering any combination of FM and Direct Units with or without the Two Channel Compander Unit.

For direct recording the overall record-reproduce frequency response is from 20 Hz at a tape speed of 38,1 mm/s, extending up to 60 kHz at a tape speed of 381 mm/s. For FM recording the frequency response is from DC up to 12,5 kHz at a tape speed of 381 mm/s and 1,25 kHz at a tape speed of 38,1 mm/s.

The two Channel Compander ZM 0054 is designed for unattended recording of non-stationary signals such as aircraft takeoff and flyover noise, mechanical vibration as a function of engine speed etc. During recording it compresses the amplitude of the input signal and on playback expands it reinstating it in correct proportion to the original signal. In this way non-stationary signals with dynamic range of over 70 dB (Lin) may be recorded and reproduced, without actually altering the signal to noise ratio of the Recorders or reducing their four channel record-reproduce capability.

The heart of the tape transport is a low inertia, drive motor, featuring electronic control by means of a sensitive servo amplifier system. For tape speed settings of 38,1 and 381 mm/s (i.e. 1,5 and 15 in/s) accurate to within ± 0,25%, the motor is phase locked to a reference frequency derived from an internal crystal oscillator. Two front panel lamps show which particular tape speed setting is selected, as well as indicate when the tape transport has locked onto the correct speed.

Tape Speed	Cumulative Peak-Peak (IRIG 106.66 - 77)	Weighted Flutter (DIN 45-507)
38,1 mm/s	< 0,7% (0,5 to 313 Hz)	< 0,1%
381 mm/s	< 0,5% (0,5 Hz to 2,5 kHz)	< 0,06%

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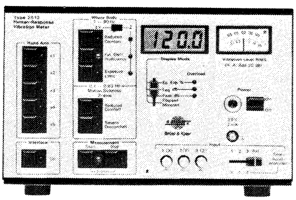
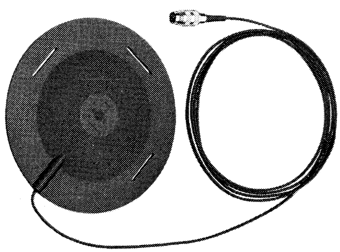
Typical flutter values of the 7005 and 7006 are indicated in the table.

Human-Response Vibration Meter Type 2512 and Triaxial Seat Accelerometer Type 4322





An entirely new area of vibration measurement, concerned with the effects of vibration on the human body, is opened up by the Human-Response Vibration Meter Type 2512. The instrument is designed in accordance with current standards and draft standards to carry out frequency-weighted measurements of both whole-body (including motion sickness) and hand-arm vibration. From these measurements, the equivalent continuous vibration level and the vibration exposure are calculated, and compared with the appropriate criterion, which is preselected from the recommended criteria stored permanently within the instrument. The measurement's maximum peak value, its equivalent continuous vibration level, and the current exposure (in % of that allowed), as well as the elapsed time, are available on the digital display at any time. In addition, the instantaneous signal level is continuously displayed on a moving coil meter for convenient monitoring during measurements.

Input is via three switch-selectable microsockets on the front panel for connecting B & K Uni-Gain Accelerometers (including the Triaxial Accelerometer Type 4321), or via a special socket on the rear panel, for connecting the Triaxial Seat-Accelerometer Type 4322 (for measurements on seated subjects). Results can be output from sockets on the rear of the instrument, digitally via an IEC interface e.g. to an Alphanumeric Printer Type 2312 or the Digital Cassette Recorder Type 7400, or in analogue form to a Level Recorder Type 2306. In addition, there are sockets for connecting an external filter, e.g. the Tunable Band Pass Filter Type 1621. A three-position switch allows selection of internal filters only, external filters only, or both filters simultaneously.

The instrument is fully portable, being powered from internal batteries, and weighs only 3,1 kg. (6,8 lb), including batteries. Used with B & K Uni-Gain Accelerometers including the special Triaxial Seat-Accelerometer Type 4322, the 2512 forms a compatible, calibrated system which is easy to set up and straightforward to use in the field or in the laboratory. It is therefore especially suitable for measurements on all types of vehicles, vibrating working environments, and on hand-held power tools.