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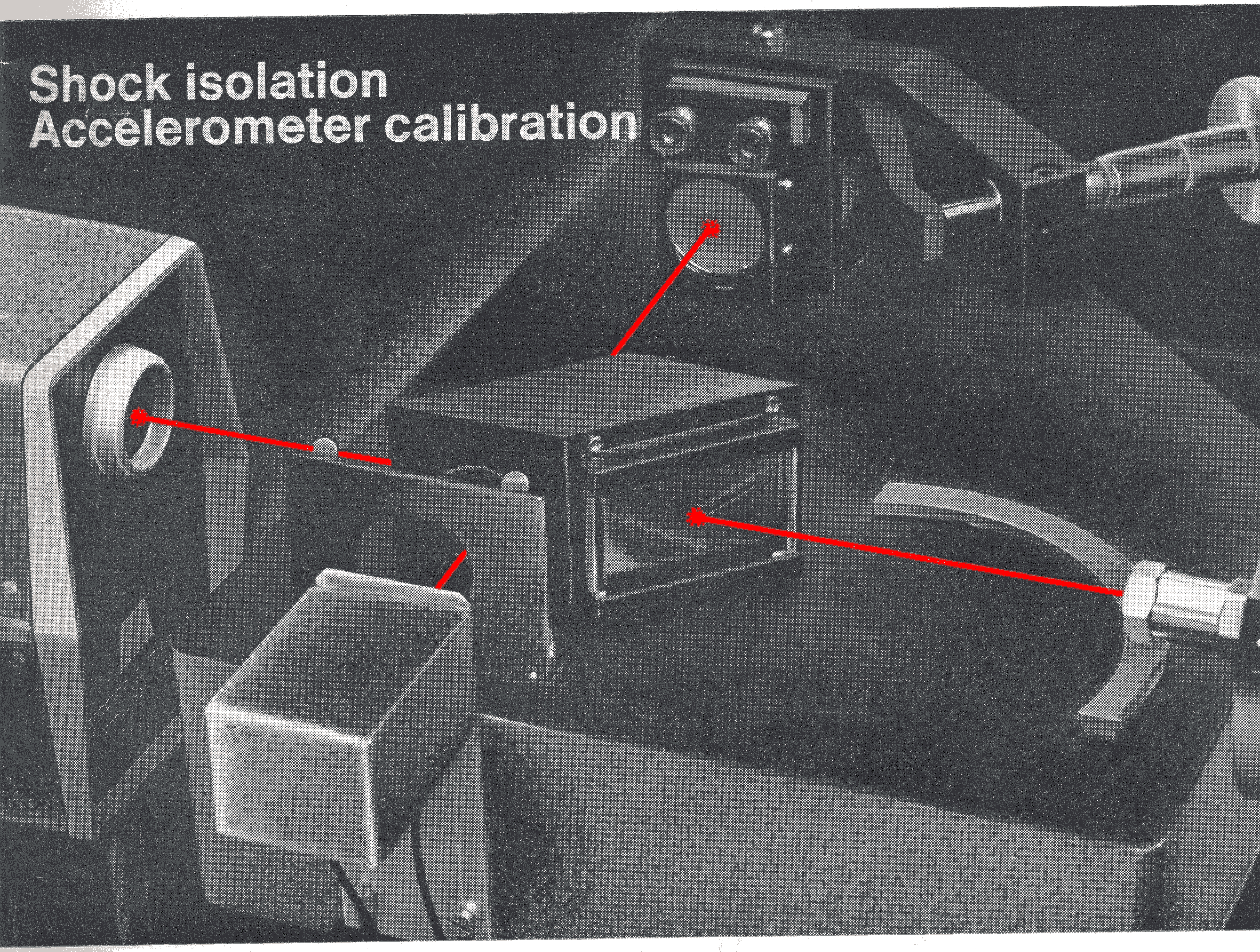

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TECHNICAL REVIEW

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Contents

Shock and Vibration Isolation of a Punch Press

by

H. P. Olesen and *D. T. Delpy*

ABSTRACT

Punch presses are machines which can produce powerful transients of both force and moment. This could result in large movements of a press, which for reasons of operator's safety must be limited.

This paper describes a case where the press design, although good for punching and drawing operations, was inadequate from the viewpoint of the vibration engineer. The paper shows how the shock isolation problem was solved and also points to the need for further written information from the manufacturers of machine isolators about the properties of the isolators, both static and dynamic.

The paper also proposes the press manufacturers should have the possibilities of shock and vibration isolation in mind when new presses are being designed, as good properties in this respect can easily be obtained at little or no expense if considered during the early design stages.

SOMMAIRE

Les presses à découper sont des machines qui peuvent avoir des régimes transitoires puissants à la fois en force et en déplacement. Cependant, pour la sécurité de l'opérateur, l'amplitude de leurs mouvements doit souvent être très stictement limitée.

Cet exposé décrit un cas ou la conception de la presse, bien que parfaite pour les opérations de découpage, était tout à fait inadaptée du point de vue de l'ingénieur en vibrations. Nous décrirons comment le problème de l'isolement aux chocs a été résolu et nous attirerons l'attention sur le besoin d'informations écrites sur les propriétés statiques et dynamiques des isolants de la part des fabricants d'isolants pour machine.

Nous suggérons aux fabricants de presses de garder présent à l'esprit qu'il est possible d'obtenir une excellente isolation aux chocs et aux vibrations à moindre frais si l'on s'en occupe dès le début de l'étude d'une nouvelle machine.

ZUSAMMENFASSUNG

Exenterpressen können während des Betriebes sehr starke Stöße und Momente in ihre Fundamente einleiten. Andererseits dürfen diese Maschinen aus Sicherheitsgründen oft nur sehr geringe Relativbewegungen zu ihrer Umgebung aufweisen.

Dieser Aufsatz beschreibt einen praktisch aufgetretenen Fall, in dem die Maschine zwar

ihre Funktion erfüllte, jedoch vom Standpunkt des Schwingungstechnikers gesehen ein sehr unbefriedigendes Verhalten zeigte. Die Maßnahmen zur Schwingungsisolierung werden diskutiert. Gleichzeitig wird darauf hingewiesen, daß die Herstellerunterlagen über Maschinenisolatoren ausführlichere Angaben hinsichtlich des statischen und dynamischen Verhaltens enthalten sollten.

Ferner wird herausgestellt, daß die Hersteller von Exenterpressen bei geringen oder gar keinen Mehrkosten zu besseren Konstruktionen gelangen können, wenn sie die Möglichkeiten der Stoß- und Schwingungsisolierung bereits im Entwurfstadium einer neuen Maschine berücksichtigen.

Introduction

A punch press which complied with forthcoming safety regulation was installed in the Brüel & Kjær factory in Nærum.

Except for a new type of coupling, the press was very similar in design to older models of the same make. This press, however, had to be secured much more rigidly in order to prevent it from moving across the floor. A small foundation was cast on the concrete floor and the press was secured on top of the foundation by means of a layer of felt soaked with waterglass.

In this way the movement of the press was very much restricted. Unfortunately the felt-waterglass layer transmitted a high level of vibration to the floor, causing impulsive noise in the offices below. The annoyance caused in these offices necessitated an investigation of the press installation. A number of measurements was carried out and an isolation system was designed. As the practical aspects of such a design may be of general interest, it was decided to describe this example in some detail.

Working principle

In the punch press an electric motor maintains the speed of a heavy flywheel. By means of a coupling the rotation of the flywheel is transferred to the main shaft which carries an eccentric. This converts the rotation to a linear motion through a connecting rod to which one part of the working tool is fixed. The other part of the tool is secured to the frame of the press. The working operation is carried out when the moving part of the tool is pressed through the material to be punched.

The forces occurring are indicated in Fig.1. The reaction from the material (F) is added to the horizontal reaction from a vertical guide to give the total force in the connecting rod. Similar reactions are applied at the main shaft bearing, the result being that the forces and reactions are balanced out, but that two couples are formed. One couple, the action, $M_1 = FL \tan\theta$ tends

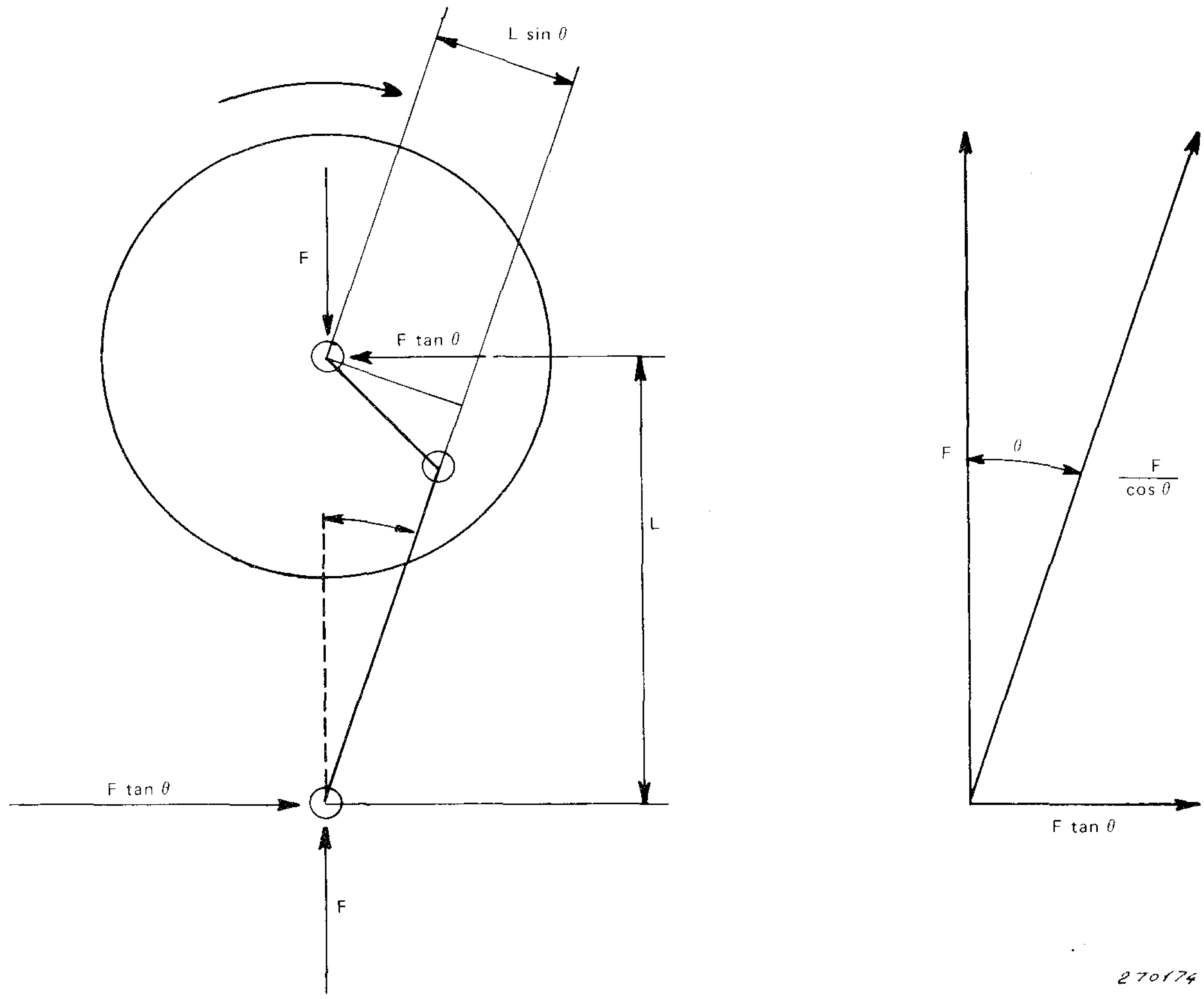

Fig. 1. The forces occurring in the press during the stamping process

to rotate the press in a clockwise direction. The other couple, the reaction, $M_2 = (F/\cos\theta)(L\sin\theta) = FL\tan\theta$ acts counterclockwise at the main shaft and results in a reduction of the flywheel speed.

When the press is operated for a single stroke, some consideration must be given to the coupling, because its kinetic energy is almost instantly transferred to the press when it is braked to stop. In Fig.2 is shown a diagram of the couples applied to the press frame during one working cycle. At t_o the coupling connect the flywheel and the main shaft. The resulting reduction of flywheel speed causes the motor to supply more energy and thereby a small counterclockwise couple is applied to the press until speed is normal again.

At t_1 punching occurs. A clockwise couple is formed. Its magnitude and duration depends on punching force, material thickness and on the initial angle θ. The motor again supplies power to raise the speed and a counterclockwise couple is applied. At t_2 the coupling and the main shaft are braked to stop and their kinetic energy is transferred to the press. This

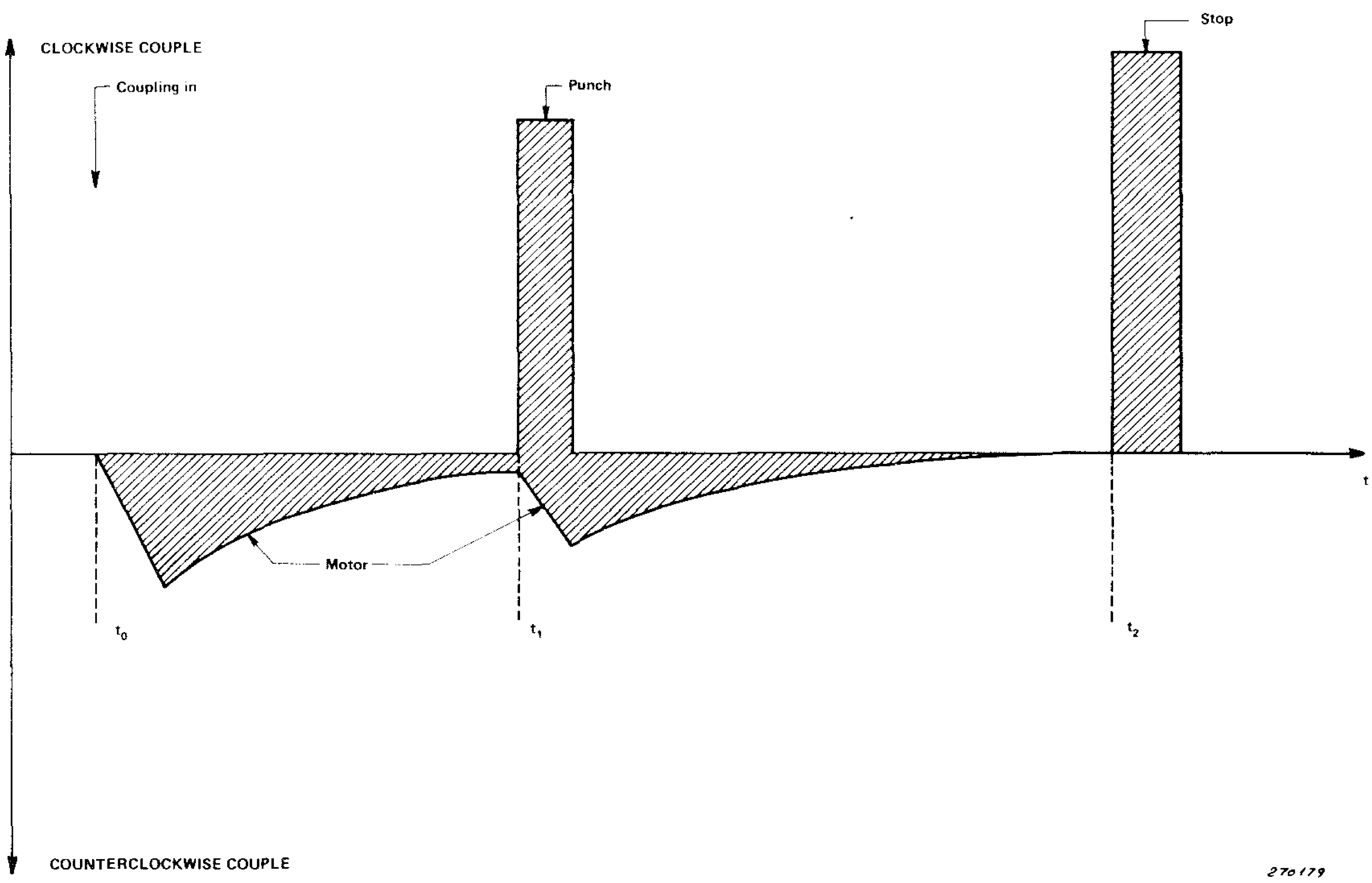

Fig.2. The couples which act on the press frame during one working cycle

energy is of such magnitude that it explains the violent movement of the press and renders the use of heavy tools superfluous, when the isolation system is tested.

Measurements

The vibration of the punch press and the floor was measured at various points, of which three are indicated in Fig.3. The measuring arrangement shown in Fig.4 employs two Piezoelectric Accelerometers Type 4332, the outputs from each going via a Preamplifier Type 2625 and a Measuring Amplifier Type 2606 to be recorded on a tape loop on the Type 7001 FM Tape Recorder. The recording is monitored by an oscilloscope and the Type 5559 Tape Splice Noise Eliminator*, which facilitates the inspection when the signal is played back immediately after recording. Several recordings were taken with the accelerometers in different configurations on the floor and on the punch press. It was noted that the greatest acceleration amplitude occurred when the punching cycle ended and the clutch was braked to stop. At all other times it was not possible to measure any signals correlating with the machine-movement. This is well in accordance with the above mentioned energy consideration as the actual stampings produced did not demand great forces.

*The working principle of this instrument is the same as that of the electronic gate described in reference 4.

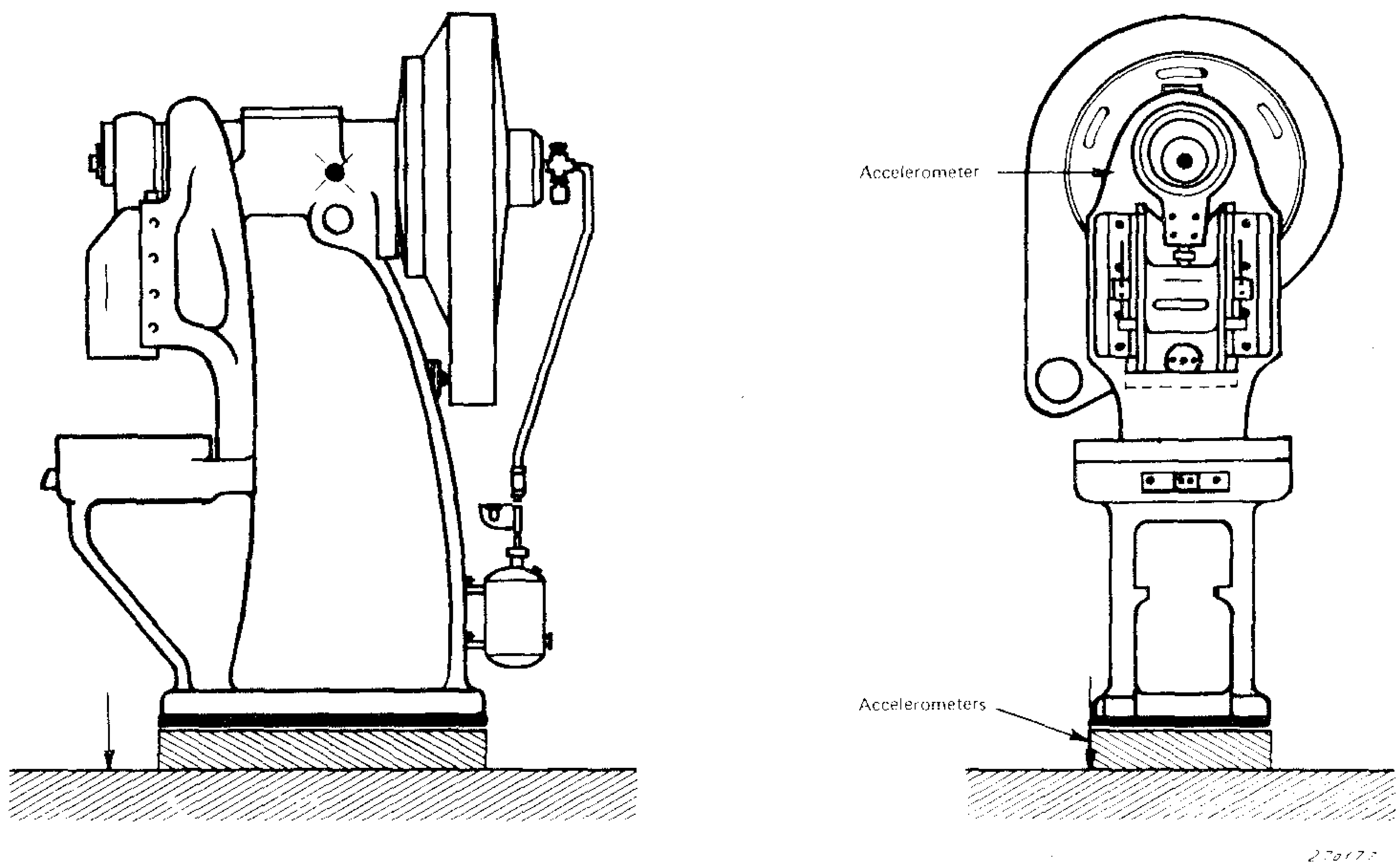

Fig.3. Measuring points on the press and the floor

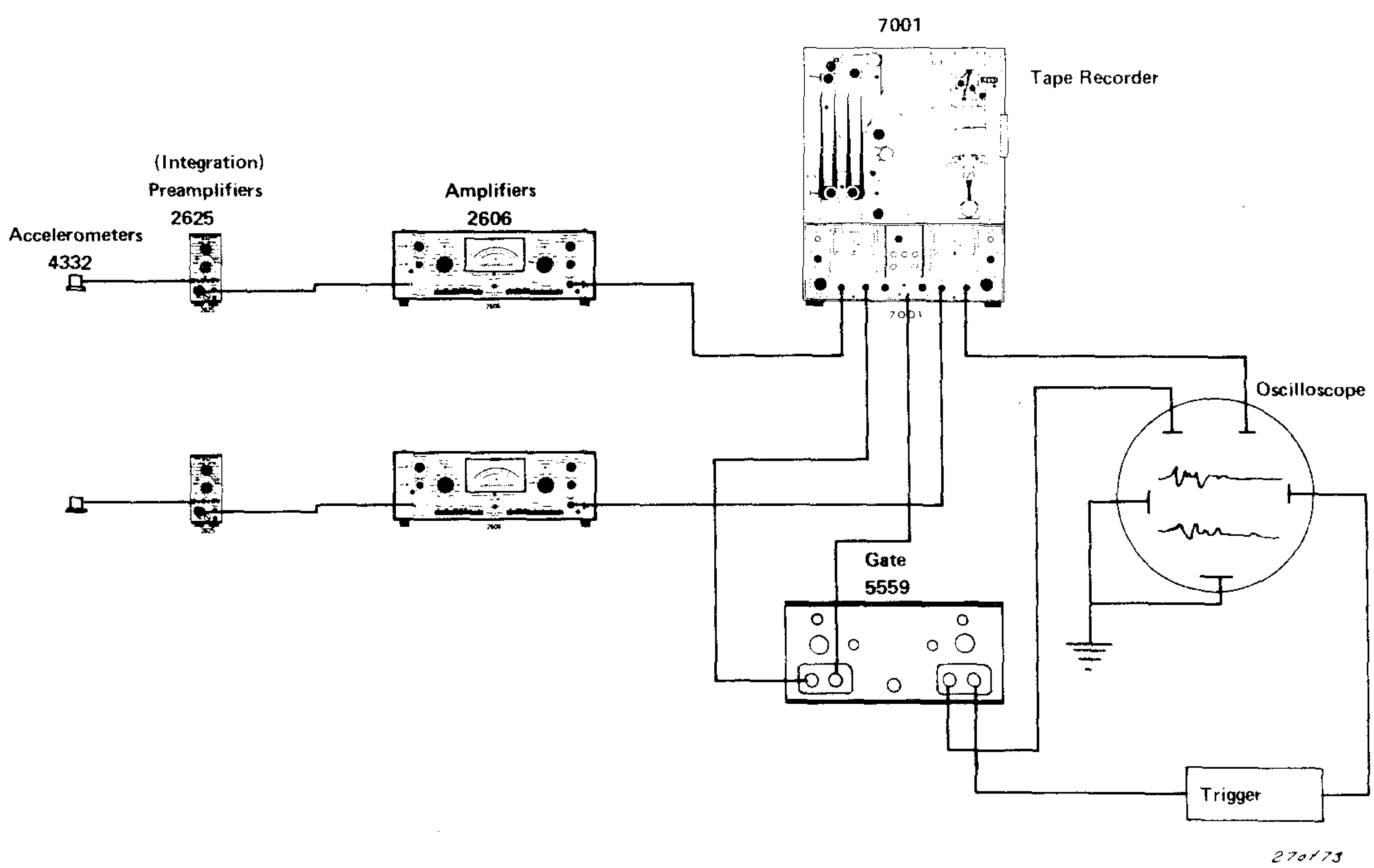

Fig.4. The Measuring arrangement used for the experiments

At random there appeared other, relatively high level signals in the floor and to some extent in the punch press. These signals seemed to be due to the working of other machines in the workshop and they were not considered important for the experiment.

The signals measured on the press at the stopping time were high level, high frequency oscillations with a duration of approximately 10 msec. After a double integration, a 10 Hz displacement signal was predominant. This signal had a much longer duration, which correlated well with that of the visible motion of the press, and it was considered to be a natural frequency of the press, felt-with-waterglass system. The signals in the press were transmitted to the floor with only little attenuation and the high frequency part of it is thought to be especially responsible for the noise produced.

Theory of motion for a punch press

A punch press which is mounted on elastic isolators and which is subjected to an instant velocity shock will show both angular and translatory movements, and these motions will be coupled together. If the press configuration is considered symmetrical the angular motion will only be present in the plane of the applied couple and the translatory motion will be horizontal along an axis in that plane. Any motion along the vertical axis is considered due to other excitation and it is not coupled to the other two motions.

In Fig.5 is shown a schematic view of the coupled two motions. From this the equations of motion can be formed:

$$-m\frac{d^2x}{dt^2} - k_x x - C_x\frac{dx}{dt} + k_x a\alpha + C_x a\frac{d\alpha}{dt} = 0$$

$$-I\frac{d^2\alpha}{dt^2} + k_x ax + C_x a\frac{dx}{dt} - k_x a^2\alpha - C_x a^2\frac{d\alpha}{dt} - k_y b^2\alpha - C_y b^2\frac{d\alpha}{dt} + I\Omega_o\frac{d1}{dt} = 0$$

where

m	is the mass of the press.
I	is the moment of inertia of the press about an axis perpendicular to the plane of movement.
a	is the vertical distance from isolator to center of gravity.
b	is half the distance between isolators in the horizontal (x) axis of movement.
k_x and k_y	are the total isolator stiffnesses in the horizontal and vertical axes respectively.
C_x and C_y	are the total damping coefficients in the horizontal and vertical axes respectively.
x	is the horizontal displacement.
α	is the angular displacement about the center of gravity.
$I\Omega_o\frac{d1}{dt}$	is the applied couple.
Ω_o	is the initial angular velocity of the press which equals an angular acceleration pulse.

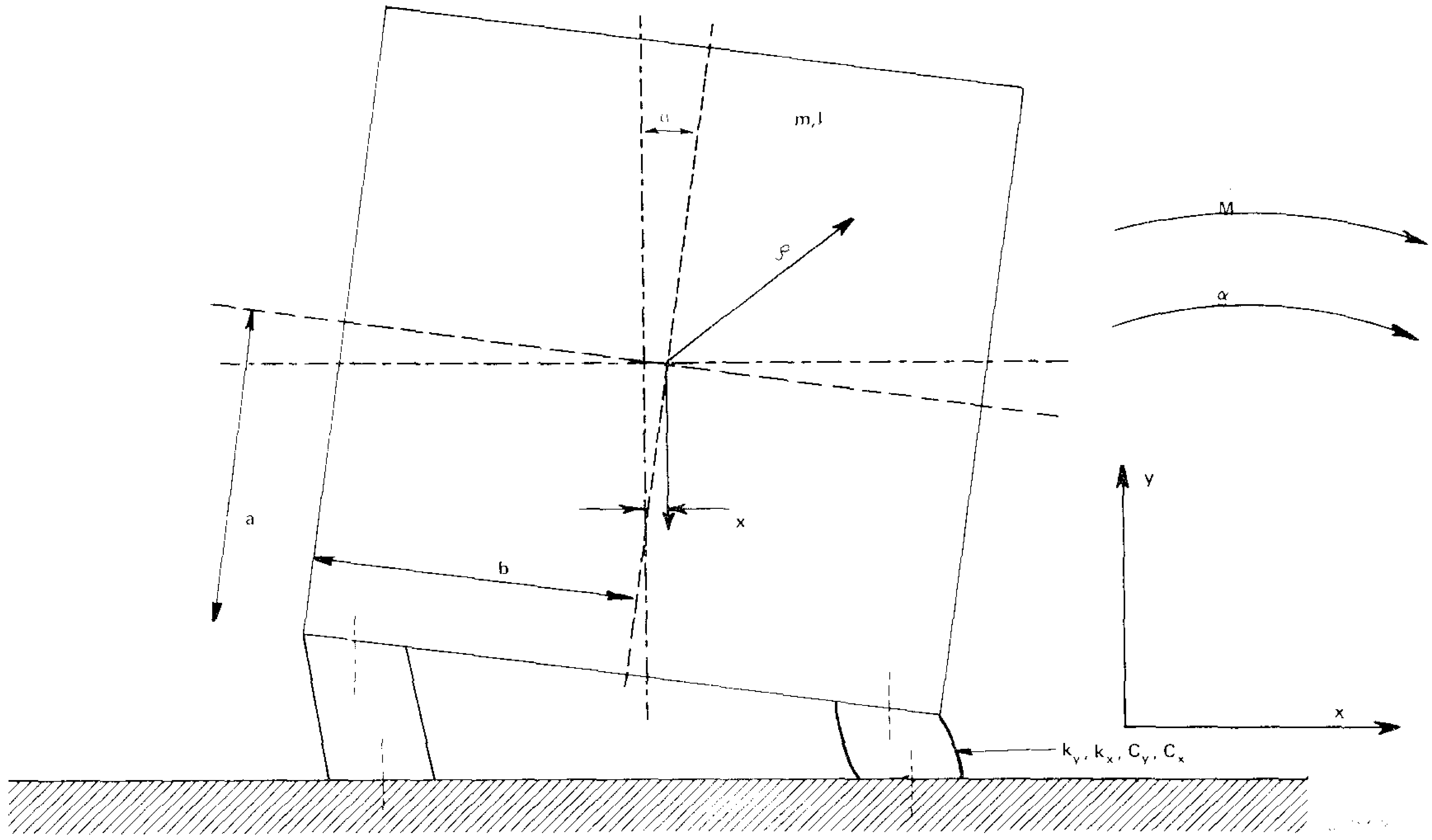

Fig.5. A schematic view of the coupled motions of the press

When Laplace transforms are applied to these two equations, the following expressions for α and x can be obtained

$$\alpha = \frac{\Omega_o \left(S^2 + S\frac{C_x}{m} + \frac{k_x}{m}\right)}{S^4 + S^3\left(\frac{C_x}{I}a^2 + \frac{C_y}{I}b^2 + \frac{C_x}{m}\right) + S^2\left(\frac{k_x}{I}a^2 + \frac{k_y}{I}b^2 + \frac{C_xC_y}{mI}b^2 + \frac{k_x}{m}\right) + S\left(\frac{C_xk_y}{mI}b^2 + \frac{k_xC_y}{mI}b^2\right) + \frac{k_xk_y}{mI}b^2}$$

$$x = \frac{\Omega_o\, a \left(S\frac{C_x}{m} + \frac{k_x}{m}\right)}{S^4 + S^3\left(\frac{C_x}{I}a^2 + \frac{C_y}{I}b^2 + \frac{C_x}{m}\right) + S^2\left(\frac{k_x}{I}a^2 + \frac{k_y}{I}b^2 + \frac{C_xC_y}{mI}b^2 + \frac{k_x}{m}\right) + S\left(\frac{C_xk_y}{mI}b^2 + \frac{k_xC_y}{mI}b^2\right) + \frac{k_xk_y}{mI}b^2}$$

The denominator will *normally* have the following roots:

$$S = -d_1 - j\omega_1;\ -d_1 + j\omega_1;\ -d_2 - j\omega_2;\ -d_2 + j\omega_2;$$

And the resulting time functions have the form

$$\alpha = 2\,\Omega_o\left[e^{-d_1 t}P_1\cos(\omega_1 t + \varphi_1) + e^{-d_2 t}P_2\cos(\omega_2 t + \varphi_2)\right]$$

$$x = 2\,\Omega_o\,a\left[e^{-d_1 t}Q_1\cos(\omega_1 t + \theta_1) + e^{-d_2 t}Q_2\cos(\omega_2 t + \theta_2)\right]$$

Normally the roots and the factors of these expressions must be calculated by numerical methods, but under the special assumption that $C_y/C_x = k_y/k_x = C$, an analytical solution for d and ω can be derived. The condition may be rarely satisfied in practice, but the resulting solution throw some light on the behaviour of the parameters involved.

$$d_1 = \frac{C_x}{2\,m}\,\frac{1 + A + BC}{2}\,\left(1 + \sqrt{1 - \frac{BC}{(1 + A + BC)^2}}\right)$$

$$d_2 = \frac{C_x}{2\,m}\,\frac{1 + A + BC}{2}\,\left(1 - \sqrt{1 - \frac{BC}{(1 + A + BC)^2}}\right)$$

$$\omega_A{}^2 = \frac{k_x}{m}\,\frac{1 + A + BC}{2}\,\left(1 + \sqrt{1 - \frac{BC}{(1 + A + BC)^2}}\right)$$

$$\omega_B{}^2 = \frac{k_x}{m}\,\frac{1 + A + BC}{2}\,\left(1 - \sqrt{1 - \frac{BC}{(1 + A + BC)^2}}\right)$$

$$\omega_1 = \sqrt{\omega_A{}^2 - d_1{}^2} \qquad \omega_2 = \sqrt{\omega_B{}^2 - d_2{}^2}$$

where

$$A = \frac{a^2}{\rho^2};$$

$$B = \frac{b^2}{\rho^2};$$

and ρ is the radius of gyration of the press; $\rho = \sqrt{\frac{I}{m}}$;

The function $\frac{1 + A + BC}{2}\left(1 \pm \sqrt{1 - \frac{BC}{(1 + A + BC)^2}}\right)$ is shown in Fig.6.

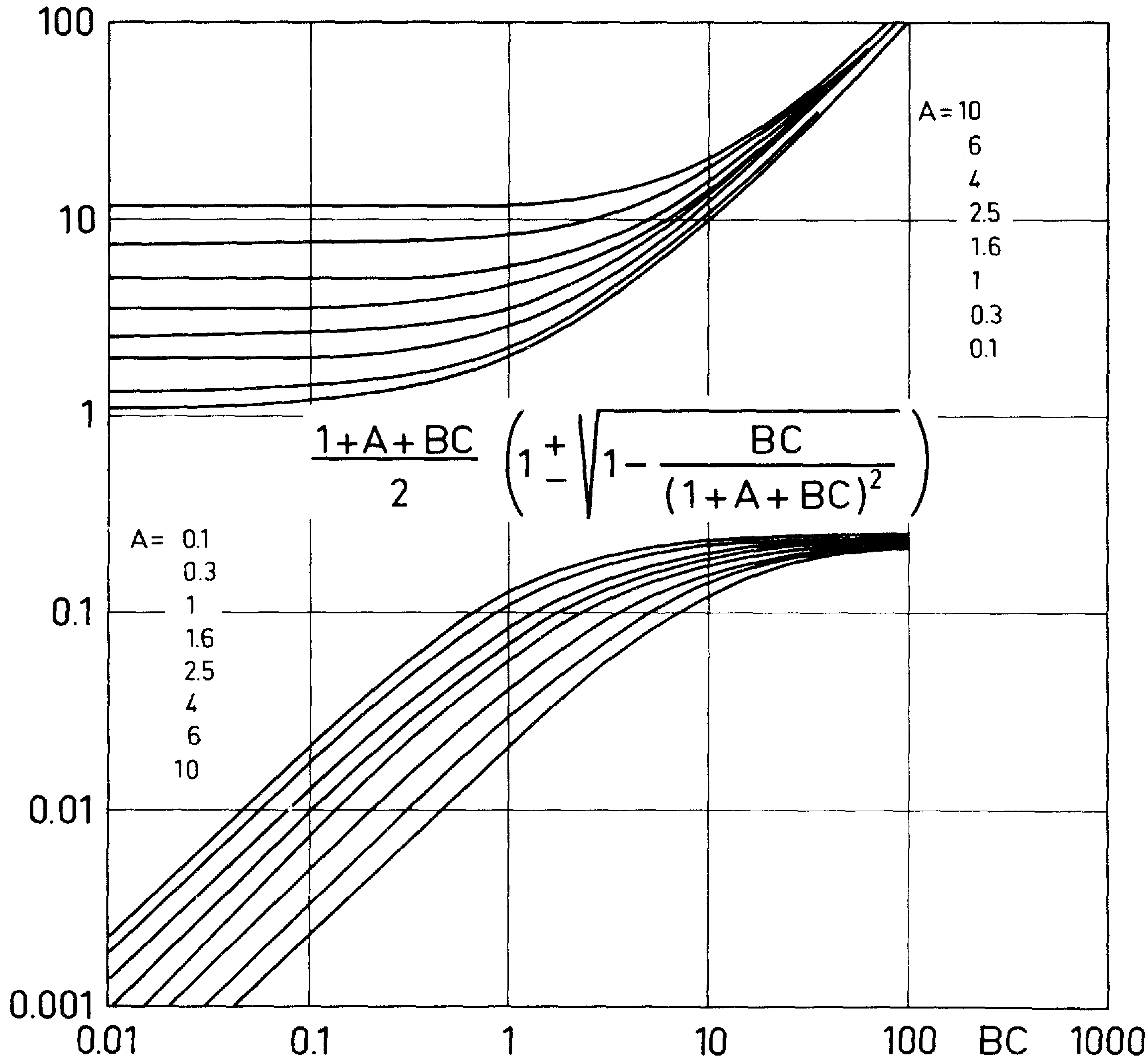

Fig.6. Curves showing the relation between the coupled frequencies

The design of a shock isolation system

The application of the above formulae necessitates detailed knowledge of the press properties and of those of the available isolators. Looking into the technical data given by the press manufacturer the only data to be found were the total weight of the press, the punching force, the work done per punching cycle and the punching frequency. As can be seen from the formulae further data such as height of the centre of gravity, the radius of gyration and the moment of inertia are required for a theoretical design of a proper isolation system.

Similarly, looking into the technical data published by a number of isolator manufacturers it was found that the information necessary for isolation design was scarce, and many manufacturers seem to publish certain static deflection factors only. In working with a pure translational, single degree of-freedom system such data might be sufficient in that

$$\omega_o \cong \sqrt{\frac{g}{\Delta_{stat}}}$$

where Δ_{stat} = static deflection of the mass. However, for more complicated systems, such as the isolation problem discussed in this paper, information on static deflection only, is not sufficient.

The lack of information about the press and the isolators deemed an exact calculation of the isolation system to be impossible. The equations derived, however, were useful for obtaining an estimate of the system performance-trend for design variations. All necessary figures were therefore roughly estimated – those for the press from the blueprints and the design notes, and those for the isolators from their static deflection curve and from their geometrical form in conjunction with curves for rubber stiffness in compression and shear.

With the data thus obtained, the motion of the press was estimated for different isolator stiffnesses and for different support-configurations.

The calculations indicated that in order to decrease angular displacement the base of support should be broadened and rather stiff isolators should be

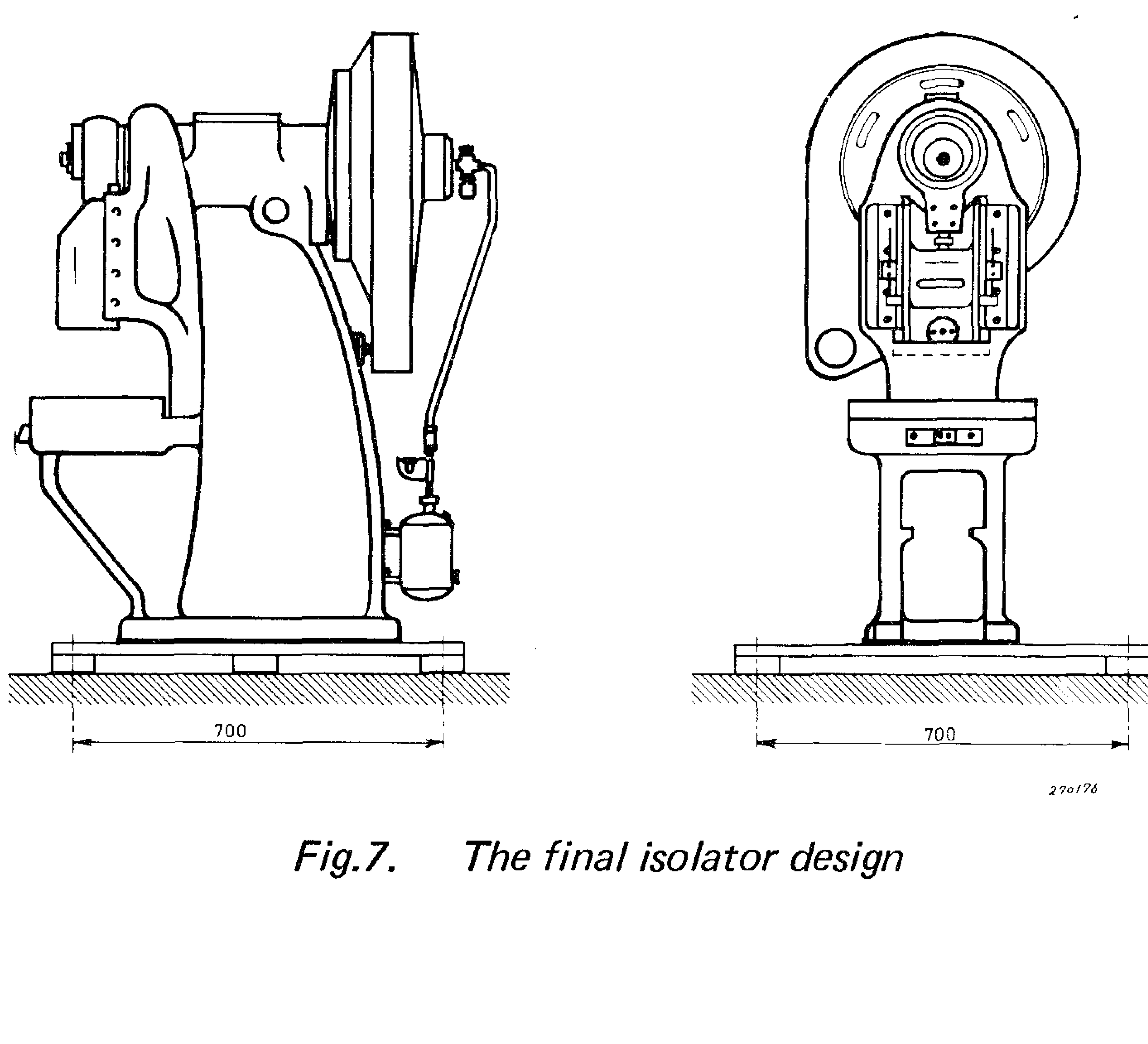

Fig.7. The final isolator design

used, and it was decided to include a 20 x 800 x 800 mm steel base-plate in the design to allow a distance of 700 mm between supports (see Fig.7). Measurements were then carried out with the arrangement shown in Fig.4. The high frequency acceleration signals from the press to the floor were now app. 24 dB attenuated by the isolators. The low frequency displacement signal now existed at 5.4 Hz and 0.93 Hz, and the max. displacement was a little too high for comfortable operation.

The frequency of 5.4 Hz was considered to be too close to the second harmonic of the punching frequency which is 2.5 Hz in the automatic mode. It was therefore decided to adjust the frequencies by adding a further pair of isolators to the machine, making a total of three on each side.

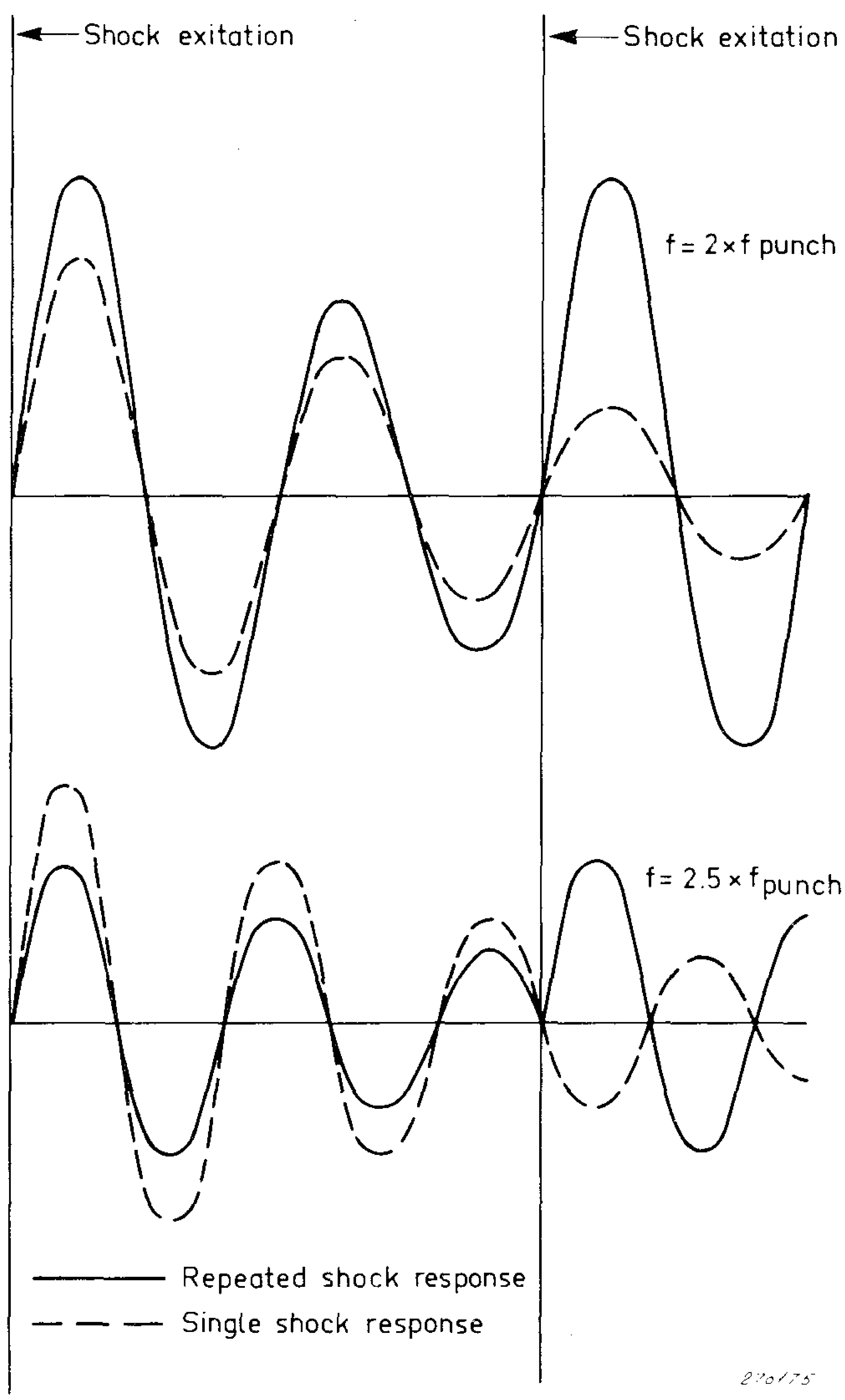

Fig.8. The resulting vibration of a system which is excited in phase or in antiphase

since $\omega_x = \sqrt{\frac{k_x}{m}}$

and the two coupled frequencies

$$\omega_1 = F_1 (\omega_x) \text{ and } \omega_2 = F_2 (\omega_x)$$

When the stiffness is increased by 1.5 the frequencies will increase by $\sqrt{1.5}$ thereby giving new frequencies of 6.6 and 1.14 Hz. In addition the displacement of the press will be reduced, as requested by the operator.

The example (for one frequency) in Fig.8 shows that by shifting a frequency in this way one punching excitation will tend to counteract the vibration from the previous one instead of amplifying it, as it would when the frequency was not shifted. The alteration was made and the performance so obtained was judged satisfactory.

Conclusion

Shock isolation of various machines is a subject on which there exists some good literature. The main limitation to the practical use of this literature is that there is so little written information available on the relevant properties of isolators and machines. It is therefore gratifying to see that the International Standards Organization (ISO) has been working with the subject. This work has resulted in the Draft ISO Recommendation No. 2017*. This document first defines a terminology and then proceeds to specify which data should be supplied from the user of isolators (vibration properties of the machine and of the supporting structure) and which data should be supplied by the isolator manufacturer.

The requested information seems to be comprehensive: For the isolators it includes static and dynamic stiffness in and about three axes, damping in three axes as well as environmental conditions and other information important to the vibration engineer. The user of isolators is similarly requested to state the isolation problem by describing the forces and couples occurring, as well as the moment of inertia and other relevant figures for the machine to be isolated and for the supporting structure.

The fulfilment of these recommendations will be an important step forward in the practical application of vibration and shock isolators, as isolation systems can then be thoroughly calculated during the design stage.

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*Document ISO/TC 108 (Secretariat-38) 107E Vibration and Shock — Isolators — Specifying Characteristics — (Guide for Selecting and applying Resilient Devices).

Meanwhile the vibration engineer must in most cases make use of trial and error methods, for example, the method described in this paper. This is possible to do for comparatively small systems, where unsatisfactory results can often be regulated towards optimum without introducing prohibitive cost. However, for large systems where a regulation may require reconstructions which could prove extremely expensive in installation costs and in production delays, this is not true.

The demands for vibration data from the machine manufacturers points to the fact, that they should have vibration isolation in mind when designing new machines. Besides reducing transmission, such isolation would tend to reduce the severity of some of the forces attacking bearings and other important machine members. A study of the effect of the height of the centre of gravity and of the geometry of the supporting plane would suggest a lower and broader design for modern presses (and as stated by a punch press manufacturer: The only reason that the heavy flywheel is placed in the machine top to day is really that in old-fashioned workshops all machines were belt-driven from the same axle under the roof).

In future design where vibration properties have been considered it would also be natural to integrate shock isolators in the press design.

Acknowledgement
The author would like to express his thanks to "Povl Møllers Machine Factory" for supplying design details and for stimulating discussions.

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Appendix

The design of an isolation system necessitated some knowledge of the press properties and of the available isolators.

The press
Some of the necessary information could be taken from the manufacturers brochure. Other necessary figures were not directly known and had to be calculated from the blueprints and the design notes for the press which were kindly supplied by the manufacturer.

The method of derivation is indicated below.

Height of the centre of gravity (a)
On scale drawings (Fig.A1) the machine was divided into segments. The volume of each segment was calculated and added to a total volume. Since the total mass was known, the mass of each segment could be derived. The height of the centre of gravity over the base of the machine is then given by the formula

$$a = \frac{\Sigma_1^{20} \; ml}{M}$$

where

l	=	height of each segment over the base of the machine
m	=	mass of the segment
M	=	total mass of the machine

The above was calculated for the press alone and for the press with a 100 kg supporting plate under the base.

Moment of inertia (I)
The moment of inertia was calculated for the two cases above using the formula

$$I = \Sigma_1^{20} \; m\,r^2$$

where r = distance of each segment from the centre of gravity

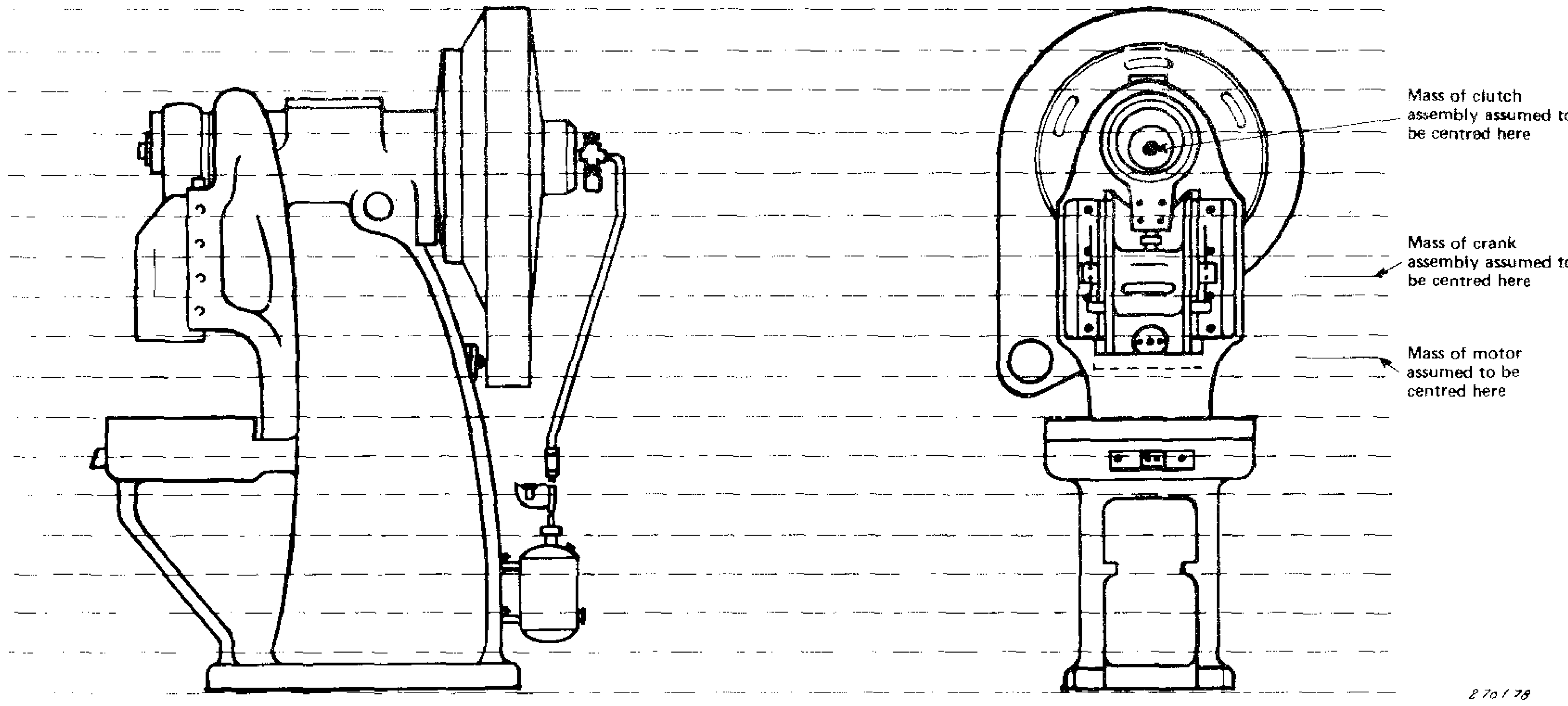

Fig.A1. The punch press divided into segments

Radius of gyration (ρ)
Using the values of I calculated above, the radius of gyration was found by the formula

$$\rho = \sqrt{\frac{I}{M}}$$

Initial angular velocity of the press (Ω_o)
The kinetic energy of the coupling (E_c) was considered to be transferred instantaneously to the press frame (actually in a few milliseconds).

$$E_c = 1/2\ I_c \omega_c^2 = 1/2\ I\ \Omega_o^2$$

Then

$$\Omega_o = \omega_c \sqrt{\frac{I_c}{I}}$$

Here I_c = the moment of inertia of the coupling (calculated from the blueprints)

ω_o = $2\pi f$ where f is the working frequency of the press.

Vibration Measurement by a Laser Interferometer

by

Torben Licht

ABSTRACT
The theory of vibration measurements by a laser interferometer is outlined, and its advantages against using a spectral lamp are discussed. The actual measuring set-up is described, and the results obtained by accelerometer calibration are given. Line of future improvements and fields of application are also discussed.

SOMMAIRE
Cet article expose la théorie qui s'applique aux mesures de vibrations par interféromètre à laser et étudie les avantages d'une telle méthode par rapport au procédé qui emploie une lampe spectrale. La chaîne de mesure utilisée est décrite et les résultats obtenus par l'étalonnage des accéléromètres sont donnés. Les possibilités de développement futur ainsi que les domaines d'applications sont étudiés.

ZUSAMMENFASSUNG
Die Theorie der Schwingwegmessung mit dem Laser-Interferometer wird dargelegt und die Vorteile des Lasers gegenüber Lichtquellen mit gefiltertem Licht werden diskutiert. Ein praktisch erprobter Meßaufbau wird beschrieben und die damit erhaltenen Ergebnisse bei der Accelerometer-Kalibrierung dargelegt. Ferner werden zukünftige Verbesserungen der Anordnung und weitere Anwendungsgebiete diskutiert.

Introduction

The sensitivity calibration is one of the most important features in the manufacture of piezoelectric accelerometers.

The normal production calibration involves a back to back fixture, where the standard accelerometer is very precisely calibrated (e.g. at NBS) and the two outputs are compared at a single frequency.

In order to be able to make calibrations in a wider frequency range and with greater accuracy, the laser interferometer described in this paper was constructed.

Theory for ideal interferometer

The principle of operation is sketched on Fig.1. The light beam is travelling in the x-direction with propagation factor k and angular frequency ω. The beams are represented by the electric field vectors, E, E_1 and E_2, and the actual path lengths the two beams have to travel are l_1 and l_2. The losses are represented by R_1 and R_2. d is the displacement of mirror 2 from its zero position.

Because the beams are reflected in identical ways the polarization properties of the light have no influence on the final result, and it is unnecessary to take phase shifts by the reflections into account.

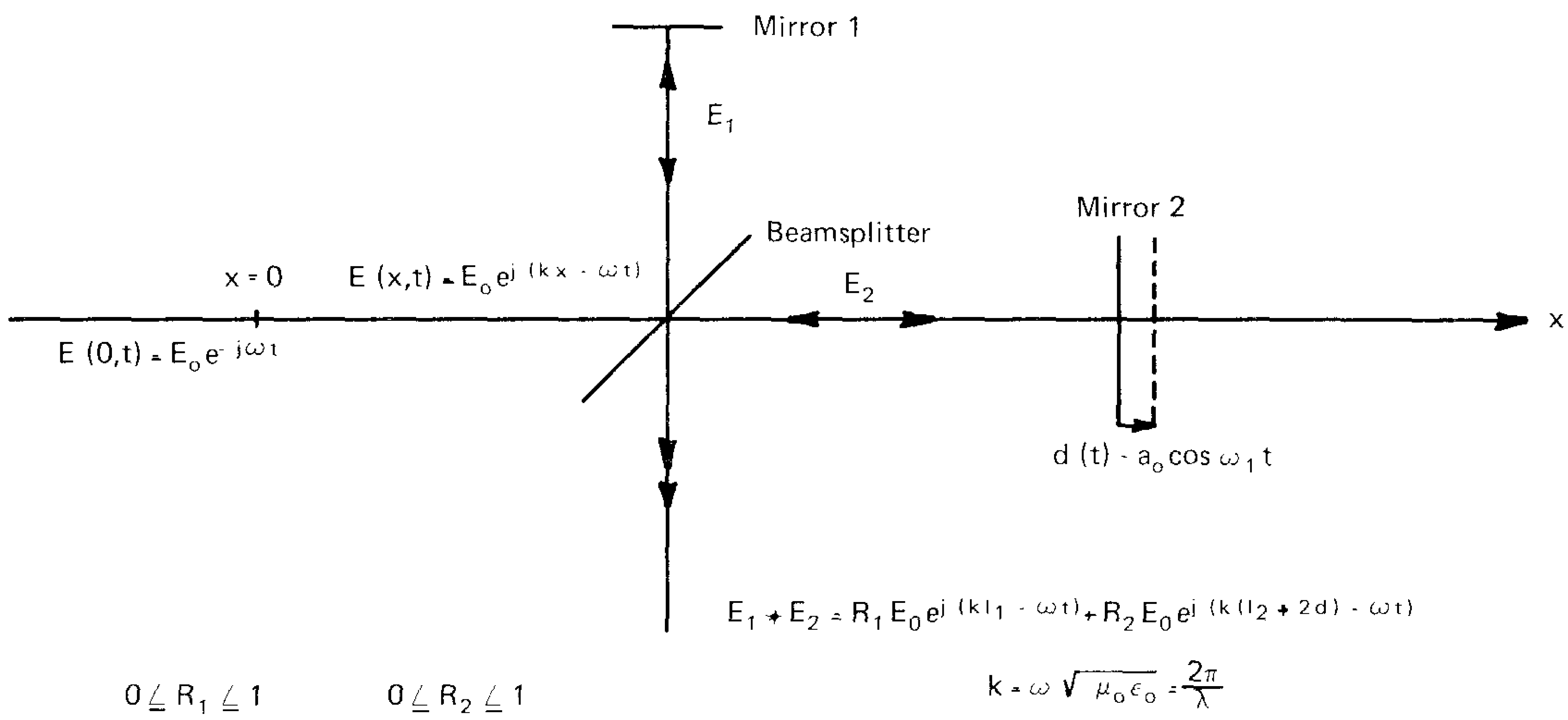

Fig. 1. The principle of the laser interferometer.

By using normal electromagnetic theory it can be shown that the intensity of the combined beam is given by the expression

$$I(t) = C|E_1 + E_2|^2 = CE_0{}^2 \left[R_1{}^2 + R_2{}^2 + 2R_1R_2 \cos k \ (l_2 - l_1 + 2d)\right]$$

$$= A + B \cos \frac{2\pi}{\lambda} (l_2 - l_1 \ + 2 \, a_0 \cos \omega_1 t)$$

where A, B and C are constants.

The intensity is a maximum for the condition

$$(2\pi/\lambda)\ (l_2 - l_1 + 2d) = 2\, n\pi$$

and therefore the distance corresponding to the distance between two intensity maxima is given by

$$2\,d \ = \lambda \text{ or } d = \lambda/2.$$

The number of maxima for one vibration cycle would be

$$4\,a_o/(\lambda/2) = 8\,a_o/\lambda = R_f \text{ (''frequency ratio'')}$$

and thus $a_o = (\lambda/8)R_f$

Hence by counting the frequency ratio we can immediately find the vibration amplitude.

If the intensity expression is expanded in series by means of the formulae

$$\cos(m\cos x) = J_o(m) - 2J_2(m)\cos 2x + 2J_4(m)\cos 4x - \ldots$$

$$\sin(m\cos x) = 2J_1(m)\cos x - 2J_3(m)\cos 3x + 2J_5(m)\cos 5x - \ldots.$$

then the following expression for the Fourier component at the vibration frequency, ω_1 can be found.

$$a_1 = \frac{\omega_1}{\pi} \int_{-\pi/\omega_1}^{\pi/\omega_1} I(t)\cos\omega_1 t\,dt$$

$$= -B\,\frac{\omega_1}{\pi}\sin\frac{2\pi}{\lambda}(l_2 - l_1)\,J_1\left(\frac{4\pi a_o}{\lambda}\right)$$

J_1 is the Bessel function of first order. If, therefore, the minimum points in the ω_1-component are determined the tabulated zero-points for the Bessel function can be used to find the amplitude a_o.

Measuring system

The system which has been used is shown in Fig.2. The laser has an output power of 1 mW, and the detector is a normal Si-phototransistor (BPX 25). The pulse generator is used to obtain a well defined signal for the counter input instead of the internal crystal oscillator. The B & K Frequency Analyzer Type 2107 is used to select the appropriate frequency when the zero-point method is used.

Laser or spectral lamp

In theory the interferometer should operate with light at a single frequency. The degree to which this is necessary in practice depends on the distance we want to measure. If for example we want to measure 10 g at 50 Hz we need to measure a distance of 2 mm. In Fig.3 is shown the intensity from a light source versus frequency. It's easy to show that the distance at which the two parts at f_1 and f_2 will extinguish each other is given by $l = C/(2\Delta f)$

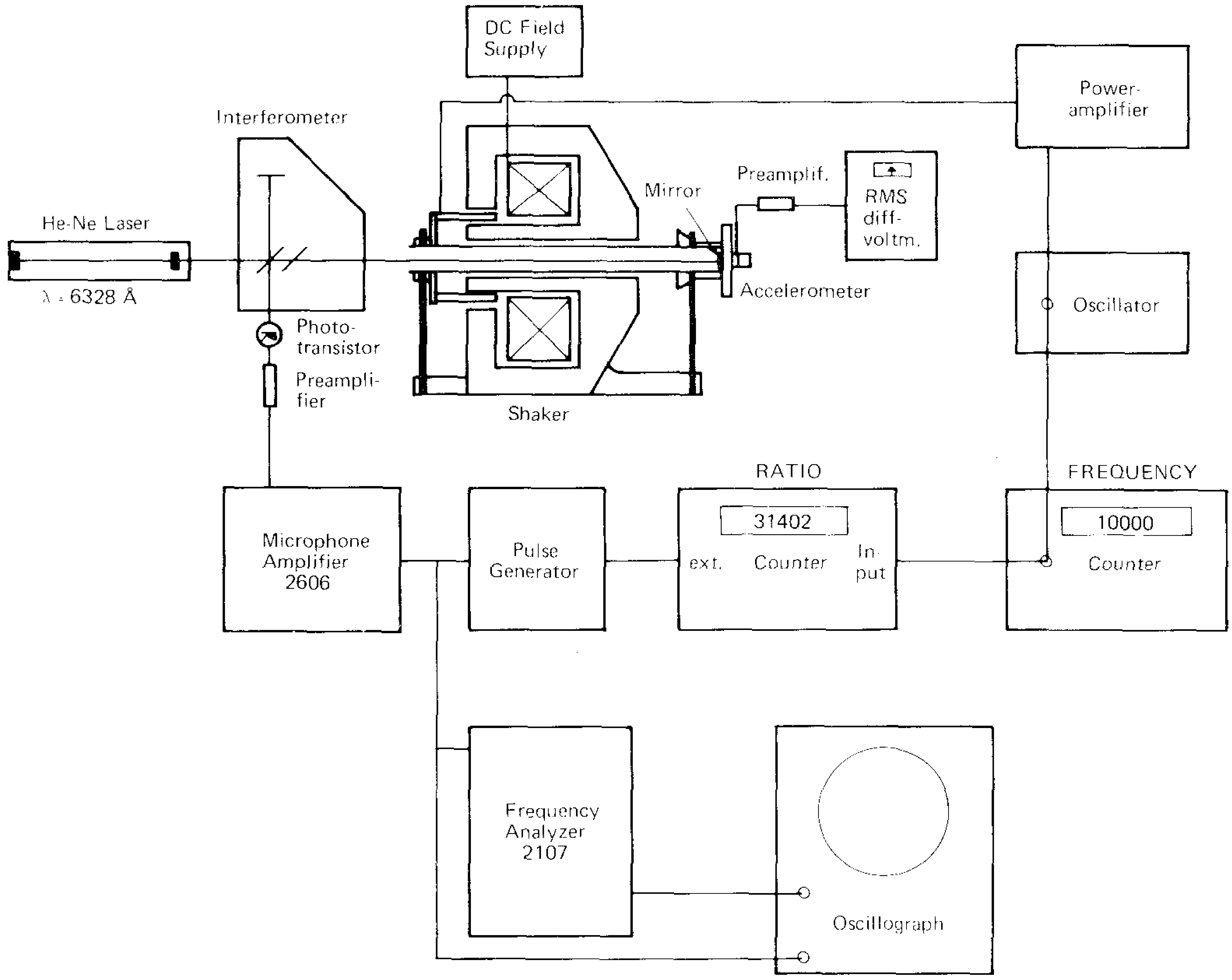

Fig.2. The measuring arrangement.

where C is the velocity of light. If we use l = 2 mm and λ = 500 nm, we get $\Delta f/f = 1.5 \cdot 10^{-4}$ and $\Delta\lambda$ = 0.075 nm. The best filters available have $\Delta\lambda$ = 1 nm and thus the high pressure, high intensity lamps, which have a broad spectrum, are not usable. Remaining possibilities are the low pressure vapor lamp and operation of the laser in the TEM_{00}-mode. Both of these have a coherence length of the order 20 cm.

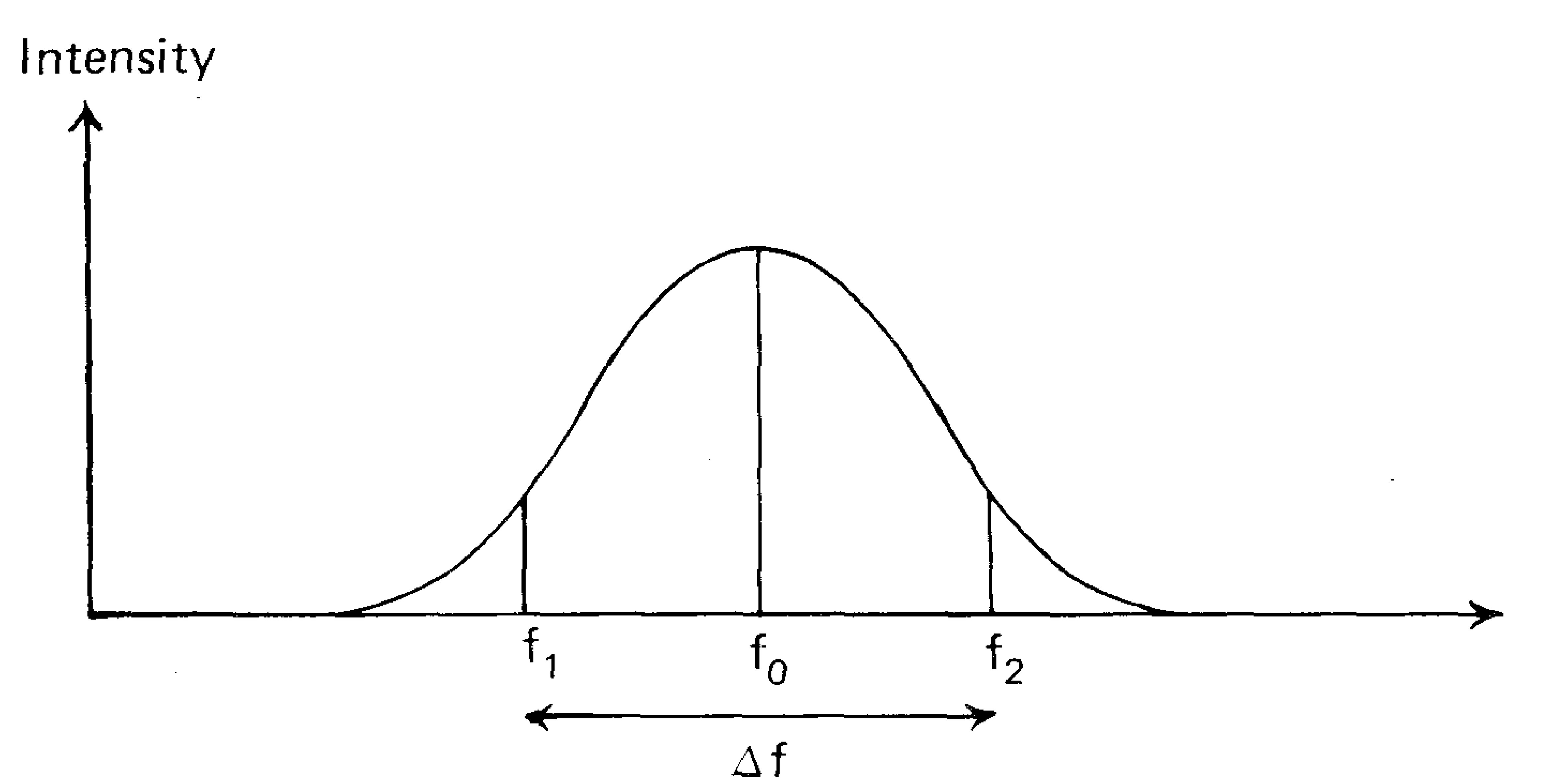

Fig.3. The spectral distribution of light from a light source.

It can be shown (ref. 1) that the intensity ratio between a lamp, with a typical surface brightness b = 10^{-2} W/cm^2, and a laser with power P (here 1 mW) at the focal point of an optical system is given by

$$F = \frac{I_{laser}}{I_{lamp}} = 2.6 \cdot \frac{P}{b \cdot \lambda^2} = 6.5 \cdot 10^7$$

Even without optics the laser will still be better by a factor of about 10^3 than a lamp together with a well designed optical system.

The natural neon line has a width of 1400 MHz and the laser used here can oscillate at discrete frequencies at a distance of 550 MHz giving three lines as shown in Fig.3. With this line system it can be shown that the path lengths in the two interferometer arms can be an odd number times the laser resonator length without disturbing the measurement. This special feature together with the intensity which allows the measurements to be done in full daylight and without optics, makes alignment easy and clearly shows the advantages of using the laser.

Accelerometer calibration

On Figs.4 and 5 the calibration results from two different accelerometers are shown. The results shown for Type 4339 consists of two series of measurements obtained by the frequency ratio method and two series by the zero-point method. Additionally, the results of a reciprocity calibration of the

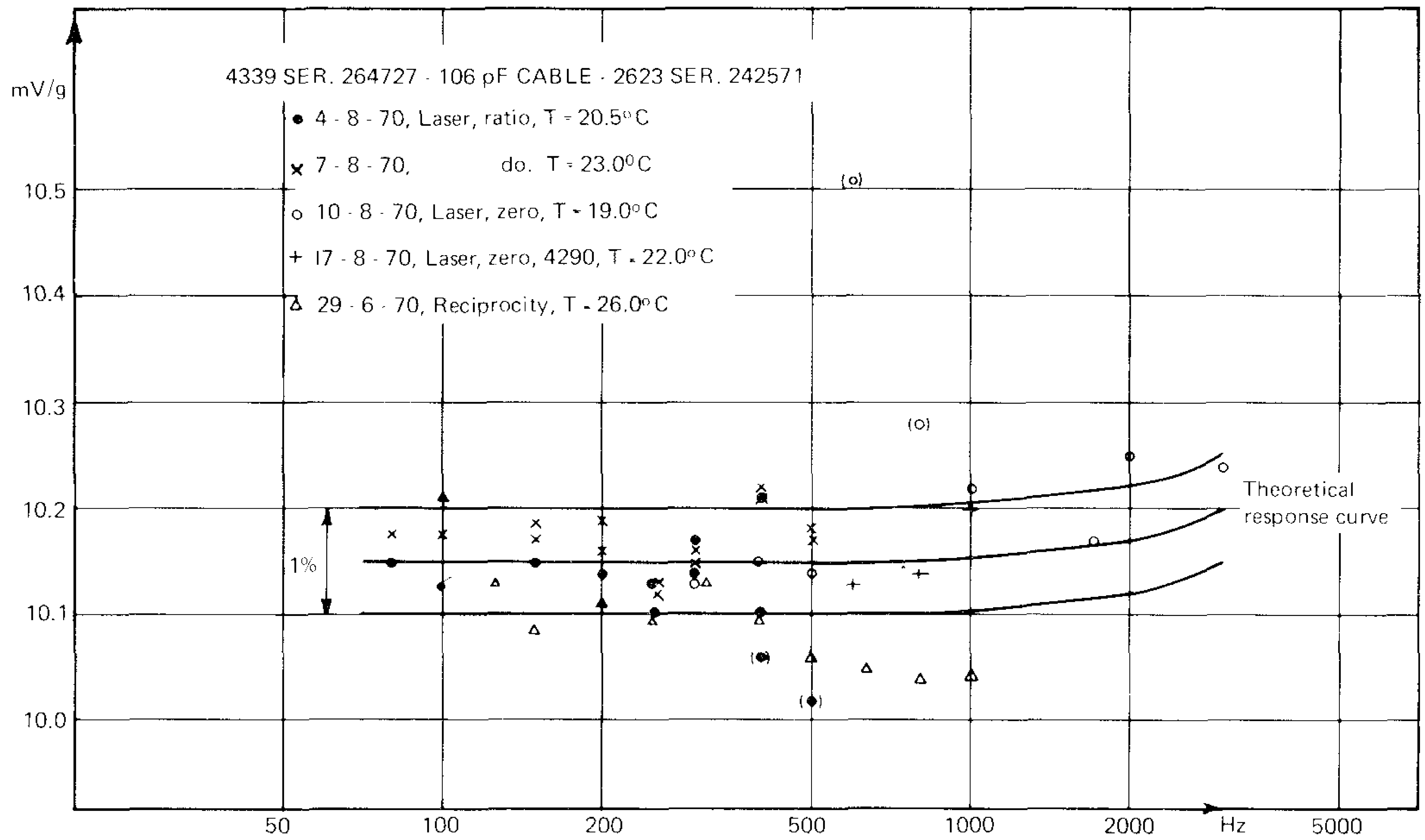

Fig.4. The calibration results of a Type 4339 accelerometer.

same accelerometer are shown. It has to be mentioned that the reciprocity calibration was performed at a temperature about 5°C higher than the laser calibrations. This temperature difference will decrease the sensitivity by about 0.5%. With this in mind the results are in quite good agreement, and an accuracy of ±0.5% is estimated between 80 and 1000 Hz. The results from the frequency ratio method which are low at 400 and 500 Hz can be improved if the ratio is kept to about 100 or higher. The results of 600 and 800 Hz, which are too high, are due to vibrations on the reference mirror because of resonances in the big shaker. When a small shaker is used, good agreement is obtained. From the results for Type 4338 it is seen that the reciprocity method, with the shaker Type 4291, can be used only from 125 to 350 Hz.

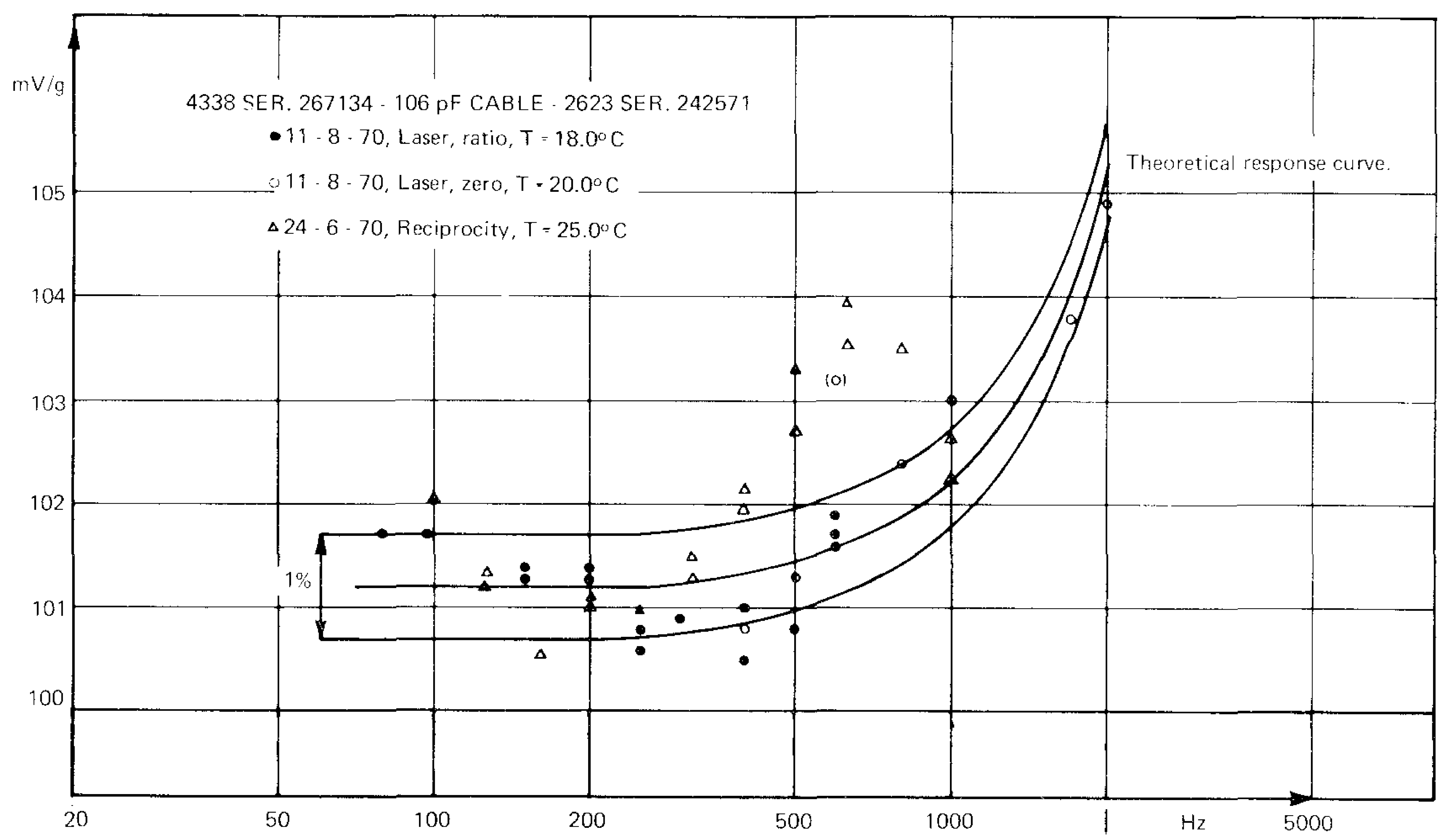

Fig.5. The calibration results of a Type 4338 accelerometer.

Fig.6 is an example of the agreement between the accelerometer output at the zeros of the Bessel function and the theoretical zero-points. The agreement is seen to be very good.

Discussion

The main draw back in the system is no doubt the undesirable vibrations which are introduced in the laser and interferometer structure.

The shaker is firmly mounted on a concrete block weighting about 1200 kg

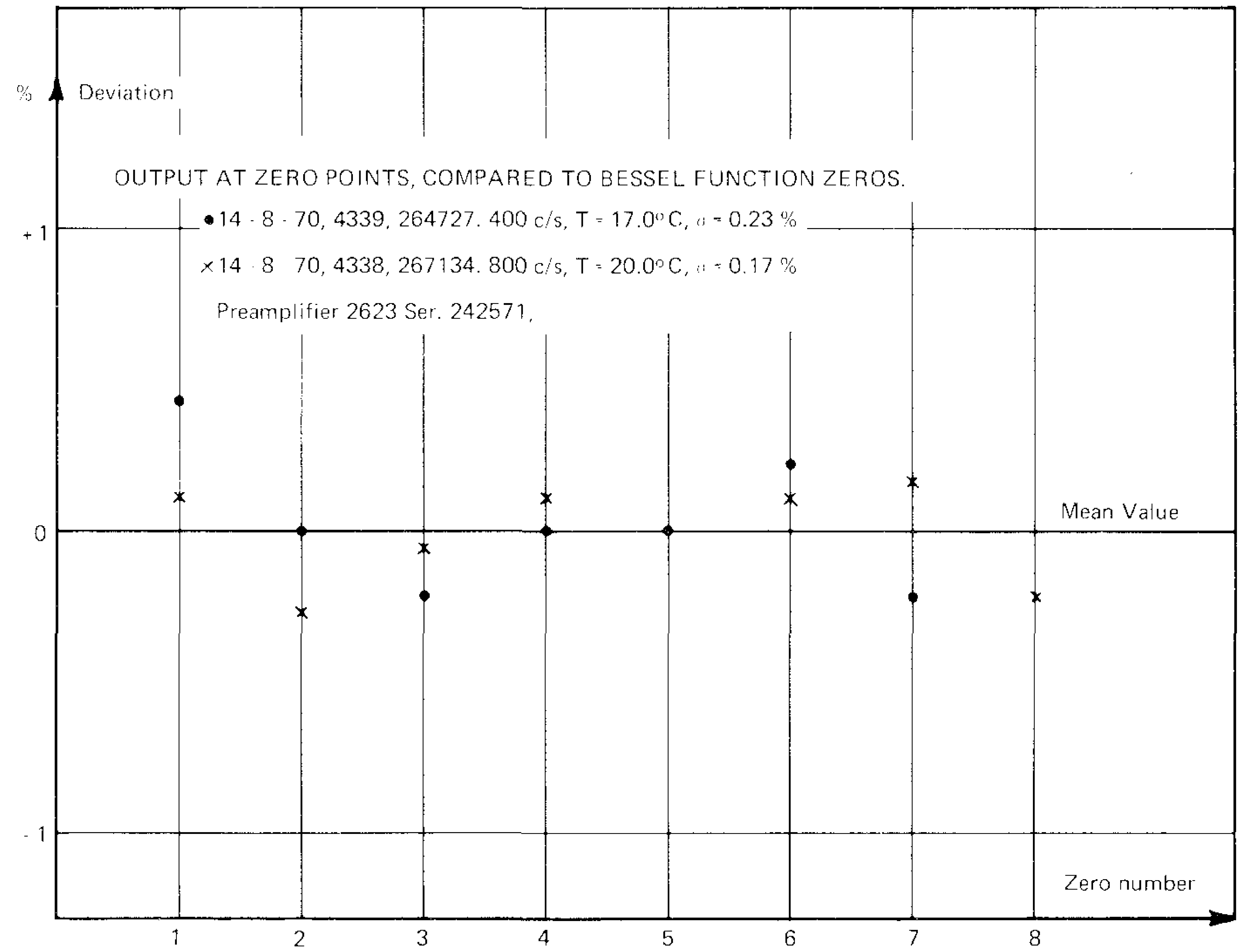

Fig.6. A plot of the deviation between accelerometer outputs at the theoretical zero points and at the Bessel function zeros.

and supported by springs having a resonance at 1 Hz. The laser and interferometer are mounted on the same block and isolated by rubber layers. The system works quite well as long as the frequency is above 50 Hz and when there are no large amplitude resonances in the shaker structure or interferometer.

To overcome these difficulties in future the interferometer will be mounted on another big block and the two blocks will be stabilised by means of special air springs so that they do not move appreciably relative to each other. The building vibration could also induce difficulties but it is hoped that the air springs will damp them more effectively than the existing springs.

Other applications

Apart from the calibration of vibration pickups attempts will be made in the near future to measure the displacement of microphone membranes. The method can be applied, to many similar vibration problems.

Finally it should be mentioned that by an optical FM technique it should be possible to measure shocks with an accuracy not attainable up to date.

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(5) Optical FM System for Measuring Mechanical Shock. L.D. BALLARD, W.S. EPSTEIN, E.R. SMITH, S. EDELMAN. N.B.S. Journal of Research 73 C, Nos. 3 and 4, p.75-78, Jul. – Dec. 1969.

A portable Calibrator for Accelerometers**

by

*Reinhard Kühl**

ABSTRACT

The Accelerometer Calibrator Type 4291 offers the following possibilities:

1) Generation of a defined acceleration level.
2) Check of the acceleration level of 1 g by the "shatter" method.
3) Comparison with a calibrated accelerometer.
4) Reciprocity method of calibration (using further auxiliary equipment).
   A formula is given, which reduces the measurement of the difference between absolute and relative motion to the measurement of electrical quantities only.

SOMMAIRE

Le nouvel excitateur type 4291 offre les possibilités suivantes:

1) Génération d'un niveau défini d'accélération.
2) Contrôle du niveau d'accélération de 1 g par la méthode de la "crécelle".
3) Comparaison avec un accéléromètre étalonné.
4) Etalonnage par réciprocité (avec utilisation d'un materiel auxiliaire).
   Une formule est donnée, qui réduit la mesure de la différence entre mouvement absolu e relatif à des mesures de quantités électriques.

ZUSAMMENFASSUNG

Der neue Kalibrator Typ 4291 bietet folgende Möglichkeiten:

1) Erzeugung einer definierten Beschleunigung, welche unter Berücksichtigung der Aufnehmermasse und der Generatorfrequenz mit Hilfe eines relativen Geschwindigkeitsempfängers gemessen wird.
2) Bezugnahme auf die Erdbeschleunigung nach der Prallmethode.
3) Vergleich mit einem geeichten Beschleunigungsaufnehmer.
4) Reziprositätsmethode (unter Mitverwendung weiterer Hilfsmittel).
   Zu 4) wird eine Formel angegeben, die den Unterschied zwischen den absoluten und relativen Bewegungen auf die Messung elektrischer Größen zurückführt.

---

*Reinhard Kühl KG., B & K's representative in Germany.

**) The device described in this article has been treated in an earlier article (T.R. Nr. 4, 1969). In the present paper, however, the reciprocity calibration method is more thoroughly explained. In the previous article a somewhat different terminology was used, and, unfortunately, printing errors have distorted the meaning of the sensitivity derivations on page 15, which should, therefore, be disregarded.

Normally, extremely heavy moving coil systems are used for calibrating accelerometers. They are often restricted to one place and cannot be used outside the laboratory.

The new Accelerometer Calibrator, Type 4291, is a portable instrument weighing only 2.7 kg. It incorporates a double magnet system with two mechanically coupled moving coils (Fig.1), one of which operates as driver and the other as a velocity pick-up. It contains a battery-operated generator and an indicating section, but the two coils can also be connected to external instrumentation.

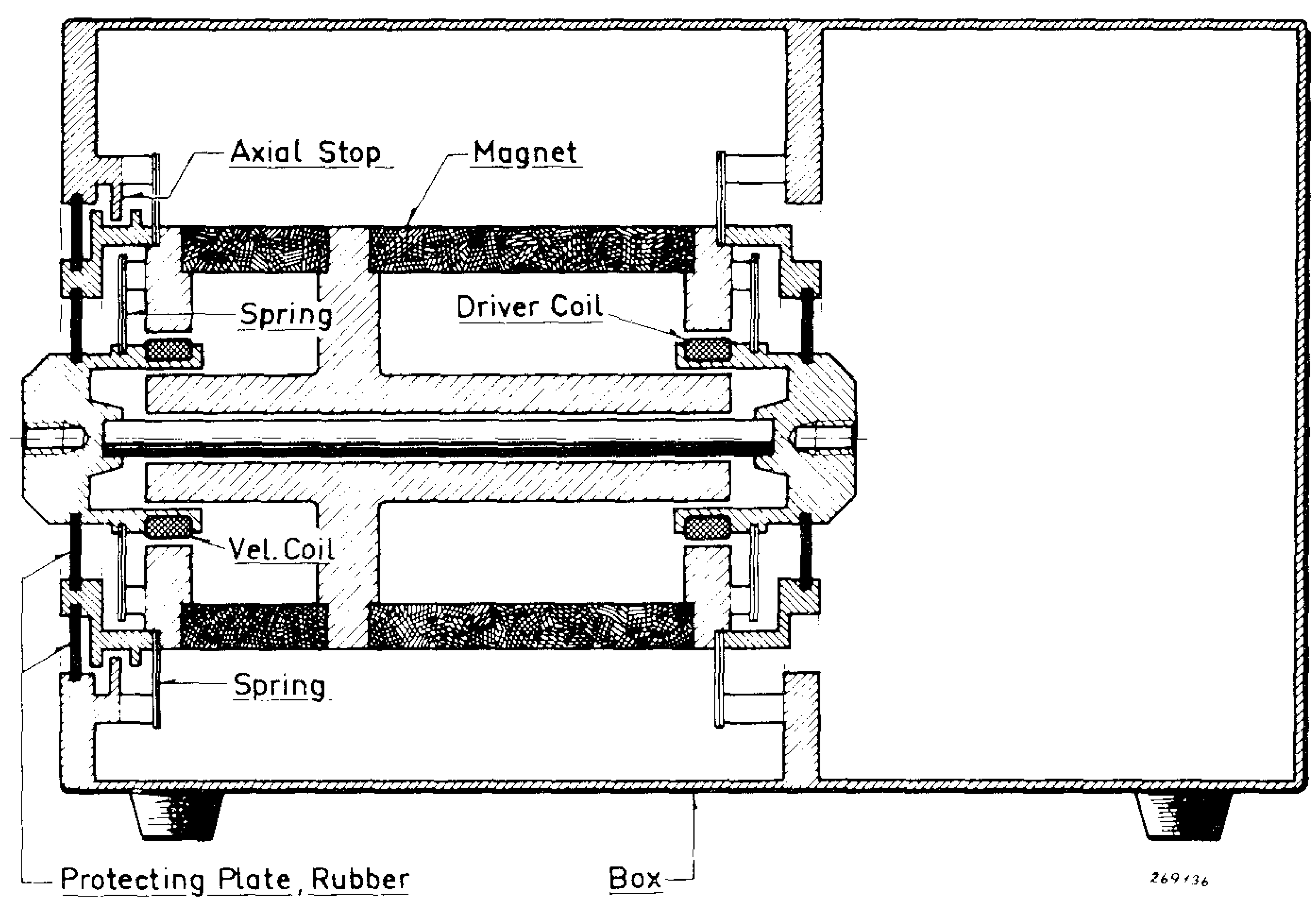

Fig.1. Cross-sectional view of the Accelerometer Calibrator Type 4291

The magnet weighs 1.2 kg and is isolated from the casing by springs. Since the magnet is also excited into motion by the force of the driving coil, to which the accelerometer is attached, the ratio of the absolute motion of the moving coils to their motion relative to the magnet is affected by the accelerometer mass. This effect is compensated for 0 to 100 g accelerometer mass by adjusting the meter needle on the scale of the indicating meter.

The peak acceleration is the 9.81 m/s^2 (RMS-value, 6.94 m/s^2) with max $\pm$2% deviation.

The meter scale also shows a partial range of $\pm$ 10% around 1 g acceleration level.

The meter reading is the velocity pick-up voltage which is related to the acceleration by the generator frequency (79.6 Hz or $\omega = 500\ s^{-1}$ in agreement with DIN 45666). An integration network has not been incorporated as it's time constant would not be more stable than the generator frequency.

The advantage of the selected operating level (1 g peak) is that it can be checked very easily by the "shatter" method. For this purpose the system must be installed vertically. Four supporting feet stored inside the casing can be screwed in threaded holes on the rear panel.

With the instrument placed vertically a test mass can be placed on top of the accelerometer to give a rattling noise when the acceleration level exceeds 1 g peak. When rattling commences (exactly at 1 g peak), distortion of the pick-up voltage can be observed on an oscilloscope.

The attainable accuracy depends on the test mass, which should not be greasy or magnetic. In a test series various turned parts, coins and nuts with a mass of about 1 g were used, errors between 1% and 10% due to air cushion, adhesion or unparallel natural movements occurred.

More reliable results are obtained with a calibrated accelerometer. Both ends of the moving system of the calibrator are provided with threaded holes, so that two accelerometers (with a total weight of up to 0.1 kg) can be compared with each other. It should be taken into account that the moving system including the two coils and their coupling bar does not weigh more than 16 g and is therefore only of limited rigidity. Hence the comparison error will increase with the weight of the accelerometers and frequency although with 50 g accelerometers and at 80 Hz it still does not exceed ± 1%. The second mounting platform is accessible after removal of the base plate and space is provided in the casing for mounting the second accelerometer. If the two accelerometers have different masses, the heavier one should be mounted on the driving side of the moving system.

The sensitivity of an accelerometer can also be determined very accurately (independent of the built-in electronics and a calibrated reference accelerometer) by the reciprocity method if the following equation allowing for the difference between the absolute and relative movements of the system is used:

$$S_{acc} = \sqrt{\frac{M}{\omega\,(Y_m A_o - Y_o A_m)}}$$

where

S_{acc} = sensitivity of the accelerometer in Vs^2m^{-1}
ω = angular frequency $2 \pi f$ in s^{-1}
M = additional mass in kg
Y = (velocity coil current)/(accelerometer voltage) in A/V
A = (unloaded velocity coil voltage)/(accelerometer voltage)

Y_o and A_o are measured with the accelerometer alone, Y_m and A_m with an additional mass M attached to the moving platform.

Practical measurement is carried out as follows: The accelerometer is screwed with a cable clip on the front moving table which is nearest to the velocity coil. A trace of vaseline is applied as a contact agent.

Since the accelerometer, it's cable and the preamplifier can be considered as an electrical unit, the voltage at the output of the preamplifier can be measured and thus the calculated sensitivity S can be referred to this output.

The use of an additional mass makes it possible to express the transducer sensitivity in terms of measured electrical quantities and avoids the necessity of weighing the moving system and the magnet structure.

Several cylindrical parts made of non-ferromagnetic material were used with an axial threaded hole (10–32 NF). The diameter and quality of the flat supporting surfaces are similar to those of the Brüel & Kjær accelerometers. These surfaces are also lubricated with a trace of vaseline. A threaded pin is glued in on one side, so that one or more parts, to form a mass, can be mounted between the accelerometer and the moving table if required. The parts should be weighed to within ± 1 mg. (The parts manufactured for the test weighed 0.02150 kg).

It is convenient if the additional mass M equals the mass of the moving system including the accelerometer, as in this case $Y_m/Y_o = 2$.

In both the assemblies – except for the additional mass – all other parts such as accelerometer, cable, cable clip and stud bolt must be the same.

A frequency counter on a 10 second time basis is recommended for frequency measurement. The above formula is valid only for the frequency range which is well away from the natural frequencies of the system.

Depending on the weight of the accelerometer, the following ranges are recommended:

Mass of accelerometer:	Recommended frequency range:
16 g	300 Hz – 1.0 kHz
30 g	200 Hz – 500 Hz
50 g	180 Hz – 300 Hz

Weaker partial resonances may also affect the measuring results within the recommended frequency ranges. Hence it is advisable to repeat the measurement at different frequencies.

Corresponding measured values must, however, always be determined at the same frequency.

A calibrated series resistor is required for measurement of the moving coil current (see Fig.2). Two contact terminals, which must not touch each

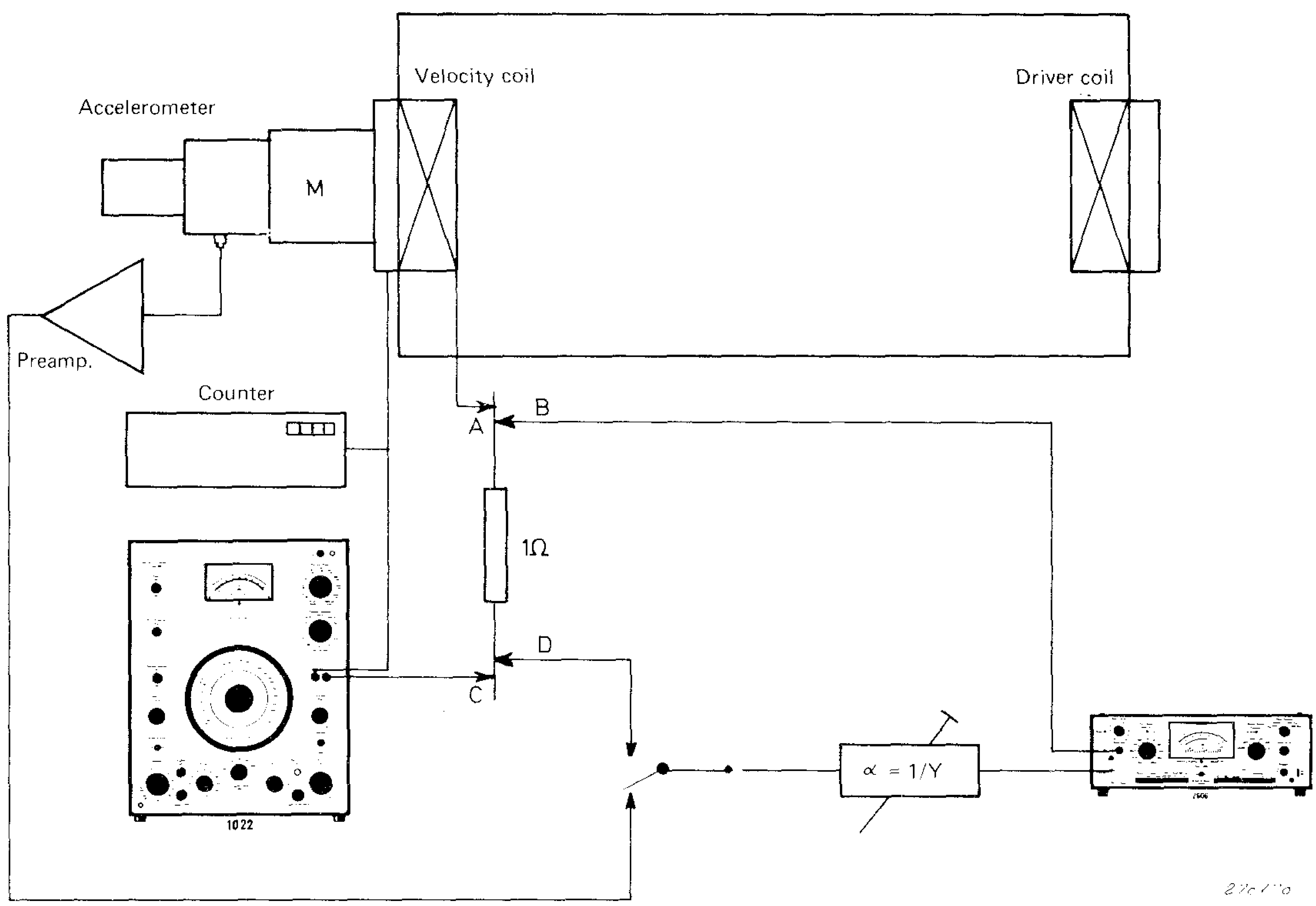

Fig.2. Measuring arrangement to determine Y. The attenuator is used to adjust the 2606 meter to read the same voltage across the measuring resistor as that given by the previously measured accelerometer voltage. The attenuation factor α now equals 1/Y.

other, are attached to each of the resistor wires. The two outer terminals A and D are connected to the coil and the generator respectively, the two inner terminals B and C to the voltmeter.

Apart from leads B and C, no further connections may be made between the generator and voltmeter (ground loops).

The resistance between terminals B and C should be exactly 1 Ω, so that the current can be directly read off the voltmeter.

During measurement of A (see Fig.3) the generator (e.g. Beat Frequency Oscillator Type 1022) is connected to the driver coil and the voltage at the unloaded velocity coil is referred to the voltage of the accelerometer preamplifier output.

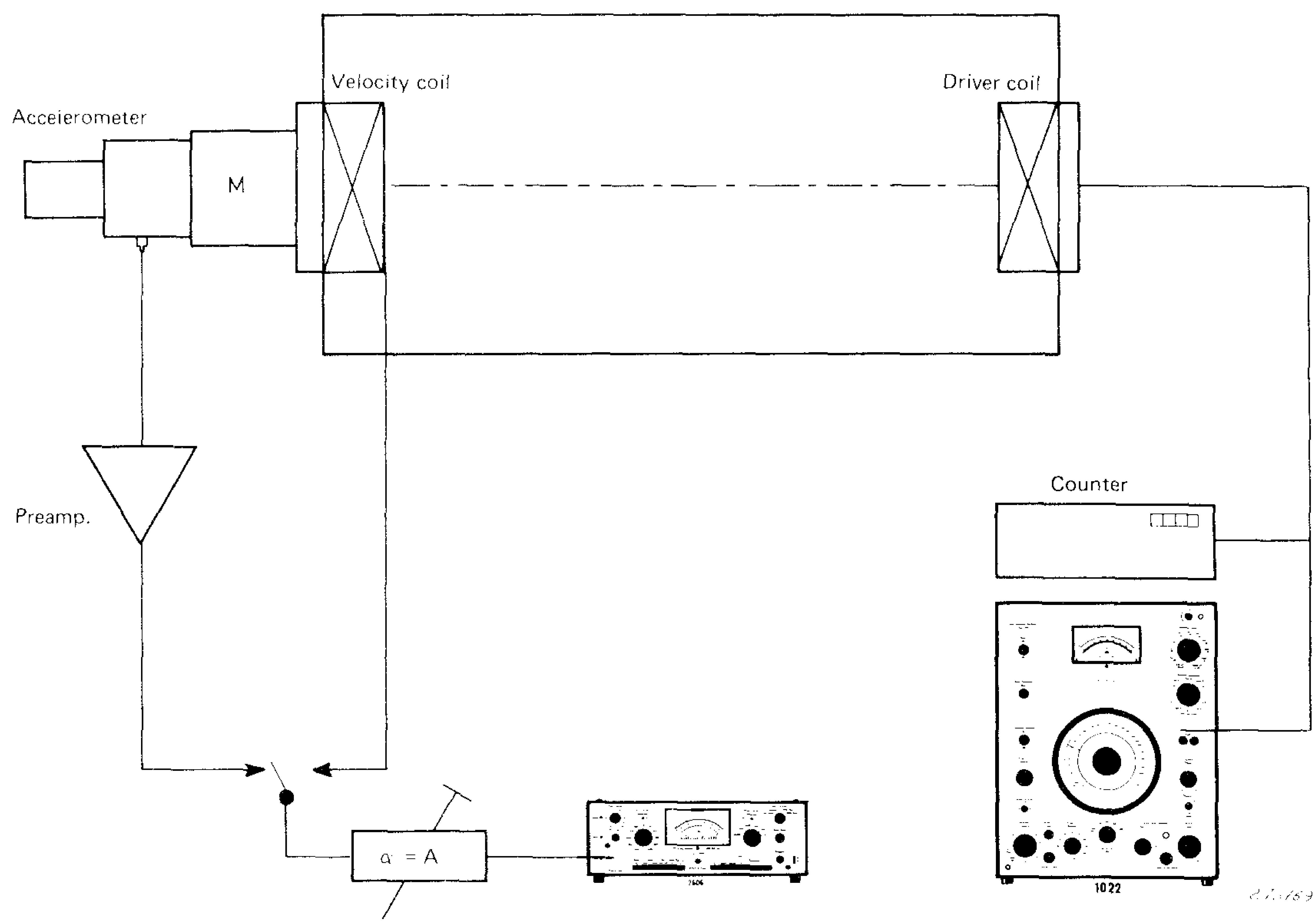

Fig.3. Measuring set-up to determine A. The attenuator is used in the same way as shown in Fig.2, this time to find $\alpha = A$.

An uncalibrated voltmeter will suffice for measurement of the ratio A and the admittance Y, if a calibrated attenuator is used. A rectifying electronic instrument, e.g. Measuring Amplifier Type 2606, can be used as voltmeter. One of the test results is given below as an example.

$$
\begin{aligned}
M &= 0.06469 \text{ kg} \\
f &= 294.8 \text{ Hz} \\
Y_o &= 4.15 \text{ A/V} \\
A_o &= 0.254 \\
Y_m &= 8.44 \text{ A/V} \\
A_m &= 0.263 \\
S_{acc} &= 5.76 \text{ mVs}^2\text{m}^{-1} \\
\times 9.81 &= 56.5 \text{ mV/g}
\end{aligned}
$$

Brief Communications

The intention of this section in the B & K Technical Reviews is to cover more practical aspects of the use of Brüel & Kjær instruments. It is meant to be an "open forum" for communication between the readers of the Review and our development and application laboratories. We therefore invite you to contribute to this communication whenever you have solved a measurement problem that you think may be of general interest to users of B & K equipment. The only restriction to contributions is that they should be as short as possible and preferable no longer than 3 typewritten pages (A 4).

Electro Acoustic Ear Impedance Indicator for Medical Diagnosis

by

Å. Rypdal. *

Introduction

Electro acoustic impedance meters are used to detect small *changes* in the impedance of the ear. Today they are commercially available as very sensitive electro acoustic measuring bridges, but they are rather expensive.

Laboratories which possess apparatus for hearing aid tests can easily supplement this equipment to obtain an impedance indicator with a generally satisfactory sensitivity. The necessary additions are an oscillator to supply a carrier frequency (probe tone) to the ear, and an air-tight system which has to be made manually. The combined measuring arrangement is shown in Fig.1.

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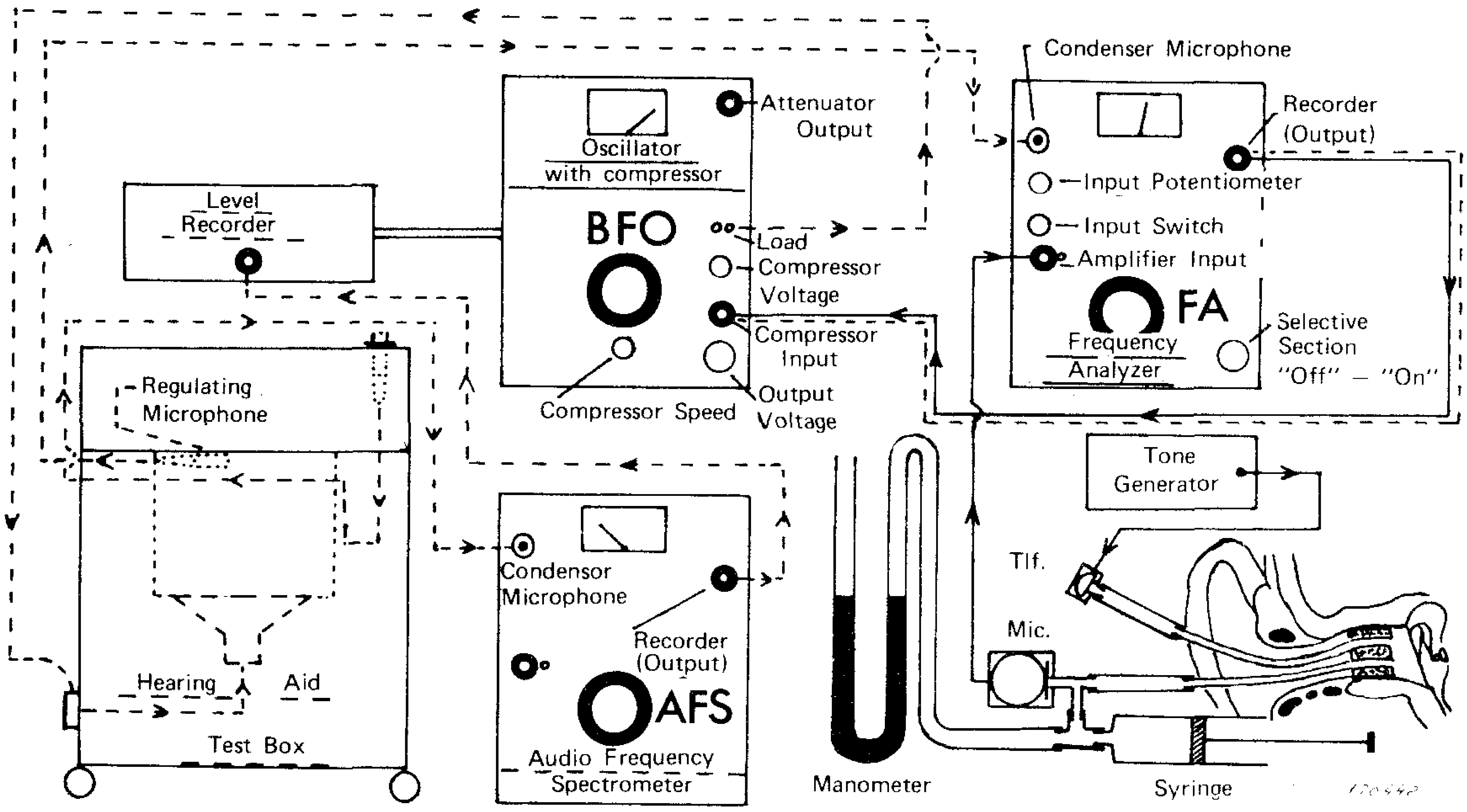


Fig. 1. *Measuring arrangement suitable for either testing hearing aids or for impedance indication*

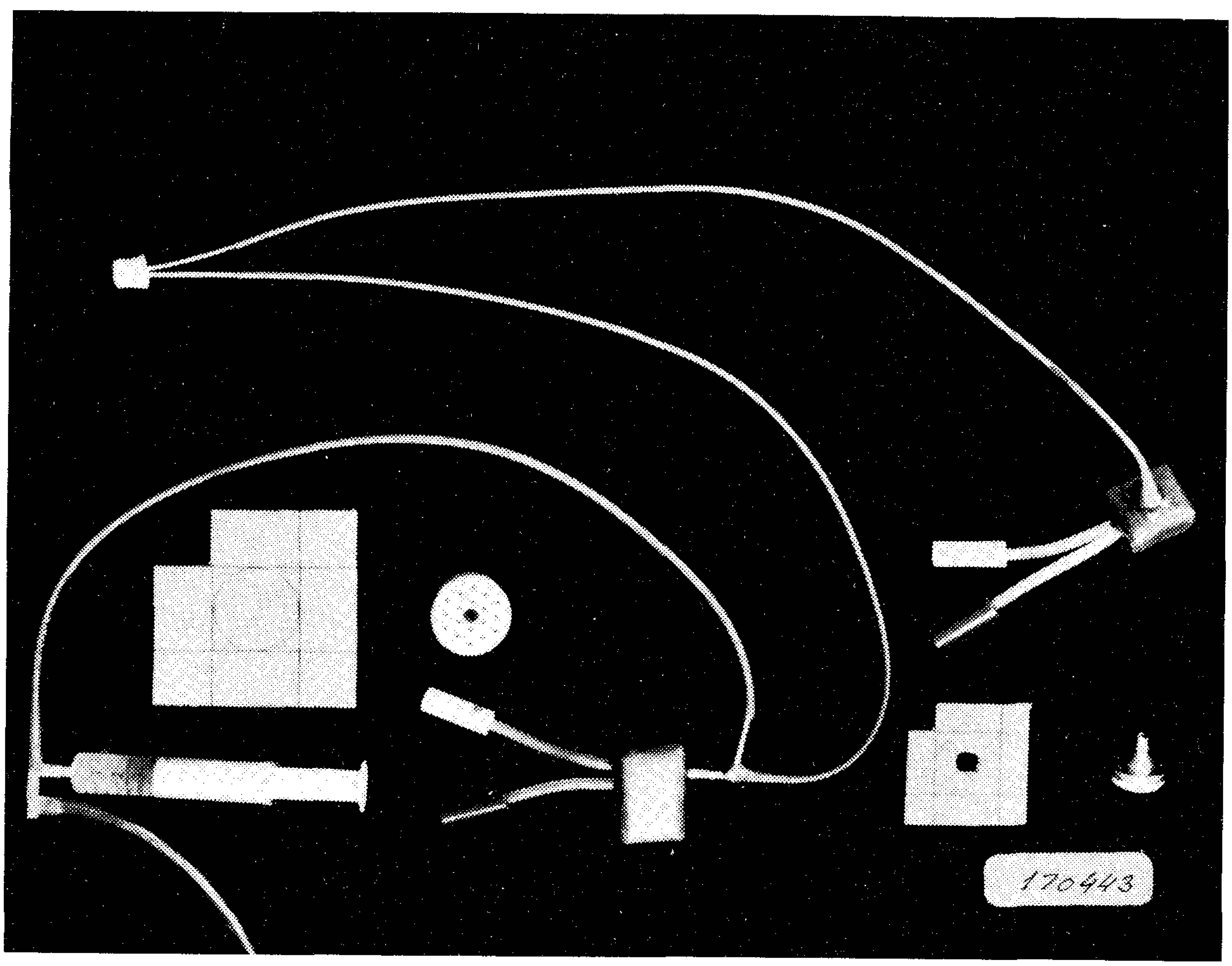


Fig.2. *The "hand-made" air-tight system.*

The "Hand-made" system

The air-tight "hand-made" system consists of an earplug connected to a hearing-aid telephone and a crystal-microphone (Tandberg TM3). The internal pressure can be regulated by a syringe and measured by a simple manometer made of a piece of transparent plastic tube. The telephone and microphone housings are made of small cardboard boxes lined with rubber paste to minimize internal volumes and finished with a polyester coating on the outside to ensure air-tightness.

From the telephone a catheter (rubber tube) leads to the earplug which is made of sponge rubber with closed pores and with two polyethylene connecting tubes. The microphone is connected to a copper tee from which a catheter leads to the earplug and another to a plastic tee, to which the pressure regulating syringe and the plastic tube manometer are connected. The complete air-tight system is shown in Fig.2.

The Electronic Measuring Arrangement

Fig.1 shows the measuring arrangement. The dotted lines are the connections for hearing aid measurements, and the full lines are the connections necessary for indication of very small impedance *changes*. The arrangement consists of an oscillator[1]) feeding the telephone in the air-tight system. The sound pressure thus produced, is measured by the crystal microphone and the resulting signal amplified by a Frequency Analyzer Type 2107 (hereafter called FA) which is used as a selective amplifier and voltmeter[2]). The FA is sufficiently sensitive to perform tympanometry, the procedure of which is explained in the following.

Tympanometric measurements

A probe tone (most frequently 220 Hz) is applied to the telephone. The sound pressure level is adjusted to give a median needle position of the FA (at about 75 dB SPL).

The regulating syringe is then adjusted for minimum deflection of the FA needle. Now the sound absorption has reached its maximum and the sound

---

1) Since the Beat Frequency Oscillator included in the Hearing Aid Test Apparatus is used as a sensitive instrument for indication of changes in impedance, another oscillator must be used to feed the telephone. The author has sometimes used a practical, inexpensive oscillator belonging to the laboratory, and sometimes an old audiometer discarded for its original purpose.

2) Type 2112 or 2113 Audio Frequency Spectrometers can be used as a selective amplifier and voltmeter if a Type 2107 Frequency Analyzer is not available.

reflection from the ear drum its minimum. The air pressures inside and outside the ear drum are now equal, and the manometer shows the middle ear pressure relative to the atmospheric pressure.

A significant subnormal middle-ear pressure indicates an impaired function of the Eustachian tube (ear trumpet).

From this point the air pressure in the external auditory canal is continuously varied from −20 to + 20 cm water pressure, and the deflections of the FA needle are carefully inspected during the procedure.

Very rapid backwards and forwards deflections of the FA meter needle are often observed around the pressure balance point in cases with a thin scar in the ear drum.

Finally, to obtain a tympanogram, the Level Recorder Type 2305 is connected to the output of the FA, the air pressure is varied in small steps and the resulting changes in ear impedance are indicated by the level shifts of the recorder stylus.

A normal tympanogram shows a minimum level when the air pressure in the external auditory canal is close to the atmospheric pressure. From that minimum the level goes up steeply for a slight increase or decrease of the air pressure. By further increasing or decreasing the air pressure in equal steps, the level will continue to go up but at a decreasing rate to asymptotically reach a maximum level.

With respect to the hard of hearing, normal tympanograms are found in all cases of stapes fixation (otosclerosis) without any other combined disorders of the middle ear or ear drum, and in all cases with only sensorineural lesions. Several types of tympanograms are recorded by pathological changes in the ear drum and/or in the middle ear.

A flat, straight line tympanogram (which can easily be recognized by careful inspection of the FA meter needle only) is produced by the following conditions, a): perforation (hole) in the ear drum, b): abundant fluid in the middle ear, c): the ear drum fixed by adhesions, d): severely retracted ear drum caused by excessively subnormal middle ear air pressure.

With respect to other types of pathological tympanograms, the undulating curves with broad peaks and varying, partly large amplitudes, shall here be mentioned. They are seen by disruption of the ossicular chain in the middle ear.

Middle ear muscle reflex measurements

For investigations other than tympanometry, a much more sensitive indicating arrangement is desired. This is especially the case for examinations associated with the contractions of the middle ear muscles: the stapedius- and the tensor tympani muscle. Such contractions cause very small impedance changes, resulting in very small variations of the needele position on the FA. Therefore, to obtain better detectable results, the Beat Frequency Oscillator (B.F.O.) Type 1022 is used as a *variation-sensitive voltmeter.*

Normally the Type 1022 is used to deliver an audio frequency voltage to a test arrangement. The signal level can be kept constant at a point of the test circuit by feeding a voltage proportional to the signal back to the compressor circuit of the B.F.O. Here the signal is rectified and averaged, and then used to control a voltage controlled amplifier in the oscillator circuit. If the controlled signal level becomes too high, the compressor voltage goes up, thereby reducing the amplifier gain and oscillator output until the specified condition at the measuring point is reestablished. The speed of correction depends on the averaging time constant, and is selected by the compressor speed knob which allows four different correction speeds from 30 dB/sec to 1000 dB/sec.

In the present arrangement the B.F.O. is not used in the usual way. The output from the FA is as usual led to the compressor input: the B.F.O. is set at any frequency and its output voltage knob is turned to maximum. The output socket is not connected.

Fig.3. A patient prepared for impedance testing. Note the air-tight system suspended from the angle-poise lamp.

The compressor voltage knob of the B.F.O. is now used to adjust the needle of the meter scale to a reference point on the far right. Now any change in the sound pressure level in the external auditory canal amplified by the FA changes the compressor voltage and the gain of the oscillator circuit, thereby changing the meter position. The needle deflection will be approximately 20 times that of the FA.

As a rule a compressor speed of 30 to 100 dB/sec is sufficient for indication of ear impedance changes caused by contraction of the stapedius muscle[3]) when the reflex is triggered acoustically by audiometer tone stimulations to the contralateral ear.

The acoustically triggered stapedius muscle reflex is bilateral. The audiometric tones or the sound from a Bárány's noise box, which impinge upon the one ear (termed the stimulated ear), elicit contraction of the stapedius muscle in both ears, but are registered by the other ear, supplied with the plug and the probe tone and termed the indicating ear.

Normally, a stapedius muscle reflex audiogram (which is registered objectively) will show reflex threshold for the different tones about 70-90 dB above the hearing threshold of the stimulated ear. If the reflex is evoked at essentially lower dB values than here mentioned it indicates a cochlear type of hearing defect with the recruitment phenomenon.

However, for indication of the tactile elicited contraction of the stapedius muscle, the reflex triggered by a short duration contact to the auricle-skin of the homolateral ear, a faster meter needle deflection is usually necessary, and the maximum compressor speed of 1000 dB/sec is, therefore, desirable. The same is true also for the combined stapedius/tensor muscle contraction reflex, elicited by lifting the upper eylids.

Using the higher compressor speeds may, however, cause an instability of the meter needle on the B.F.O. This might necessitate a lowering again of the compressor speed.

Fig.4 shows a simplified scheme of the human ear. The tendon of the stapedius muscle is attached to the head of the stapes close to its articulation with the anvil (incus). Contraction of this muscle draws the stapes head outward and downward, decreases the stapes movements and changes the ear impedance. But, no impedance change will take place by contraction of *only* this muscle, if the stapes is fixed in the oval window (otosclerosis). An impedance change occurs in this case, however, if the tensor muscle contracts. As mentioned the tympanogram is normal in this case.

---

3) The topographical diagnoses of facial nerve palsies, of clinical value: At a point where the facial nerve passes in the neighbourhood of the stapes, the stapedius nerve fibres leave the facial nerve and enter the stapedius muscle. As a rule the facial nerve lesion is situated peripherally to that point if the stapedius muscle reflex can be easily elicited.

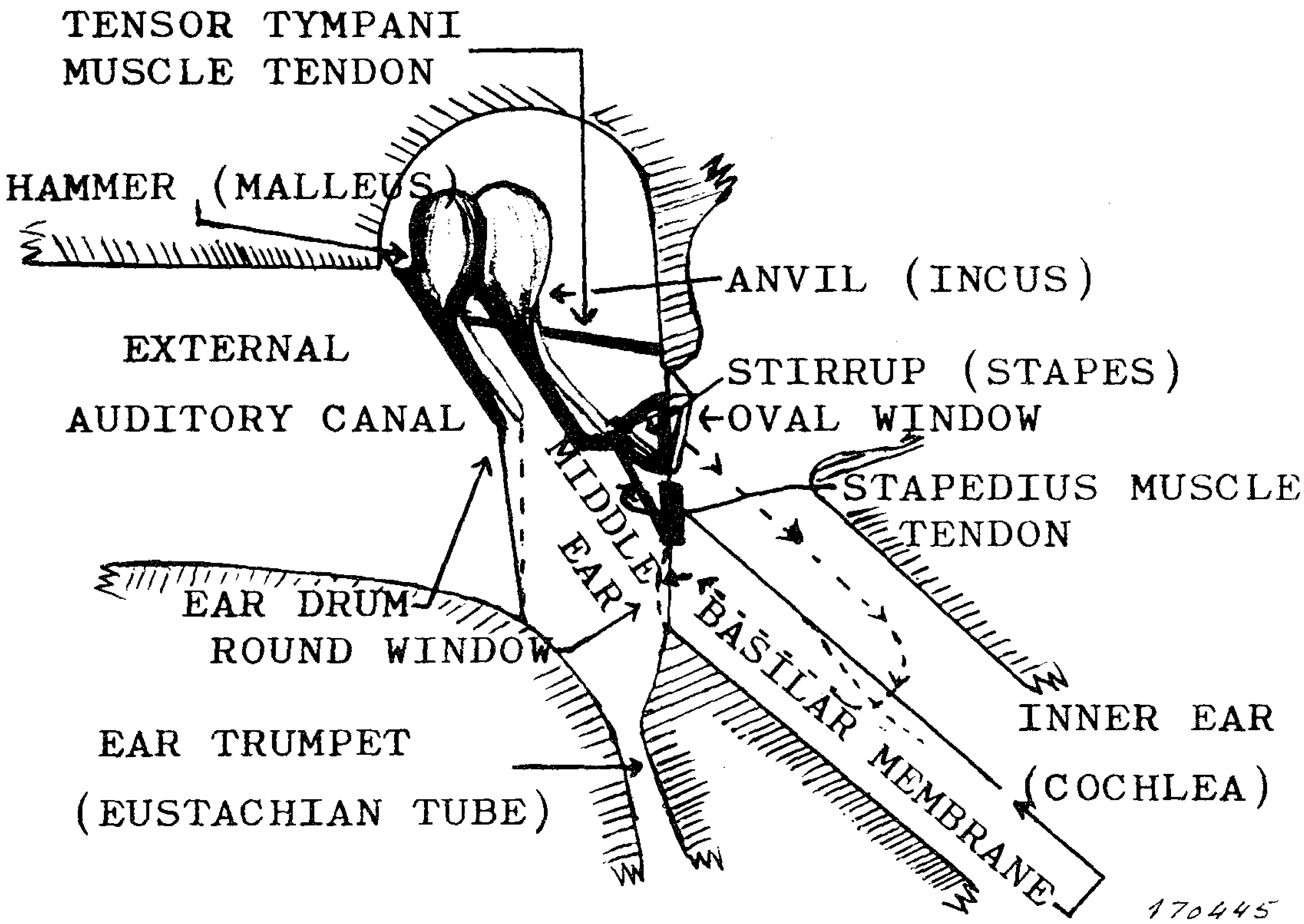


Fig.4. A simplified drawing of the human ear.

The tensor tympani muscle tendon attaches to the handle of the hammer, placing the ear drum under tension. In distructions of the ossicular chain, the tympanograms, as a rule, are not normal. With disruption corresponding to the anvil, contraction of the stapedius muscle with displacement of the stapes will not alter the impedance, but contraction of the tensor muscle will now force the ear drum inward in an exaggerated degree, resulting in an impedance change *larger* than normal.

With further regard to the diagnostic values of registered ear impedance changes elicited by reflex contractions of the two middle ear muscles, the following scheme set up by Gisle Djupesland in INTERNATIONAL AUDIOLOGY Vol. VIII No. 4, October 1969, page 547, is here presented.

Size* of impedance change in relation to type of stimulus in various middle ear lesions

Middle ear lesion	*Acoustic stim.*	*Tactile stim.*	*Lifting upper eyelid*
Subnormal middle ear pressure (25–125 mm water)	+ or ++	–	+ or ++
Fixation of stapes (otosclerosis)	–	–	+ or ++**
Ossicular chain defect corresponding to stapes crura	++	– or +	++ or +++
Ossicular chain defect corresponding to incus	–	–	+++
Partial defect of the ossicular chain corresponding to the long process of incus	+	–	+++
Fixation of malleus and incus	–	–	–

* The impedance indicator has a linear voltmeter scale grade from 0–100. Needle deflection on this meter reflects the degree of imbalance caused by changes in impedance which were observed and recorded according to the following key:

– = Absent (no deflection of the voltmeter needle)
\+ = Small (voltmeter needle deflection $\stackrel{=}{>}$30)
++ = Normal (voltmeter needle deflection 35–95)
+++ = Abnormally large (voltmeter needle deflection $\stackrel{=}{>}$100)
** Diphasic.

In his investigations he has used a commercial electro acoustic measuring bridge, which is somewhat more sensitive than the supplemented hearing aid test apparatus used by the author for years.

Conclusion

The Ear Impedance Change Indicator is obtained by simple and low cost supplements to an ordinary Hearing Aid Test Apparatus. The change from hearing aid tests to ear impedance indication is easily performed, and in the following manner:

On the FA the input switch is changed to amplifier input, the selective section is switched on and the selectivity is adjusted. (See Fig.1).

The loudspeakers terminals are disconnected from the sockets of the B.F.O.

By tympanometric measurements the recorder socket of the FA is connected to the Level Recorder.

In his medical work, the author has found this supplemented equipment very useful as a combined instrumentation for tympanometric and middle ear reflex investigations for diagnostic purposes.

PREVIOUSLY ISSUED NUMBERS OF BRÜEL & KJÆR TECHNICAL REVIEW

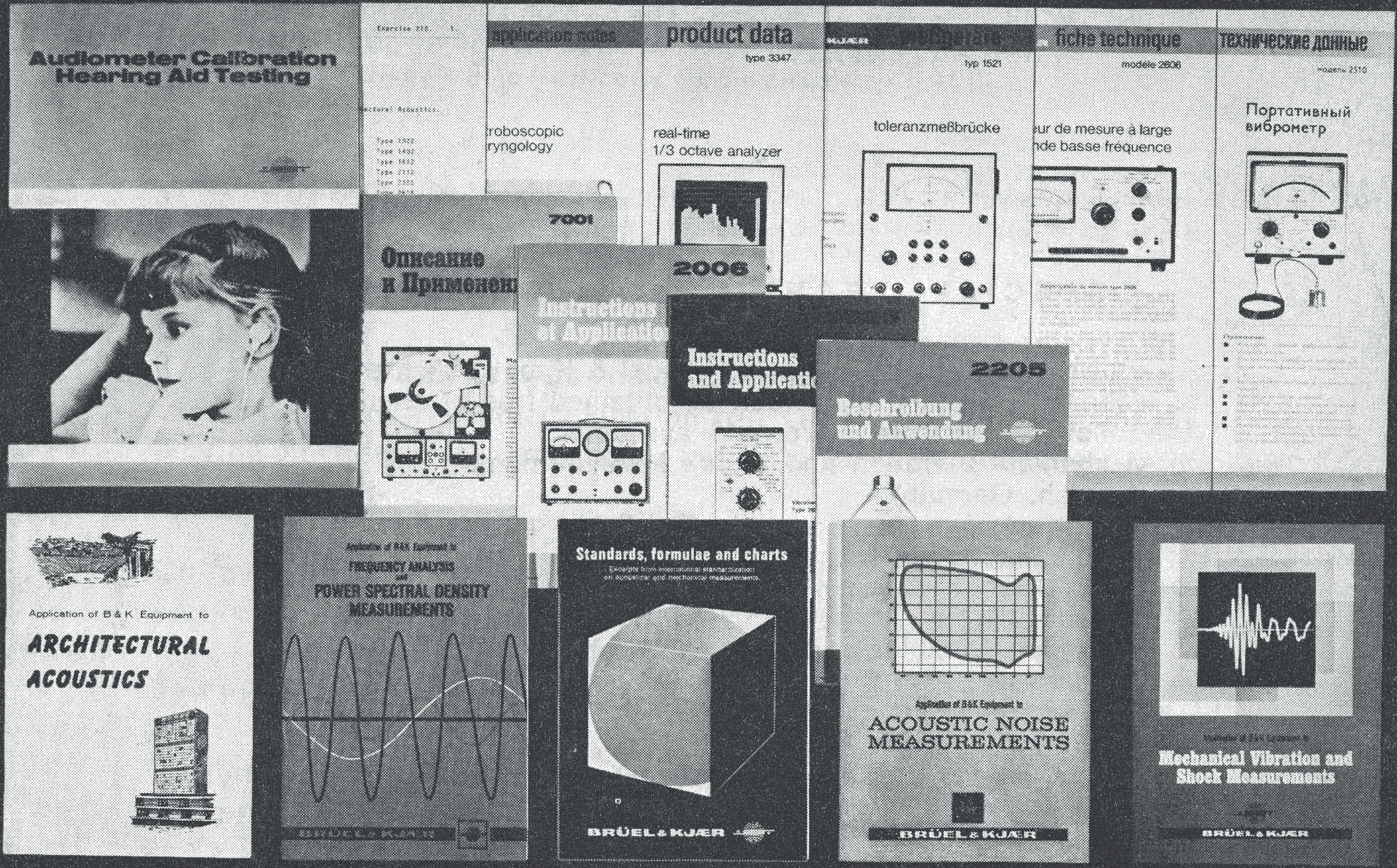
(Continued from cover page 2)

SPECIAL TECHNICAL LITERATURE

As shown on the back cover page Brüel & Kjær publish a variety of technical literature which can be obtained free of charge.
The following literature is presently available:

- Mechanical Vibration and Shock Measurements (English, German)
- Acoustic Noise Measurements (English)
- Architectural Acoustics (English)
- Power Spectral Density Measurements and Frequency Analysis (English)
- Standards, formulae and charts (English)
- Lectures and exercises for educational purposes (a list of available papers is obtainable in English)
- Instruction manuals (English, German, French, Russian)
- Short Catalogue and Main Catalogue
- Product Data Sheets (English, German, French, Russian)

Furthermore, back copies of the Technical Review can be supplied as shown in the list above. Older issues may be obtained provided they are still in stock.



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