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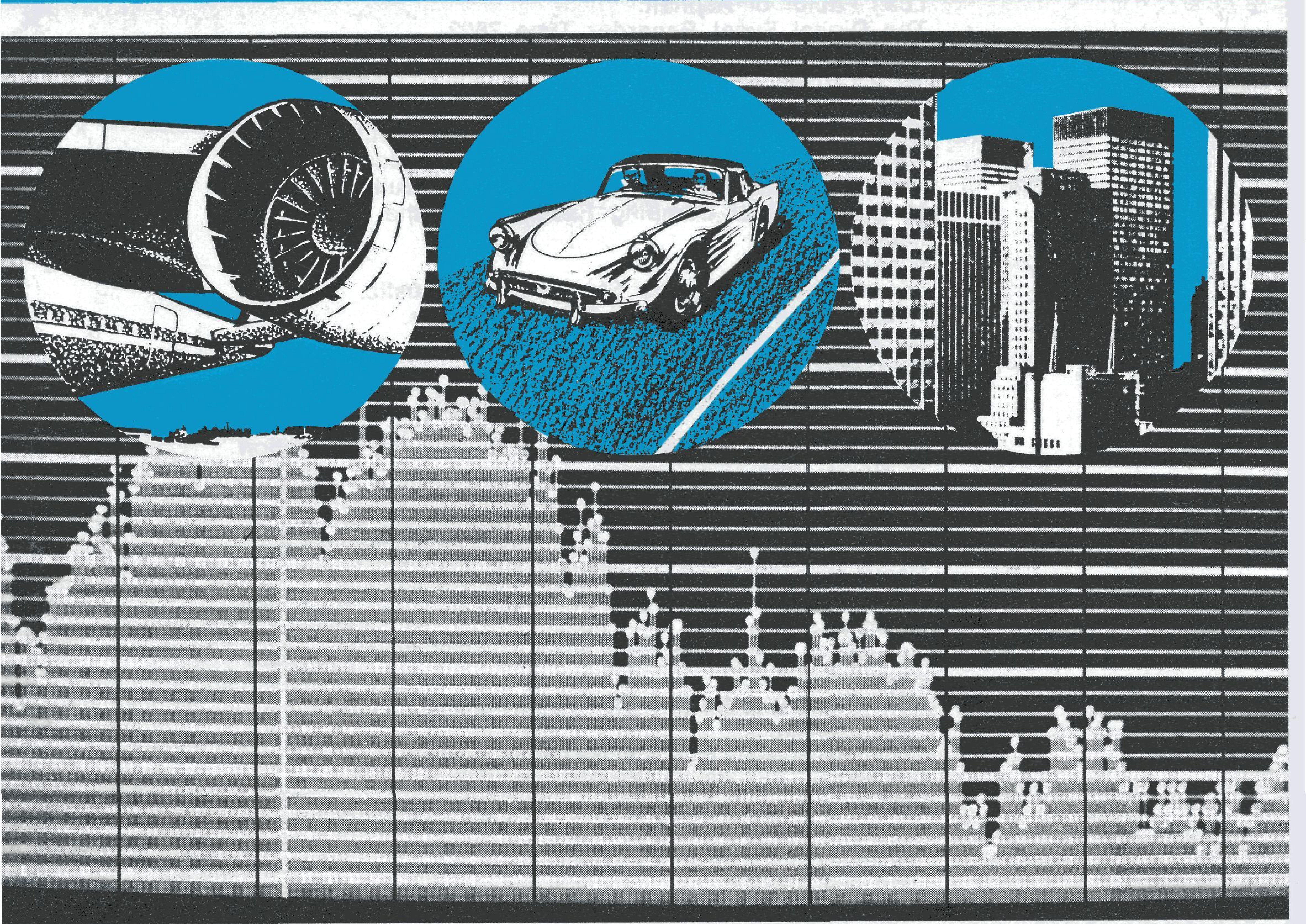

Noise Dose Infrasound Impeller Response

BRÜEL & KJÆR

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TECHNICAL REVIEW

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Contents

Sources of Error in Noise Dose Measurements*

by

L.S. Christensen M. Sc.
and J.R. Hemingway M. Phil.

ABSTRACT

Measurement of industrial noise dose can be in error if stationary microphones are used. The design of a personal noise dose meter is described. Possible errors due to body shielding and reflection effects were investigated in the laboratory. The personal dose meter was also tested in an industrial environment. Body shielding and reflection effects were found to be small and minimized by measurement at the ear position. In some industrial cases highly directional sound fields produce errors which can be minimized in the same way.

SOMMAIRE

La mesure de la dose de bruit industriel peut être inexacte si l'on utilise des microphones fixes. L'article décrit la réalisation d'un dosimètre de bruit personnel. Les erreurs possibles dues aux effets de réflexion et d'écran du corps ont été étudiées en laboratoire. Le dosimètre personnel a aussi été essayé dans un environnement industriel. Les effets de réflexion et d'écran du corps ont été trouvés faibles et minimisés par des mesures au niveau de l'oreille. Dans certains cas industriels, les champs sonores très directifs introduisent des erreurs qu'on peut minimiser de la même façon.

ZUSAMMENFASSUNG

Für die Messung der Lärmbelastung am Arbeitsplatz eignet sich ein Taschendosimeter besser als ein stationäres Gerät. Schallfeldverzerrungen am Körper haben im allgemeinen nur einen geringen Einfluß auf die Meßergebnisse, im Zweifelsfall kann das Mikrophon in Ohrnähe getragen werden.

Introduction

Criteria for occupational noise exposure in Western Europe and North America can generally be referred to two sources: In USA and Canada the "Occupational Safety and Health Act" OSHA (succeeding the "Walsh-Healey Act") and in Europe ISO Recommendation 1999 (Assessment of Occupational Noise Exposure for Hearing Conservation Purposes).

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* This paper was initially presented at the Inter-Noise '73 Conference, Copenhagen, August 22-24 1973

In both cases the criteria are based on measurements of the equivalent continuous noise level L_{eq}, provided the noise is not of an "impulsive" or "tonal" nature (in which case special measurements or L_{eq} modifications are prescribed). In the case of a constant noise level, L_{eq} is defined simply as the Sound Level measured in dB(A), while L_{eq} for a non-stationary noise level is calculated on the basis of a prescribed trading relationship between Sound Level and exposure duration; for OSHA this is 5 dB(A) per duration factor 2, for ISO 3 dB(A) per duration factor 2. For example, according to ISO 93 dB(A) for 4 hours is equivalent to 90 dB(A) for 8 hours or 96 dB(A) for 2 hours. (Fig. 1.)

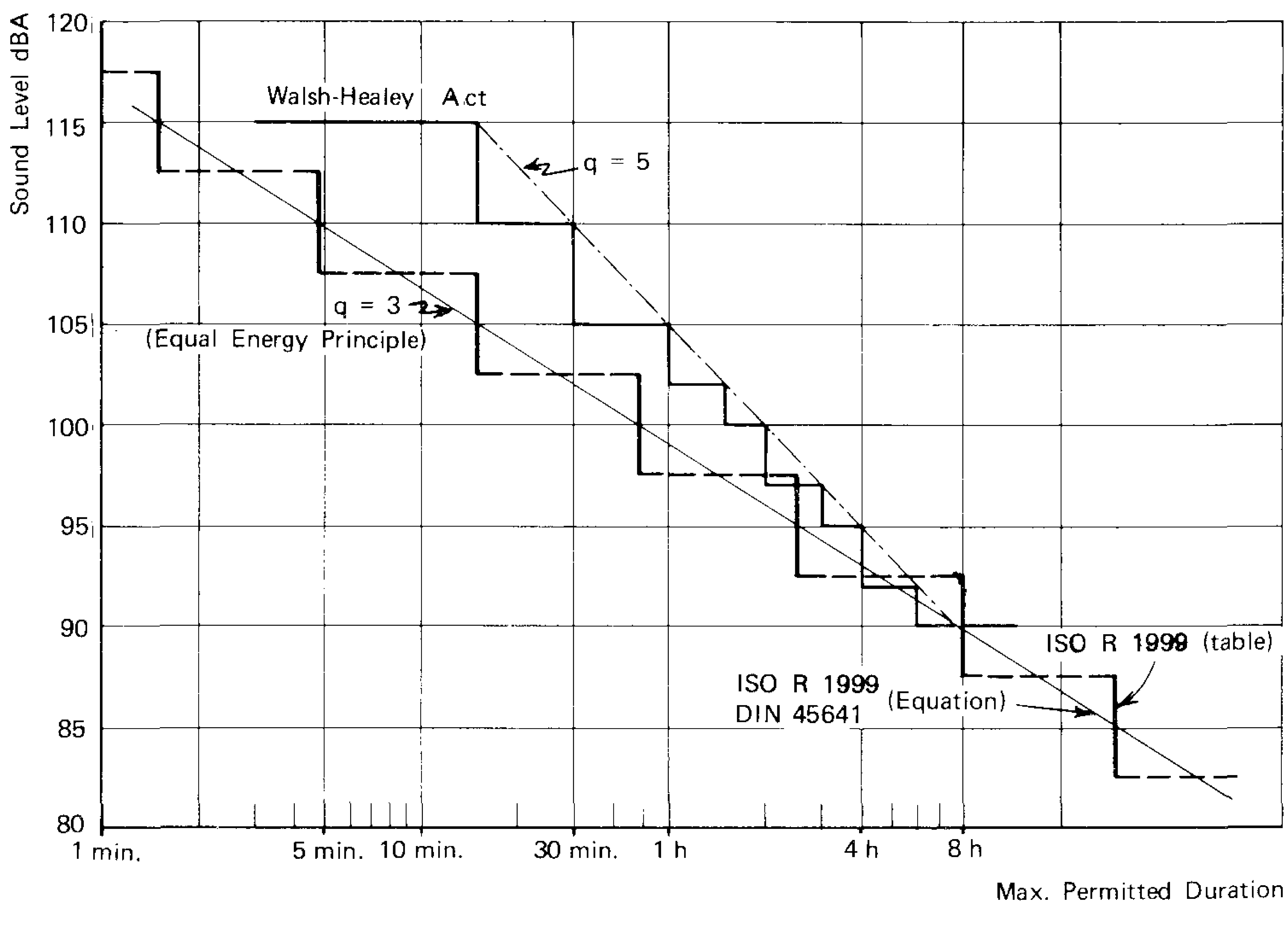

Fig. 1. The Relationship between Sound Level and Duration for the Walsh-Healey Act and ISO R 1999 (for ISO Applying the Criteria 90 dB(A) for an 8 Hour Workday and No Corrections)

The risk of damage to hearing at L_{eq} = 90 dB(A) (at present the most common value for maximum acceptable L_{eq}) is indicated in ISO 1999 as 18% at exposure 40 hours per week, 50 weeks per year for 40 years; a person has 21% chance of more than 25 dB hearing loss in consequence of occupational noise exposure. Hearing loss is described as the average loss at 500, 1000 and 2000 Hz, intelligibility of speech being the measure of loss. Besides the 21%, there is a 33% probability of hearing loss referred to the effect of age.

In the criteria mentioned, the following factors of uncertainty are inherent:

1. Application is restricted to broadband noise with no "impulsive" character and the limits of application are vague.

2. The relationship between L_{eq} and hearing loss is not well established (exemplified in the difference between OSHA and ISO).

3. Noise exposure is assumed to be constant for very long periods of time (many years).

4. The definition of what constitutes "hearing loss" is rather arbitrary.

5. The choice of maximum permitted L_{eq} (i.e. the accepted risk of hearing loss) is rather arbitrary.

6. Individual differences in susceptibility to hearing loss are not accounted for.

Some of these factors are dependant on the political and economical background of society — the distribution of power — while others also depend on the state of medico-acoustical knowledge and the measurement technique available. However, in most countries controversy is centred around the introduction of effective noise limits at all so for a while the weaknesses mentioned above are of rather academic interest.

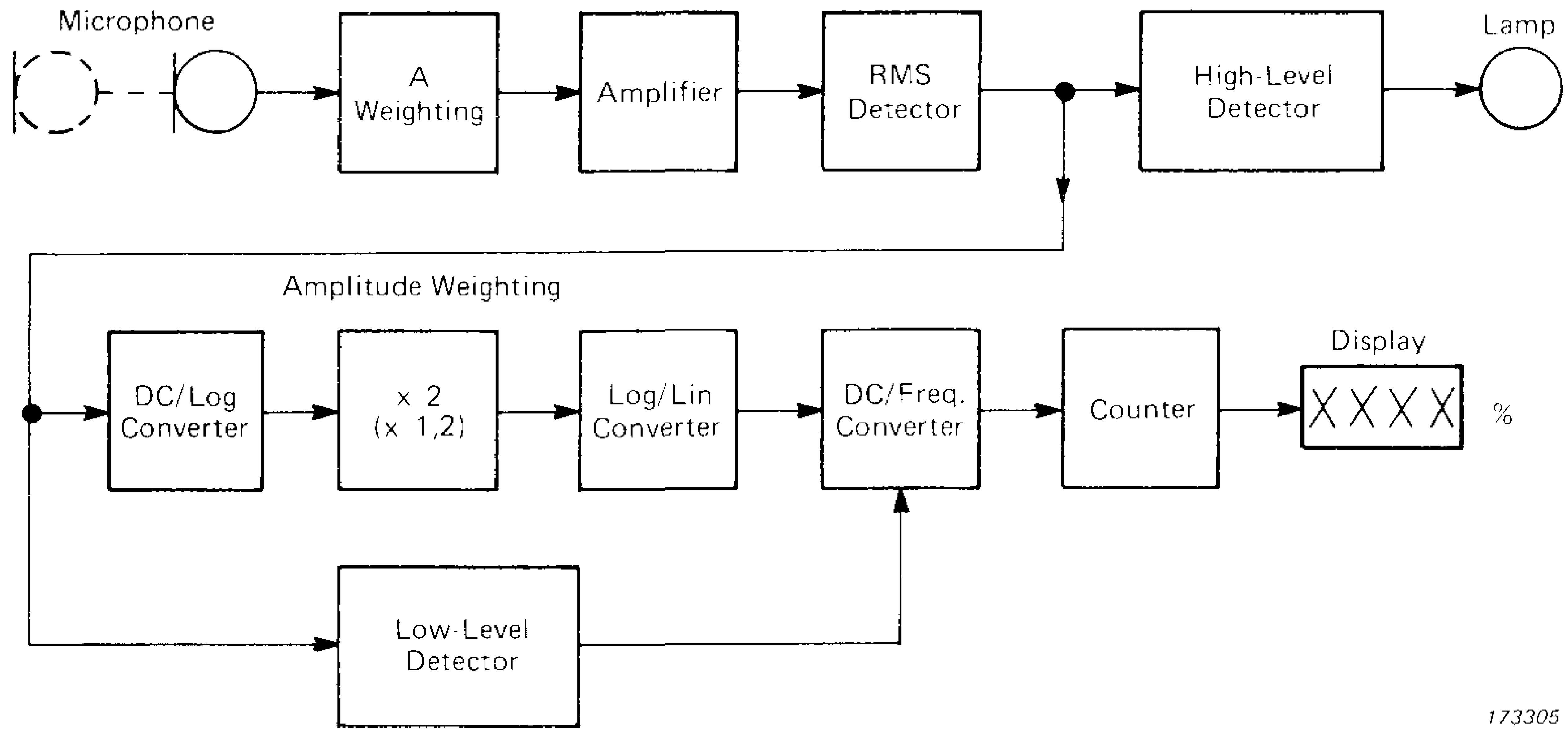

Fig. 2. Block Diagram of a Personal Noise Dose Meter (B & K Types 4424/4425)

Noise Dose Meter Design

There are numerous ways to arrive at the Equivalent Continuous Noise Level given an electrical output from a measurement microphone; various schemes for sampling, storing and processing may be employed. However, the simplest principle employs a combined microphone-processor-storage unit as exemplified in the block diagram of the B & K Type 4424/4425 Noise Dose Meter (Fig.2).

Since this is a personal noise dose meter, the condenser microphone may be mounted either integrally with the dose meter or clip-mounted near a person's ear (the effects of microphone placement will be discussed below).

The "A" filter, amplifier and rectifier circuits are similar to the circuitry used in Sound Level Meters. However, in this case, they are followed by two level detectors and an amplitude weighting network. One level detector registers exceedance of a fixed upper level as required by some standards (e.g. OSHA); the other inhibits measurement below a fixed lower level as permitted (or prescribed) by the various standards. The amplitude weighting network provides the emphasis on high levels over low levels which is indicated by the trading relationship between duration and level. Thus, in the ISO case, a 3 dB(A) level increase corresponds to half the duration and a 6 dB(A) level increase (level x 2) corresponds to one quarter the duration (duration/2^2). In this case, therefore, the amplitude weighting function is a squaring function. In the OSHA case, since 5 dB(A) (not 3 dB(A)) level increase corresponds to half the duration, the weighting function exponent becomes 2 x 3 dB(A)/5 dB(A) = 1,2. To provide for the two different exponents, the amplitude weighting network is designed as a log-multiplier-antilog circuit, whereby the multiplier is set to either 2 or 1,2. (This is the basic difference between the 4424 and the 4425 dose meter).

Next, the DC level is converted into a sequence of pulses, the frequency of which is proportional to the level. The number of pulses are then counted and displayed on a 4-digit percentage display. The instrument as a whole is calibrated such that the figure 100% will be displayed after 8 hours' exposure to an L_{eq} of 90 dB(A) (at present a common limit for permitted daily noise dose). If desired, the actual L_{eq} in dB(A) may be easily derived from this % figure. The instrument also has an "accelerated measurement mode" providing more than 100 times faster indication so that measurement periods of less than 5 minutes may be used; this facility was used for the sample measurements in industry described in a later section.

Sources of Error in a Personal Noise Dose Meter

In noise dose measurements according to ISO or OSHA, the required quantity is L_{eq} measured at the ear position of the exposed person, when the person is absent so as not to disturb the measurement.

If the sound field and the placement of the person are stationary, the measurement problem is solved by an ordinary Sound Level Meter, which will indicate L_{eq} in dB(A).

As a rule, however, the sound field will change with time within the workday and from day to day; it is then necessary to monitor the noise level for the time required to calculate a representative L_{eq} (using the rules of computation mentioned earlier). Stationary equipment for more or less automatic L_{eq} measurement is commercially available.

Quite often, however, the position of a person is not fixed and L_{eq} must be derived analytically (time-and-motion studies); or a personal dose meter used, of which several types have recently become available. By carrying the microphone attached to the person, errors caused by his movements are eliminated, but new sources of error are introduced because of body shielding and reflection. The amount of error depends on the sound field and microphone placement.

Laboratory Investigation and Results

A high-frequency narrow band point sound source of high directionality under free field conditions may well lead to errors of 10 dB or more, but this case hardly ever occurs in practice. More often, a large number of broadband noise sources are located in fairly well reflecting surroundings, resulting in a reverberant field with a more or less "haystack"-shape frequency spectrum.

In order to evaluate the probable error under such conditions, the following experiment was performed:

In a "typical" factory hall, 80 m^3 with Reverberation Time around 0,6 s, a loudspeaker was placed at one end and fed with pink noise so as to generate a flat spectrum from 100 — 8000 Hz at a measurement position in the centre of the room, The signal received by a measurement microphone was "A" filtered and recorded on a polar chart on a level recorder. A comparison was then made between the level recorded by the microphone alone and the level recorded when the microphone was placed on a person rotated in synchronism with the recorder. Various microphone positions — at the ear, collar, breast pocket and hip — were tried with resulting directional effects increasing in that order. Fig.3 is a typical recording made with the microphone at the breast pocket position. Maximum deviation is around 1 dB(A).

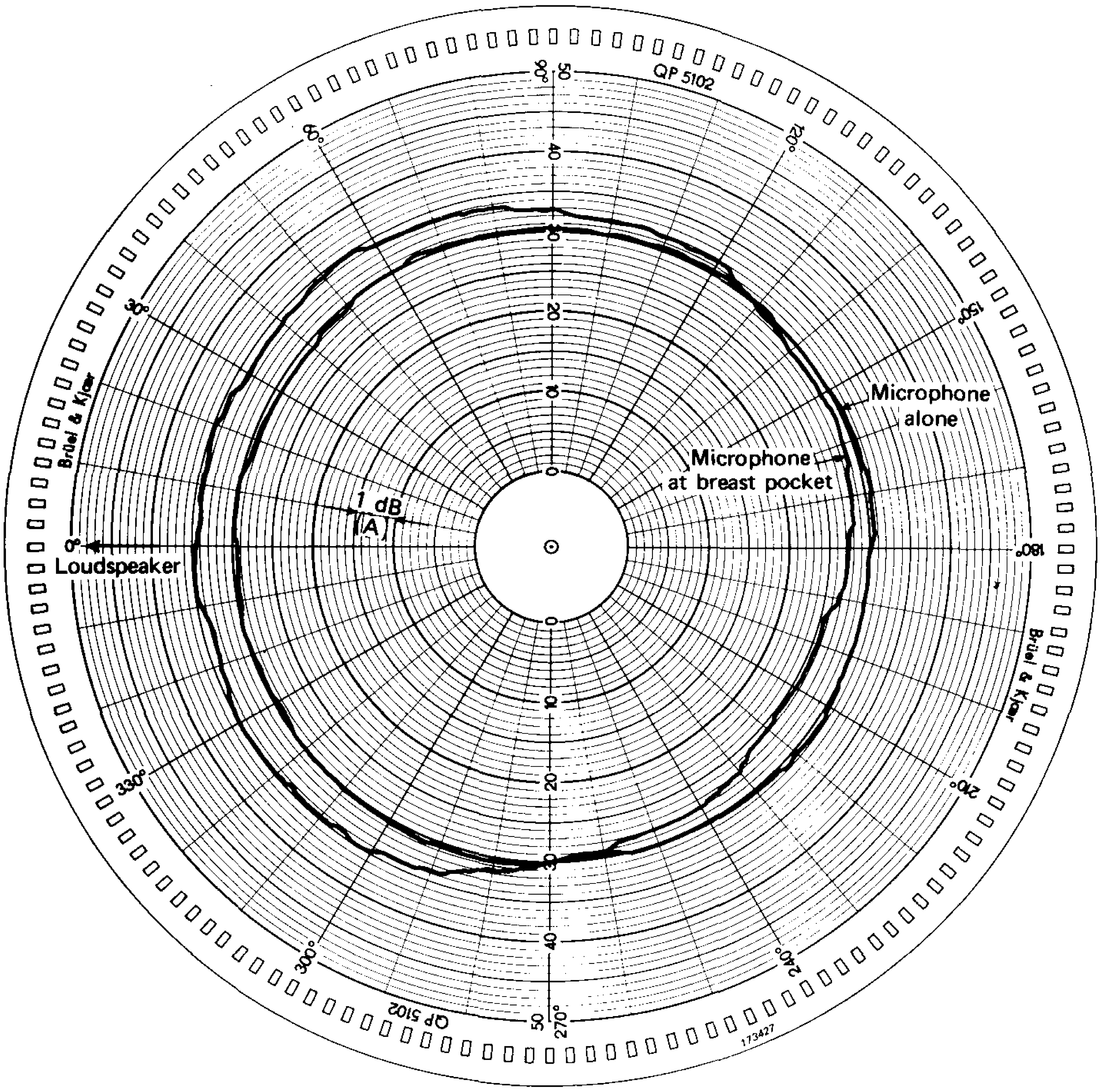

Fig.3. Directional Effect of Wearing a Microphone at the Breast Pocket

A similar set of measurements was made in a reverberant chamber to evaluate the error under near-ideal random incidence conditions. In this case directional effects were minor and the following results were recorded (Table 1).

Microphone Position	Error dB(A)
Ear	+ 0,3
Lapel	+ 0,3
Breast Pocket	–0,6
Hip Pocket	–0,4

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Table 1.

In this case, errors amount to around 0,5 dB(A). Also, third octave analysis was performed, still using the "Microphone alone" level as a reference (Fig. 4).

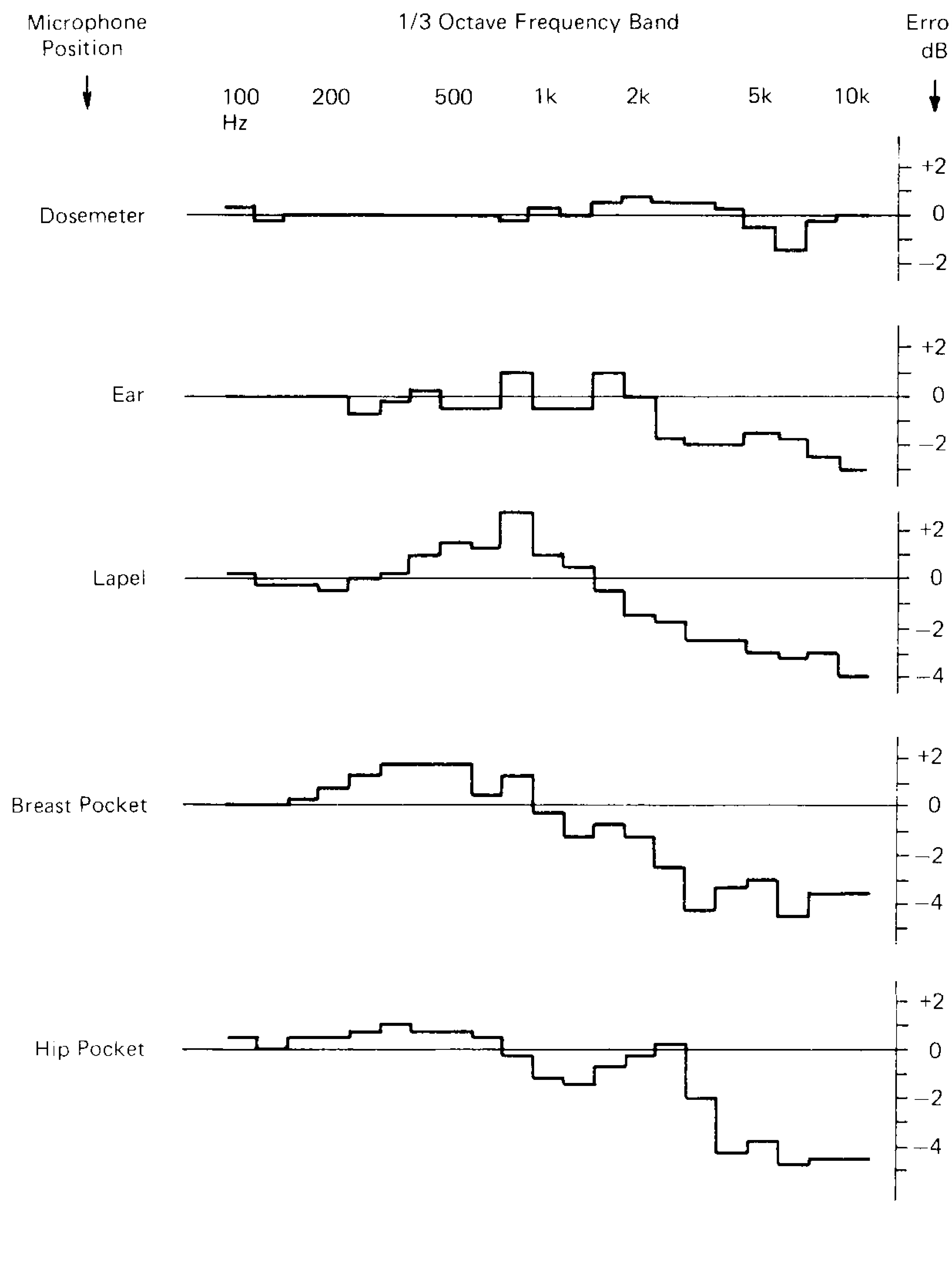

Fig. 4. Errors due to Microphone Position, in Third Octave Bands

The errors are seen to be insignificant up to 200 Hz; between 200 Hz and 2 kHz 2 dB errors are encountered while up to 5 dB errors may occur between 2 and 10 kHz. Bearing in mind the uncertainties arising from clothing, details of microphone placement and unknown reverberant characteristics the ear position is preferable over other on-body positions.

Industrial Investigation and Results

In addition to the laboratory testing described above, a B & K personal Noise Dose Meter (Type 4424) was tested in the industrial environment of the Midlands and North of England. This field work had two main objectives. First to test the performance of the Dose Meter when measuring noises of high crest factor and high level and secondly to investigate the effects of microphone positioning in a real industrial situation. A secondary objective was to subject the instrument to the typical industrial conditions of heat, dust and rough handling.

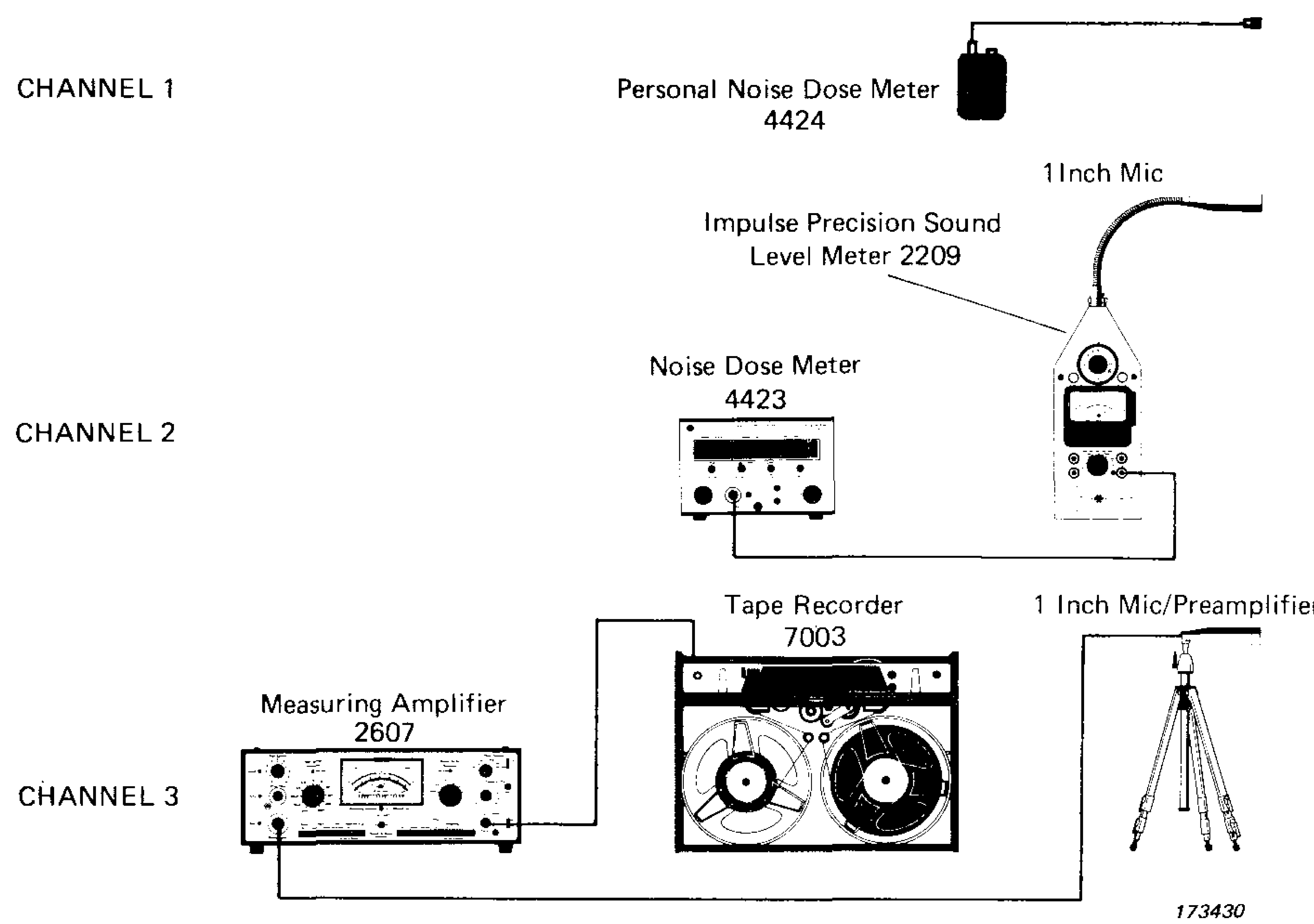

Fig.5. Instrumentation for the Industrial Investigation

The measurement set-up used for the field testing was comprehensive, containing three separate measurement channels (Fig.5). The first channel was the personal Noise Dose Meter itself with associated condenser microphone mounted directly on it, or using an extension cable, hand held near the other measurement microphones, lapel or hard hat mounted. Channel two allowed simultaneous analysis of the sound field using the B & K Noise Dose Meter (Type 4423)*. The Sound Level Meter in this channel was also used to take Fast, Slow, Impulse and Peak measurements where possible. The final measurement channel allowed tape recording of the sound fields for further analysis and documentation purposes. In situations where no power supply was available, Chan-

*) Described in TR 2 — 1972

nels 2 and 3 were combined, the Sound Level Meter feeding directly to the Portable Tape Recorder, and the resulting tapes analyzed later using the large Noise Dose Meter.

The measurement durations for the industrial testing varied from 30 s to 10 minutes with 3 minutes as the usual duration. In all cases the duration was chosen to give a representative measurement of L_{eq}. The measurements were performed to the ISO specification of 3 dB(A) change in level for a duration factor of 2. Typical results of the industrial testing are shown in Table 2.

Type of Noise or Machine	Sound Level Meter Readings dB(A) Slow (Eye Ave)	Peak (Max)	Crest Factor (dB)	Large Dose Meter L_{eq} dB(A)	Personal Dose Meter L_{eq} dB(A)	Personal Dose Meter Microphone Position
Air operated drop hammer	110	132	21	106	105 105	Breast Pocket Lapel
Mechanical forging press	–	–	13	100	99 98	Breast Pocket Lapel
Arc welding	106	124	14	106	103 105	Lapel Near other mics.
Chipping Hammer	113	135	17	115	108 112 115	Operator's Ear Operator's Lapel Near other mics.
Moulding Machine	104	126	20	103	101	Near other mics.
12 ton drop hammer	122	143	21	109	107 112	Near other mics. Operator's lapel
6 1/4 ton drop hammer	–	–	14	94	94	Near other mics.
Coil build up line	–	–	–	96	97 95	Near other mics. Operator's lapel
Smelting Shop, refining	–	–	–	90	90	Near other mics.
Excavator Cab Noise	–	–	12	87	88	Operator's Ear

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Table 2.

The results are shown plotted out in full in Fig. 6. These results will now be discussed with reference to the objectives of this investigation. The personal Noise Dose Meter was designed to operate in the range 80 dB(A) to 120 dB(A) with a "Slow" time constant. Only in one case was 120 dB(A) Slow exceeded, the peak level indicated in this case being almost up to the level causing instantaneous ear damage. The Dose Meter accurately measured the highest value of L_{eq}, 115 dB(A), found during the testing.

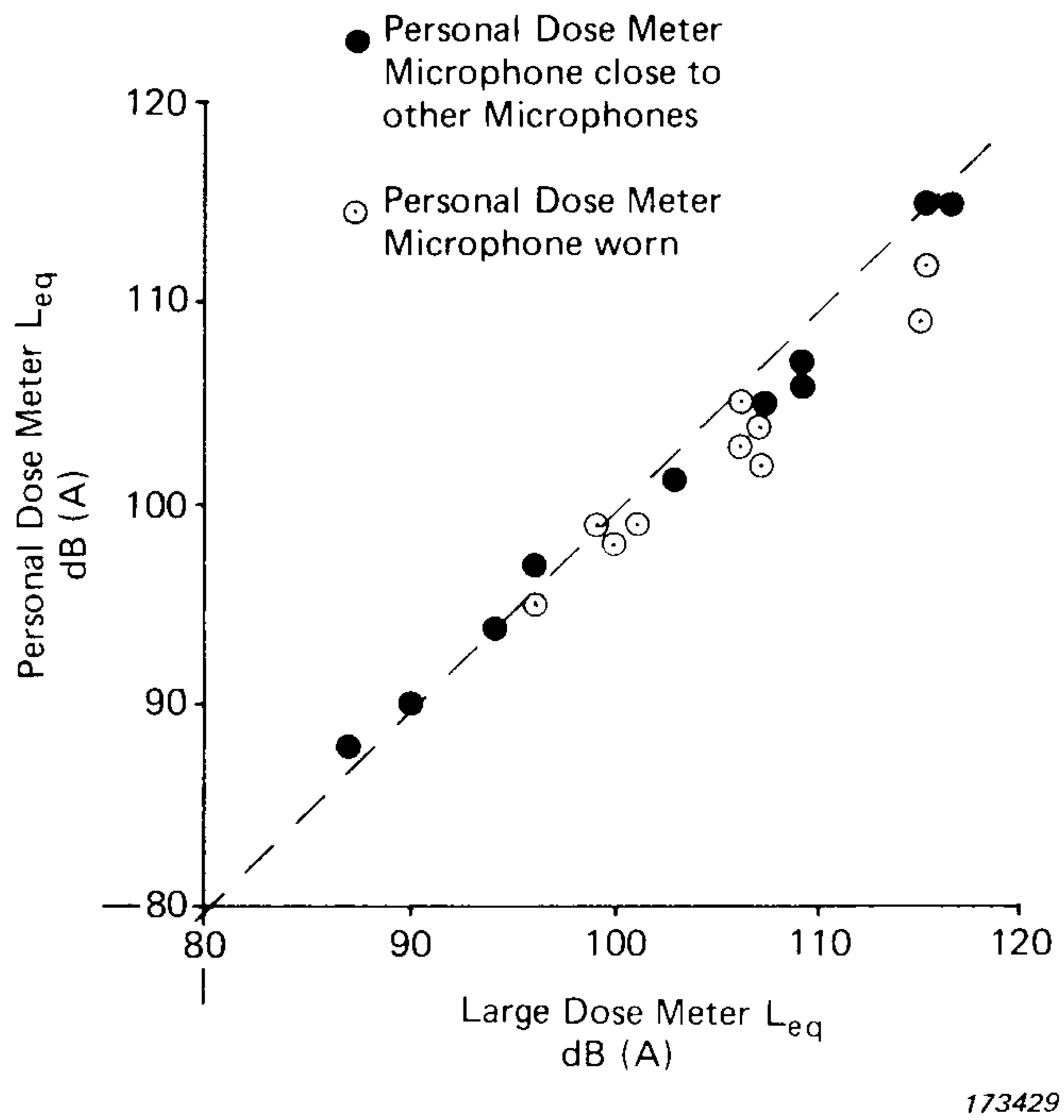

Fig. 6. L_{eq} Comparison of Large and Personal Noise Dose Meters

The personal Moise Dose Meter has a quasi-RMS detector of the variable squaring type which can produce errors for large Crest Factor signals. During the industrial testing, however, very high Crest Factor signals, up to 21 dB, were measured with a maximum deviation of only 2 dB. (The rectifier in the large Noise Dose Meter has no Crest Factor limitation).

It was found that significant errors can arise when attempting to measure noise dose with a stationary microphone. Differences of as high as 5 dB were noted between stationary microphones placed in the optimum position for machine operator convenience and the lapel mounted personal dose meter microphone. Errors of up to 2 dB arose even when an attempt was made to follow the operator's ear. This method is also inadvisable because of the inconvenience caused to the operator. Wandering personnel (managers, foremen and maintenance staff) are very difficult to assess for hearing loss risk without a personal noise dose meter.

Finally it was found that significant errors due to microphone position only occurred in strongly directional sound fields, in one case a 4 dB change in level being observed between lapel mounting and close to ear mounting.

Environmental considerations dictate that personal Noise Dose Meters should be dustproof, reasonably heat resistant and, more important, of robust construction. This final point is particularly applicable to the microphone.

Conclusions

A noise dose meter can facilitate measurements of industrial noise in cases where a simple sound level meter reading is not sufficient because of level variation with time. Considerable errors can arise when attempting to measure the noise dose with stationary microphones. These errors can be overcome by providing the machine operator with a personal noise dose meter which he wears all day. In this way variations in his noise exposure due to irregular working/not working machine cycles, local movement near his machine and lunch breaks, rest periods etc. will be correctly taken into account.

Use of a personal noise dose meter can, however, lead to further errors due to body shielding and reflection effects. Laboratory investigation of these effects indicated them to be small in typical cases and minimized at the ear position. Industrial testing also showed that occasionally highly directional sound fields can produce significant differences depending on microphone position. Both of these results indicate that the personal noise dose meter microphone should be ear mounted to measure the machine operator's noise dose accurately.

Acknowledgements

The co-authors of this report would like to express their thanks for the useful assistance of the following: Garringtons Ltd., Steel Castings Research and Trade Association, Drop Forging Research Association, British Steel and Massey Ferguson in England and the Technical University of Denmark.

Infrasonic Measurements*)

by

Per V. Brüel and Hans P. Olesen

ABSTRACT

Large infrasonic sound pressures are reported to be found in several environments such as in automobiles, in "tube trains", in high buildings etc. These noise signals produce unpleasant effects on man such as loss of balance and certain psychological effects when the sound pressure levels exceed the hearing threshold which is 100 — 140 dB re 20 μPa in the 1 — 20 Hz range.

This paper describes the infrasonic environment measured in high buildings in windy weather, in automobiles, and near the test site for large aero-engines.

Further it reports on measurements to check the response of man to infrasonic sound pressures, by vibrating the flexible walls of a small office using a vibration exciter and, thereby, producing high infrasound levels in the room.

SOMMAIRE

D'importantes pressions infrasonores se rencontrent dans différents environnements tels qu'automobiles, métro, grands bâtiments, etc. Ces bruits ont des effets nuisibles sur l'homme, par exemple une perte d'équilibre et certains effets psychologiques lorsque les niveaux de pression acoustique dépassent le seuil d'audition qui est de 100 à 140 dB par rapport à 20 μPa dans la gamme 1 — 20 Hz.

Cet article décrit l'enrivonnement infrasonore mesuré dans de grands bâtiments par temps venteux, en automobile et près du site d'essai de gros moteurs d'avions.

Il décrit en outre des mesures effectuées pour vérifier la réponse humaine aux infrasons en faisant vibrer les cloisons flexibles d'un petit bureau à l'aide d'un excitateur de vibrations et en produisant ainsi de hauts niveaux infrasonores dans la salle.

ZUSAMMENFASSUNG

Infraschall ist gelegentlich unangenehm spürbar
in Hochhäusern bei böigem Wetter,
während der Autofahrt bei unverschlossenen Fenstern,
in der Nähe von Triebwerk-Prüfständen,
im U-Bahntunnel,
an Deck von Motorschiffen.

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*) This paper was initially prepared for presentation at the Inter-Noise '73 Conference, Copenhagen, August 22 — 24th 1973

Im Frequenzbereich 1 Hz bis 20 Hz liegt die Wahrnehmbarkeitsschwelle etwa zwischen 140 dB und 100 dB re 20 μPa. Höhere Pegel können das Wohlbefinden und den Gleichgewichtssinn stören. Zwecks subjektiver Versuche wurde eine leichte Trennwand mit einem Vibrator erregt, wodurch hohe Infraschallpegel im Raum erzeugt werden konnten.

Lately, there has been an increasing interest in sound of very low frequencies. Several articles describe the low frequency sound which exists in the ocean and is found all over the world. Infrasound is also found in the atmosphere with variable strength. One source of this sound is thunderstorms. These may take place far away from the places where the infrasound is noticed, and this is because the damping of the low frequency sound is very small compared to the attenuation in the air of normal audible sound.

However, the most interesting cases seem to be those where man is subjected to infrasound in man-made environments. The sound may be produced either by working machines or, for example, by the interaction of wind with a structure. This is seen both in the case of an automobile interior when running at moderate to high speeds and in high buildings in windy weather. In London complaints have been reported about rattling doors and windows caused by infrasound from buses (9) and recent studies in the U.S.A. have indicated that vibrating bridges, excited by traffic, emit infrasonic waves which may be a threat to human beings and buildings (10).

Other interesting phenomena can be observed near operating aerospace engines, e.g., a large manufacturer of aeroengines has a problem concerning an indisposition among his office personnel, which was believed to have some connection with the low frequency sound from engines running in test beds.

Instrumentation

The infrasonic signals were measured by means of the combination of a Microphone Carrier System and the special Condenser Microphone Type 4146 with a nearly closed leakage tube which allows measurements down to 0,1 Hz. Also a Precision Sound Level Meter can be used, but then measurements can be carried down only to 2 Hz. In both cases the signals are recorded on a portable FM tape recorder for analysis in the laboratory (see Fig. 1). Before each set of measurements a pure tone calibration signal was recorded on the magnetic tape.

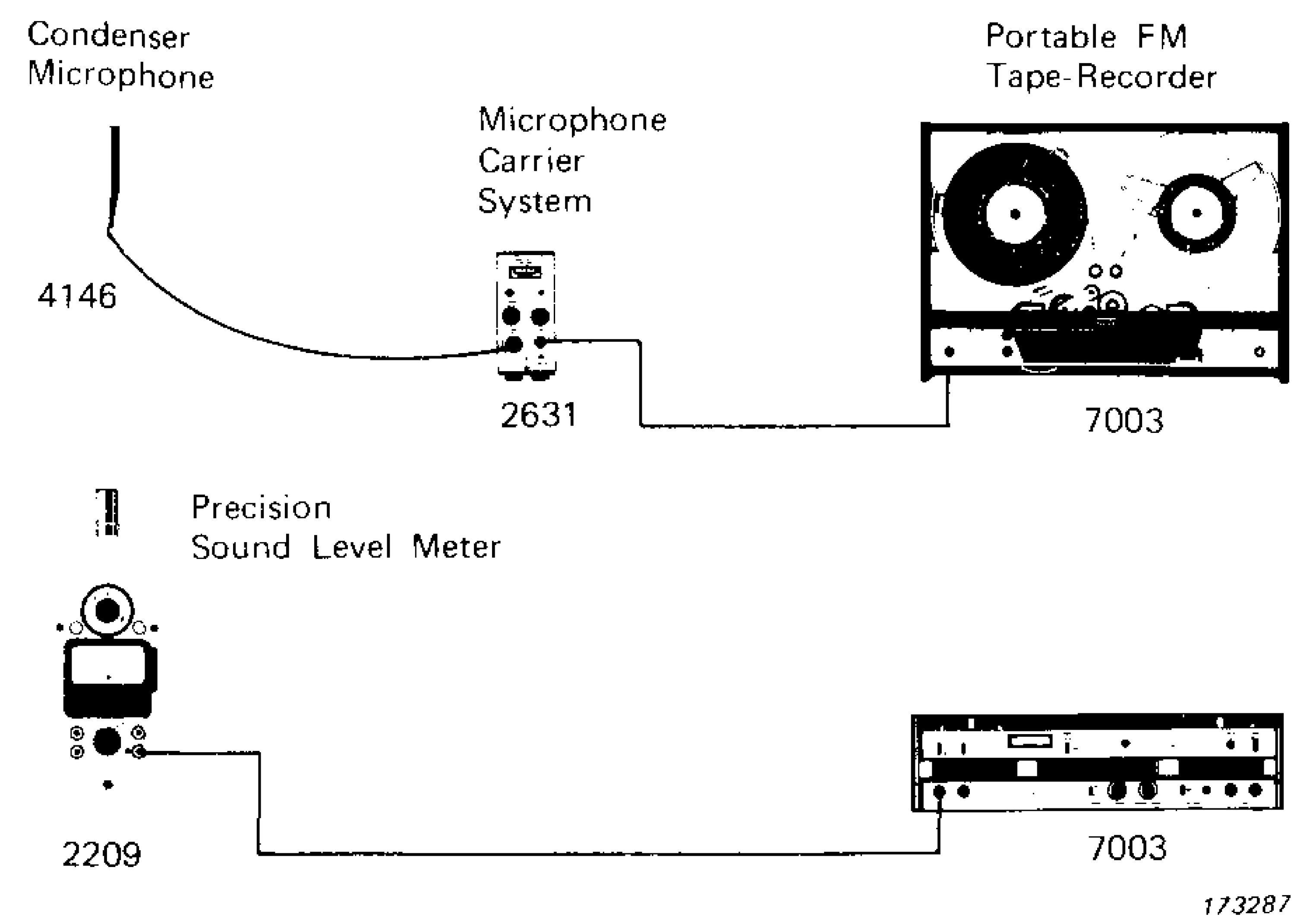

Fig. 1. Low frequency sound recording arrangements

Several different systems would be possible for the frequency analysis of the infrasonic signals. However, to minimize analysis time and to obtain relatively fine frequency resolution, the two systems shown in Fig.2 were chosen.

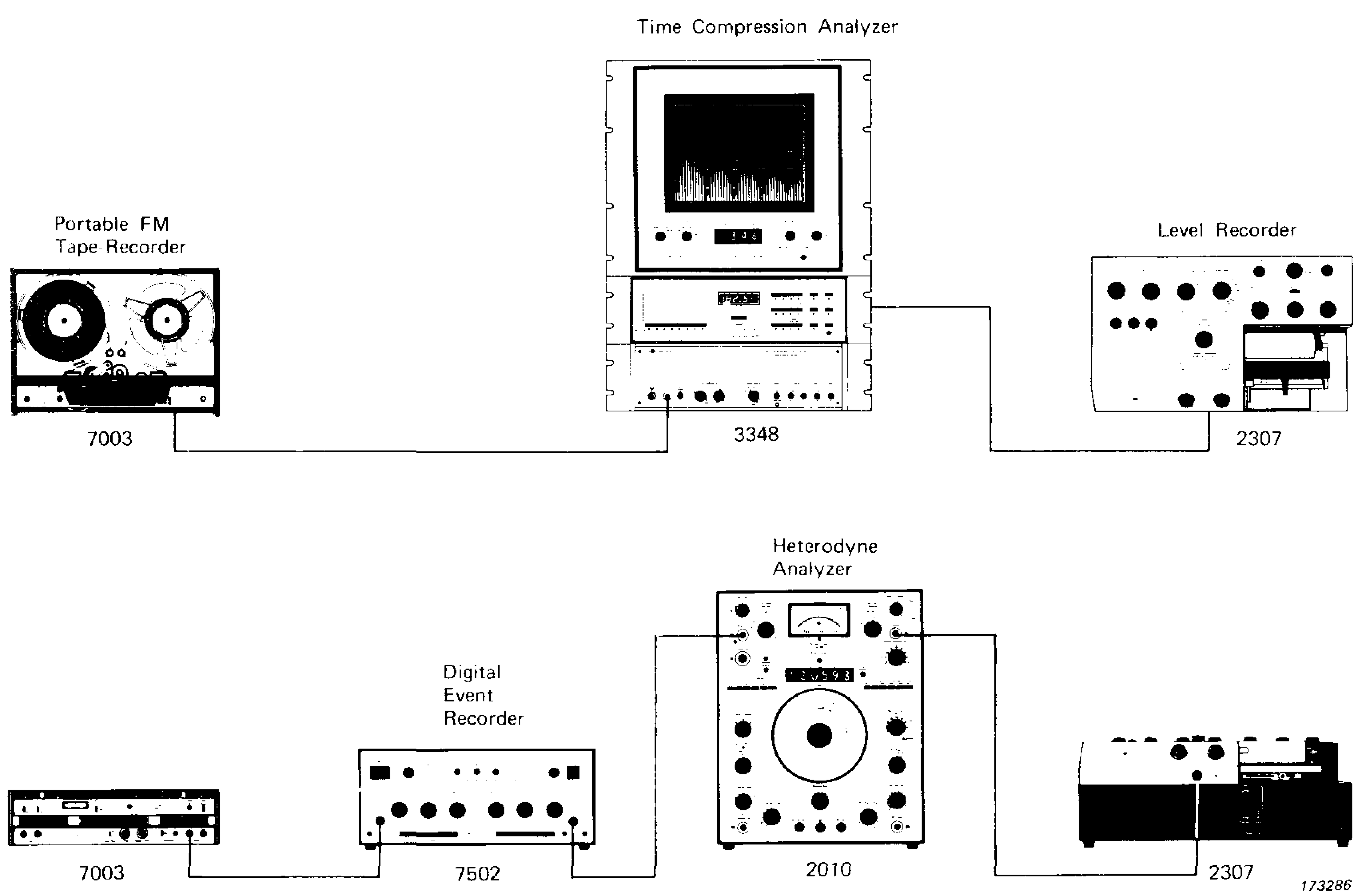

Fig. 2. Laboratory arrangements for frequency analysis

The system shown at top consists of a 400 line time compression analyzer with a graphic level recorder as the permanent recording device.

To carry out the analysis the recorded signal was played back from the tape recorder into the analyzer. Although the frequency analysis of one spectrum can be carried out in 45 mseconds, time should be allowed to collect statistical independent data. Therefore, for frequency resolutions of 0,05 Hz and 0,125 Hz which were most frequently used, the recorded signal lengths were 160 and 64 seconds respectively. Thereby 8 spectra were measured and averaged (providing a BT product of 8). The results are shown as photographs of the C.R.T. display in Figs.8—11 and as recorded on a graphic level recorder in Figs.3 and 7.

The other system shown in Fig.2 below consists of a digital event recorder, a heterodyne analyzer and a level recorder. The signal from the tape recorder was in most cases recorded on the digital event recorder for 100 seconds at a sampling rate of 100 samples/second (1 OK memory). The signal was played back by the digital event recorder at 100000 samples/second, whereby the original upper frequency of 25 Hz was transformed by a factor of 1000. The frequency transformed signal was analyzed by the heterodyne analyzer with a 30 Hz filter in the frequency range 0— 20000 Hz, thereby yielding an effective frequency resolution of 0,03 Hz in the range up to 20 Hz referred to the original signal. (Figs.4—6).

Measurement of infrasound in high buildings

As reported by professor R.W.B. Stephens (4) certain amounts of infrasound are to be found in high buildings.

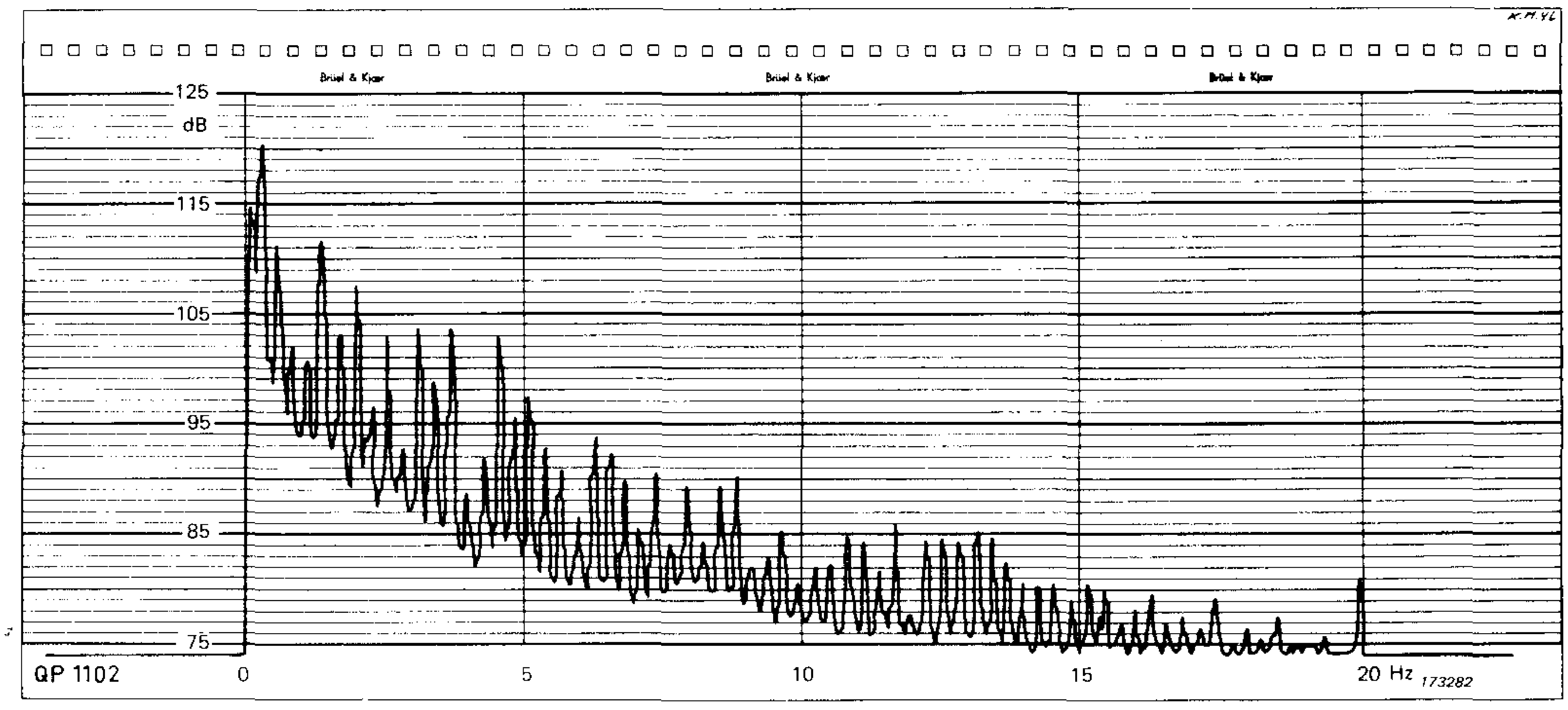

Fig.3. Low frequency wind excited noise in a 14 storey building in stormy weather

Measurements were carried out in two high buildings. In one case the infrasound was recorded in a flat at the 13th floor of a 14 storey building. The recording was carried out over 2,5 hours in which the wind velocities were increasing to those in stormy weather. The frequency analysis (Fig.3) showed a large number of distinct frequencies which continued with increasing levels over the 2,5 hour period (increases of approx. 14 dB).

In the second case the infrasound was recorded in an office at the top floor of the 16 storey Main State Hospital in Copenhagen (Figs.4 and 5). In this bulding people were complaining about sickness when the wind was blowing. The sound spectra did show large variations over the 1 hour recording period, Fig.4 shows a spectrum where very little infrasound exists on account of the relatively quiet weather and Fig.5 shows the much higher infrasound level during a hail storm.

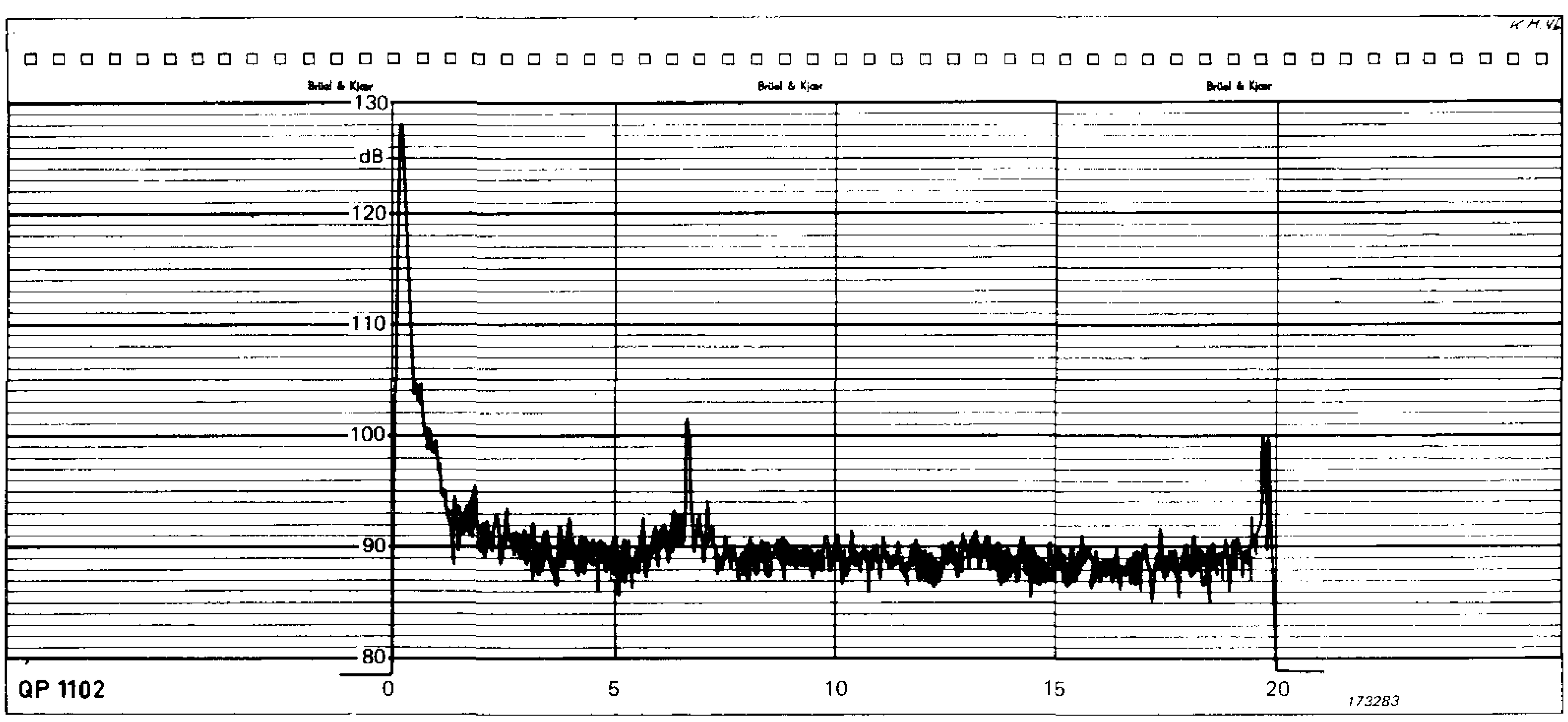

Fig.4. Low frequency wind excited noise in a 16 storey building (very little wind)

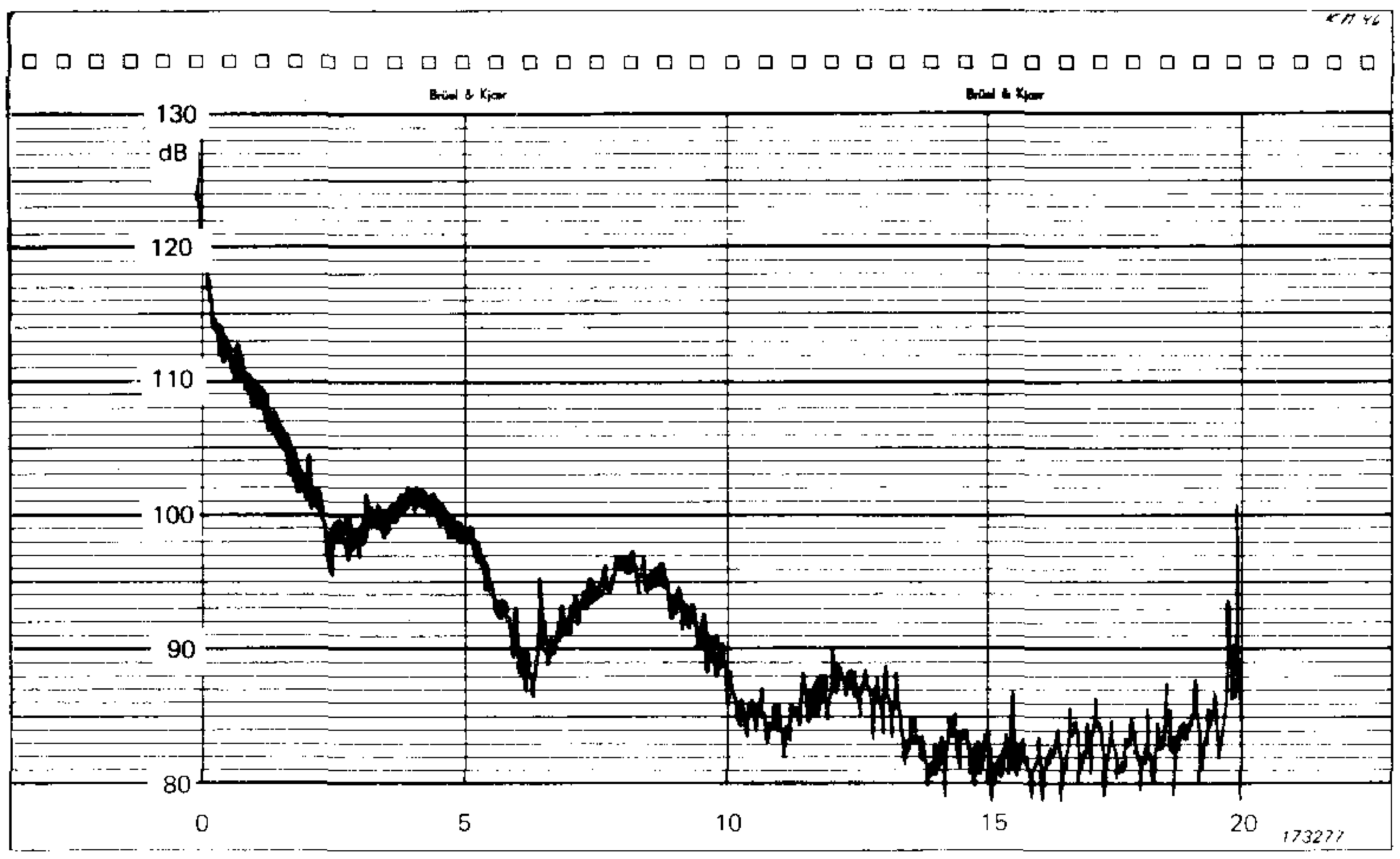

Fig.5. Low frequency wind excited noise in a 16 storey building (hail storm)

Infrasound in the transportation environments
The sound was recorded in a number of motor cars for which two analyses are given in Figs. 6 and 7. Fig. 6 displays the sound spectrum inside a station car driven at 100 — 110 km/h with one side window half-way open. Typical peaks are found at approximately 15 Hz. Fig. 7 shows the spectrum for an automobile with a much smaller air volume, driven with the sun roof removed. Here the signal peak is at approximately 26 Hz, in some cases supplemented by a certain resonance phenomenon at 32 Hz.

Measurements were carried out in other automobiles, with similar results, and in other transportation environments for which further measurements would be required.

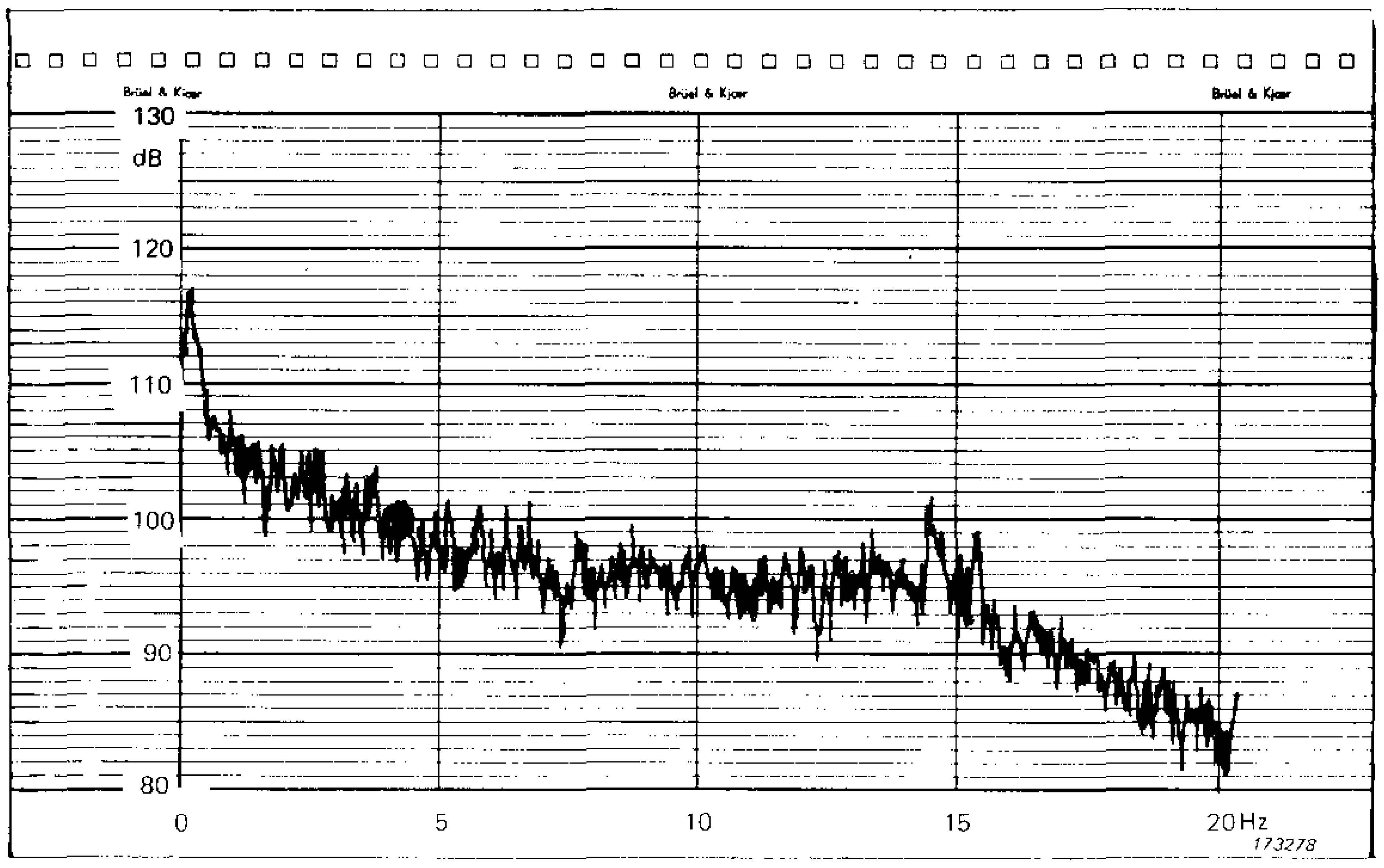

Fig. 6. Spectral distribution of sound pressures in a Volvo station car

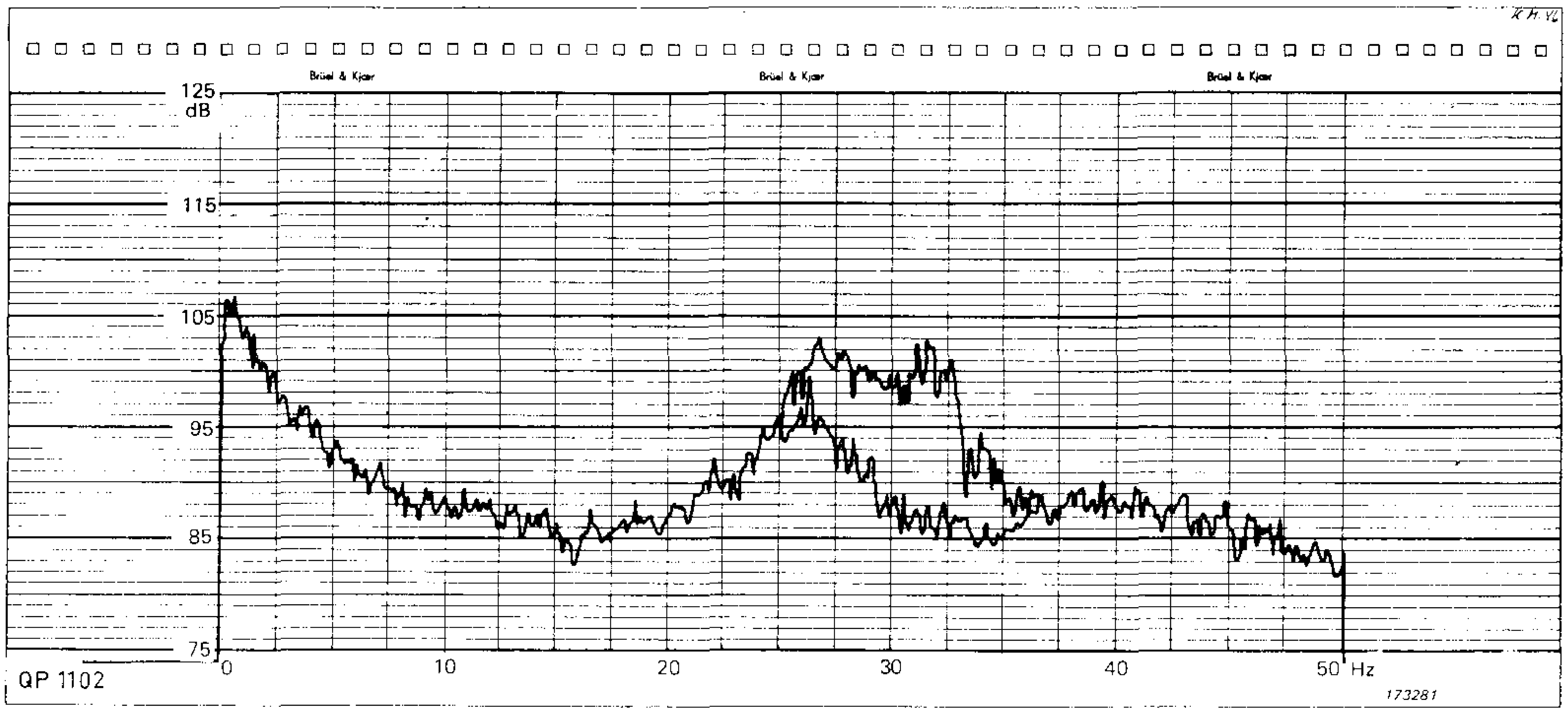

Fig. 7. Spectral distribution of sound pressures in a Fiat 500

An aeroengine test installation

Measurements were carried out at an aeroengine manufacturer's plant, where the indisposition of the office personnel was reported. Measurements were carried out both close to the test beds and in the office buildings. Fig.8 shows the infrasound spectrum very near the test bed.

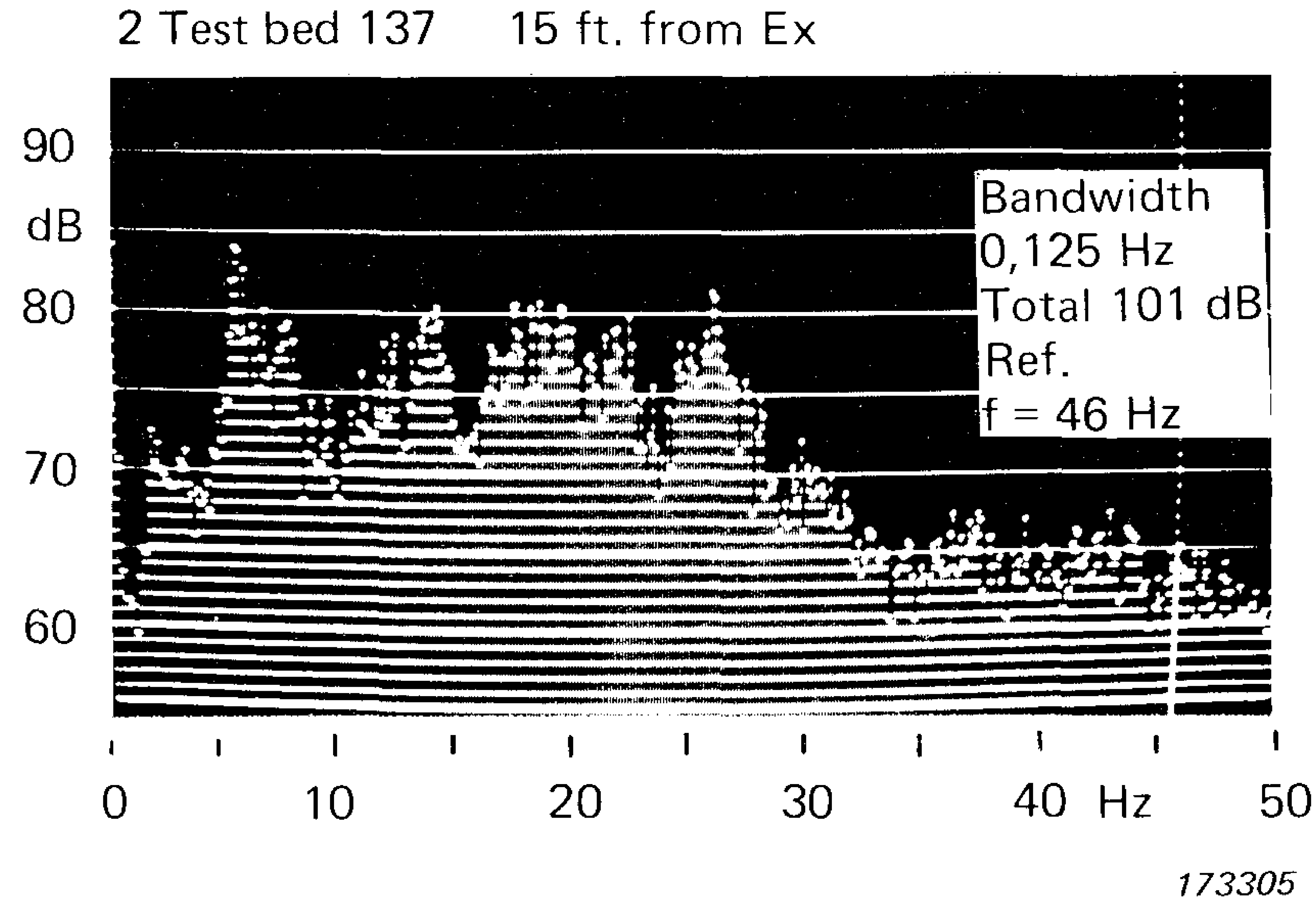

Fig.8. Frequency analysis of infrasound near an aeroengine test bed

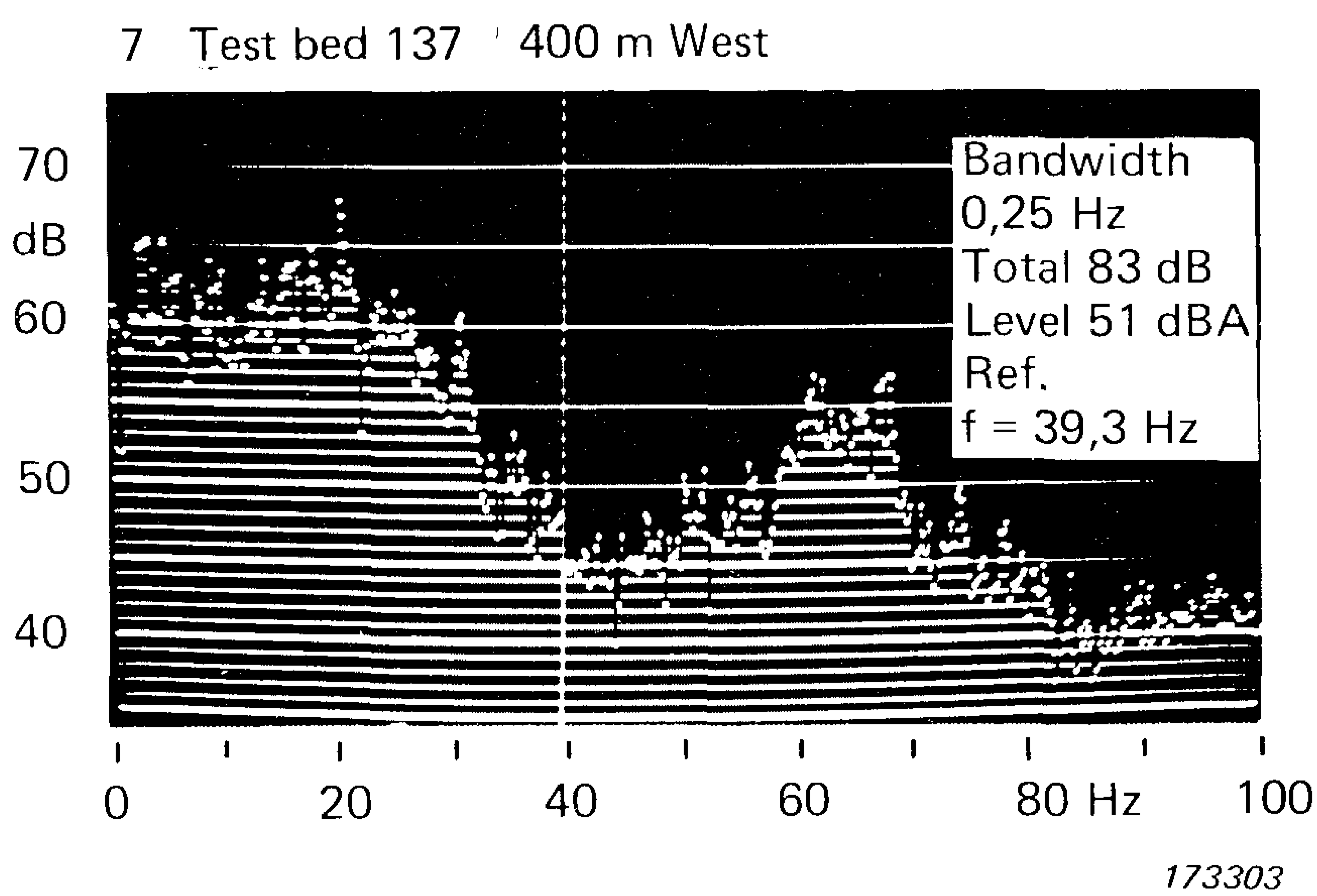

Fig.9. Frequency analysis of infrasound at a distance from an aeroengine test bed

Fig.9 shows the spectrum 400 m away from the test bed, near a house from which complaints had been registered (note the frequency scale goes to 100 Hz). Figs.10 and 11 show the spectral distribution of infrasound in two offices. It is seen that although there are certain amounts of infrasound present, the levels are below the threshold normally given for infrasound.

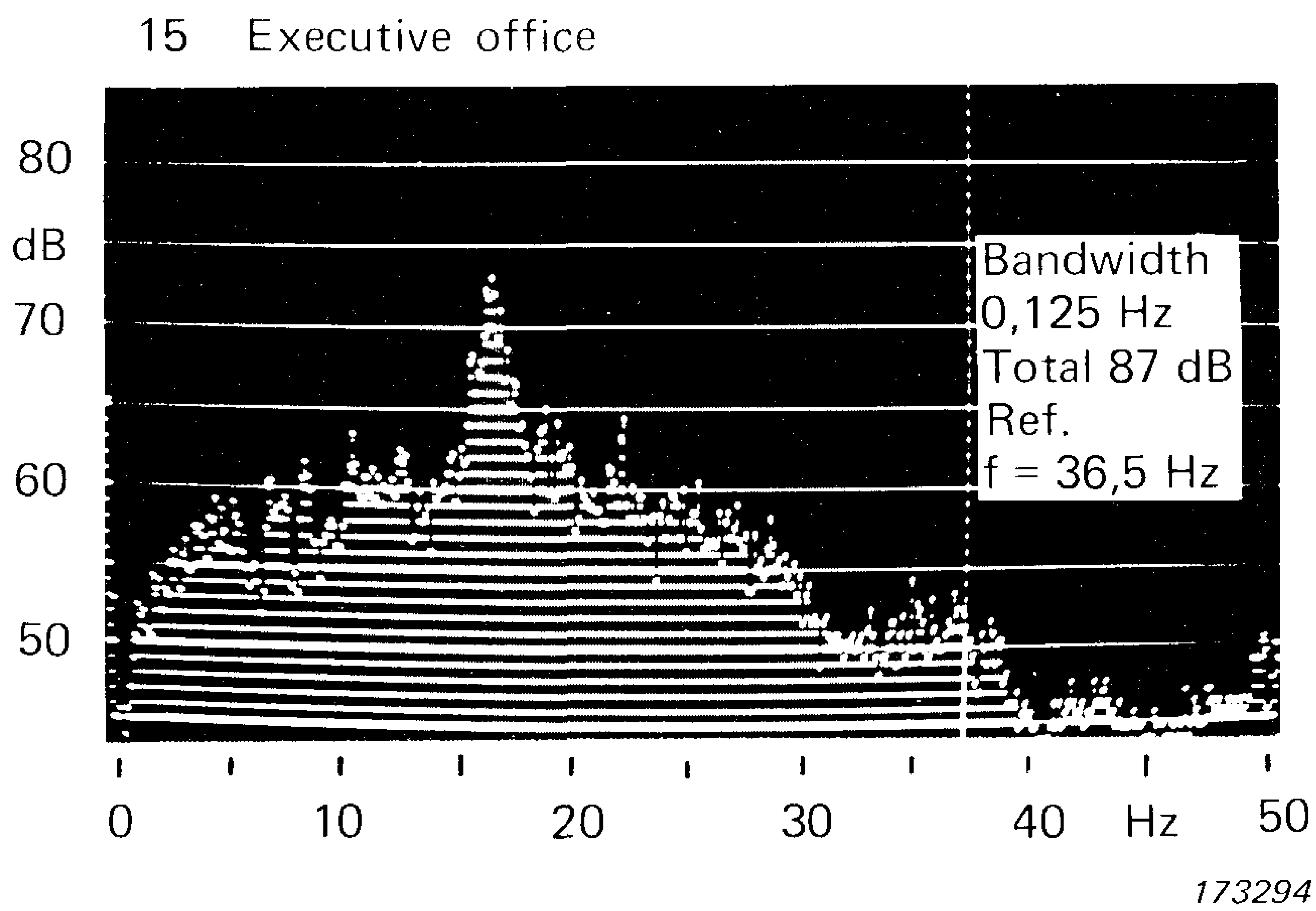

Fig.10. Infrasound in an office due to aeroengine testing

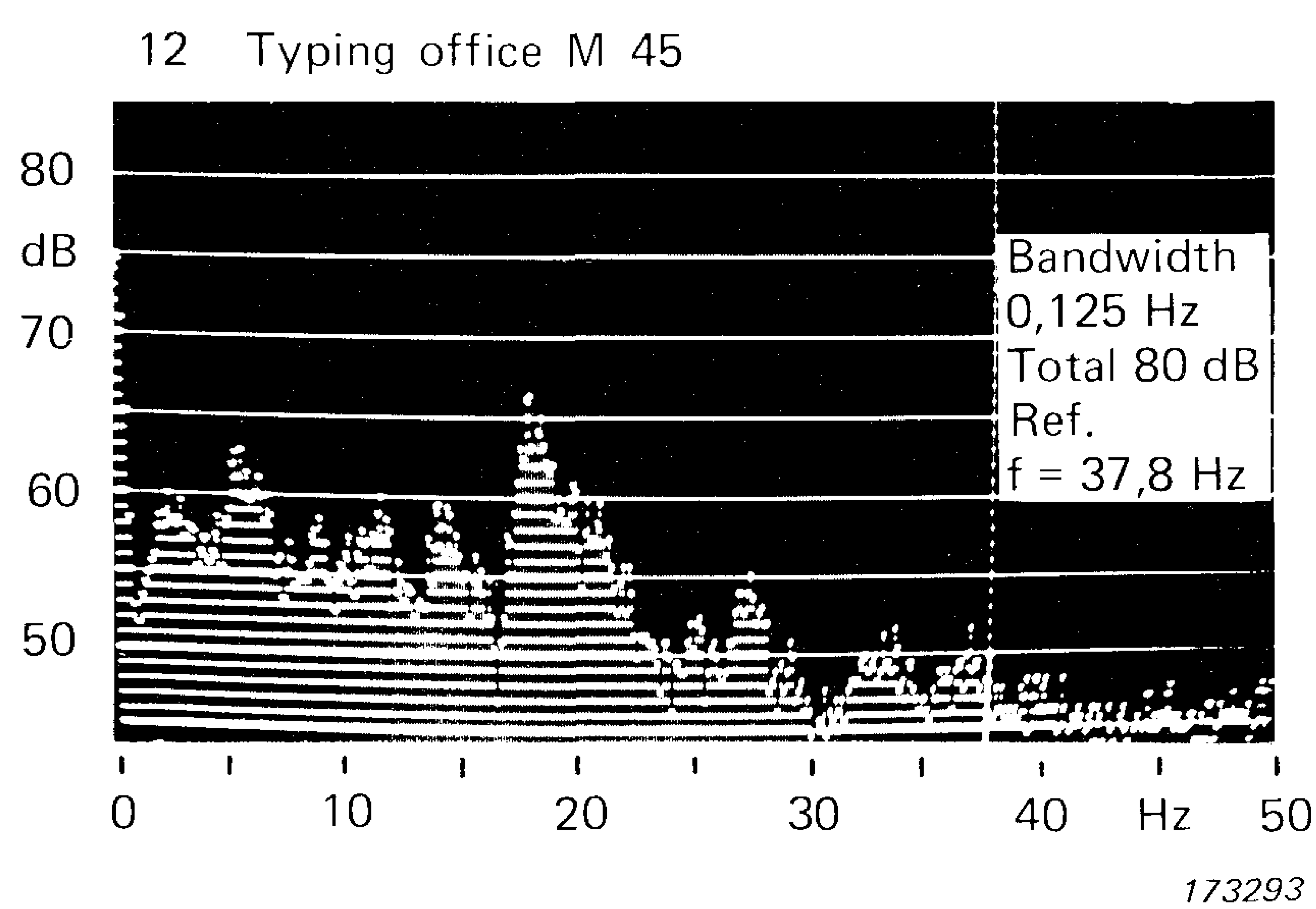

Fig.11. Infrasound in an office due to aeroengine testing

Generation of infrasound

To make a crude check of the response of man to infrasound, the flexible walls of a small office room were used as membranes, excited by a vibration exciter, (Figs. 12 and 13), to produce sound pressure levels of 95 to 115 dB in the frequency range from 2 — 16 Hz. The sound signal waveform was somewhat distorted (the second harmonic was measured to be between 14 and 25 dB lower than the fundamental, depending on the fundamental frequency), but it was possible to obtain crude threshold curves for detection of the infrasound and for the appearance of ill-feeling.

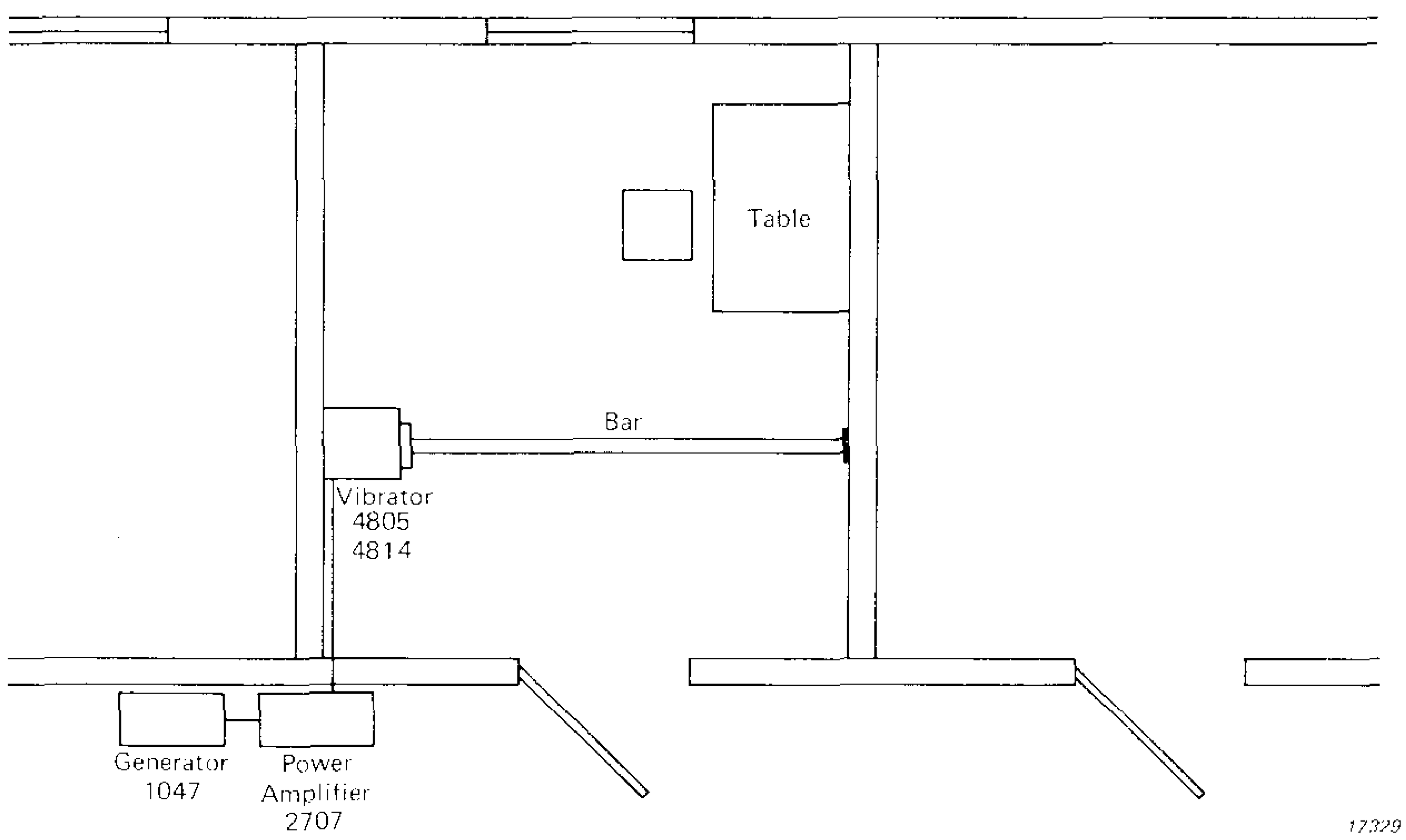

Fig. 12. A vibration exciter used to excite the walls of a small office for infrasound generation

The detection threshold levels found were lower than those given in the literature. To provoke the sense of ill-feeling, both higher sound levels and longer exposure times were required except at 12 Hz, where instantaneous and violent ill-feeling was experienced by several persons at relatively low sound levels (85 — 110 dB).

Although there are many psychological effects in these experiments which reduce the reliability of the results, the effect still appeared even for some of the persons involved who strongly believed that the whole thing was nonsense.

Fig. 14 shows the response registered by a sceptical person who exposed himself to a high sound level at one frequency each evening, while reading, in order to find the exposure time needed before a slight dizzyness appeared.

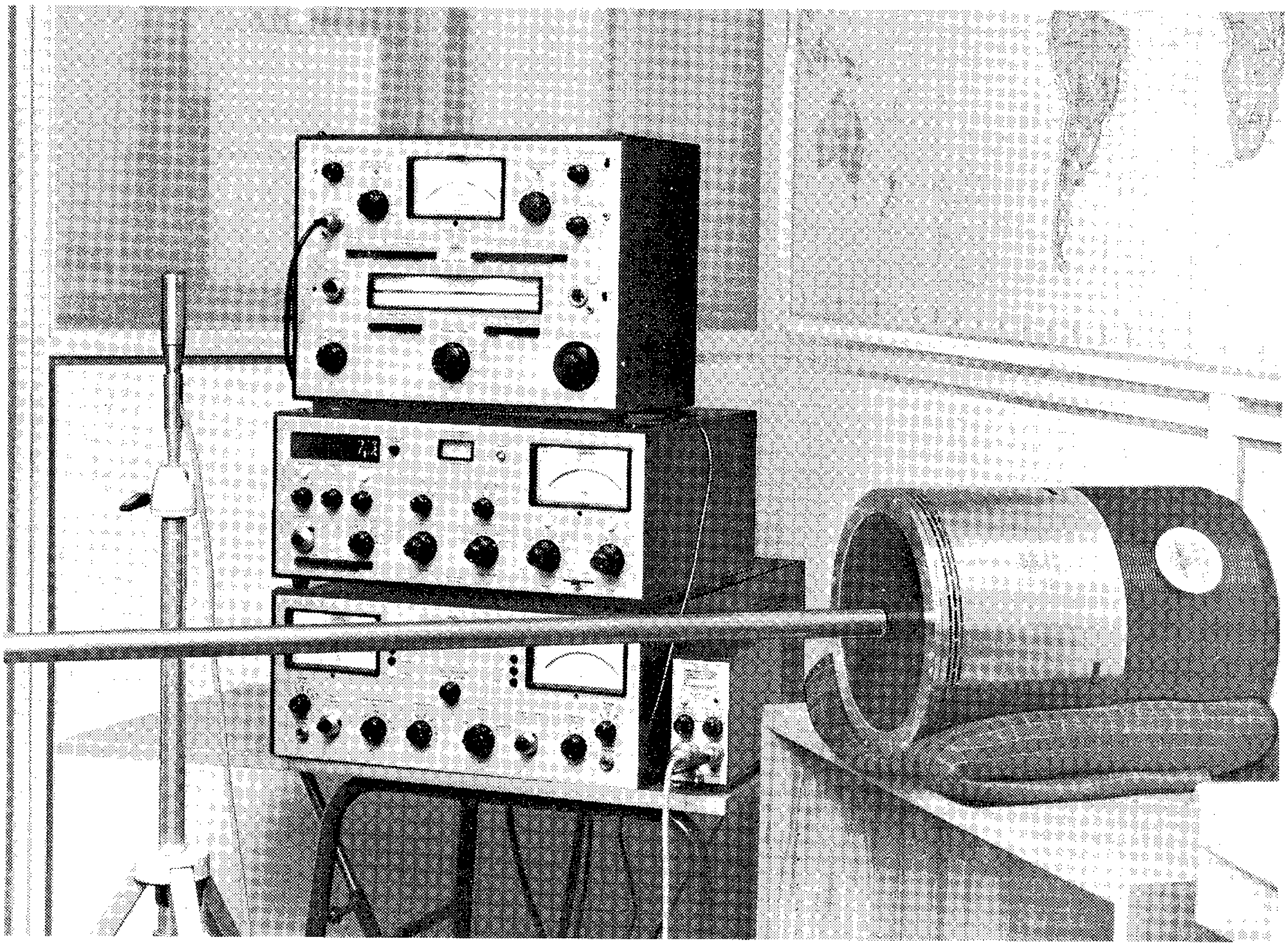

Fig. 13. A photograph of the test arrangement in Fig. 12

A similar incidence occurred at the aeroengine manufacturer's plant, where the head of the office did not believe in the complaints of his office staff. When the installed himself in the office where complaints had been most severe, in order to demonstrate that the whole thing was nonsense, he felt sea-sick himself after relatively short time.

Discussion

The measurements have confirmed that significant infrasound levels do exist, especially in man-made environments. There is also a strong indication that even low sound levels, at low frequencies may cause unpleasant effects on human beings. The effect on human beings especially, is difficult to measure as an exposure time is always involved (see Figs. 14 and 15), except at very high levels. Furthermore, as the test material is so limited and as all test parameters are not known, no attempt has been made here to point to specific threshold levels. However, the experiments showed, very clearly, that there was a tendency that even convinced sceptics were influenced to feel sea-sick at moderate infrasound exposure. As such levels are found both in automobiles, in high buildings and in other environments where people must work or live, there seems to be a great need for further investigation into the topic.

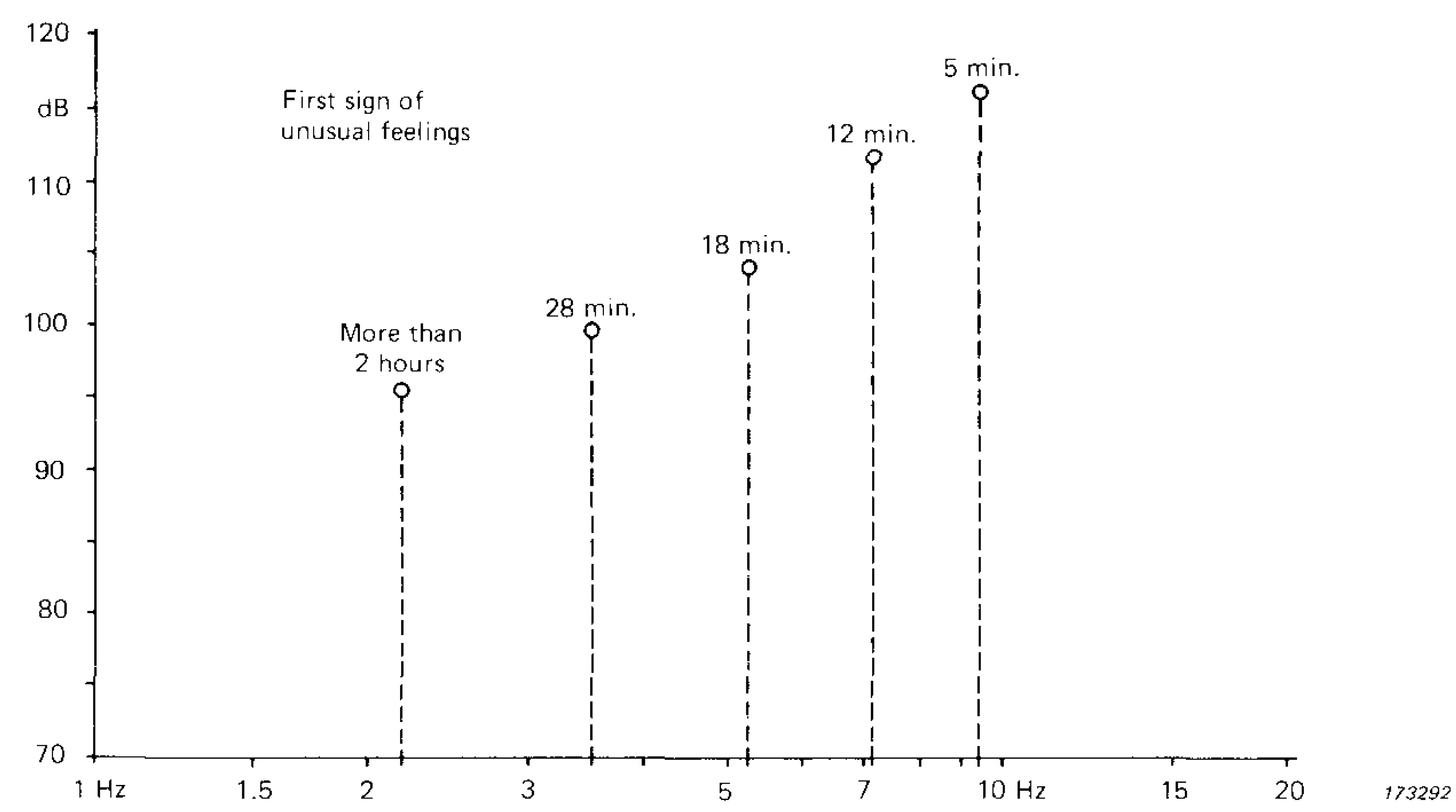

Fig. 14. The sensory response of one person to infrasound excitation

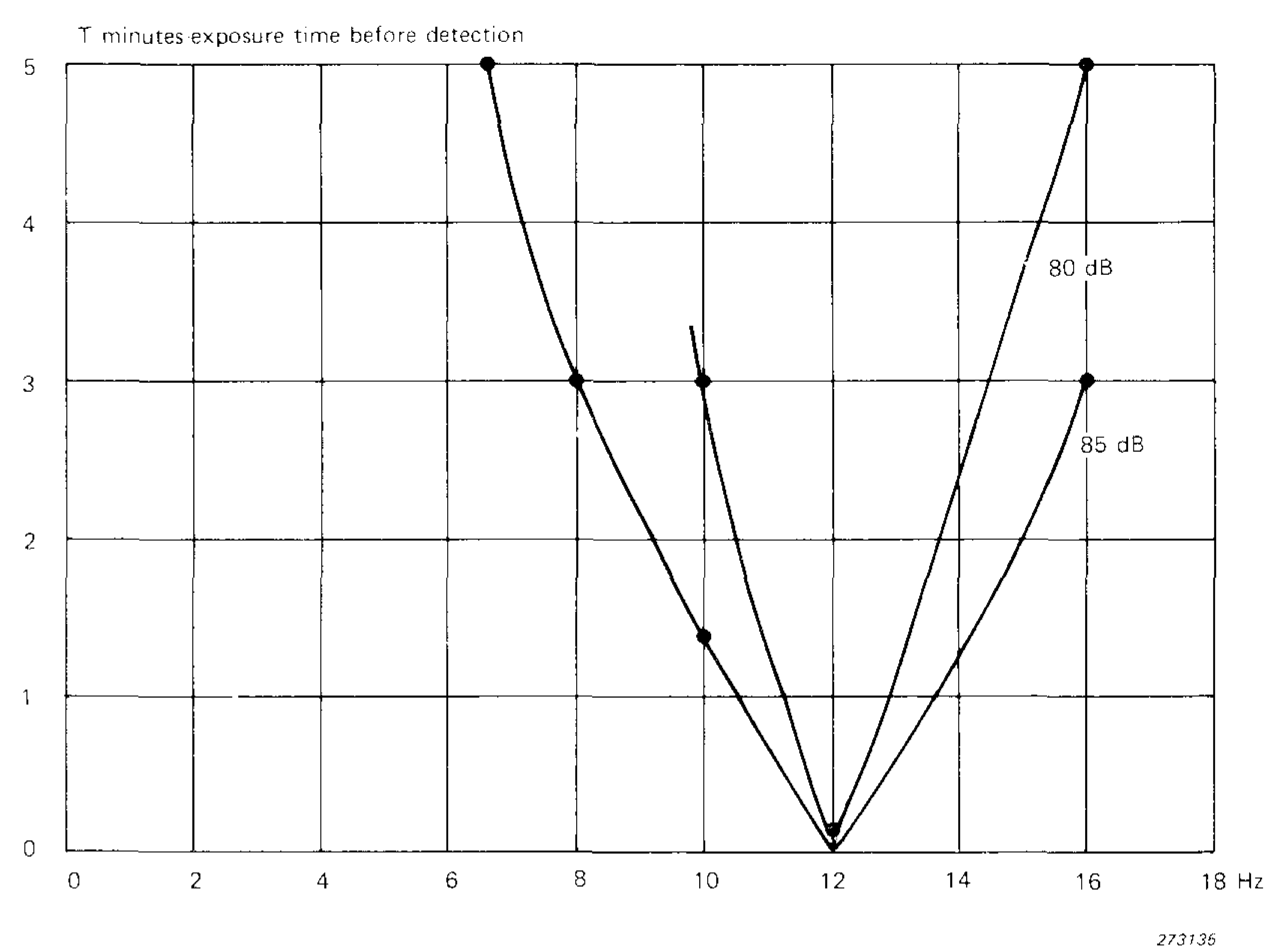

Fig. 15. The threshold/exposure time relationship around the most sensitive frequency

References

Proceedings of the British Acoustical Society, Vol. 1 No.3, Summer 1972.

Meeting on "Infrasound and Low Frequency Vibrations" at Salford University on 26th November 1971:

1. Instrumentation for Infrasound, H. G. LEVENTHALL and R. A. HOOD, Chelsea College, London.

2. Low Frequency Threshold Effect, N. S. YEOWARY, University of Salford.

3. Infrasonic Effects on the Human Organs of Equilibrium, MARGARET G. EVANS, University of Salford.

4. Natural Sources of Low Frequency Sound, R. W. B. STEPHENS, Chelsea College.

5. Low Frequency Noise in Road Vehicles, W. TEMPEST, University of Salford.

6. Some Subjective Effects of Infrasound, R. A. HOOD, H. G. LEVENTHALL and K. KYRIAKIDES, Chelsea College.

7. Low Frequency Noise and Vibration in Tankers, A. B. LEWIS and S. L. GIBBONS.

8. Annoyance Effects due to Low Frequency Sound, M. E. BRYAN, University of Salford.

Noise & Vibration Bulletin, NVB, March 1973

9. The Infrasonic Bus, abstracted from London Evening News, 16th February 1973, SIR RICHARD WAY and ROLAND MAYLE.

10. Bridge Waves, abstracted from Philadelphia Inquirer, 27th January 1973, WILLIAM DONN and NAMBATH K. BALACHANDRAN.

Determination of Resonance Frequencies of Blades and Disc of a Compressor Impeller

by

Gerhard Westphal)*

ABSTRACT

The impeller of a centrifugal compressor (turbocharger design) is mechanically excited, and its vibration response is recorded for different mountings. The paper describes the measuring set-up and procedure and concludes with a discussion of results.

SOMMAIRE

On excite mécaniquement la roue d'un compresseur centrifuge (type turbochargeur) et on enregistre la réponse en fréquence pour différents montages. L'article décrit le montage et la procédure de mesure et conclut par une discussion des résultats.

ZUSAMMENFASSUNG

Das Kompressorlaufrad eines Abgasturboladers wird mechanisch erregt und sein Schwingverhalten aufgezeichnet. Einflüsse der Laufradmontage werden untersucht. Der Aufsatz beschreibt Messaufbau und Messverfahren, die Messergebnisse werden diskutiert.

Introduction

The steady increase in rotational speed of turbochargers developed at Helsingør Skibsværft og Maskinbyggeri (HSM) has placed demands on new impeller designs and on exact knowledge of their vibrational characteristics. During normal operation an exhaust turbocharger generates typical excitation frequencies which act on the compressor impeller blades. These well known frequencies depend on the rotational speed as well as on the number and arrangement of supports or guide vanes in the compressor inlet casing, and should not coincide with the natural frequencies of the impeller blades as this could easily lead to blade damage.

The calculation of the natural frequencies of the radial blades, however, is rather difficult as the blades are supported by a very stiff hub which gradually tapers out to a thin disc.

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* Turbo-research-department of the HSM, Helsingør, Denmark

The vibrational response of such impellers has been investigated experimentally for a long time at HSM. An accurate determination of important vibrational characteristics determined partly by the impeller form and mounting on the shaft has, however, only been possible by means of the measurement set-up described in the paper.

Measurement aim

In the frequency range of 200 to 2000 Hz the resonance frequencies of a compressor impeller are to be measured with respect to blade and disc vibrations. For that purpose, the influence of the mounting of impeller on the shaft should be investigated.

a) The impeller is centered by means of splines and is fixed axially at the front end of the hub. As mechanical damping can be expected from the spline construction, both very loose and very tight fits should be investigated.

b) The impeller is fixed, non-centered, between the front and the back of the hub.

   The fixtures should be constructed so that contact resonances in the frequency range are eliminated.

Measurement set-up

The measuring points A and B on the impeller, (Fig. 1) were selected after experiments to determine representative measuring points for disc and blade vibration respectively. To avoid loading of the specimen, accelerometers with very low mass exclusively, were used on the impeller.

The signal from the accelerometer was led via a Preamplifier, Type 2625 to the Measuring Amplifier Type 2607, (Fig. 2). To obtain narrow band analysis the Heterodyne Slave Filter Type 2020 was connected to the Measuring Amplifier.

The Heterodyne Slave Filter was electronically tuned by the Beat Frequency Oscillator Type 1022. The output from the Measuring Amplifier was taken to a Level Recorder Type 2305 mounted with a linear potentiometer (ZR 0002) and to one of the channels of a double beam oscilloscope.

The impeller was mounted on the table of a Vibration Exciter Type 4801/4813 by means of a suitable fixture. The Vibration Exciter was driven by the signal from the above-mentioned Beat Frequency Oscillator via a Power Amplifier Type 2707. The Level Recorder and the Beat Frequency Oscillator were connected by a Bowden cable to synchronize paper speed with the frequency sweep. All measurements were carried out with a sweep time of 8 minutes for the range 200 Hz to 2000 Hz.

In the feedback loop the signal from the Accelerometer Type 4339 mounted on the impeller fixture was led via a Conditioning Amplifier Type 2626 and a Measuring Amplifier Type 2607 to the compressor input of the Beat Frequency Oscillator Type 1022 to keep the acceleration level of the fixture constant at 2 g RMS over the whole frequency range. The acceleration signal was also led from the output of the Measuring Amplifier to the oscilloscope and to an electronic counter which was used to measure the exact excitation frequency.

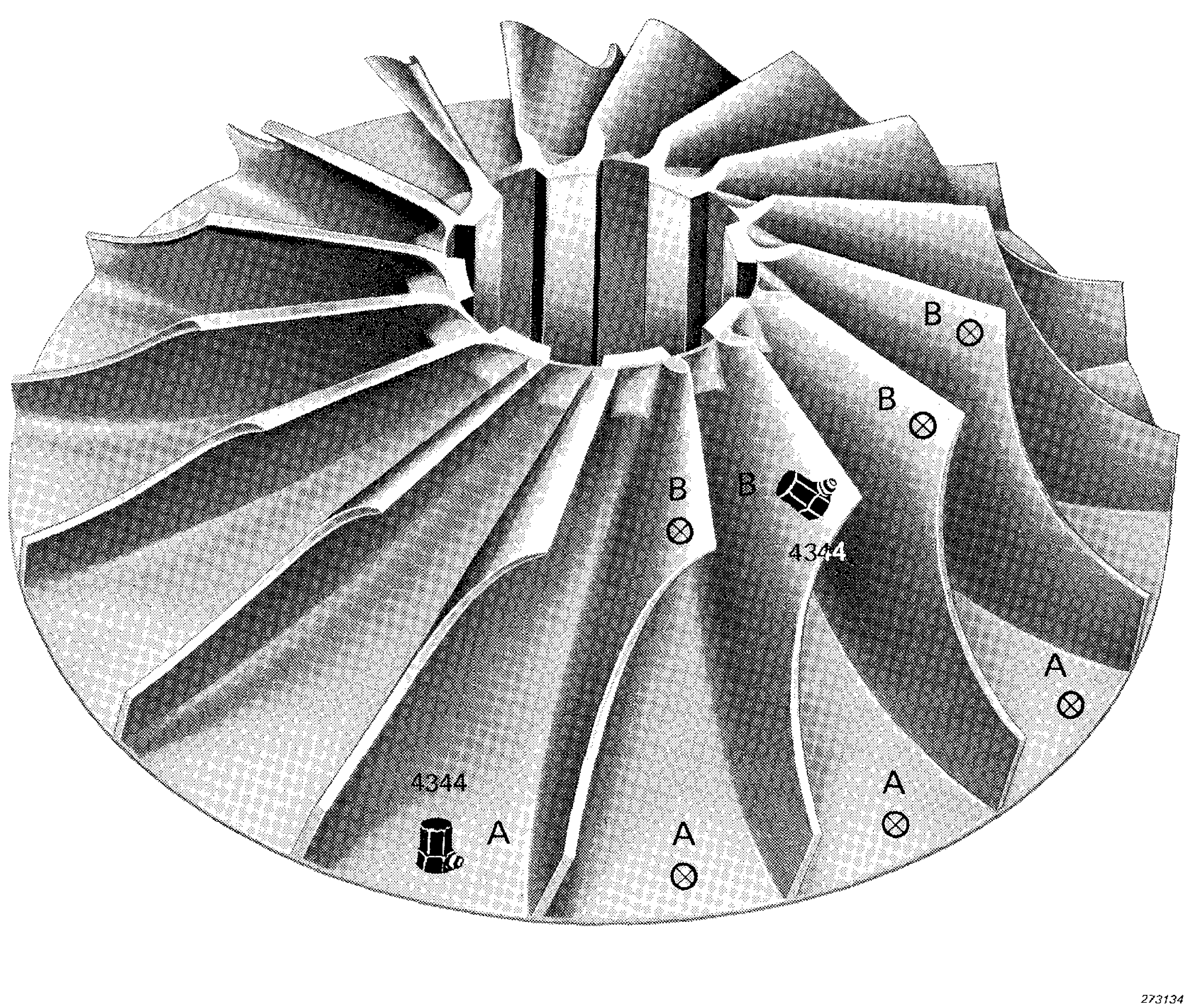


Fig. 1. Measuring points on the compressor impeller

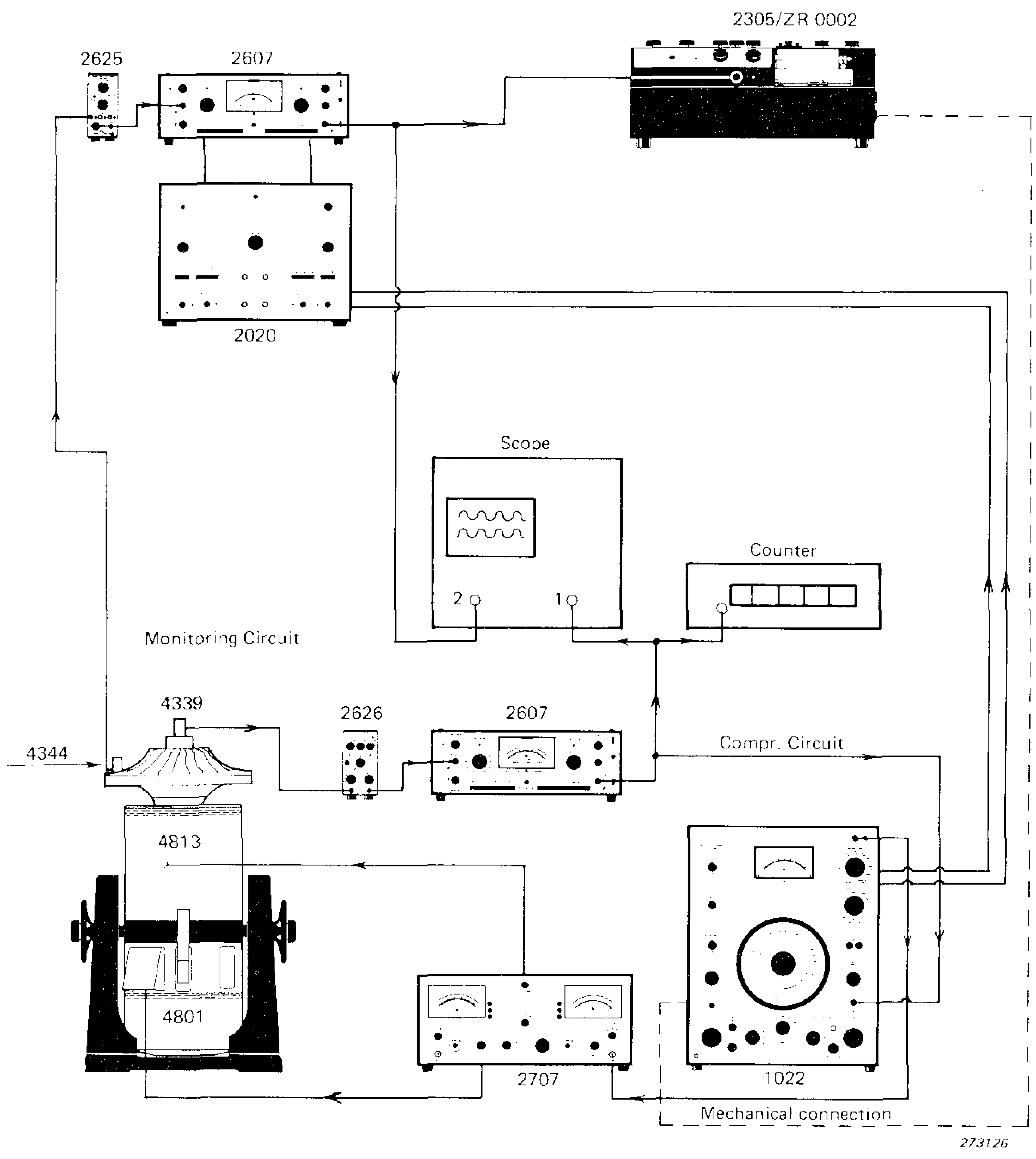


Fig. 2. The measurement set-up

Measurement results

Figs. 3 and 4 show two typical frequency spectra of the same impeller where the measurement points for Fig. 3 and Fig. 4 are 180° apart.

The "A" curves show the disc response while the "B" curves represent the blade vibrations. The levels of curves "B" are amplified 3 times relative to curves "A". The first mode of resonance of the disc (A) is found between 860 and 870 Hz, while the second mode of resonance is at about 1500 Hz.

The first mode of resonance for the blades (B) are between 1720 and 1750 Hz. Higher order resonances do not appear below 2000 Hz.

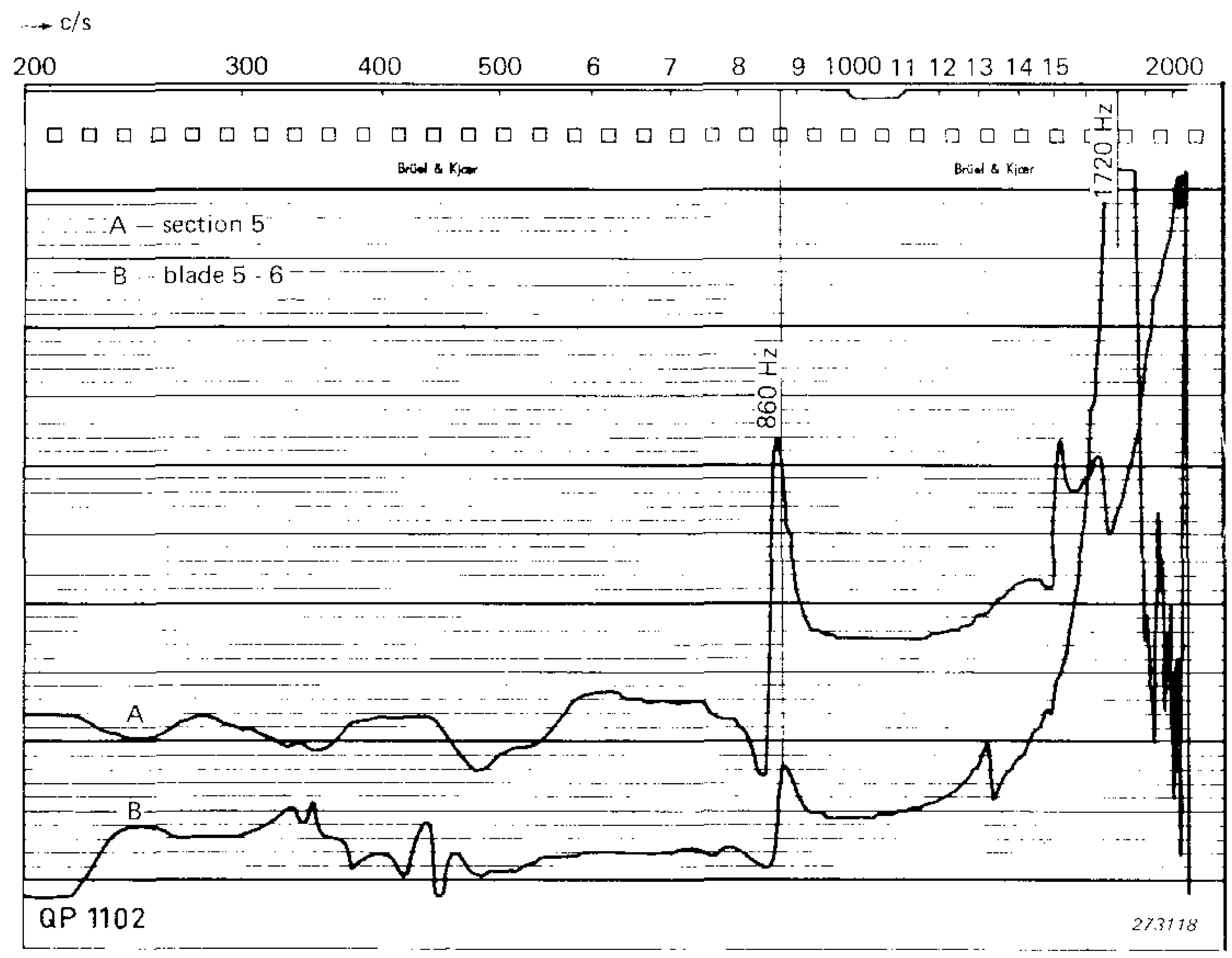


Fig. 3. Frequency response; curve A: section 5, and curve B: blade 5—6

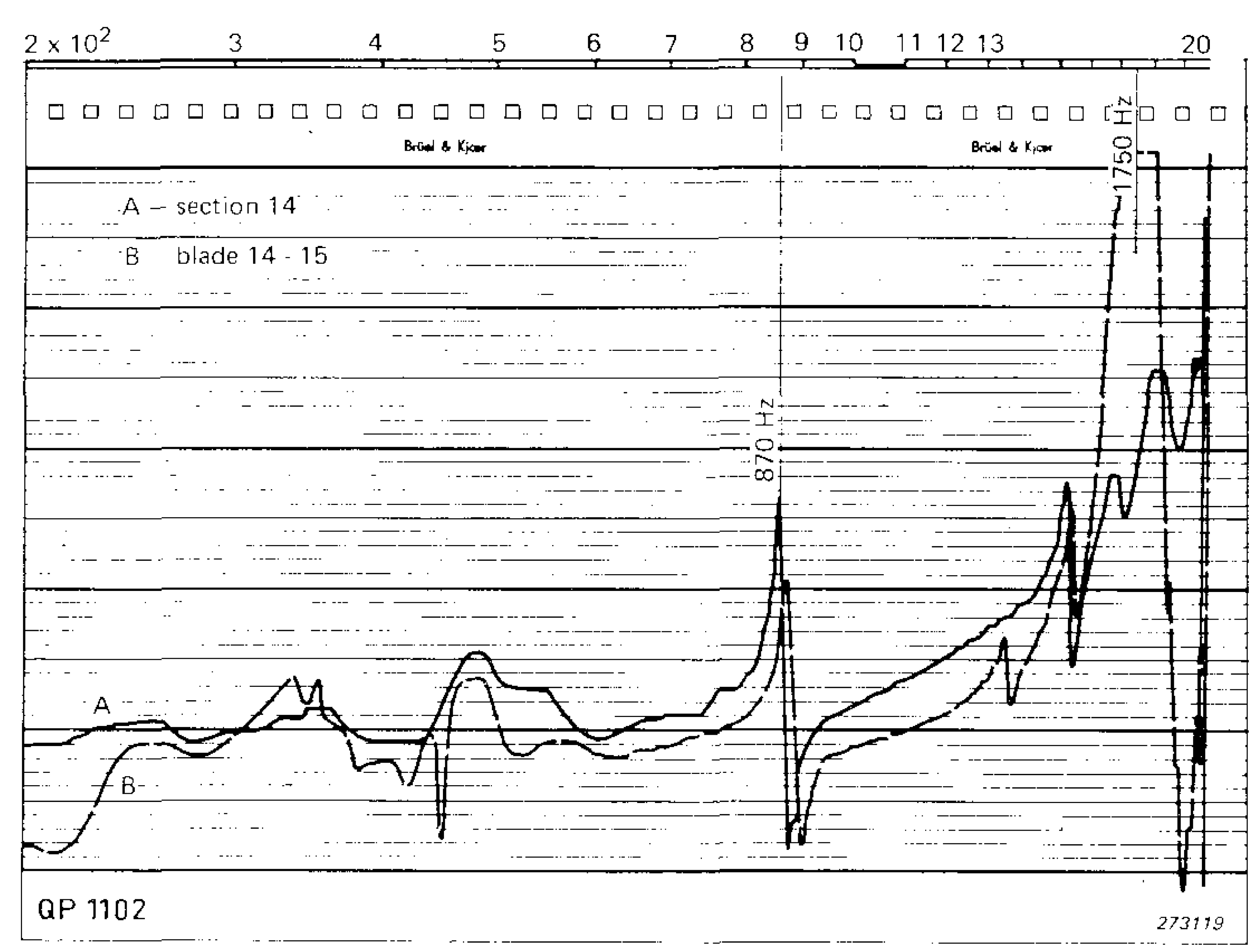


Fig. 4. Frequency response; curve A: section 14, and curve B: blade 14—15

Discussion

Since the accelerometers for the disc and the blades are not mounted in the same direction, the vibration of the disc in its first resonant mode is clearly seen to transmit the vibrations to the blades. On some of the blades the effect of the second mode of disc vibration can also be seen.

On the other hand no reciprocal effect of the blade vibration could be seen on the disc.

The disc is seen to vibrate at 860 Hz in two halves with the node line through the centre of the disc. One half of the disc vibrates in phase while the other half in anti-phase, relative to the vibration exciter table. The position of the node line is not fixed relative to the impeller and does not depend on the small differences in the disc thickness originated in the manufacturing. The node line can be determined by phase measurements around the impeller with the oscilloscope.

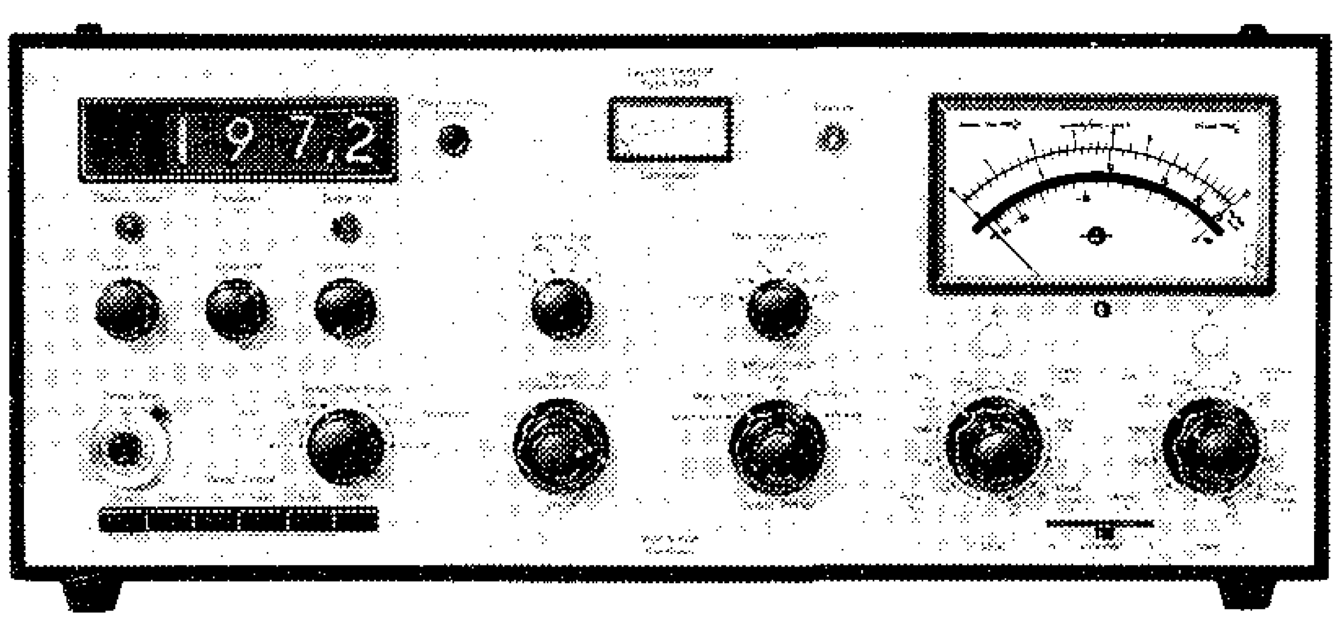
The fixing conditions of the impeller on the fixture has significant influence on the mechanical amplification factor (the Q value) of the disc vibrations while the resonance frequencies are completely independent of the fixing conditions. No influence of the impeller mounting could be seen on the blade vibrations.

Conclusion
Other resonance frequencies than those shown could, naturally, be found by a different choice of measurement points. On the impellers which were investigated, however, the highest vibration levels were found at the points "A" and "B". The vibration conditions were not influenced to a measureable degree by the use of accelerometers with lower masses.

The measuring method described here gave a quick and clear indication of the vibrational response of compressor impellers. A number of theoretically not predictable influences could easily be determined.

News from the factory

Exciter Control, Type 1047



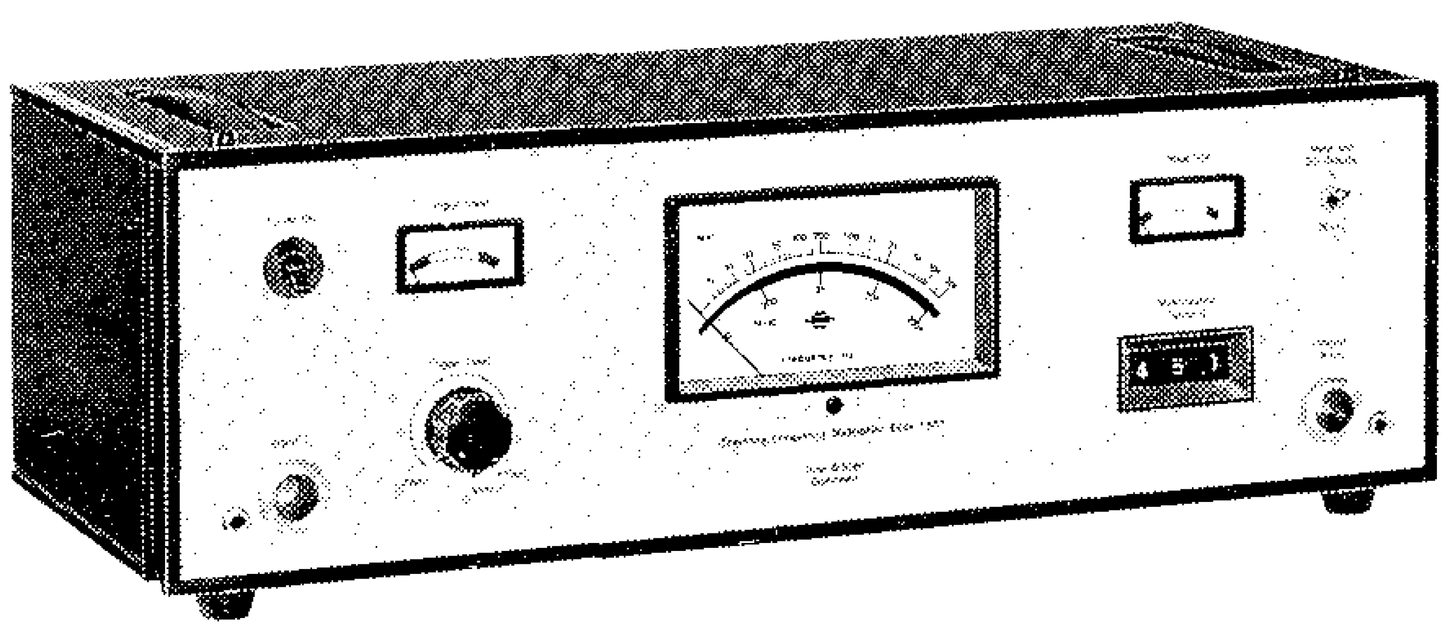
The Exciter Control which generates a sine signal from 5 Hz to 10 kHz is intended for use with all types of electrodynamic vibration exciters. The frequency of the generator is purely electronically controlled either manually or by the sweep generator permitting linear or logarithmic sweep rates. An external sweep generator may also be used. The frequency is monitored on a five digit nixie display with a resolution of 0,1 Hz or 1 Hz (push-button selection). Upper and lower frequency sweep limits may be preset precisely by 10 turn potentiometers anywhere in the frequency range. The sweep can be stopped and reversed at any frequency by push-buttons and can also be externally controlled.

For use with external recorders two outputs are provided, a DC proportional to frequency and DC proportional to log frequency. For operation with Slave Filter Type 2021, signals are provided for bandwidth changes at cross-over frequencies of 10, 30, 100, 300, 1000 and 3000 Hz.

Two vibration meter channels with common input and meter are available for maintaining constant vibration level, calibrated in SI and feet second units. Integrating circuits are included in both the channels to give a choice of acceleration, velocity or displacement control. An automatic frequency controlled cross-over is provided whereby the vibration mode and levels could be set independently in the two measuring channels. Facilities for use of additional cross-overs are incorporated by adding the required number of Vibration Programmers ZH 0100.

The compressor circuit operates over an 80 dB dynamic range and is monitored by a compressor meter. Compressor speed increases with frequency to a chosen maximum value between 10 and 1000 dB/s. Different rates of increase can be selected from 0,3 dB/s times the generator frequency to infinity in which case the chosen maximum compressor speed is valid over the entire frequency range.

Tracking Filter Type 1901



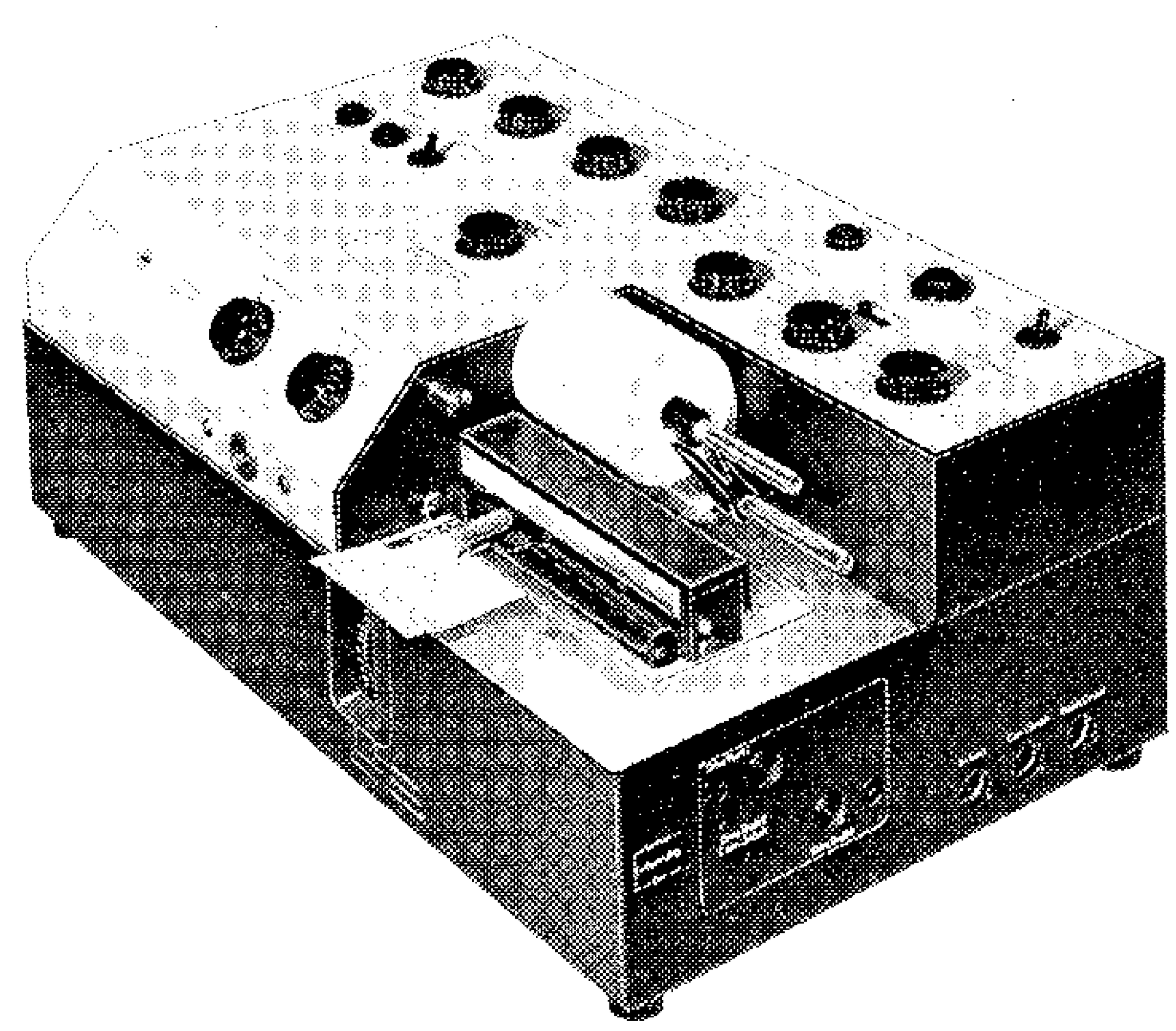
The need for carrying out frequency analysis on rotating machinery has resulted in the development of Tracking Frequency Multiplier Type 1901. The instrument automatically locks onto and tracks the fundamental or a harmonic of a signal of practically any type of periodic waveform in the frequency range 5 Hz to 200 kHz. Besides, the input signal can vary over an 80 dB range from 30 mV to 300 V RMS and is indicated on a level meter when it is within these limits. The input triggering signal after being converted to a reference frequency is fed to a phase locked loop. The high frequencies of the loop (operating on a heterodyne principle) are available to tune the Heterodyne Filters Type 2020 and 2021 and the Analyzer Type 2010 in synchronism with the low frequency input signal to the 1901.

When correct phase locking has taken place it is indicated on a meter. Since the loop can be phase locked on multiples of the input frequency, subharmonics down to 0,1 and harmonics up to 99,9 of the fundamental frequency can be analyzed with 2020 and 2021. With the Analyzer Type 2010 the range is from 1 to 999 in steps of 1. The multiplication factor N (number of the harmonic) can be selected by a simple to operate thumb wheel switch on the front panel. Facilities for automatic switching of the filter bandwidths of 2020, 2021 and 2010 are also provided.

Frequency to DC and lin to log converters are included to provide signals to the logarithmic frequency meter and to DC output switchable to be either linear or logarithmic. The DC output which can follow either the input frequency (f1) or N times (f1) is well suited to drive the Level Recorders Type 2307 or an X-Y recorder to give paper feed proportional to the fundamental or any of its harmonics. Thus the complete variation of the harmonic content of a machine with speed can be automatically plotted.

As can be seen the instrument with the appropriate filters is capable of performing a wide variety of automatic selective measurements e.g., synchronous acoustic and vibration analysis of rotating machinery, and complex harmonic analysis of loudspeakers.

Level Recorder Type 2307



Experience gained over the past years from a multitude of applications has been utilized to develop the Level Recorder Type 2307 (an advanced version of Type 2305) offering maximum versatility and optimum simplicity of operation. Major design changes have been incorporated in the paper drive system, while the recording system has been improved though basically unchanged from the Type 2305. The same interchangeable range potentiometers and recording paper can be used for the two recorders and Type 2307 will accept most of the accessory equipment designed for use with the Type 2305.

A reversible synchronous motor is the prime mover in the paper drive system. The motor used in the recorder Type 2307 has extremely short start and stop times thus removing the need for mechanical clutches as used in 2305. Hence electronic control of all paper drive functions of the 2307 has been feasible allowing numerous remote control facilities and easy manual operation. A very important feature of the 2307 paper drive system is that the paper movement in both directions can be controlled by an external DC voltage. This enables the 2307 to be used as an X-Y recorder allowing the relationship between any two varying voltages to be recorded.

In the DC recording mode Type 2307 uses a 1 kHz chopper allowing faster stable writing speeds than 2305 which utilizes a 100 Hz mechanical chopper. Also in the DC mode 2305 uses peak detection whereas 2307 utilizes average detection reducing the influence of extraneous noise.

The Level Recorder 2307 gives correct RMS detection for signals with crest factors up to 10 while the 2305 can handle crest factors only up to 5.

As safety precautions a warning lamp is included in the 2307 to indicate unstable operation of the writing system as well as a safety switch in the potentiometer recess permitting change of potentiometer without risk of damaging the wiper.

Finally on Type 2305 the highest resolving power is obtained at position 10 dB on the Range Potentiometer knob, whereas in Type 2307 an additional position 8 dB has been incorporated to give an even higher resolution.

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(Continued from cover page 2)

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DK-2850 Nærum, Denmark. Teleph.: (01) 80 05 00. Cable: BRUKJA, Copenhagen. Telex: 15316