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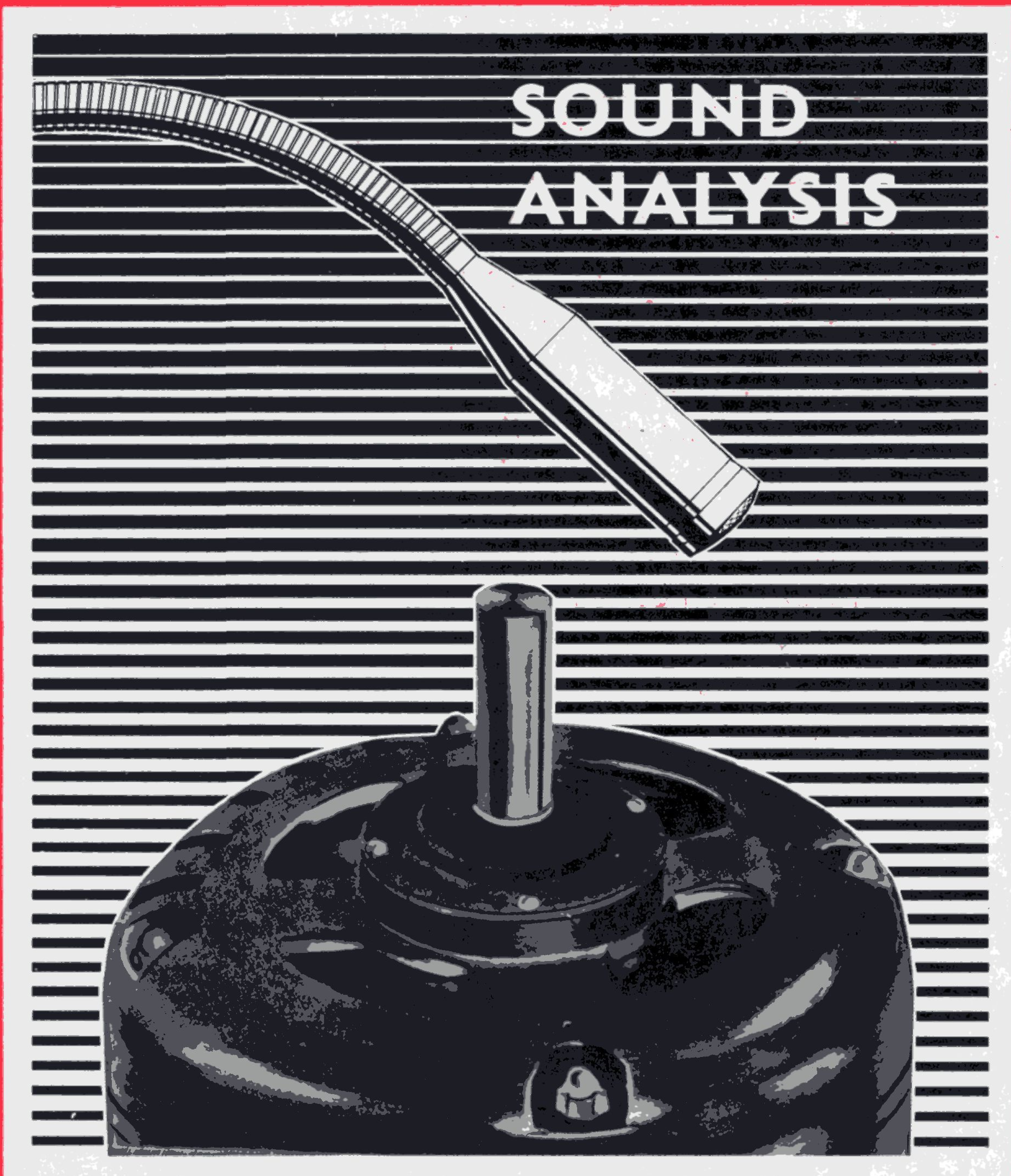

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TECHNICAL REVIEW

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Sound Analysis in Industrial Processes and Production.

by

*Per V. Brüel, D. Sc.**

Summary.

A listener's test has always been a significant part of the final check of complicated mechanical units such as gazoline and diesel engines, gear-boxes, automobile rear axles, air conditioning equipment, electric motors, domestic appliance apparatus, razors, watches etc., for if possible by the character of the sound to be able to conclude whether the mechanical units is in order or not. However, where only the human ear is used, even trained persons have great difficulty in setting an unerring limit for "go" or "no go" and moreover they find it hard to diagnose the defects. In this article an apparatus is described which objectively measures and in detail analyzes sound and vibrations as they appear in industry. The result is automatically recorded on a preprinted calibrated paper strip in a few seconds. The record may follow the examined unit either to the store room, or to the repair shop, if the unit is rejected. The apparatus makes it possible to set an unerring, uniform, and objective approval limit. In cases of "rejected" units information taken directly from the recorded curve will give a guide to the cause of trouble, thus facilitating the work in the repair department. Some practical examples from the manufacturing of air conditioning units, automobile rear axles and small electric motors are also shown.

Sommaire.

Un essai auditif a toujours une part significative dans le contrôle final d'ensembles mécaniques compliqués comme dans les moteurs Diésel et à essence, boîtes de vitesse, trains-arrières d'automobiles et équipements de climatisation d'air, moteurs électriques, appareils d'applications domestiques: rasoirs, montres, etc. dans lesquels il est possible, par le caractère sonique, de conclure si le dispositif mécanique est normal ou non. Néanmoins l'orsque l'on a recours uniquement à l'oreille humaine, même des personnes entraînées ont de grandes difficultés pour situer une limite infaillible à «bon» ou «mauvais» et en outre, il leur est très difficile de diagnostiquer les défauts.

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*) This paper was given by Dr. Per V. Brüel at the International Instrument & Measurements Conference in Stockholm, Sweden, September 1956.

Dans cet article est décrit un appareil qui, objectivement, mesure et analyse en détails les sons et les vibrations tels qu'ils apparaissent dans l'industrie. Le résultat est automatiquement enregistré en quelques secondes sur un morceau de papier préimprimé et étalonné. L'enregistrement peut suivre la pièce examinée vers l'atelier de stockage ou vers l'atelier de réparation si la pièce est rejetée.

L'appareil rend possible le classement uniforme, objectif et infaillible dans des limites déterminées. Dans le cas des pièces rejetées, les informations données directement par la courbe d'enregistrement fournissent des renseignements précieux sur les causes du défaut, facilitant grandement le travail du service réparation. Quelques exemples pratiques en fabrication de dispositifs de conditionnement d'air, de trains-arrières d'automobiles et de petits moteurs électriques sont également montrés.

Zusammenfassung.

Die Abhörkontrolle hat immer eine wichtige Rolle bei der Fertigungsprüfung gespielt. Komplizierte mechanische Einheiten wie z. B. Verbrennungsmotoren, Getriebe, Radachsen, Klimaanlagen Elektromotoren, Haushaltgeräte, Rasierapparate, Uhren usw. werden nach der Art der von ihnen verursachten Geräusche beurteilt. Dort aber, wo nur das menschliche Ohr zur Prüfung eingesetzt wird, können selbst geübte Fachleute kaum eine gleichbleibende Grenze zwischen »gut« und »schlecht« ziehen. Ausserdem finden sie es schwer, die Ursache eines Fehlers anzugeben.

In diesem Artikel wird eine Messapparatur beschrieben, mit der man den in der Industrie vorkommenden Luftschall und Körperschall objektiv messen und analysieren kann. Das Ergebnis wird in wenigen Sekunden auf einem Streifen vorgedruckten Registrierpapiers aufgezeichnet, es folgt der Maschine entweder in den Lagerraum, oder wenn diese ausgeschieden wurde, in die Reparaturwerkstatt. Die Messapparatur gewährleistet eine gleichbleibend objektive Fehlergrenze. Die beanstandeten Maschinen zeigen auf dem Diagramm Abweichungen, die unmittelbar auf die Art des Fehlers hindeuten, so dass die Arbeit in der Reparaturwerkstatt erleichtert wird. Einige praktische Beispiele aus der Produktion von Klimaanlagen, Radachsen und kleinen Elektromotoren werden gegeben.

With the introduction of complex production processes the opportunity for minute visual inspection decreases as the system becomes more automatic. Therefore it would seem to be reasonable, particularly in the case of manufactured mechanical and electrical units containing moving parts, to delay the inspection until completion of the unit. Such a system must necessarily require that initially the production system is set up and aligned in a conventional manner. If, however, in production, it is possible to apply only a final check, and by so doing obtain a figure relating to the general quality of the finished part, plus an indication of the where-abouts of possible functional faults, a further step will have been made in the direction of automatic control.

Just such a control process is available in the form of acoustical measuring apparatus.

It is thereby possible to set a standard for the acceptable noise emitted from a unit, and in the event of this level being unacceptable it is possible, by analysis, to locate the source of trouble. The measurements therefore serve a dual purpose: to make the finished product acoustically acceptable to the consumer, a point of great importance where domestic apparatus is concerned, and by the recognition of a high noise level or unusual frequency spectrums to detect and locate mechanical faults in construction.

Acoustical control is not, however, limited to the control of unit production. Application is also found in the field of chemical and material processing. Here it is possible to determine, for example, the degree of loading and, to some extent, the quality of the processed material. A typical example of the application is in the case of ball mills, used extensively in the cement industry and in power stations.

In order to substantiate the claims for acoustical methods of control it is necessary to investigate some fundamental aspects.

Air borne sound, as is well known, is a vibration of air particles. A similar phenomenon takes place in solid materials and thus it may be supposed that instruments used for acoustical measurement can as well be used for vibration measurement. In fact the only difference is in the type of unit employed to convert the vibrations into electrical signals. The microphone, in one of its

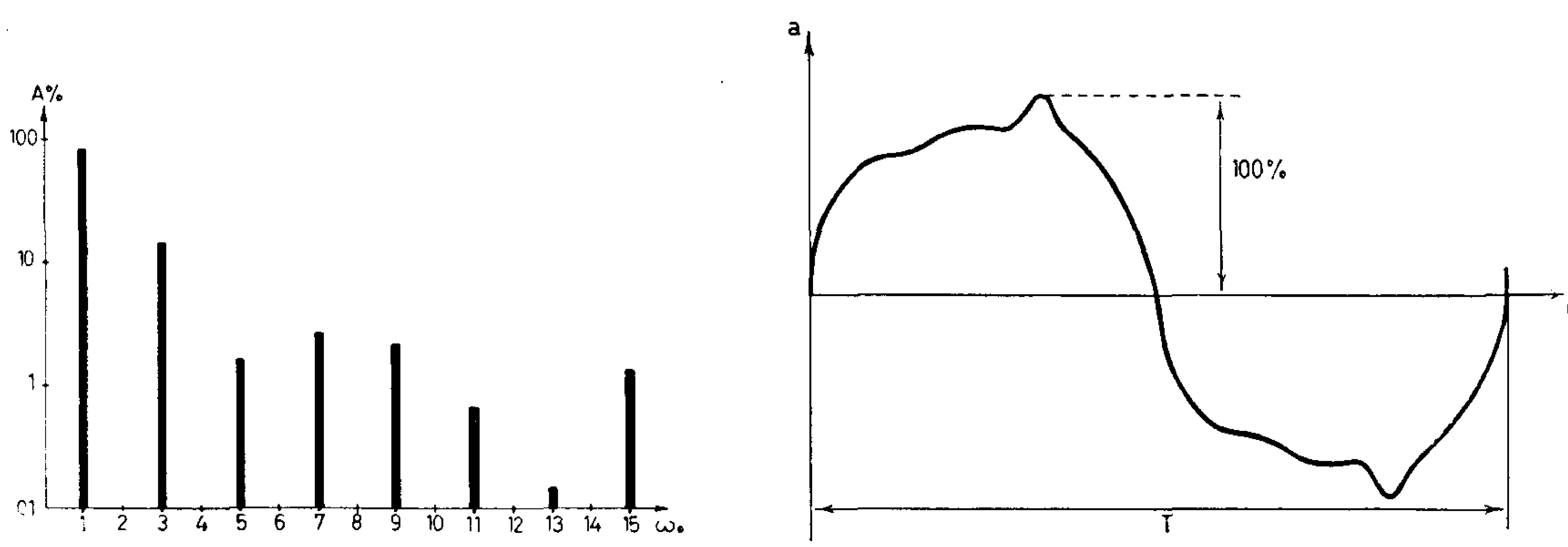
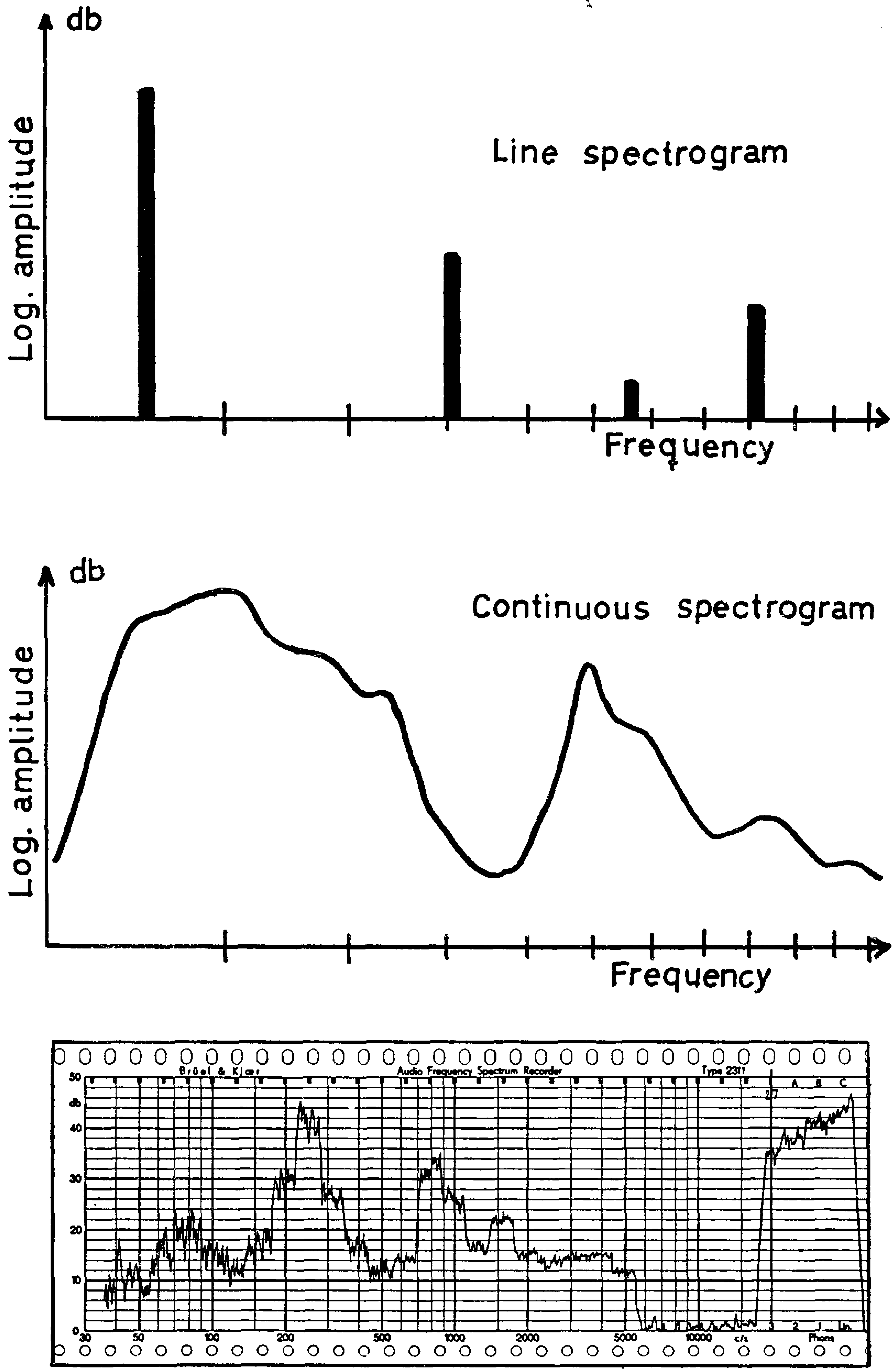


Fig. 1. Example of a complex signal, and its frequency spectrum ($\omega_0 = \frac{2\pi}{T}$).

various forms, is used to convert the pressure variations in air into suitable electrical waveforms, whilst there are a considerable number of conversion elements which may be used to convert vibrations in solid media into electrical signals.

The actual nature of the vibration waveform, and its resulting electrical signal must be analyzed if the information contained therein is to be of use



Automatic recorder spectrogram

Fig. 2.

a) Line spectrogram characterising a simple complex tone consisting of only pure tone components.
b) Continuous spectrogram of a practical noise where many frequencies are represented.
c) Typical recorded spectrogram.

Most sounds and vibrations occuring in practice are of a composite nature. The analysis of such waveforms by other than electronic methods is both difficult and tiresome. Analysis in the most ideal practical cases occures in connection with musical instruments where the sound emitted, although complex, may be seen to be composed of a fundamental frequency and various harmonics giving a line spectrogram, fig. 1.

To attempt a mathematical analysis of a waveform which may consist of a very large number of components would be a hopeless task. Particularly as the frequencies of the discrete sinusoidals composing the composite waveform, may, in connection with mechanically excited vibrations occure between very low frequencies of just a few cycles per second, up to ultrasonic frequencies of 20 kc/s—500 kc/s.

Fortunately, in general, it is the frequencies between 15 c/s and 20 kc/s which are of most interest.

The intensity of sound is normally expressed, in terms of sound pressure, in μbars = dyn/cm^2. In order that the wide range of sound pressures which can be detected and compared may be conveniently handled, a logarithmic relationship is normally used.

Mechanical vibration may be expressed in terms of the amplitude of vibration, cm, the velocity of vibration, cm/sec, or the acceleration in cm/sec^2. Which of these three is used will depend on the parameter of interest and the pick-up and electronic circuitry employed.

There are two distinct methods by which a sound may be analysed. Discrete frequency measurements may be carried out with an apparatus employing a heterodyne principle. However, this is only really suitable for line spectrograms such as the one shown in fig. 1 and 2a. The system is very accurate, and precise analysis of steady, composite sounds involving only fundamental and overtones may be obtained. However for noise or sound analysis, where the source frequency may drift, this method is quite unsuitable.

The only satisfactory method of analysing industrial noise which normally contains a continuous frequency spectrum, see fig. 2b, is to use a constant percentage bandwidth analyser, i. e. an analyser the bandwidth of which equals a certain percentage of the bands' center frequency.

A further requirement to be met with is that the intensity or pressure of the sound, or the amplitude of the vibration, be presented in an acceptable form. This may be achieved by using a "level recorder", which would record the magnitude of the sound or vibration in the particular frequency band under consideration. The most convenient type of level recorder for this purpose will write the magnitude not in linear scale but according to a logarithmic scale, so that it is possible in a single diagram to show both small and large amplitudes with the same relative accuracy. Such a level recorder normally works on the potentiometer principle which assures a high degree of accuracy.

A suitable instrumentation system would consists of a series of filters, into which a voltage proportional to the magnitude of the sound or vibration could be fed, and there split into its different frequency components. A switch should be included to select each filter individually, and the output from the filters

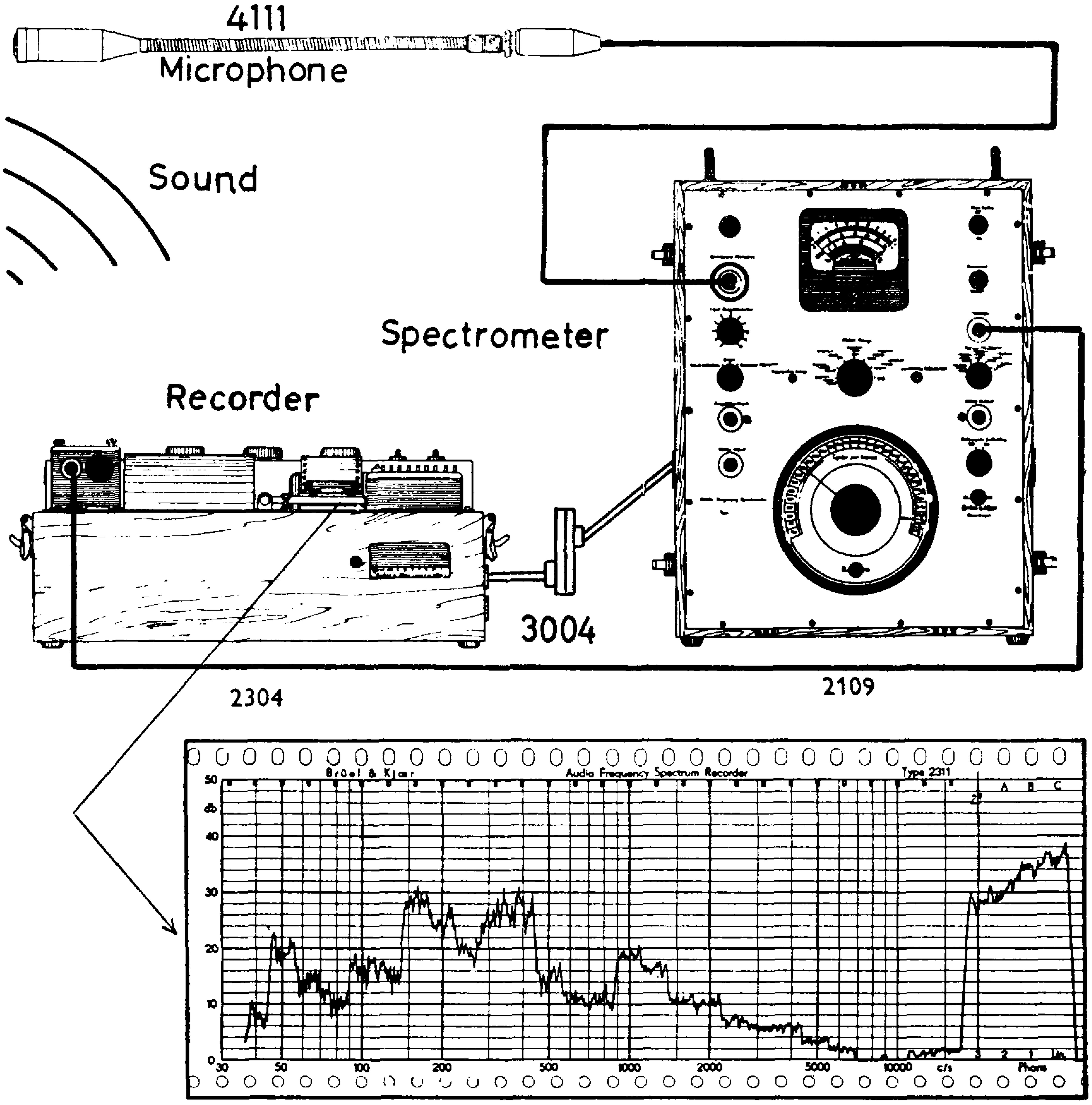


Fig. 3. Complete equipment for analysis of sound and vibration, consisting of condenser microphone (or vibration pick-up with preamplifier) spectrometer and level recorder.

should be presented so that the magnitude of a particular frequency band can be easily determined.

A system of this type can be obtained by combining the Level Recorder Type 2304 and the Audio Frequency Spectrometer, Type 2109 as shown on fig. 3.

In the figure is also shown the connection of the Condenser Microphone with cathode follower for sound level measurements, which must be replaced by the Barium Titanate vibration pick-up with preamplifier for vibration analysis.

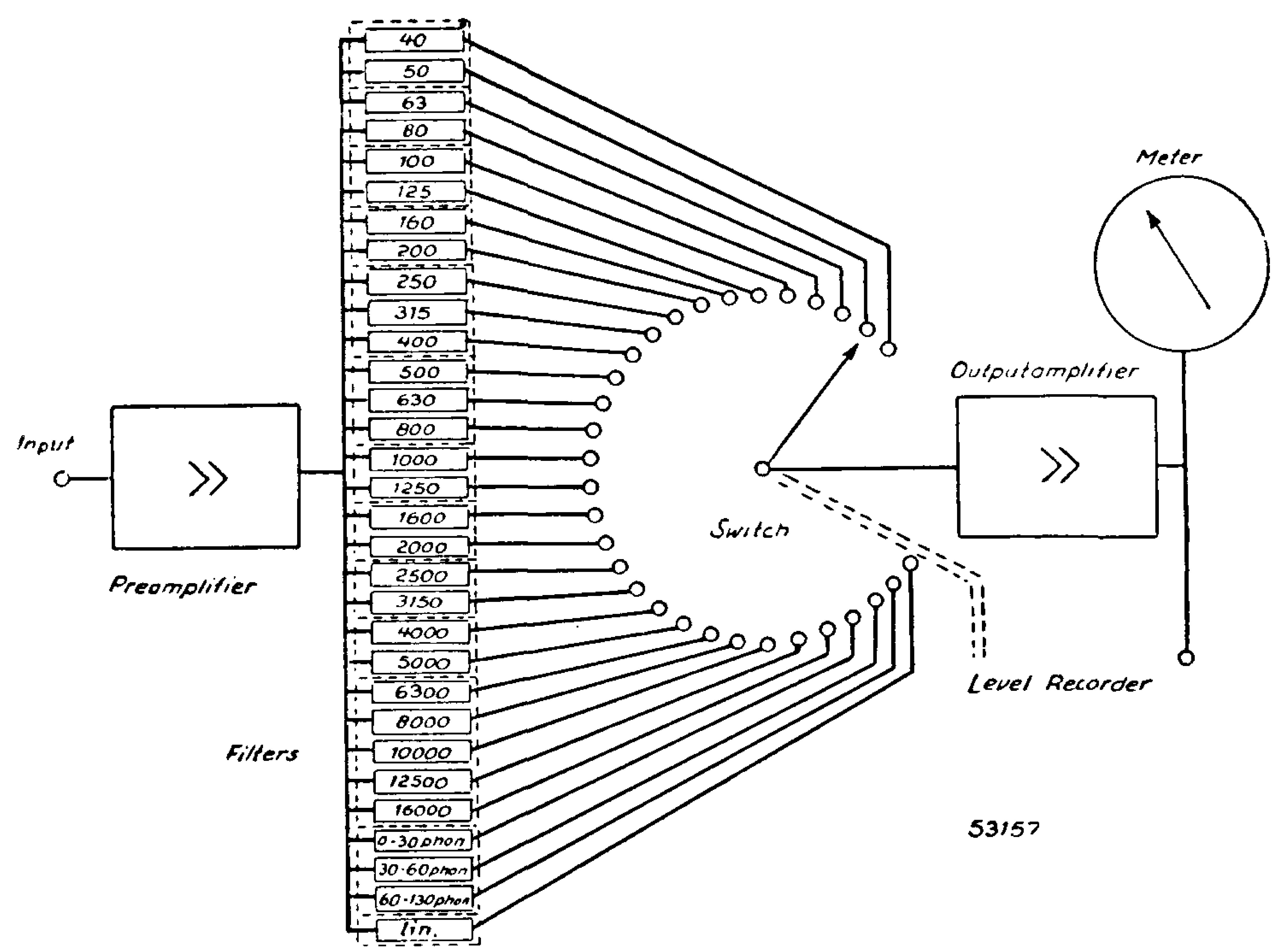


Fig. 4. Schematic diagram of the Spectrometer Type 2109.

The principle of the spectrometer part of the system is shown in fig. 4. The small voltages from the Condenser Microphone or vibration pick-up are amplified in an amplifier after which all the $^1/_3$ octave filters are connected. Usually there are 27 filters covering a frequency band from 36 c/s to 18000 c/s, but by supplying 7 extra filters the frequency range can be extended from 14 c/s to 36000 c/s. All filters are permanently in circuit, so it is not necessary to wait for some build-up time. After the filters is the main switch, which is normally driven mechanically by the Level Recorder via either a flexible shaft or a chain. The main switch successively connects the filter outputs to an output amplifier, meter and level recorder. The measured results can be recorded on preprinted calibrated recording paper. By arranging the speed of the paper feed to coinside with the rotation of the filter selector, the signal amplitudes for particular frequency bands may be readily determined.

In order to record correctly small signals of frequencies close to large signal frequencies it is required that the filters be very selective, that is signal of frequencies within the selected filter band should pass through without being attenuated and signals having frequencies outside the band be reduced to nonsignificant values, see fig. 5.

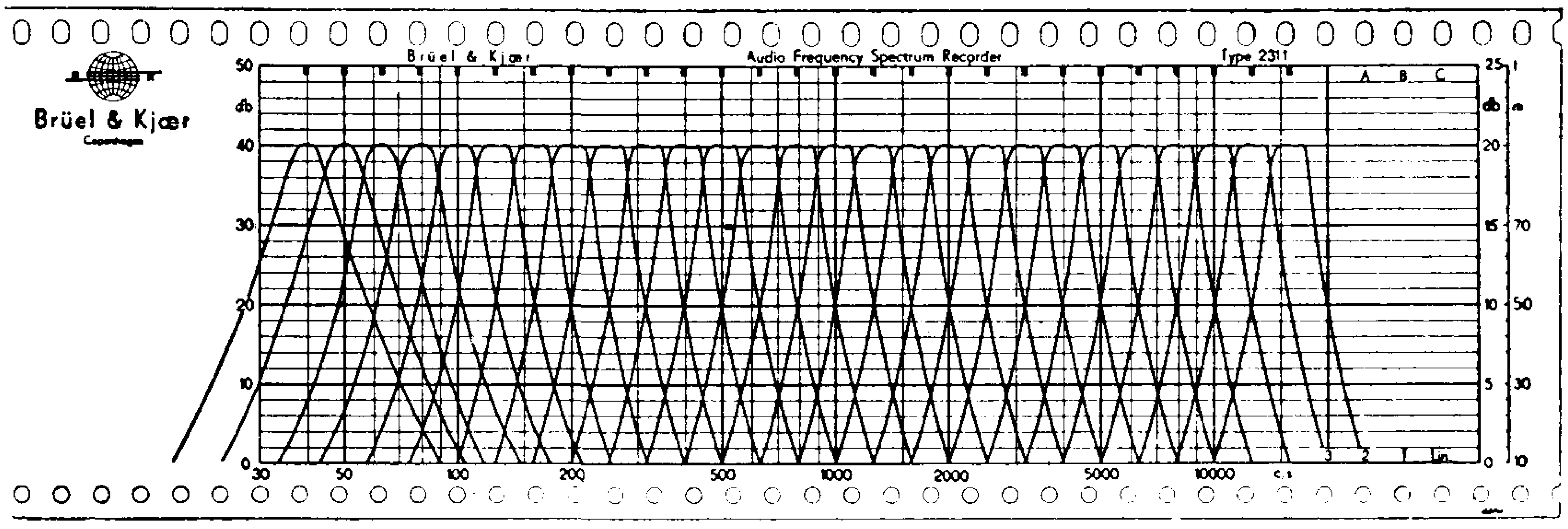


Fig. 5. The practical third-octave filter curves.

Combining the two apparatus mechanically produces a compact unit in the form of the Audio Frequency Spectrum Recorder, Type 2311, fig. 6. Here as before the filters are switched in one at a time, the input coming from a common preamplifier, and the output, after passing through a further amplifier, is used to feed the writing mechanism. The 27 one third octave filters are arranged so that the characteristic of adjacent filters cross around the 3 db point. To illustrate the use of the described instrumentation in modern industry some typical application examples will now be considered.

Analysis of the vibrations occuring in lathe cutting tools, milling cutter arbors and other machine tools can assist in the improvement of machined finishes making possible the choice of correct cutting speeds and feeds.

Simple gear trains are particularly inclined to give rise to undesirable noise and vibrations. The example shown in fig. 7 is a continuous spectrogram taken of the noise from a simple gear system. In the case considered the wheel

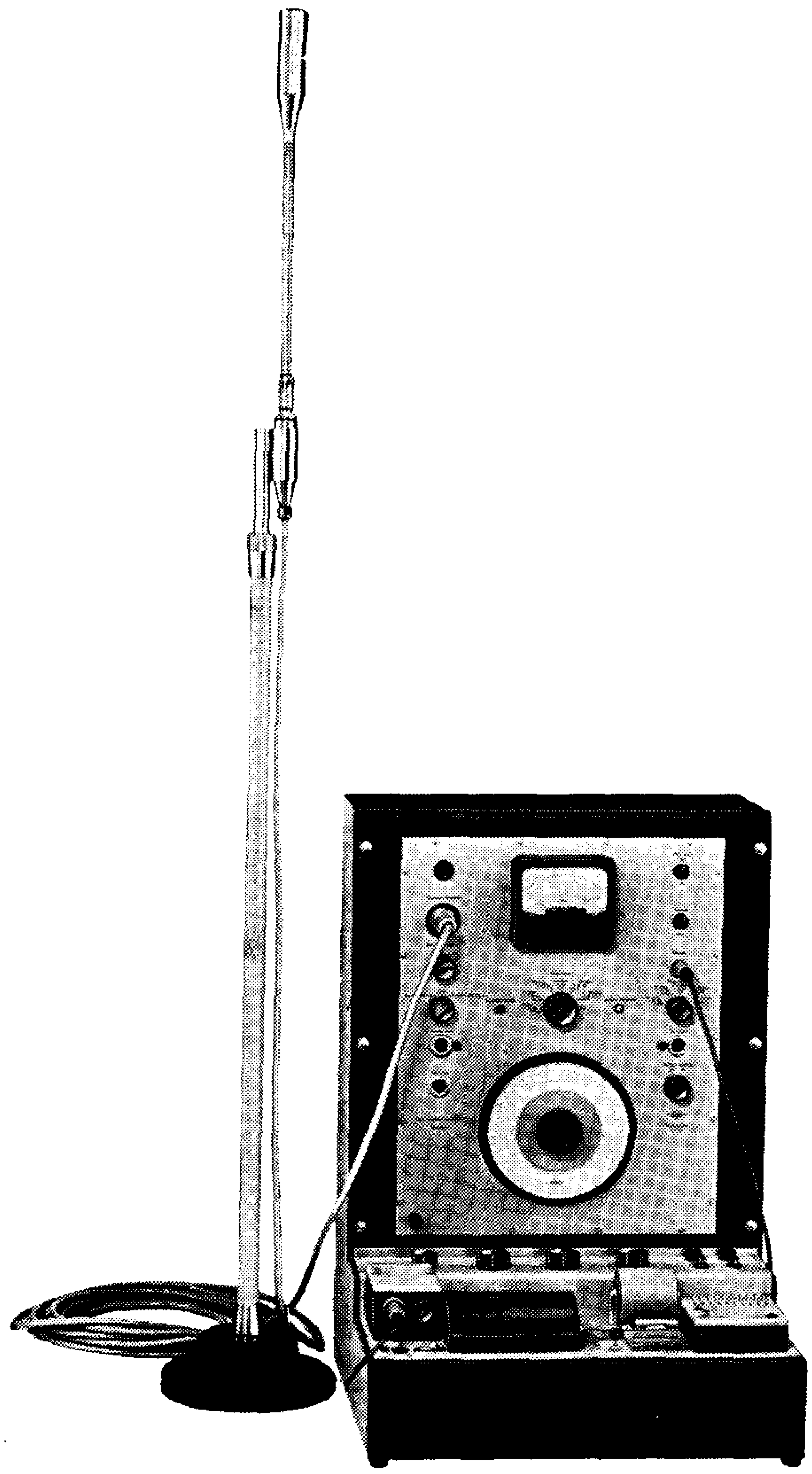


Fig. 6. Industrial unit Type 2311 with 4111 for complete analysis of air-borne sound.

having 68 teeth ran at a speed of 1100 r.p.m. thereby producing a vibrational pitch of

$$\frac{1100 \times 68}{60} = 1245 \text{ c/s},$$

the spectrogram obtained using a Vibration Pick-up and the 2311 shows quite clearly the ⅓rd octave band within which this frequency falls. It is also seen that the vibration at this frequency is 16 db up on the next highest level. The fact that the precise frequency is not indicated is of no consequence, because the only possibility within the band, is from the number of gear tooth engagements per second.

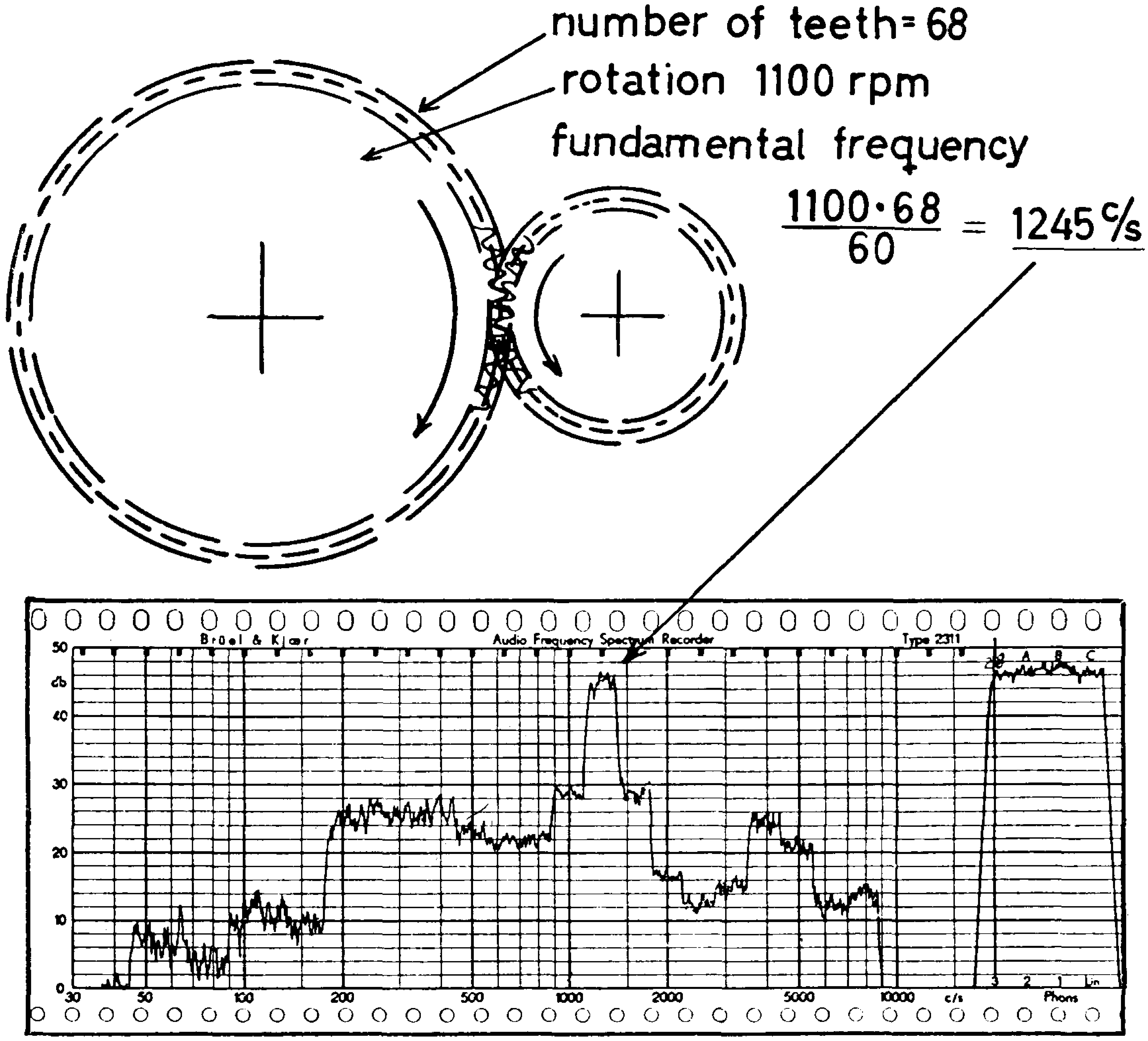


Fig. 7. Spectrogram of typical toothed wheels noise. Note the powerful vibration at tooth frequency.

The reason for the excess vibration noise was found to be caused, after optical inspection, by a bad profile form of the gear teeth. This in turn was doubtlessly due to poor cutting by the milling machine on which it was produced.

From the continuous spectrograms shown in fig. 8a may be seen typical types of recordings which may be obtained.

The spectrograms obtained by analysing the sound caused by air issuing from a pressure tool is shown in fig. 8b, the 10000 c/s component was found to be particularly annoying to persons working in the vicinity of the exhaust.

In some cases it is not particularly satisfactory to take the acoustical output of an object under investigation.

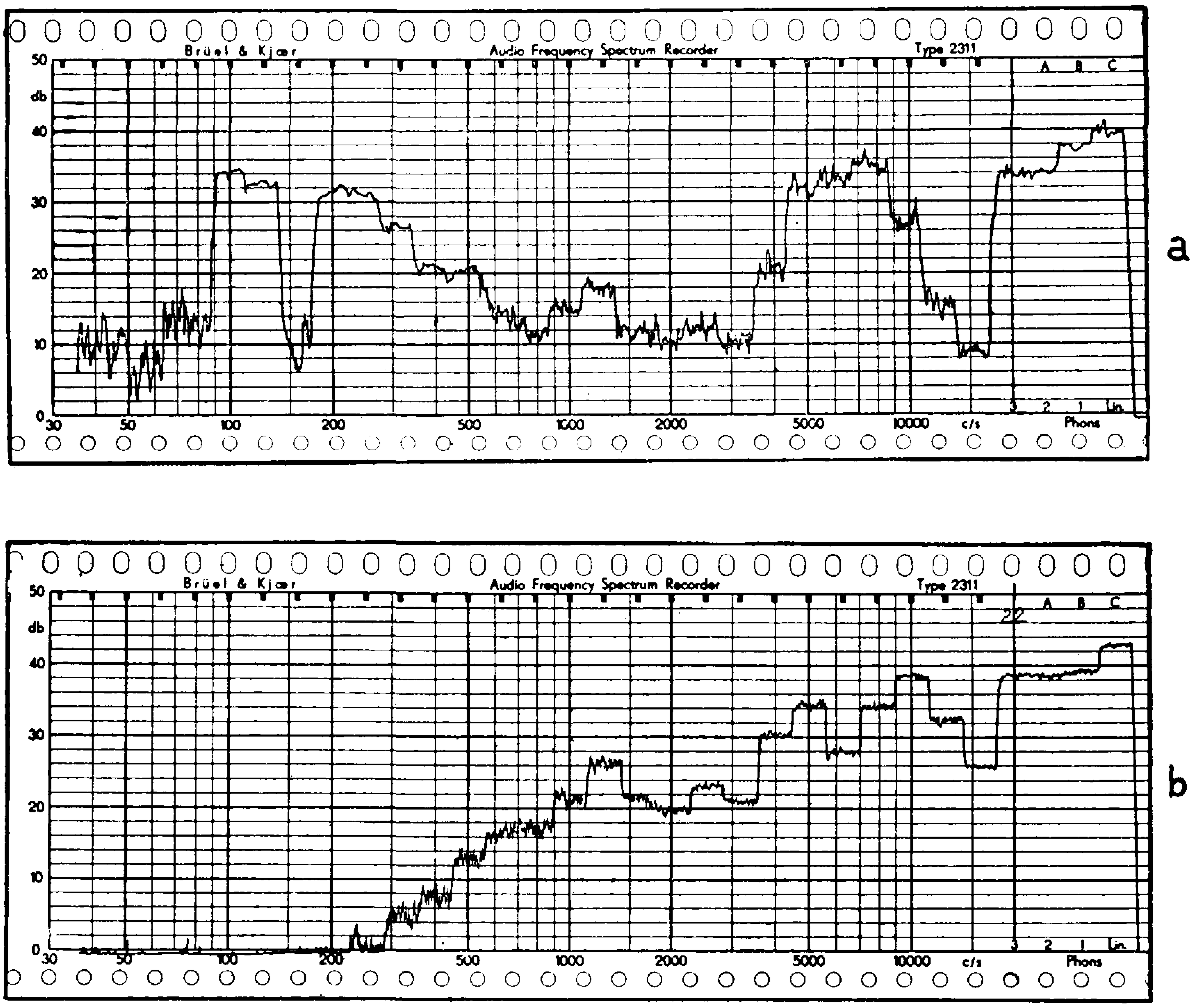


Fig. 8. a) The noise from a lathe in operation. b) Spectrogram of the noise from air streaming out of a pressure tool.

Little information could be derived from the acoustical spectrogram of the lathe, fig. 8a. Where-as the analysis of the spectrogram obtained witn a vibration pick-up, produced much useful information.

Actual production problems which have been solved by acoustical and vibration analysis, are the best argument for the further application of this technique.

A large scale producer of domestic and office air conditioning systems was somewhat dismayed a few years ago to receive an adverse Consumers Report. The report stated that of the number of units tested, a large percentage emitted too much noise. It thus became apparent that it was essential to supply the development department with apparatus for determining the optimum noise free operating conditions which could be expected. The design of the unit was altered with this object in view.

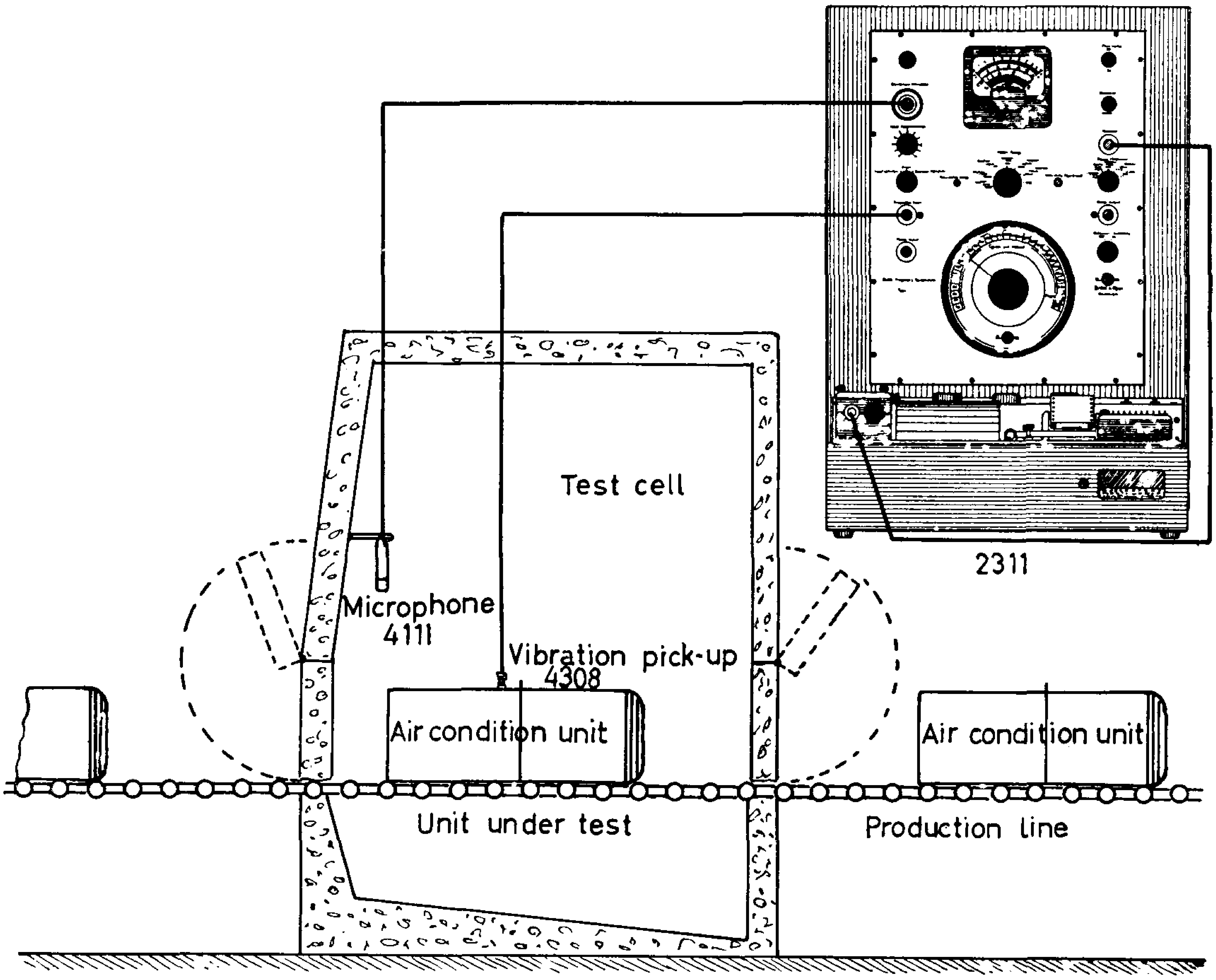


Fig. 9. Set-up for the final checking of air conditioning units on the production line. For the acoustical test the unit is placed in a sound insulating, reflecting, and integrating test cell. Both noise and vibration analysis are made.

Then in order that the finished units should not be passed through final inspection on a subjective basis, an acoustical and vibration test chamber was built into the production line. Great attention was given to ensure that the test room was isolated from factory noise, and the chamber was designed in non-rectangular form to avoid the creation of pronounced standing waves, see fig. 9.

An automatic conveyor system and pneumatically operated doors feed the units into the chamber and exclude the external noise. By ensuring that the air conditioning units are always tested in the same position it is possible to have a permanent microphone installation. As a secondary check, a vibration pick-up mounted on one particular part of the structure gave further useful data. The output of both vibration pick-up and microphone were fed into the Type 2311 and the spectrogram taken from each. From the experiments undertaken in the development department it was possible to set a maximum noise level which would be acceptable.

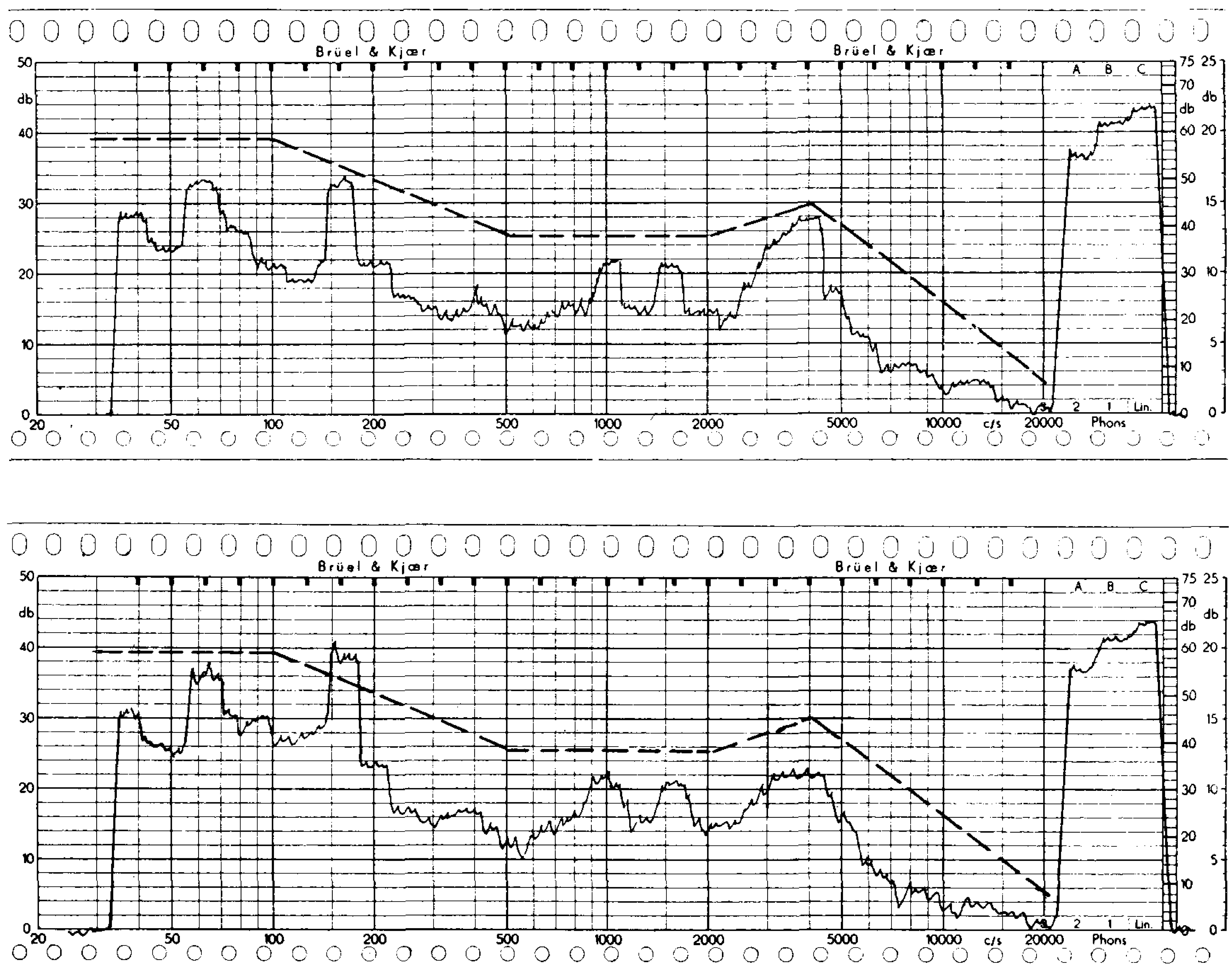


Fig. 10. Spectrograms with "go" and "no go" limits for the acoustical noise from air condition units. a) Acceptable. b) Rejected unit.

Thus by comparing the spectrograms obtained in production testing, with the standard prescribed by the development department a system of "go" and "no go" inspection was achieved.

In the event of the unit being rejected because of too high a noise or vibration level, inspection of the spectrogram revealed to the repair and rectification department the source of trouble. An excessively large amplitude around 180 c/s would indicate an unbalance in the motor, possibly a faulty winding. Likewise, too great an output at 2.500 c/s could be related to an incorrectly adjusted fan blade, fig. 10.

In practice the actual time spent in testing amounted to about 3 mins, but as the rate of production was one unit/minute it was necessary to install three test rooms and to split the production line. In addition, to ensure continuity a spare set of equipment was kept in reserve.

Obviously such a set up is quite expensive, but on the other hand the capital outlay is well worth while and is soon recovered.

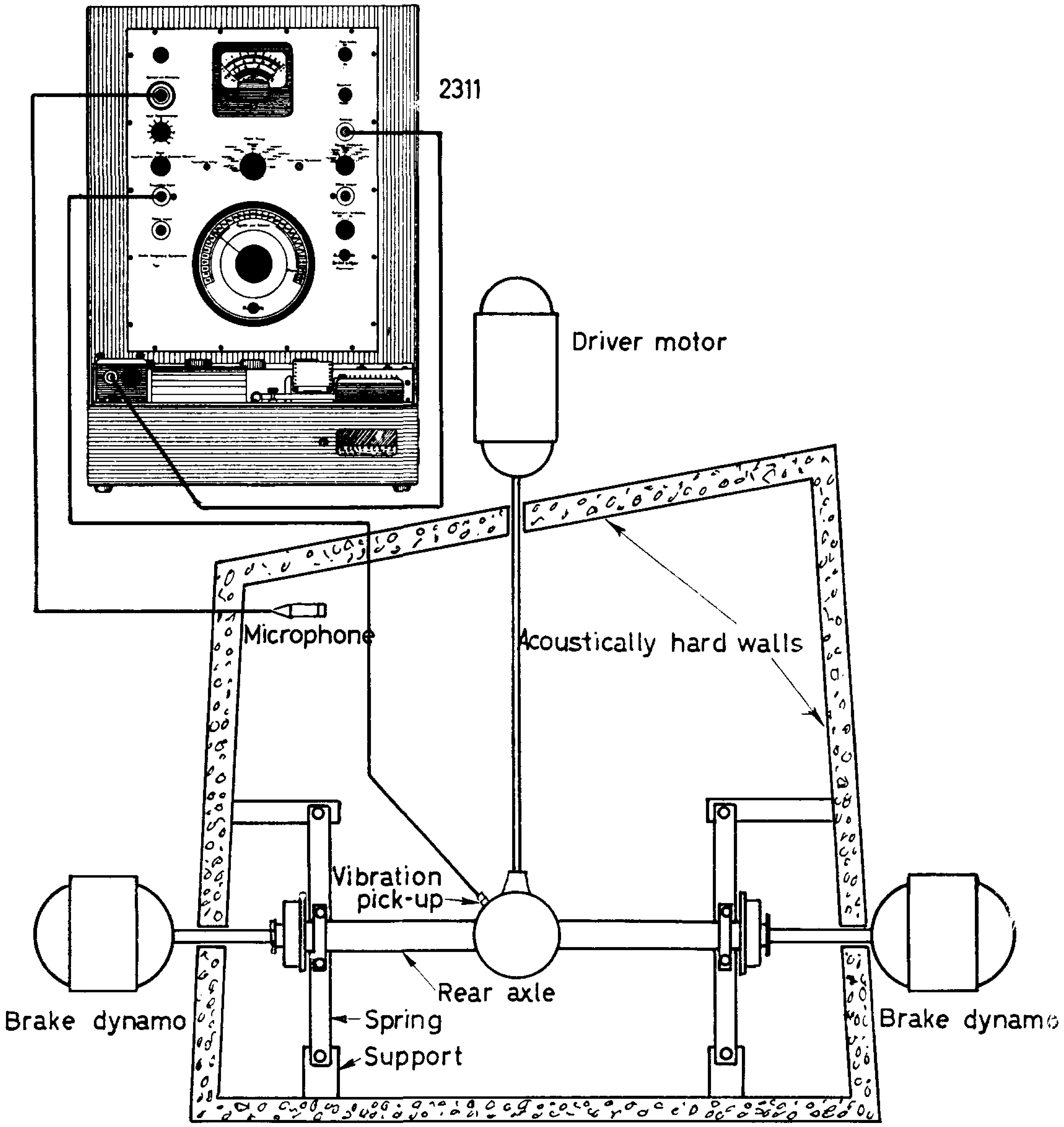


Fig. 11. Test cell for checking rear axles in an automobile factory. Both acoustical and vibration analysis are carried out.

The life expectancy of the air conditioning unit was increased, with the result that fewer repair claims were made.

Also such faults as were found, as a result of the testing, could be speedily rectified by the repair department, saving considerable fault finding time.

A second example of production line testing comes from an American automobile factory. The testing of the back axle assembly was found to be extremely difficult to control. An acoustical control system, on the production line, was suggested and tried.

It was found necessary to test the back axle under full load conditions. To achieve this an electric motor was coupled to the transmission shaft, and a dynamo to the end of the brake drums.

This system permitted the minimum use of power, because the output from the dynamos could be fed back into the motor. It was thus possible to conserve power and also to obtain a measure of the transmission efficiency.

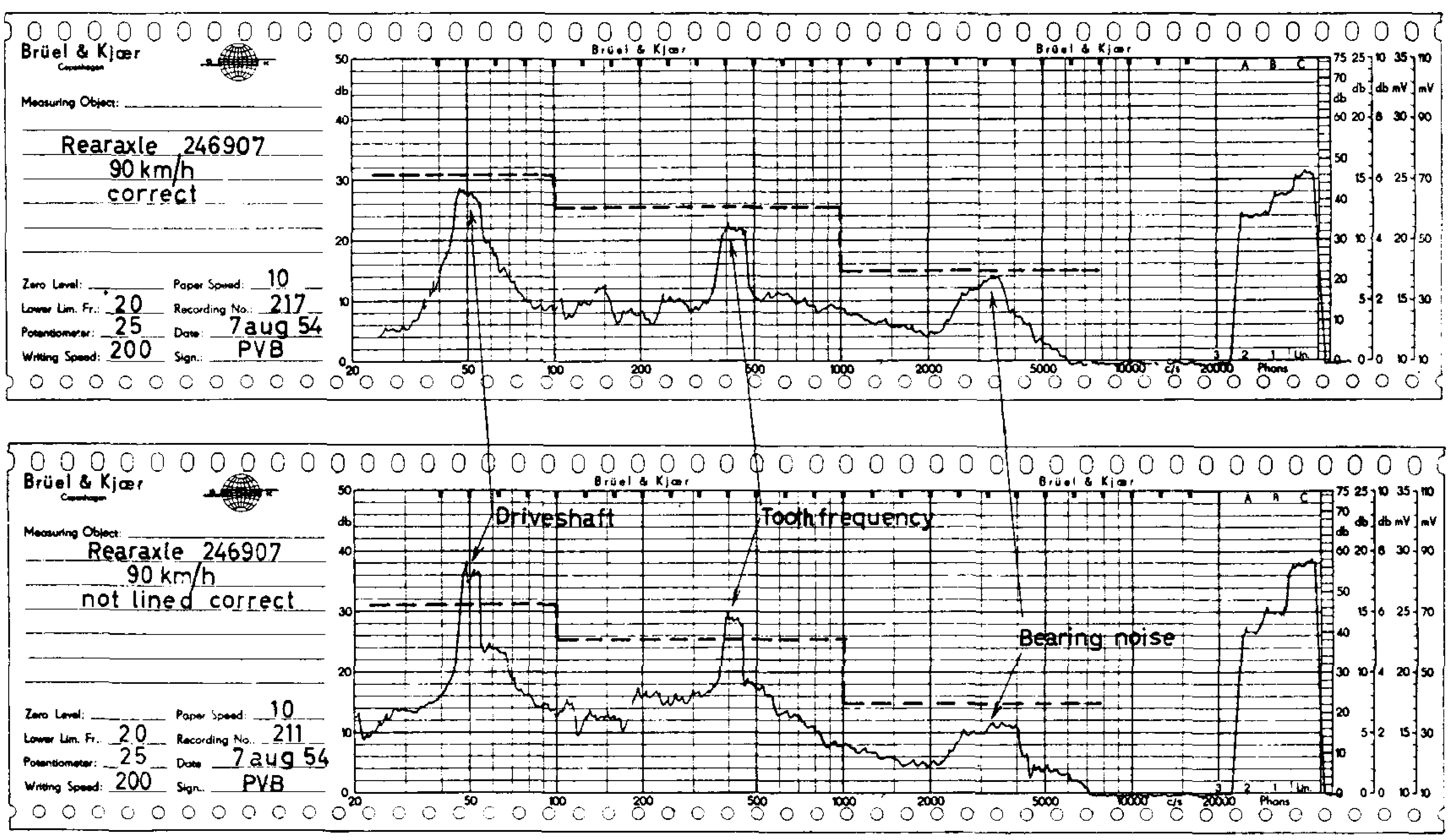


Fig. 12. Spectrograms of vibration of rear axle. a) Unit which can just pass. b) Rejected unit.

Due to the high intensity of noise in the test area, and to make the tests independent of the proximity of persons and other objects, the test assembly was enclosed in a non cubic chamber. This chamber performed two functions, the first being to reduce the noise reaching the axle assembly, by approximately 30 db. The second function was to integrate the noise emitted by the axle assembly.

Also by employing highly reflecting internal surfaces a noise level 20 db above that which would have existed under free field condition, was obtained.

The non rectangular section of the chamber ensured complete integration of the emitted sound and ensured that pronounced standing waves were not formed.

In order to obtain measuring conditions as near as possible to those existing in the car, the axle was suspended on the same type of spring suspension as would be employed in the final assembly. In addition metal plates were fitted to simulate the body structure of the car, in order that sound could be transmitted as in the vehicle itself.

To supplement the acoustical measurements a vibration pick-up was fitted to a particular point on the rear axle assembly. Two spectrograms were in this way obtained.

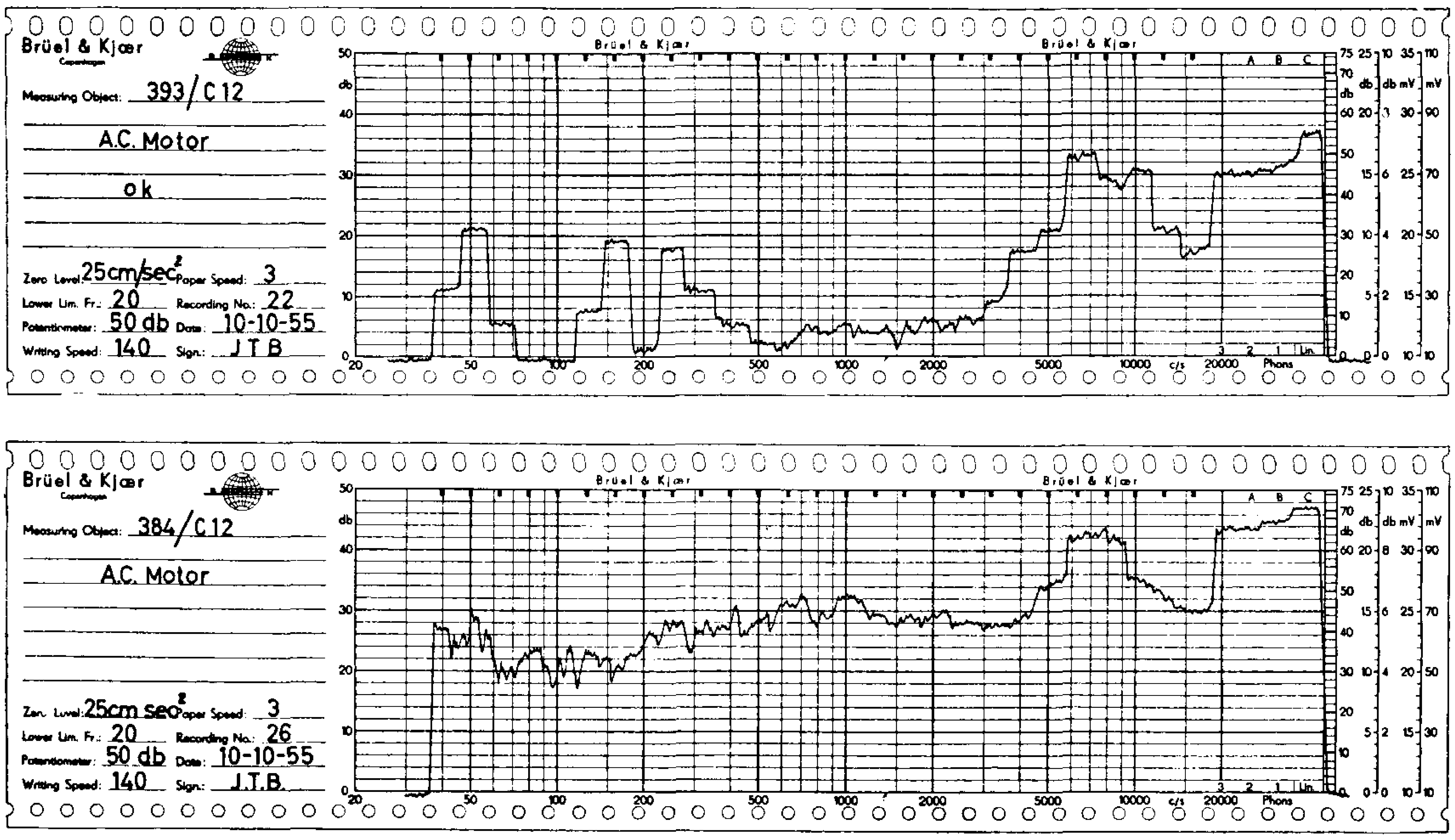


Fig. 13. Spectrogram of vibration of small electric motors: a) An acceptable unit. b) A bad unit with a too high vibration level.

Two typical acoustical spectrograms are shown. An acceptable noise level has been set and the "Go" and "No go" principle was again applied. In the examples shown peaks are indicated at the engine speed 3000 r.p.m. which produced at vibration at 50 c/s, the gear box ratio in this case being 1 : 1.

Also shown is the peak caused by the vibration from the pinion wheel, and the noise level of the bearings.

Once again a quick visual check of the spectrogram gives a clear indication of the source of trouble, should the unit not meet the standard set.

Fig. 13 shows some spectrograms of vibration test on small electric motors from which it is easy to see the pronounced difference between a good and

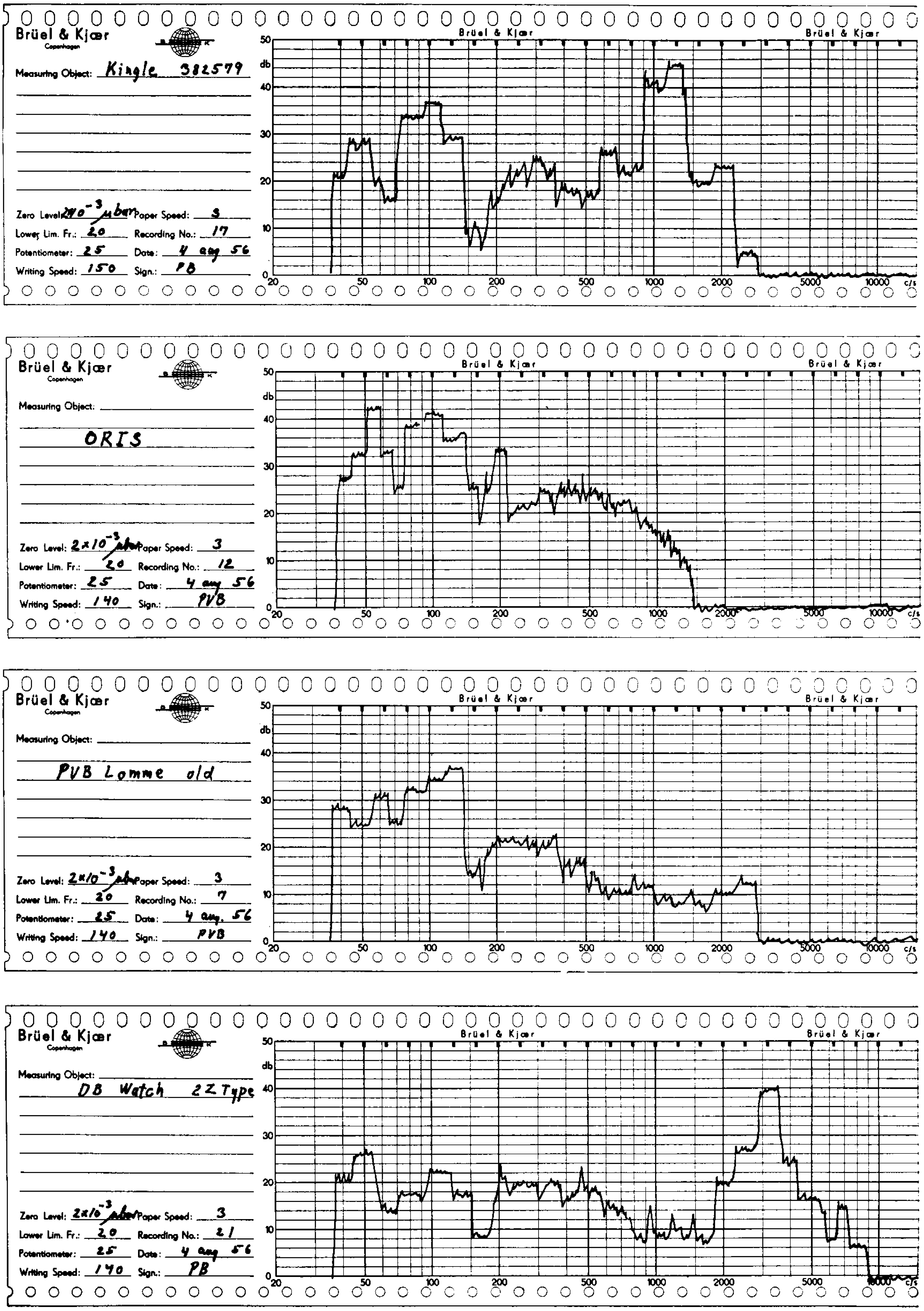


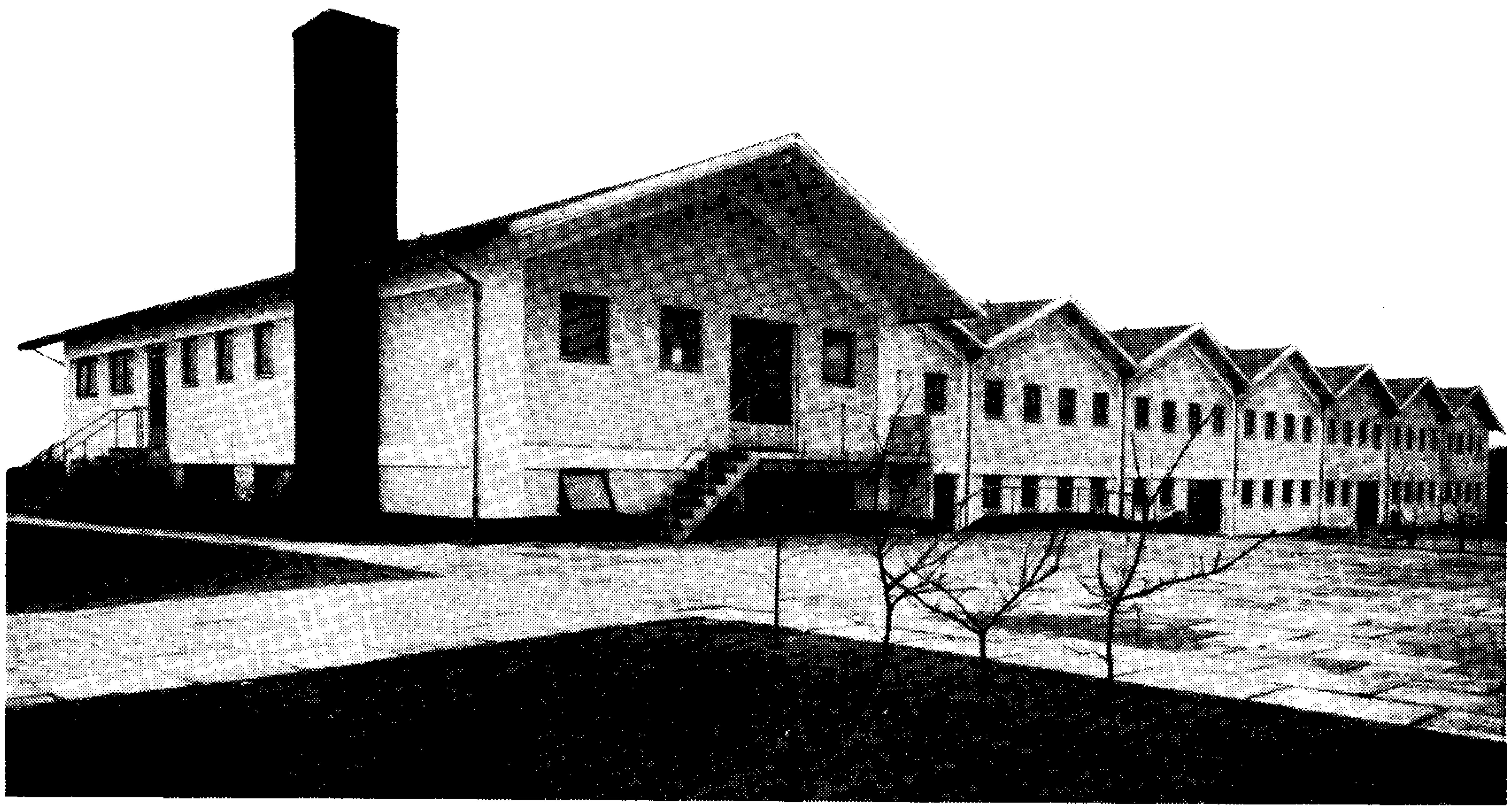
Fig. 14. Spectrograms of the noise from different watches. From the character of the noise, faults in the clock can be found.

a poor motor. It is essential that the vibration pick-up is always fastened to the same place on the motor in order to compare the different units.

In order to emphasize the versatility of this system of analysis, the fourth example to be considered concerns the production inspection of wrist-watches. As in the previous examples a sound-proof, non rectangular section, test chamber was used. The tests were purely acoustical, great care being taken to ensure that the position of the microphone with respect to the watch movement was always the same.

The three examples chosen, serve to show to whatever widening fields acoustical control may be applied. As yet the art is in its infancy but as the pace of production increases industry must constantly turn to science for the solutions to its problems.

News from the Factory:



The Factory.

The latest enlargement of the factory which started in the middle of the year 1956 has now completed. The enlargement include a two-storey building with a built-up area of 15000 sq. ft. or approximately a 50 % increase in premises. The moving in took place in January 1957. By this A/S Brüel & Kjær has increased its production ability considerably to comply with the steady rising demand for their products.

Level Recorder Type 2304.

The special circumstances which arise when the Level Recorder Type 2304 is used in connection with the Audio Frequency Spectrometer Type 2109 supplied with the Extension Filters ZS 0041 are to be considered as follows.

As the midfrequencies of the four third-octave filters in the ZS 0041 are 16, 20, 25 and 31.5 c/s respectively the lower limiting frequency of the Level Recorder Type 2304 should be lower than 16 c/s. The requisite decrease in the low frequency cut-off of the 2304 can be obtained by replacing the capacitor C 7 in the rectifier filtering network, and by operating the amplifier with full feedback i. e. turning the "Zero Adjustment" knob completely to the left.

To avoid instability and overswing, attention must be paid to the correct setting of the knobs "Writing Speed" and "db Range". In table 1 the minimum values of the "db Range" setting is given as a function of the "Writing Speed" setting for no overshoots at all.

By changing the capacitors C 4, C 8, C 9 and C 10 a lower limiting frequency of 2 c/s can be obtained. However, at the very low cut-off frequencies it is not possible to avoid overswing at any setting of the "Writing Speed" and the "db Range". Furthermore, as the changing of the capacitors and the necessary alterations to improve stability are serious operations with no practical importance when the Extension Filter ZS 0041 are used, no further discussion of the very low cut-off frequencies will be carried out in this notice.

Writing speed mm/sec	db range min.								
	10 db pot.			25 db pot.			50 db pot.		
	lower limiting frequency c/s								
max.	14	16	18	14	16	18	15	16	18
1000	75	25	20			67			
700	67	25	15		58	42			67
500	58	20	10		42	33		70	50
300	42	10	10		33	25	67	50	42
200	33	10	10		25	15	50	42	33
140	25	10	10		20	10	33	25	25
100	20	10	10	58	10	10	33	20	15
70	15	10	10	42	10	10	20	10	10
50	10	10	10	33	10	10	15	10	10
C 7 nF	550	120	85	650	120	85	160	120	85

Table 1. Measurements taken on Level Recorder Type 2304 serial number 21728 showing the minimum values of the "db Range" setting as a function of the "Writing Speed" setting for no overshoots. Furthermore, the table shows the values of the capacitor C 7 in the different cases.

Fig. 1 shows the adjustment ability in db (defined as the distance in db between the positions of the recording stylus when approaching the balancing point asymptotic from the left and the right) as a function of the "db Range" setting.

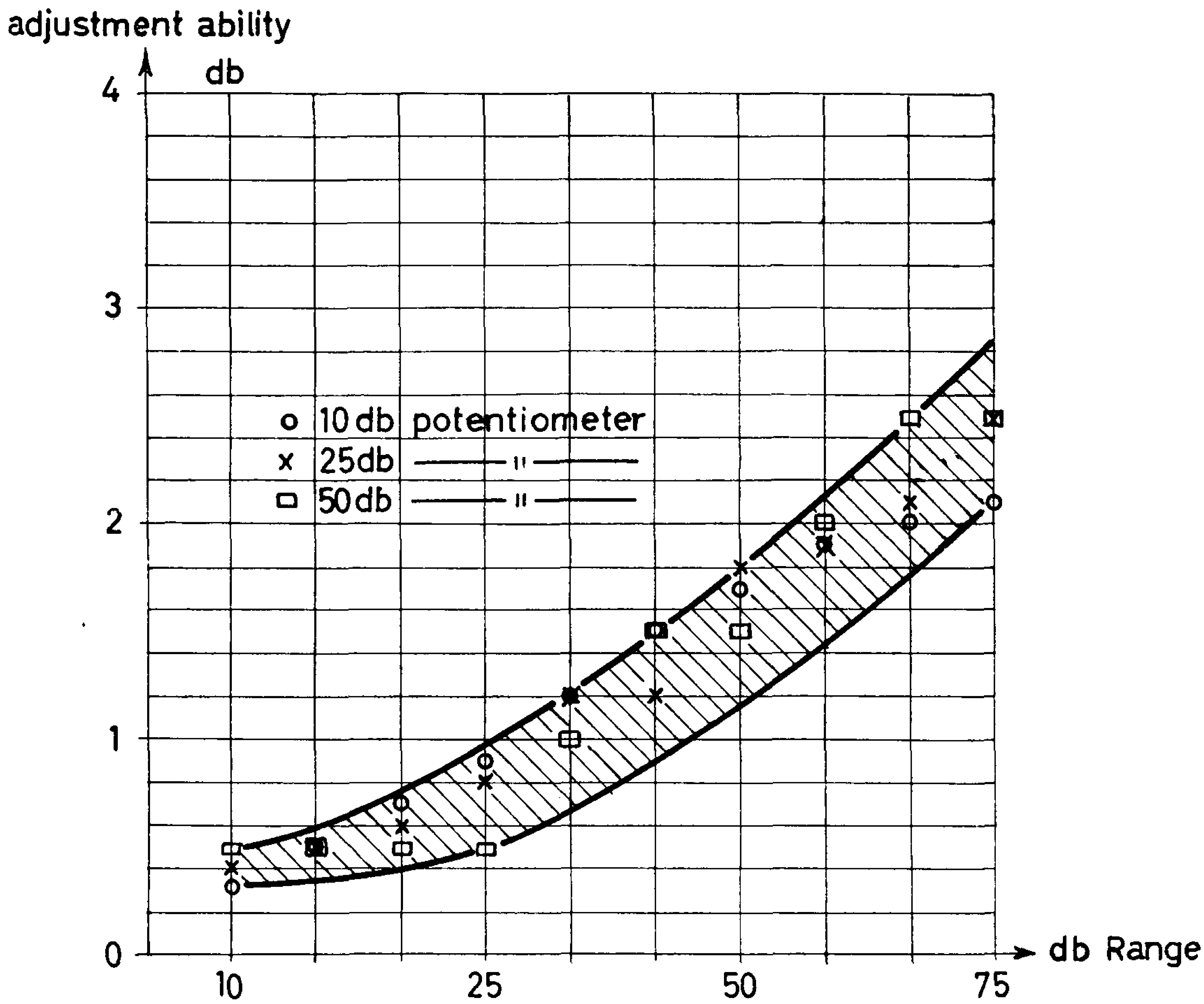


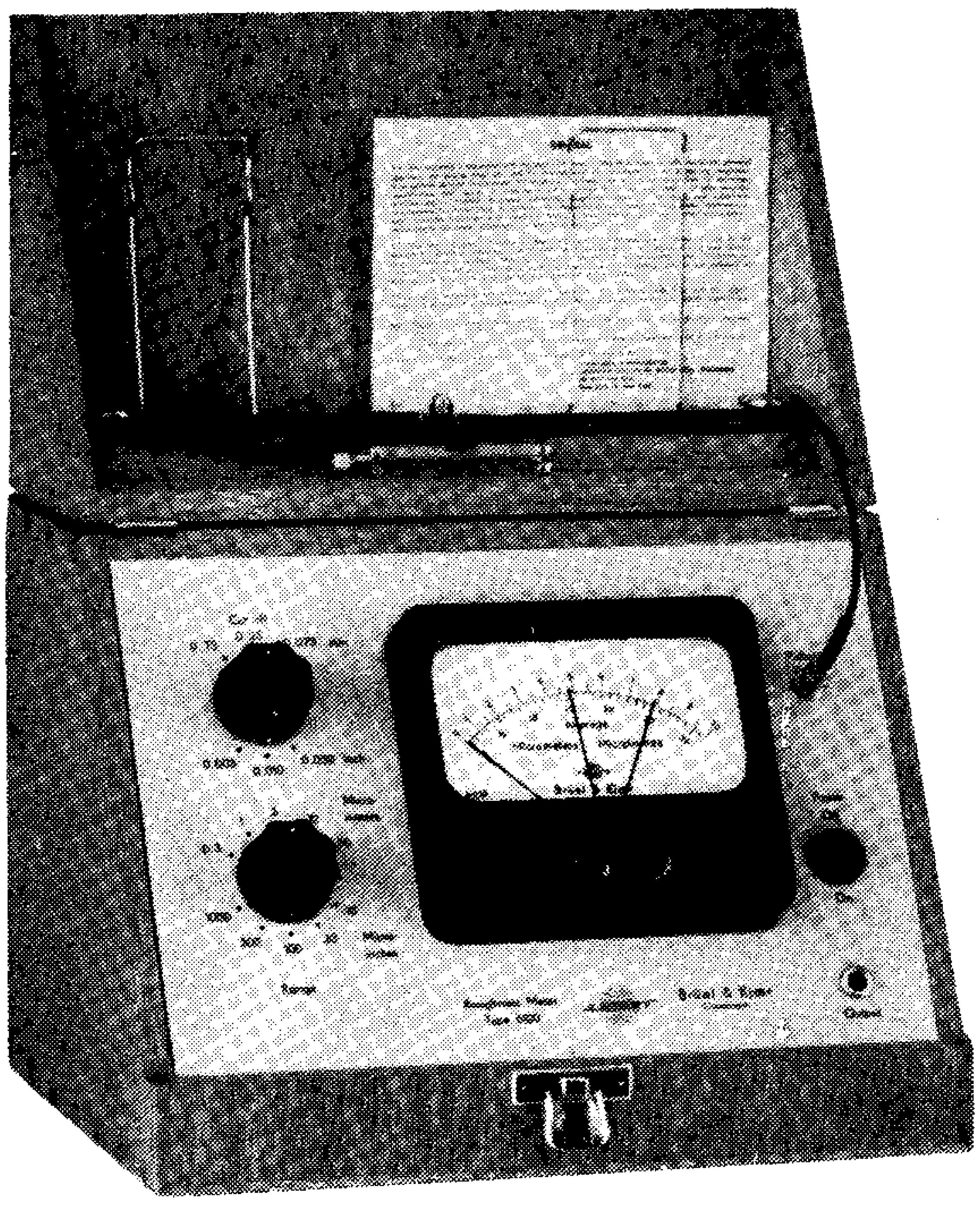
Fig. 1. The adjustment ability as a function of the "db Range" setting.

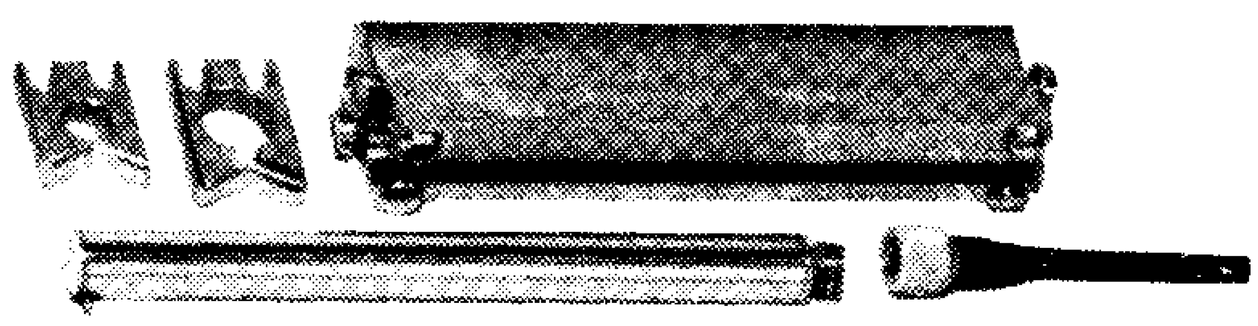
Roughness Meter Type 6100.

For the measurement and *control of surface finish roughness of machined surfaces.* It consists of a stylus type pick-up and an electronic amplifier with indicating meter calibrated directly in μmeter (and μinches). Full scale deflection for 0.3—1—3—10 and 30 μmetres and for 10—30—100—300 and 1000 μinches arithmetic average. Variable roughness width cut-off: 0.75—0.25—0.075 mm (0.03—0.01—0.003 inches) referred to a traversing speed of the pick-up of 3 mm/sec. (1/8 inch/sec.). Any traversing speed between 3 mm/sec. (1/8 inch/sec.) and 10 mm/sec. (3/8 inch/sec.) can be used. Measurement accuracy independent of traversing direction. Stylus pressure approx. 1 gramme. Minimum inside diameter of bores, in which measurements can be carried out is 6.35 mm (¼ inch). By employing the Wire Guides measurements can be taken on round wires down to 0.5 Ø (0.02 inches Ø).

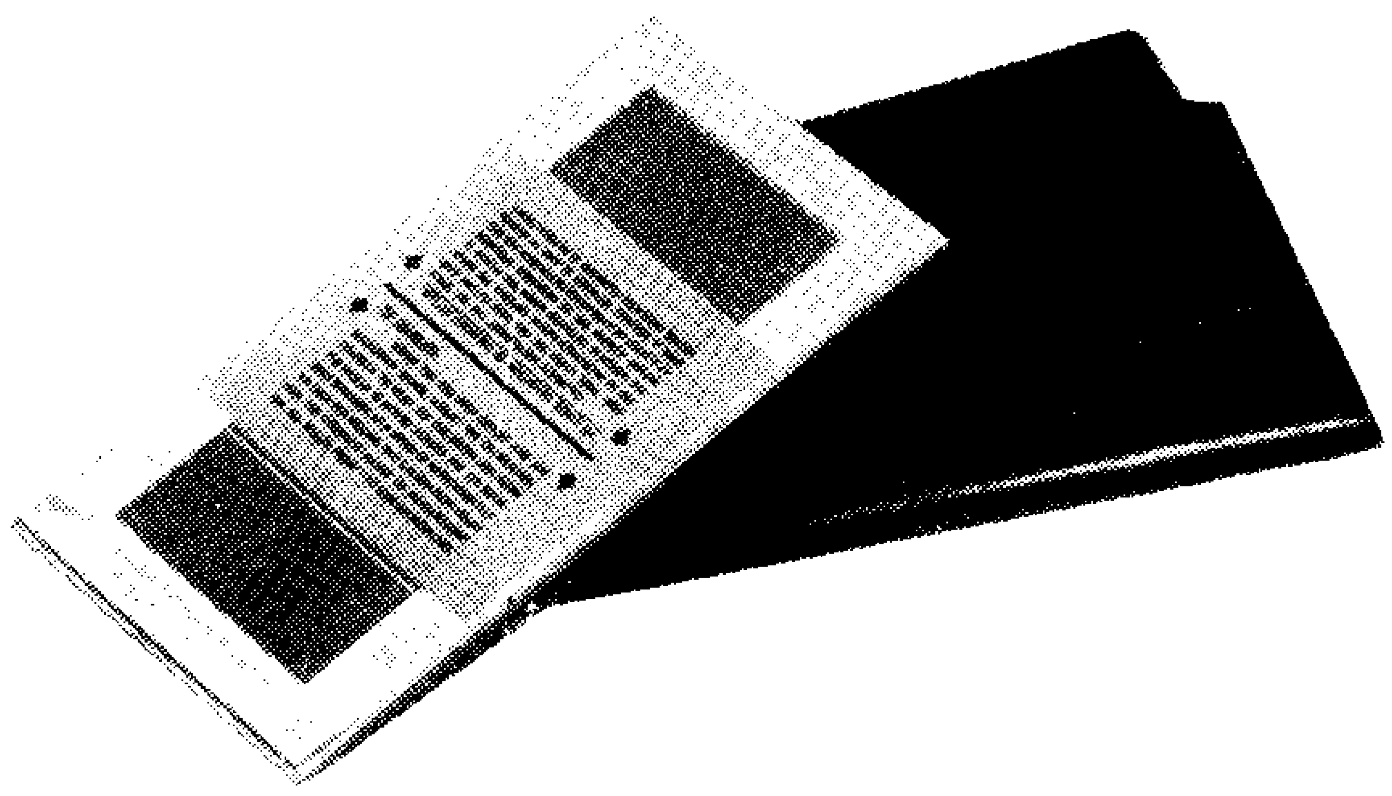
To facilitate surface roughness control during production the indicating meter is equipped with adjustable tolerance pointers. Output terminals for connection to external indicating or recording instruments.

Precision Reference Specimens MA 0011 for check and adjustment of the Roughness Meter available.





6100



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Brüel & Kjær

ADR.: BRÜEL & KJÆR
NÆRUM - DENMARK

TELEPHONE: 80 05 00
BRUKJA, Copenhagen

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