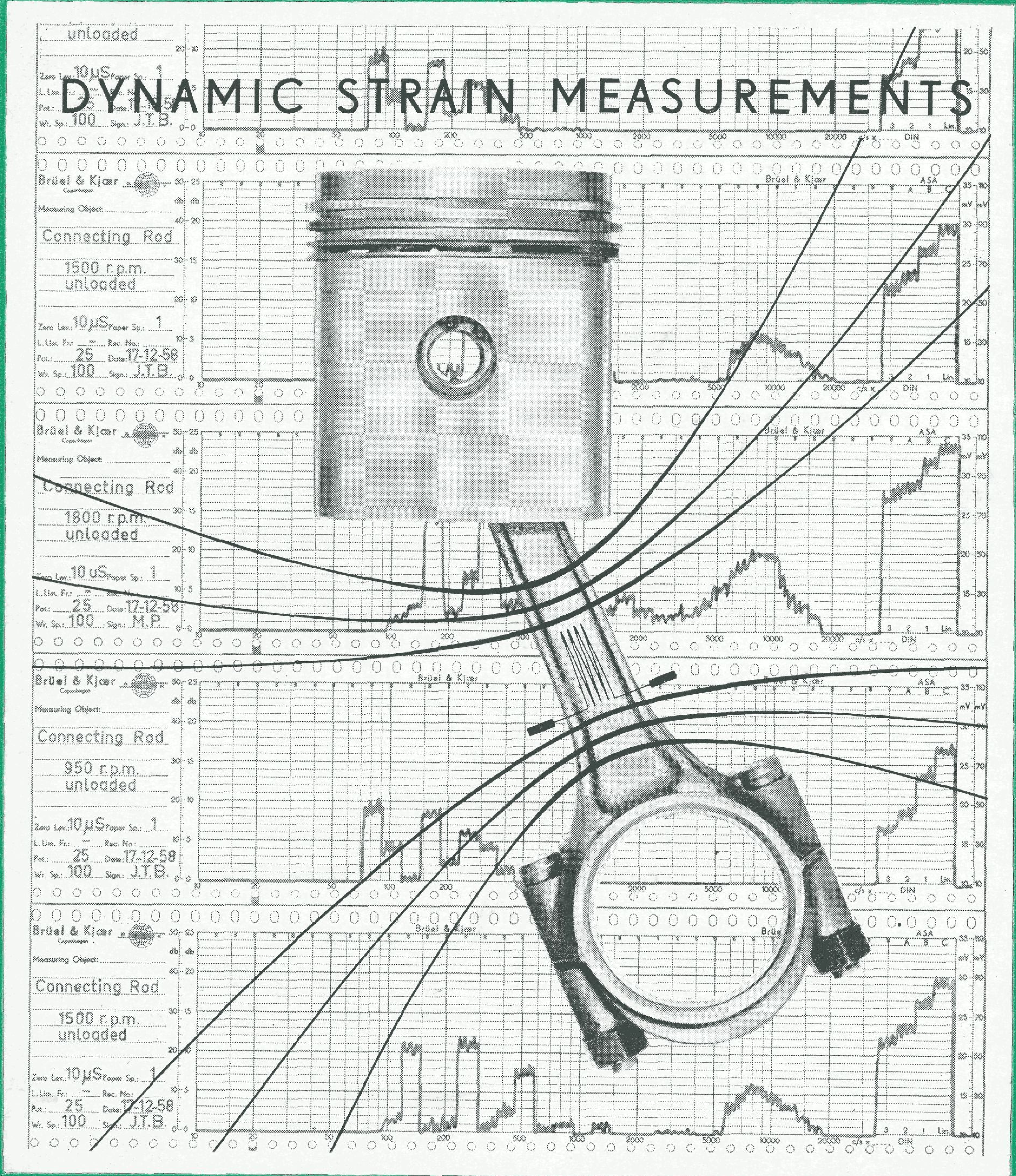
Brüel & Kjær

# Technical Review

Teletechnical, Acoustical and Vibrational Research

## DYNAMIC STRAIN MEASUREMENTS




No. 3 July 1959

## PREVIOUSLY ISSUED NUMBERS OF BRÜEL & KJÆR TECHNICAL REVIEW



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# TECHNICAL REVIEW

No. 3 - 1959

Reprint: March 1961

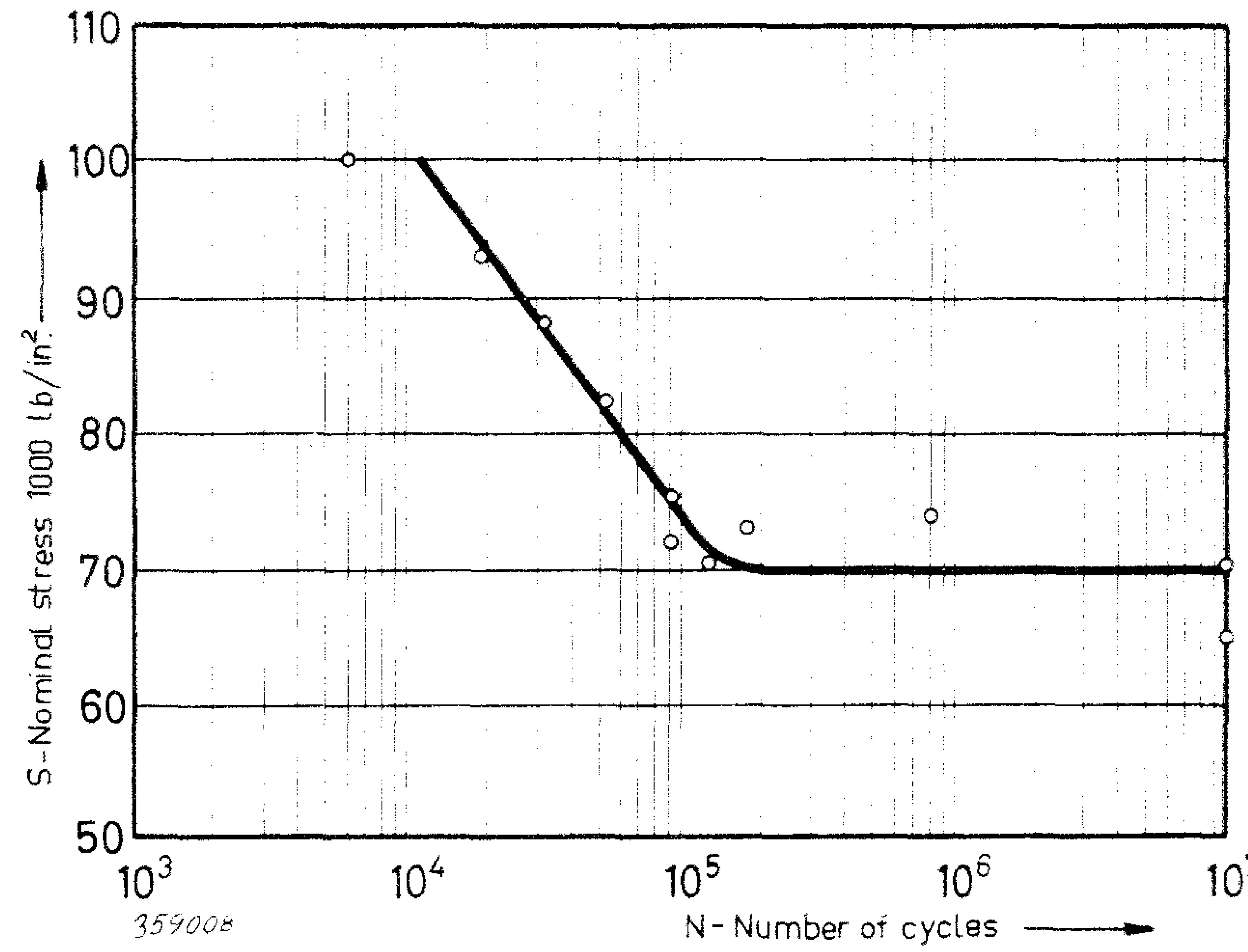


*Fig. 1. Typical S-N diagram for steel.*

The dangerous stress amplitudes will normally occur at frequencies where certain parts of the machinery resonate, i.e. frequencies equal to the natural frequencies of the machine parts. Fig. 2 shows a typical resonance curve for a single degree of freedom system. It is clear that the greatest stresses are present in this system if it is excited by a force the frequency of which is

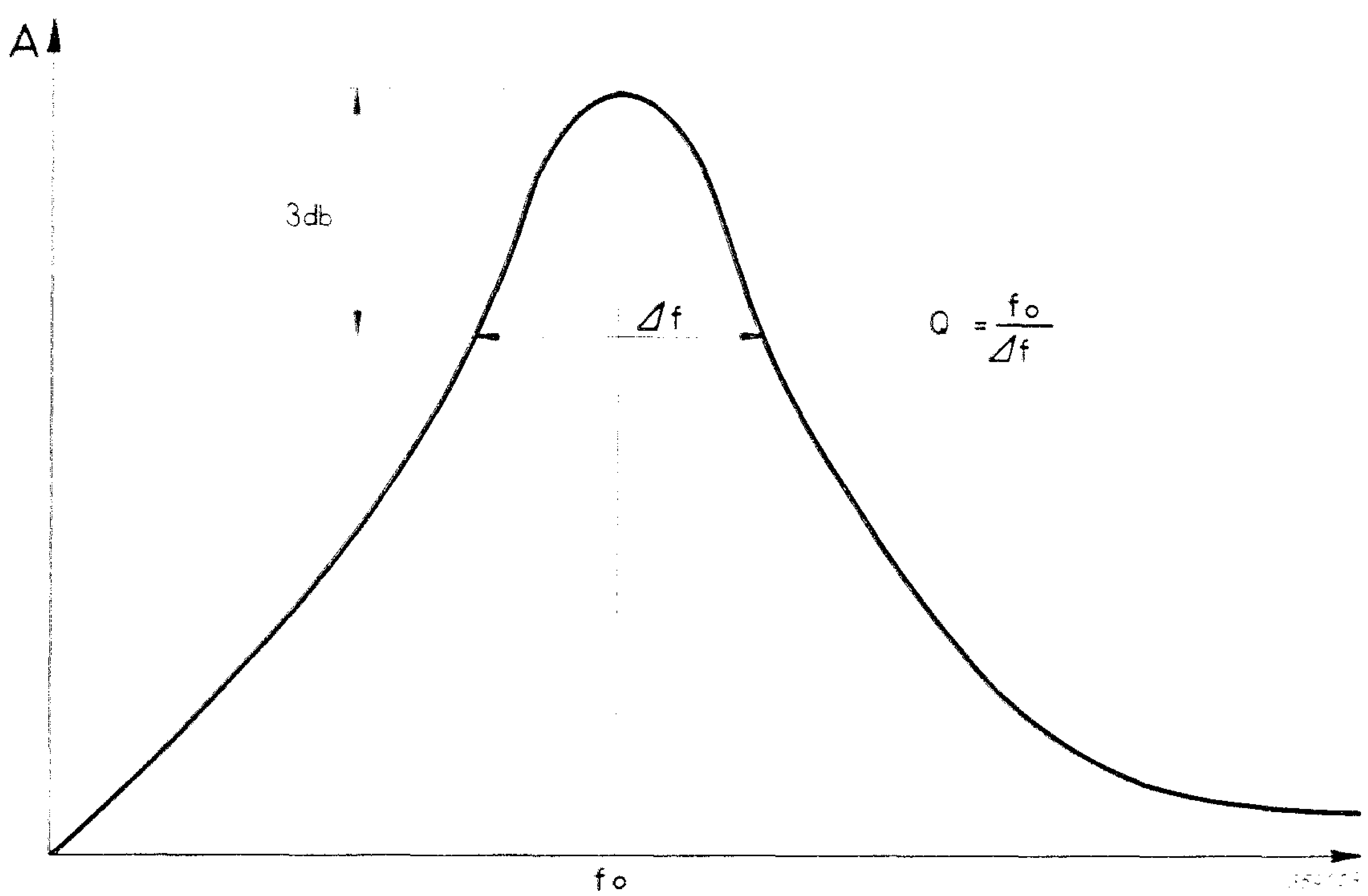


*Fig. 2. Response of simple resonant system.*

exactly equal to $f_0$. However, even if the frequency of the exciting force was not exactly $f_0$, but for example $0.8 \cdot f_0$ or $1.2 \cdot f_0$ a considerable "amplification" of the stress would take place.

Two important factors can be deduced from a resonance curve of the type shown in Fig. 2, namely the "dangerous" frequencies and the "amplification" of the stress at these frequencies.

Because the "amplification" will depend upon the manner in which the resonance is excited a reasonable approach to complicated stress problems is to design a prototype and measure the response directly by means of strain gages. From the measurements can then be evaluated whether the design is suitable or which changes should be made to improve it.

Frequency-amplitude measurements directly on the protype under actual or simulated operating conditions are also desirable, because very often parts which would seem to be critical if excited in a certain manner may, under the real conditions be much less critical, or not critical at all, depending upon the actual excitation.

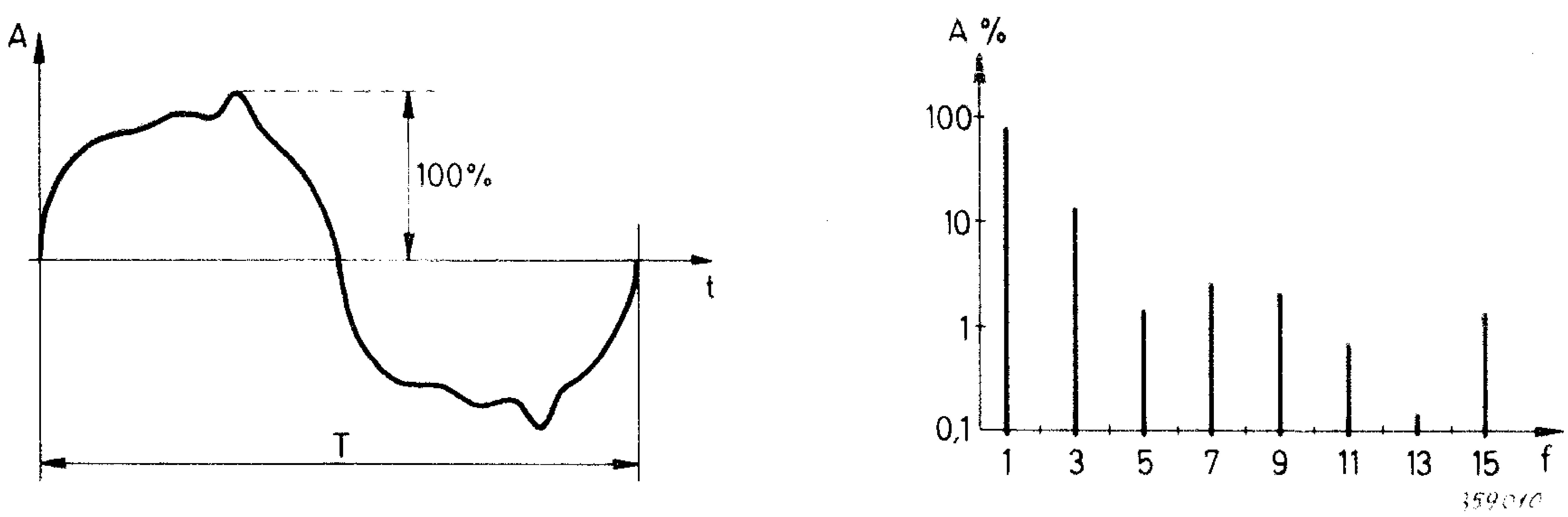


*Fig. 3. Example of periodic strain signal and its frequency spectrum.*

There are three main types of excitation spectra, namely the excitation spectrum of a force consisting of one or more sinusoidal components with almost constant max. amplitudes at the different discrete frequencies, the random excitation spectrum (i.e. a continuous frequency spectrum, the instantaneous amplitudes of which are statistically distributed according to the normal (Gaussian) distribution law), and the shock excitation. The shock-type excitation is present when a force is suddenly imposed on or released from the structure.

Fig. 3 shows a typical example of a periodic stress signal and its frequency spectrum. This type of exciting force may be present at rotating machinery, and it is of importance that none of the frequency components coincides with, or are in the immediate neighbourhood of, any resonant frequency of the machinery parts.

If this cannot be avoided the resonances in question must be heavily damped, or the magnitude of the frequency components reduced to a minimum by some other means.

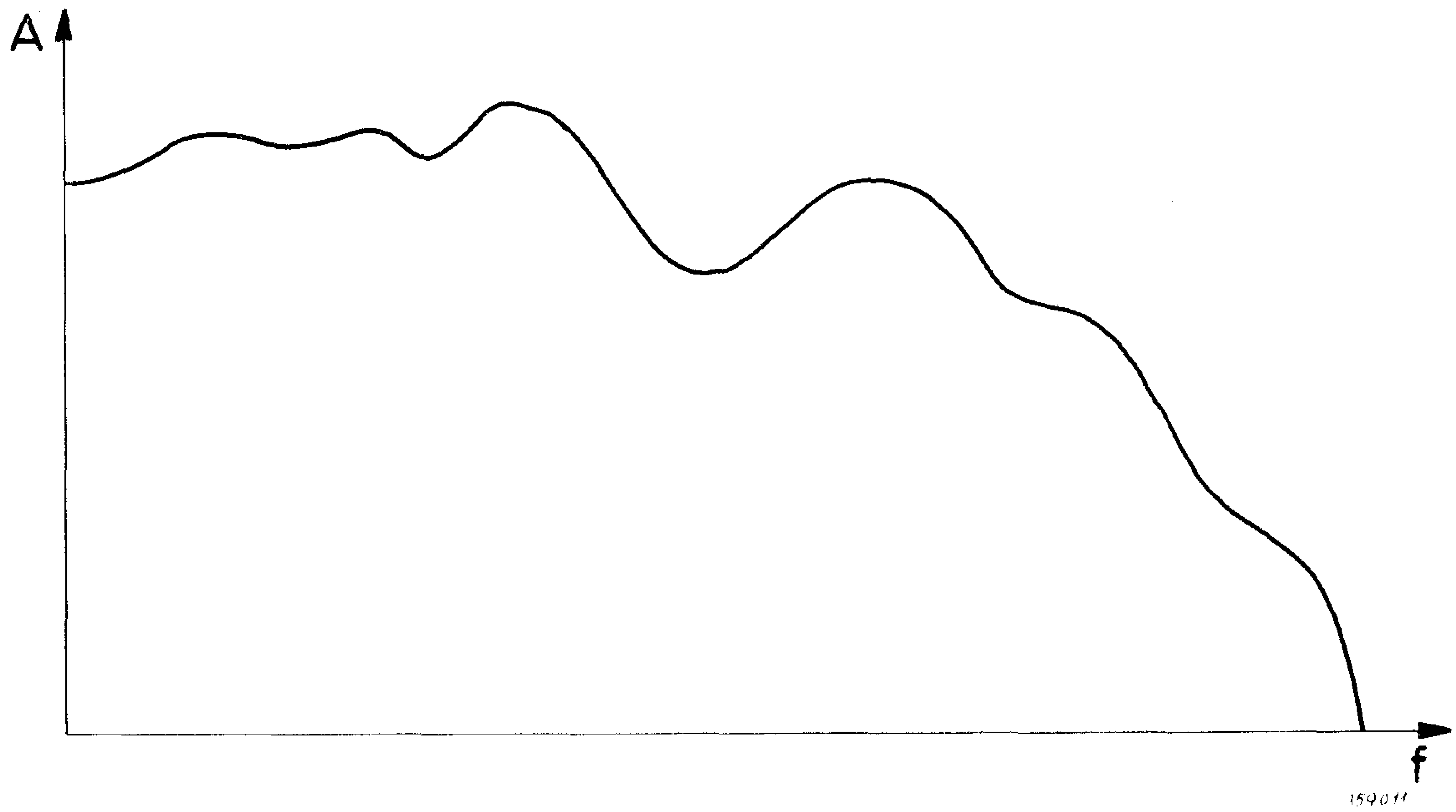


*Fig. 4. Example of random excitation spectrum.*

In Fig. 4 a continuous frequency spectrum is shown, and in Fig. 5 the response of a double resonant system (model jet air nozzle) to a random excitation spectrum is given. The response was measured by means of strain gages circumferentially mounted on the nozzle, and the strain output signal measured by means of a frequency analyzer with 1/3 octave bandwidth and recorded on a high speed level recorder. Continuous force spectra are produced by for example friction between two rough surfaces or turbulent airo- or hydrodynamic flows.

The most common type of dynamic stress excitation is a combination between the periodic force and the random force, and for a multiresonant mechanical system it is very difficult to predict its response to this type of excitation without taking frequency-amplitude measurements of the strain at different points on the structure. These measurements should, if possible, be taken under actual operating conditions to obtain a clear picture of the dangerous stresses.

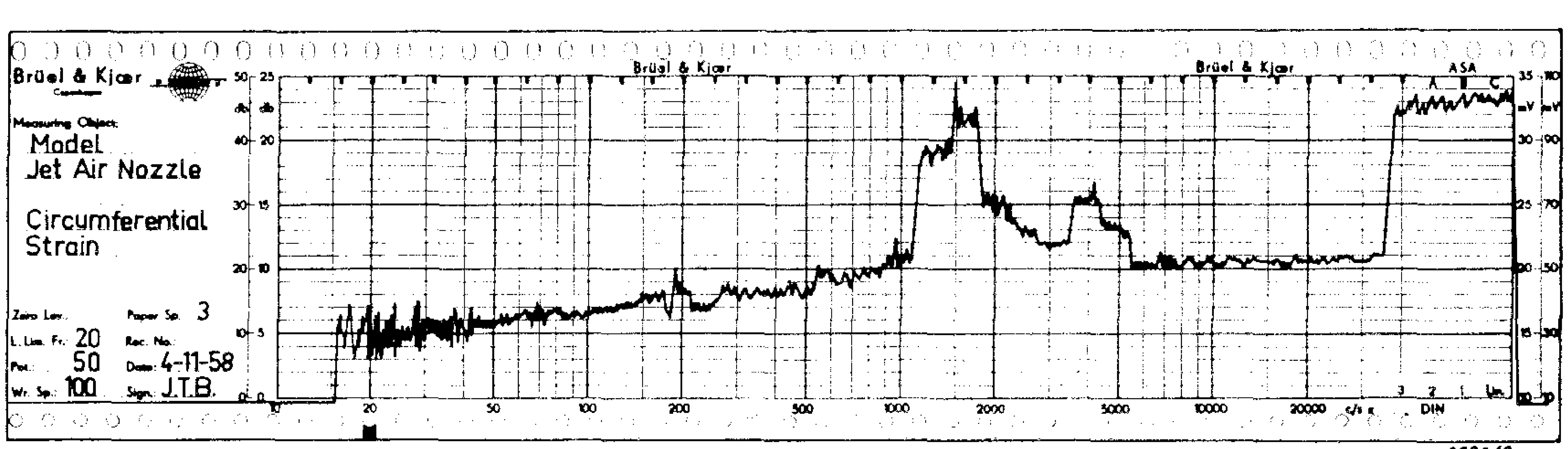


*Fig. 5. Example of strain signal from a double resonant system excited by a continuous spectrum.*

Some experiments have been made at Brüel & Kjær to measure and analyse the dynamic stress in the connecting rod of a one cylinder combustion engine and in the following a description of these experiments will be given.
Before measuring the stress in the rod under actual operating conditions its main resonances were determined.
Preliminary reverberation measurements on the rod only (rod not mounted in the engine) indicated a resonance around 6—700 c/s, but the Q-value obtained from such measurements will, because of the difference in mounting,

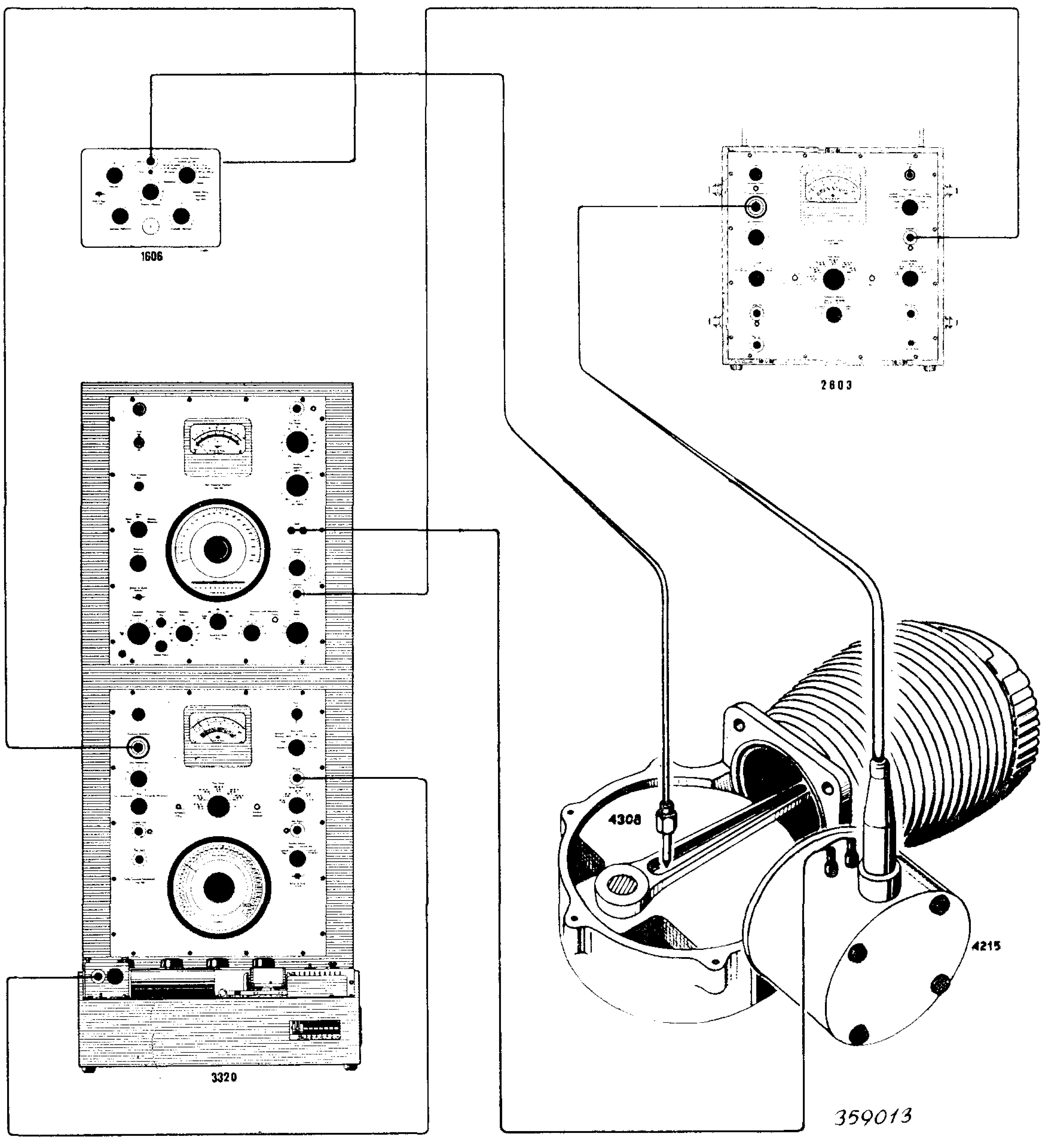


*Fig. 6. Measuring arrangement suitable for the detection of resonance in the connecting rod.*

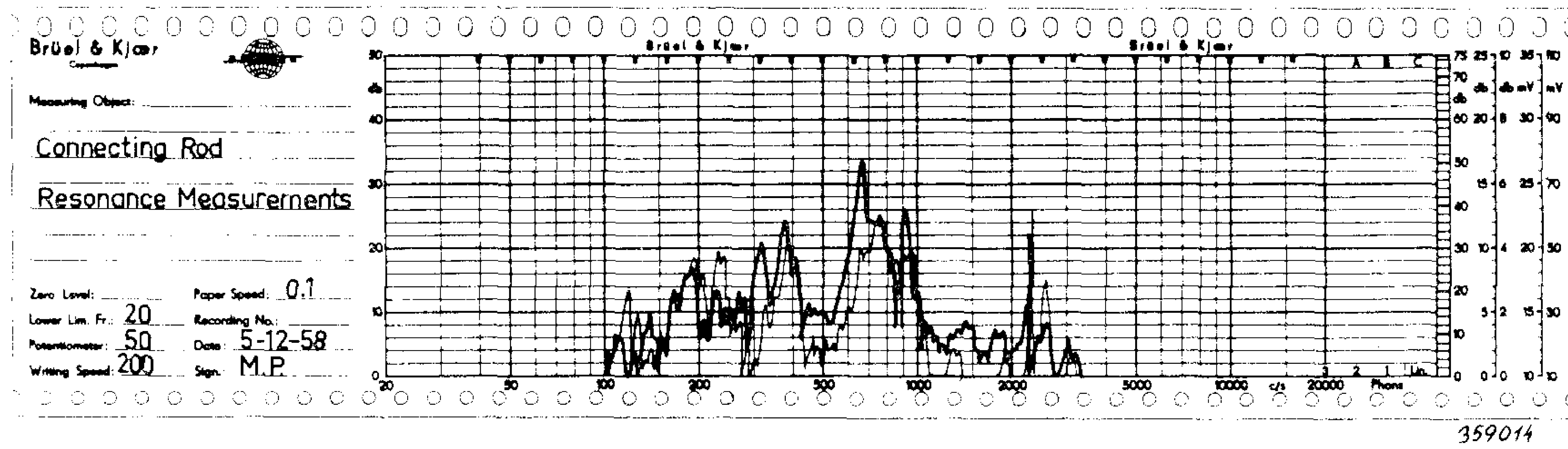


*Fig. 7. Frequency-amplitude diagram showing the resonance.*

give little or no information of practical importance regarding the danger of the resonance. It was thus decided to carry out the resonance measurements with the rod correctly mounted in the engine. To facilitate the measurements one half of the crankhouse housing was removed, Fig. 6.

An artificial voice was used to excite the rod, and the response measured by means of a vibration pick-up (accelerometer). In order to keep the exciting sound pressure level constant the output voltage from the regulating microphone of the artificial voice was amplified and used to control the output from the signal generator.

This is necessary to ensure a constant exciting force, independent of frequency

Experiments with electromagnetic excitation of the rod were also made, but the best results were obtained by means of the above mentioned sound excitation.

Measurements were taken both with the accelerometer mounted on the connecting rod itself and on the engine housing whereby the main resonance of the rod system was found to be approx. 660 c/s, Fig. 7.

Because of the many different resonance phenomena present the accelerometer was also successively placed at different points on the rod whereby the said resonance was found to be of the first bending mode type. Higher order resonances could not be detected even though measurements were carried out up to several thousand c/s.

To detect the relatively weak output signal from the accelerometer selective measuring technique was used, employing an instrument consisting of the previously mentioned signal generator, a one third octave band-analyzer and a level recorder. The frequency sweep of the generator and analyzer was driven automatically from the level recorder motor drive, and synchronized with the frequency calibrated recording paper. In this way a number of complete frequency amplitude recordings could be taken selectively in a minimum period of time.

Having determined the resonance two strain gages were mounted on the connecting rod, one on each side. By connecting the gages as shown in Fig. 8 this arrangement makes it possible to separate the bending and the elongation stresses, under the assumption that the gages are symmetrically placed with

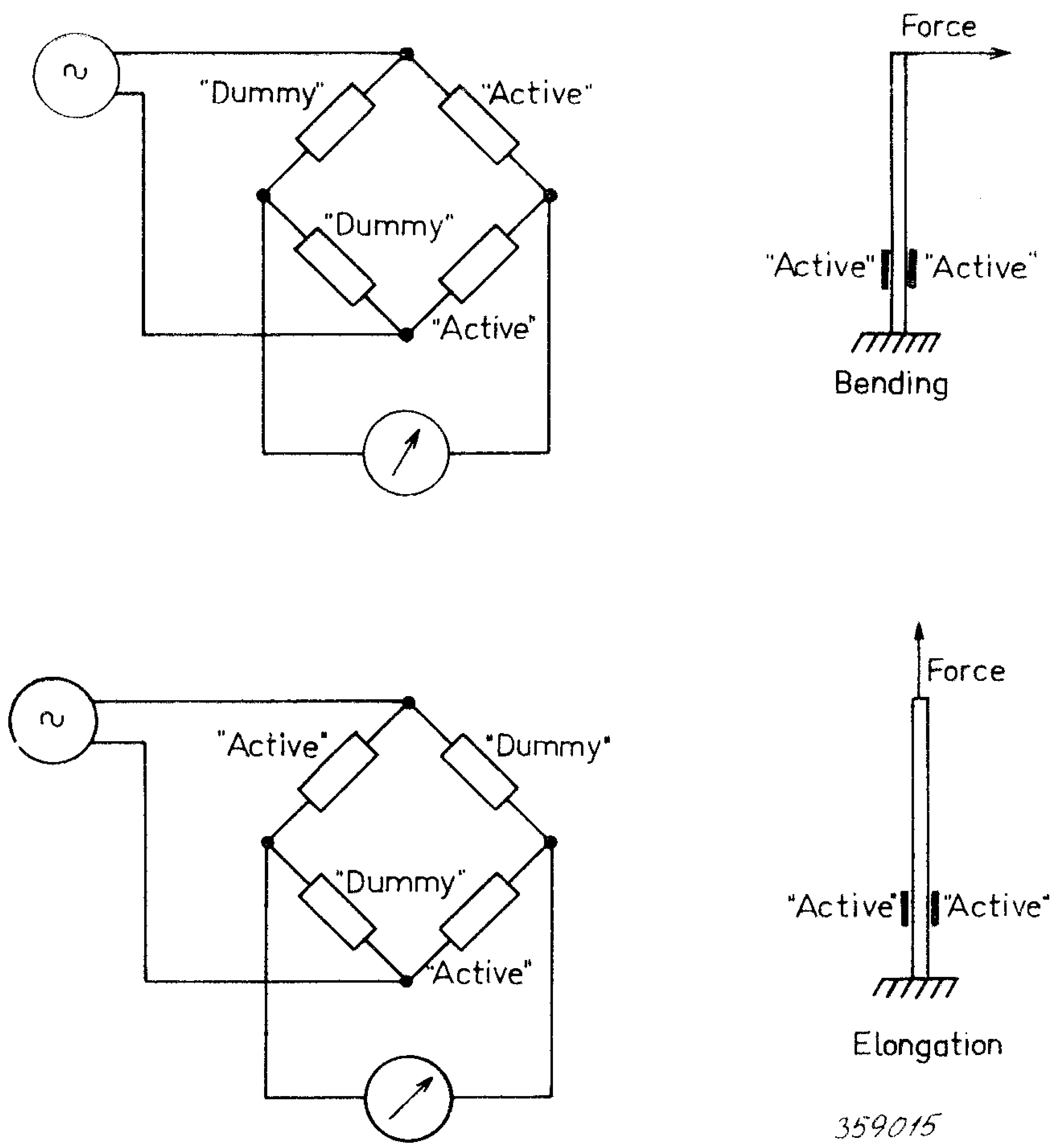


*Fig. 8. Gage connections for separate measurements of the strains resulting from bending and elongation.*

respect to the neutral axis of the rod. Some static measurements were made before the connecting rod was mounted in the engine and it was found that the bending stresses were, as presumed, by far the most critical ones.

Fig. 9 shows a sketch of the connecting rod mounted in the engine.

A special wiring outlet system was designed to avoid the very difficult task of making suitable sliprings. This system can be clearly seen from Fig. 10, and consists of a small tube, one end of which is mounted in a special bearing at the big end of the rod, the other end of the tube is sliding in a second bearing mounted on the crankhouse housing. The wires from the gages were lead from the measuring points through the small tube and out of the crankhouse. In this way the bending action on the wires at point A as well as the movement of the free end of the tube were kept as small as possible, see also Fig. 10.

Measurements of the type here described are relatively difficult to carry out because the "life" of the wires connecting the strain gages to the measuring instruments are limited. (When the engine is operated the stresses at the point B, Fig. 10, will cause the wires to break after a certain period of operation).

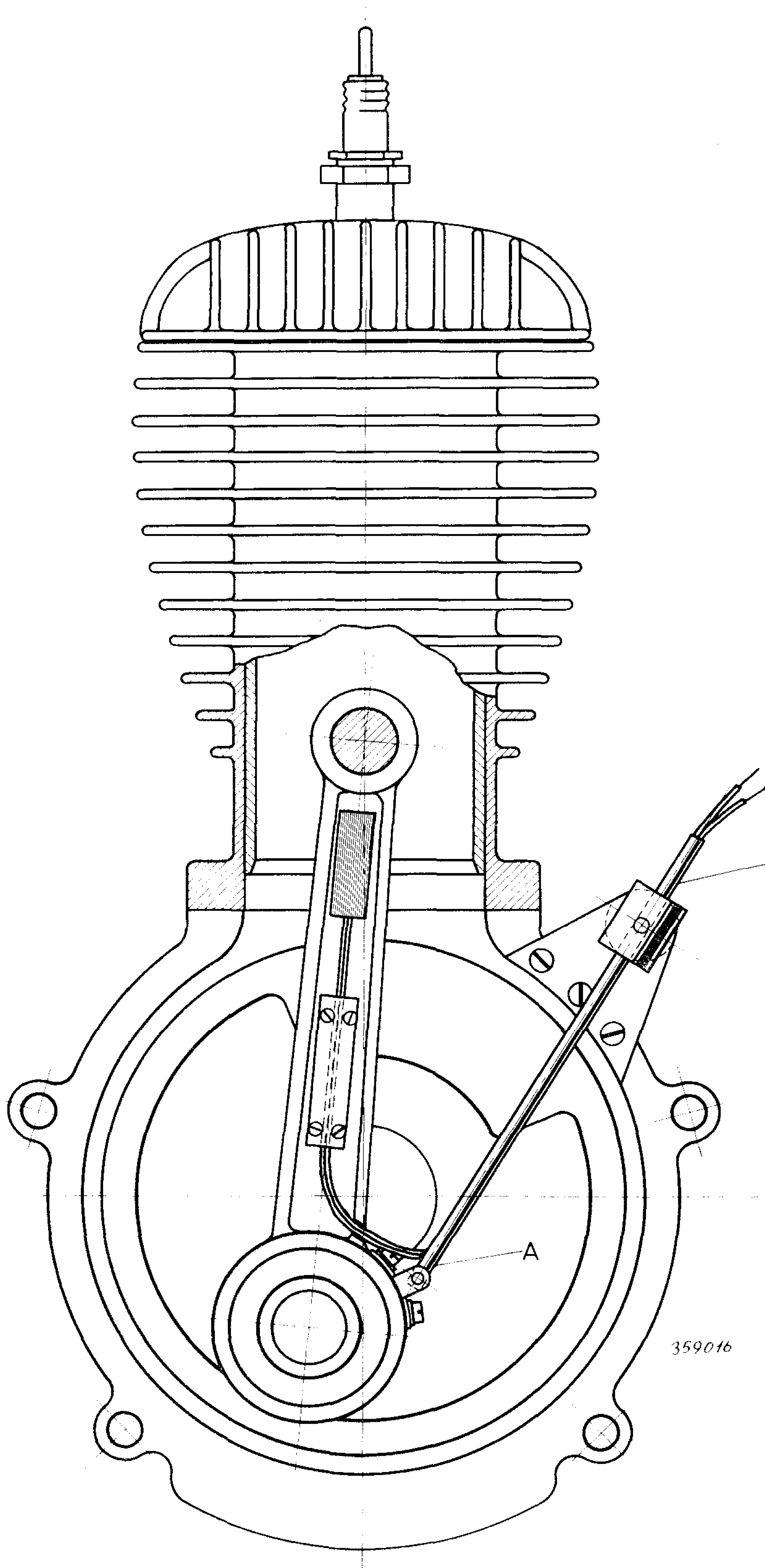


*Fig. 9. Sketch showing the connecting rod mounted in the engine.*

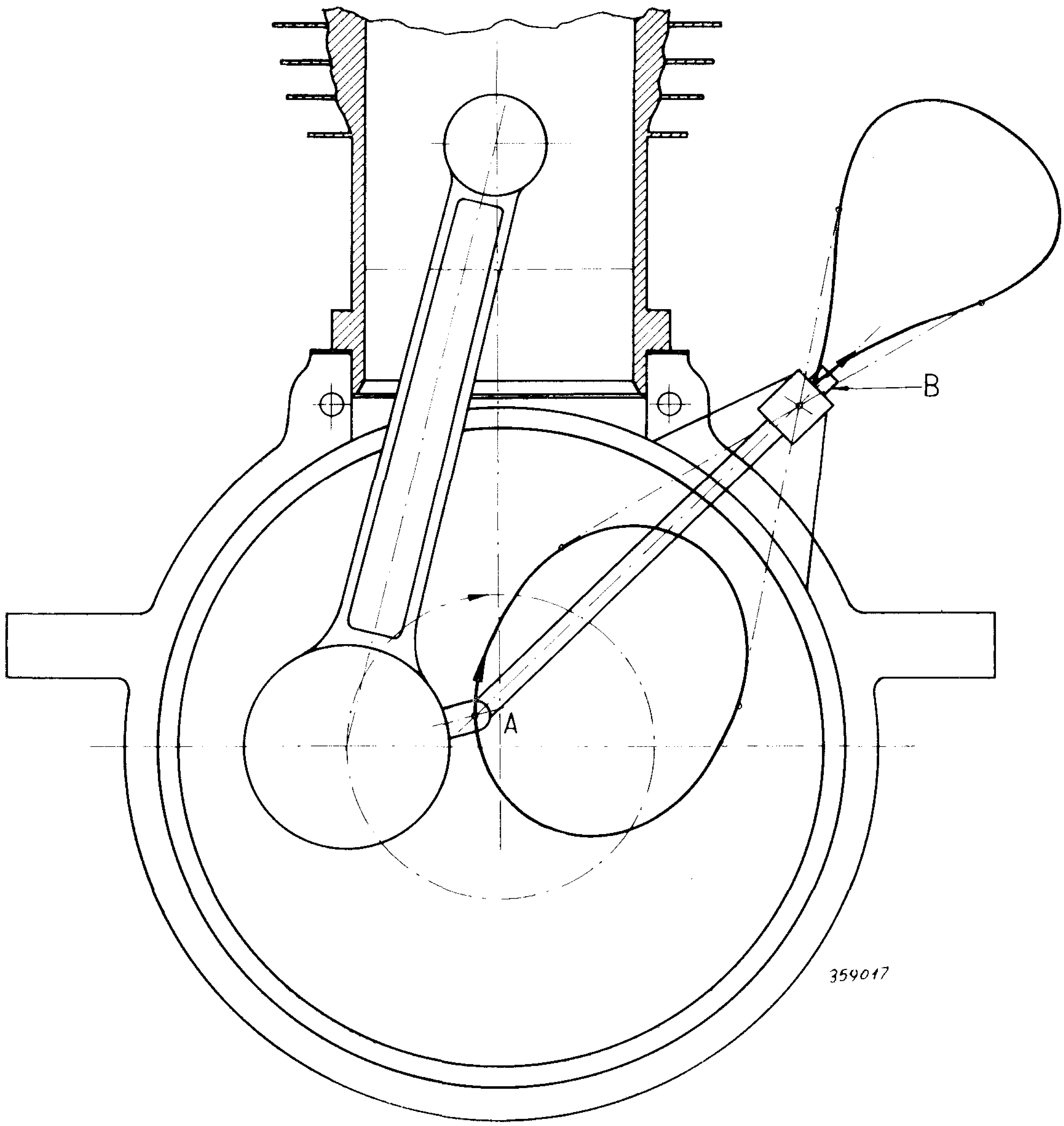


*Fig. 10. Sketch illustrating the movement of the wiring outlet tube.*

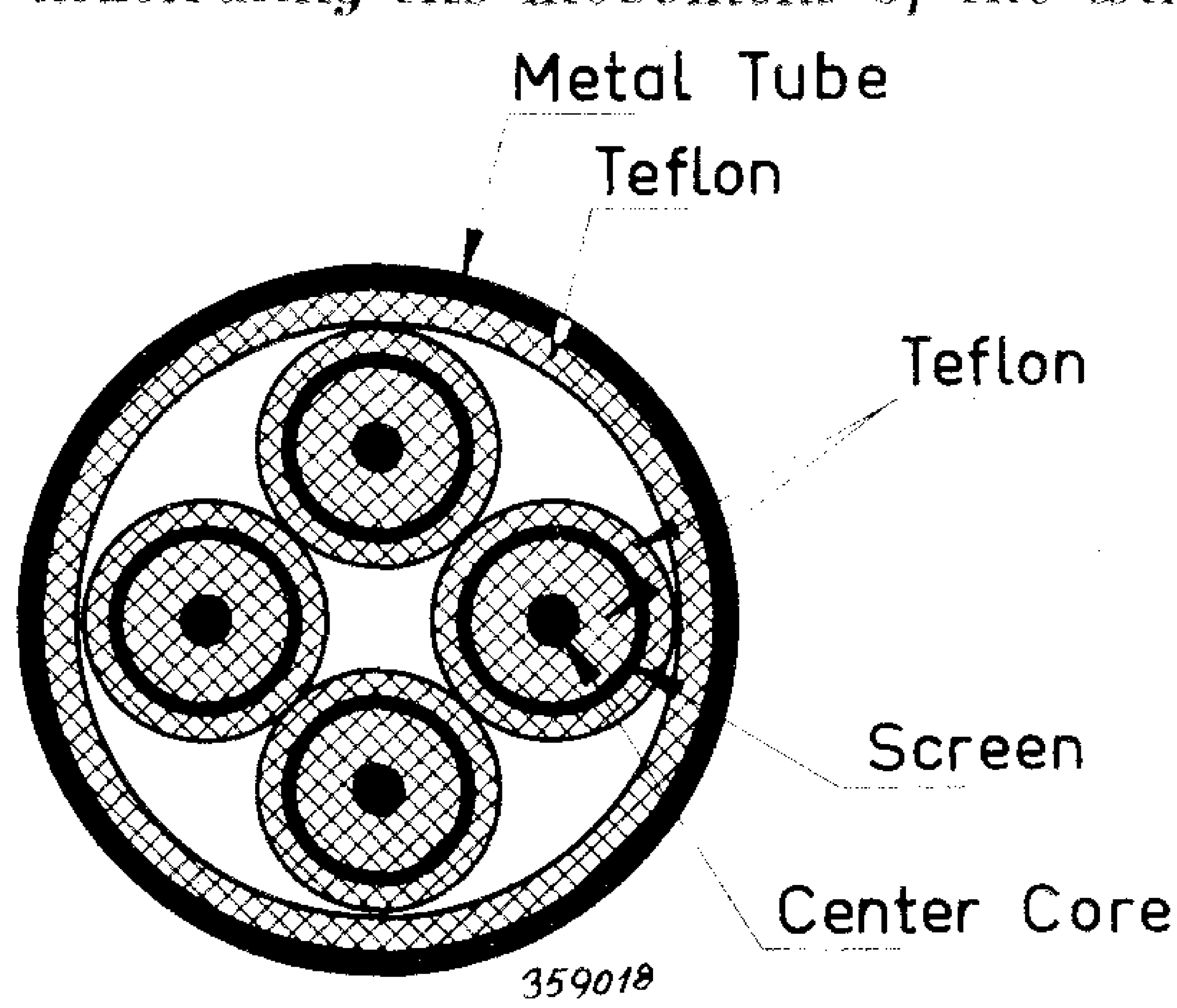


*Fig. 11. Sectional view of the wiring outlet tube with wires.*

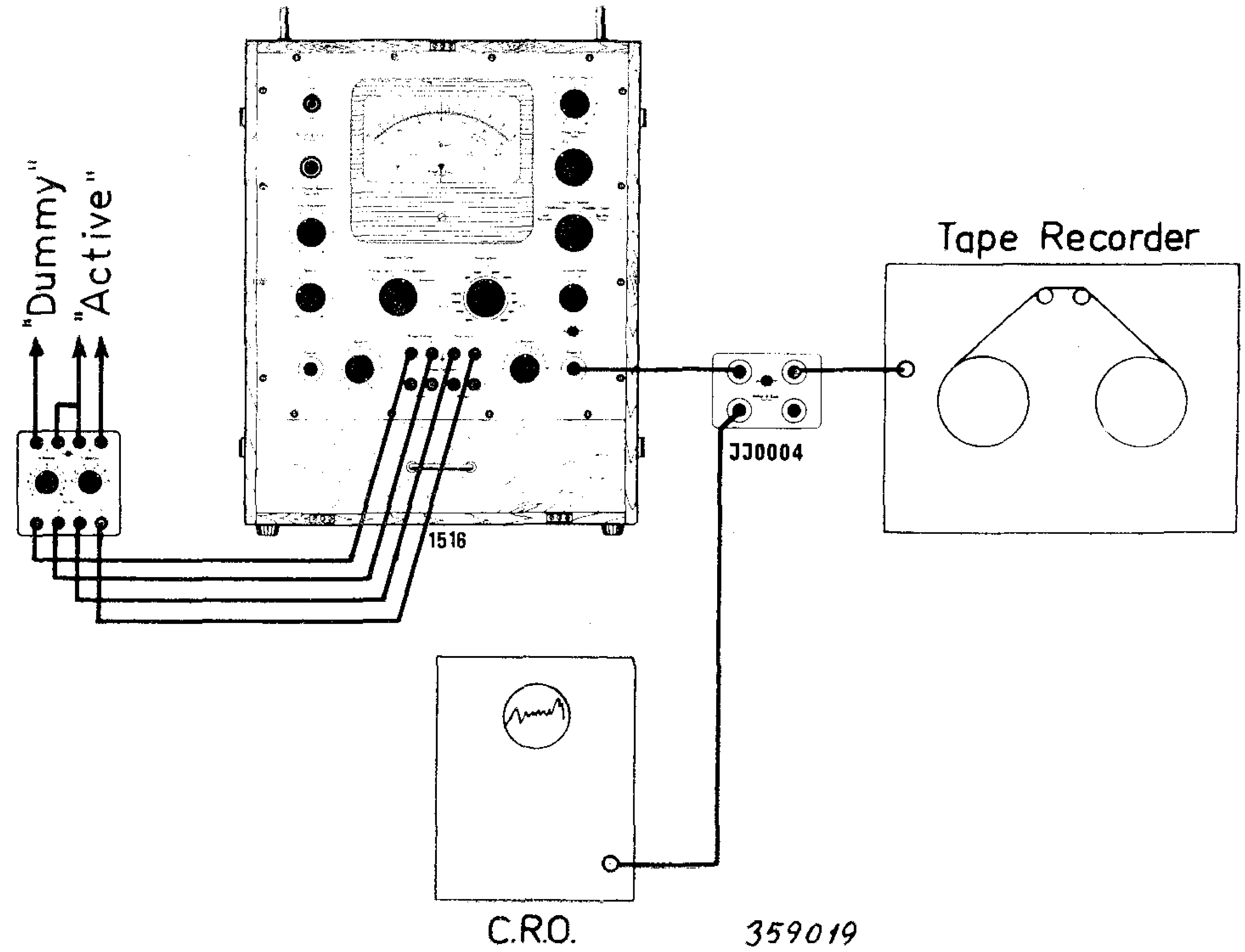


*Fig. 12. Sketch of the measuring arrangement used to detect and record the strain signal from the connecting rod during operation of the engine.*

To strengthen the wiring system as much as possible teflon-isolated screened cables were used, see Fig. 11. This solution seemed to be very satisfactory and having reassembled the engine the strain of the connecting rod was measured under actual operating conditions. The measurements were made by means of the set-up shown in Fig. 12. An advantage of the type of strain

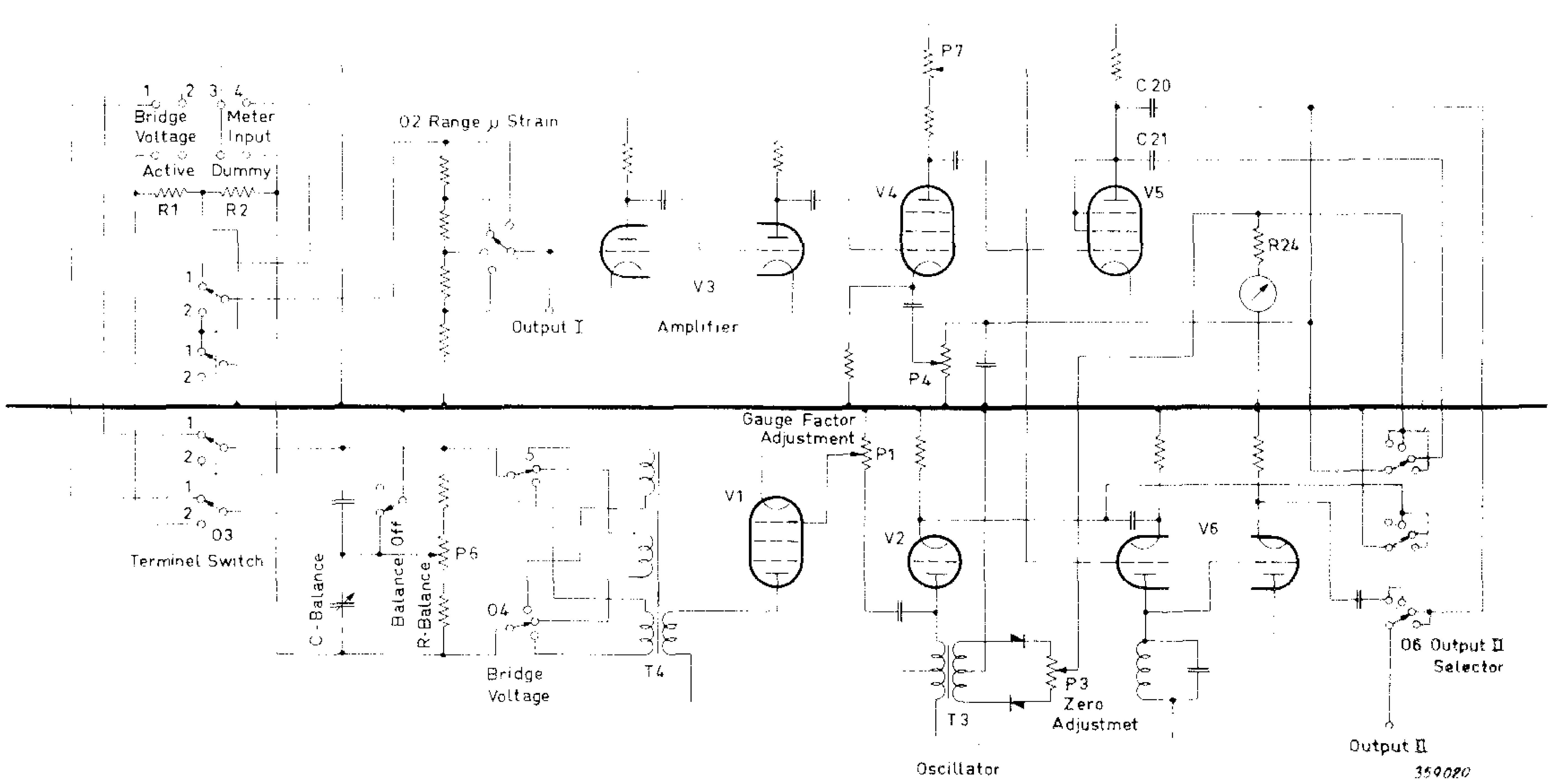


*Fig. 13. Sketch showing the principle of operation of the Strain Gage Apparatus.*

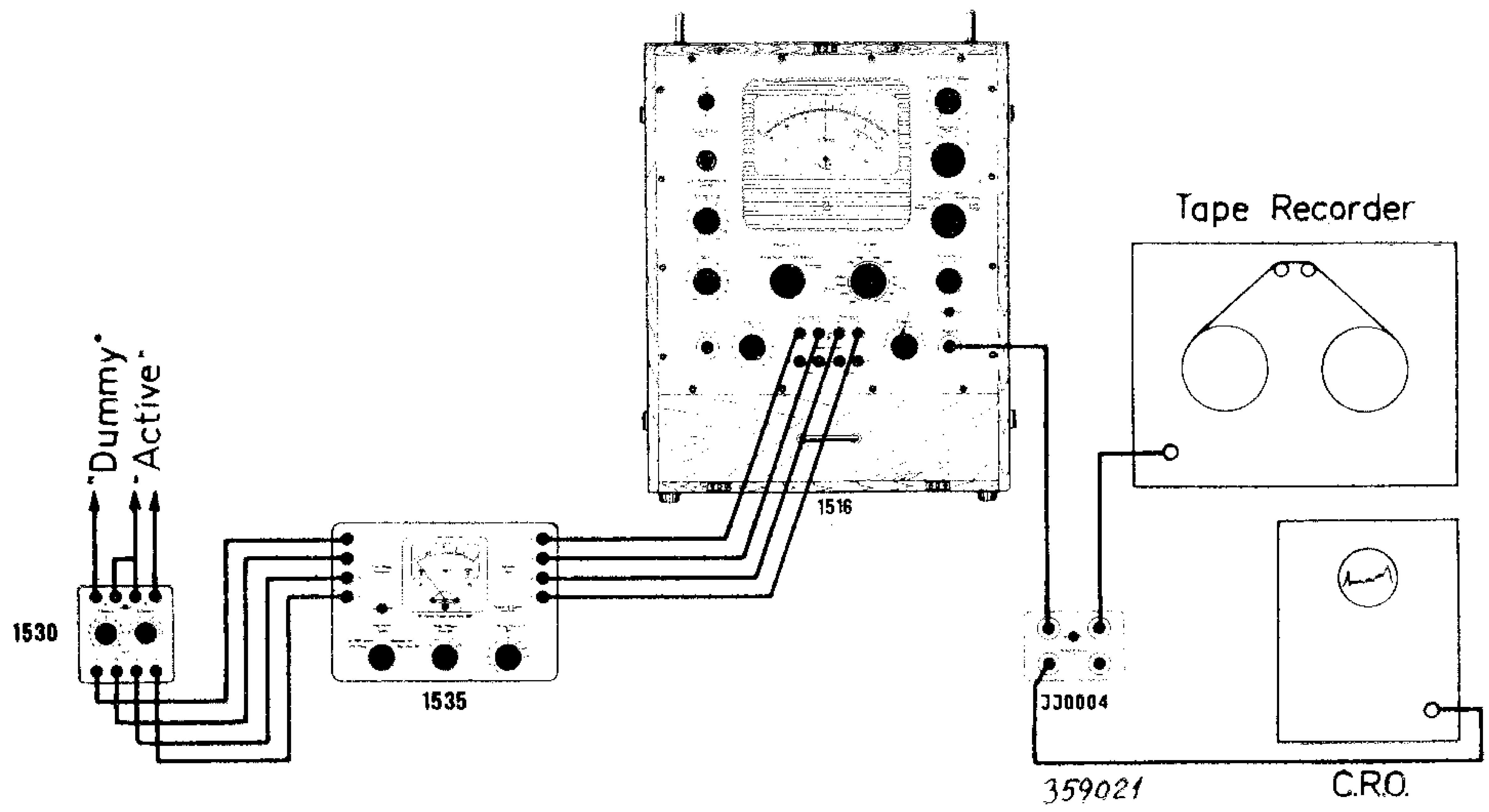


*Fig. 14. Measuring arrangement used for strain measurements at "higher" frequencies.*

gage apparatus used in the experiments is that its dynamic range covers the frequencies from 0 to 100000 c/s, whereby both the low frequency and the high frequency end of the strain spectrum could be measured.

However, as can be seen from Fig. 13, the strain gage instrument is of the carrier frequency type and the measurements of the low and high frequency components of the spectrum were thus made separately.

For the measurements of the low frequencies the 3 kc/s carrier frequency system was used, at higher frequencies the strain gage bridge was fed from a DC accessory unit, see Fig. 14.

Because of the wiring system, the engine should be operated for short periods of time only, and the measurements were therefore recorded on magnetic tape, and later on analyzed in the laboratory.

A further advantage which is gained by recording the results on tape is that the speed of the tape may be "transformed"—thereby shifting the original frequency spectrum upwards or downwards in frequency. This is especially important when it is desired to frequency-amplitude analyze low frequency signals. The frequency spectrum can then by means of tape-speed transformation be shifted upwards in frequency, and an ordinary commercially available electronic frequency analyzer can be employed for the analysis. The analysis time will then also be cut down due to the smaller time constants in the analyzer filter circuits.

The set-ups of Fig. 12 and 14 include for these reasons a tape recorder, and the experiments were carried out by first recording a few measurements, whereafter the engine was stopped and the tape analyzed in the laboratory. The measurements were then carried on, stopping the engine at certain intervals and analyzing the measured results—thereby avoiding that a series of "useless" measurements were recorded before the wiring to the

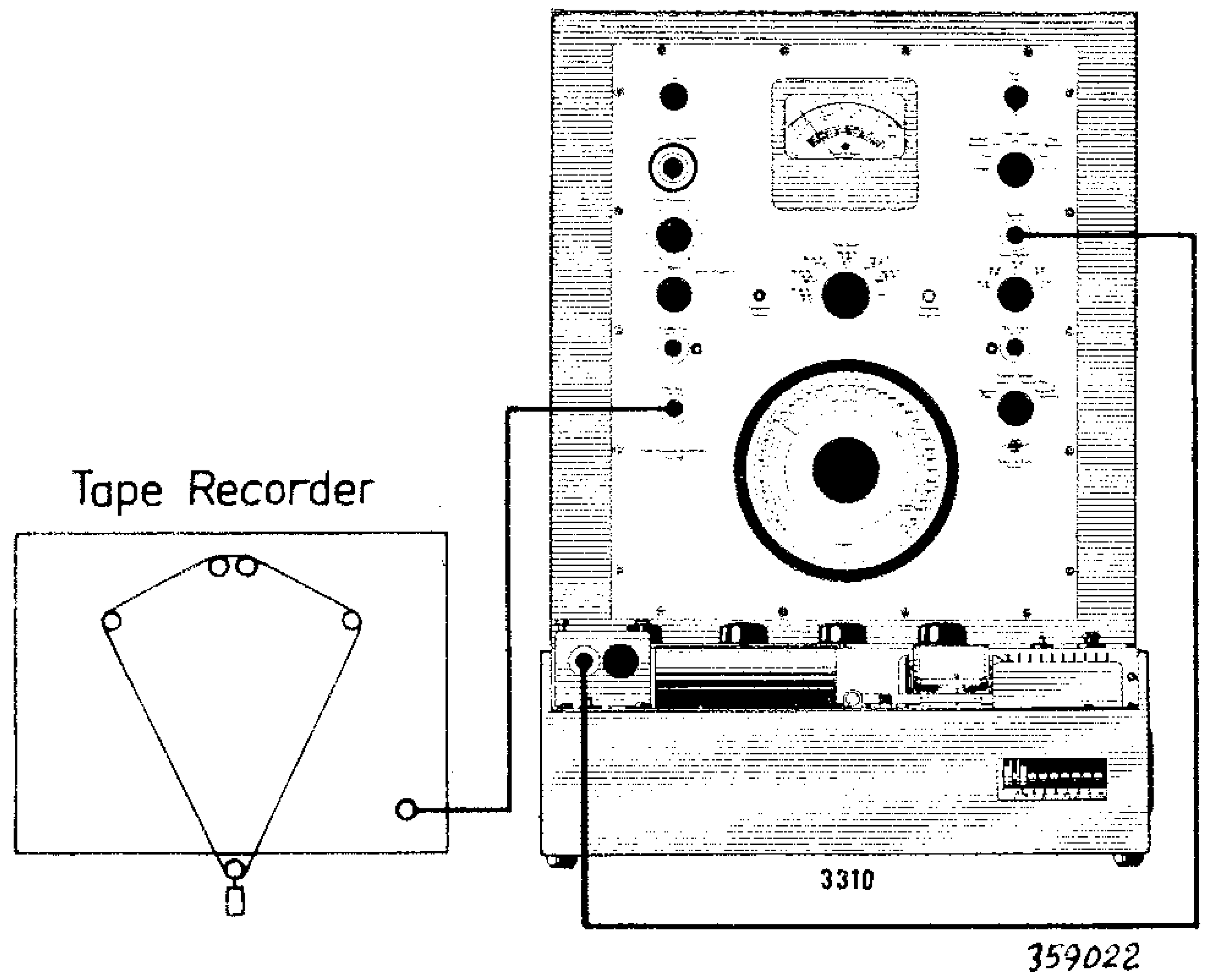


*Fig. 15. Measuring arrangement employed to frequency-amplitude analyze the strain signal.*

gages broke. Because of the relatively wide frequency band of the strain amplifier careful screening of the wires and connections had to be made to prevent the electric noise level from influencing the measured results.

To analyze the tape a measuring arrangement as shown in Fig. 15 was used, consisting of a frequency analyzer and a high speed level recorder. The analyzer consists of 30 built-in 1/3 octave filters and the necessary amplifiers.

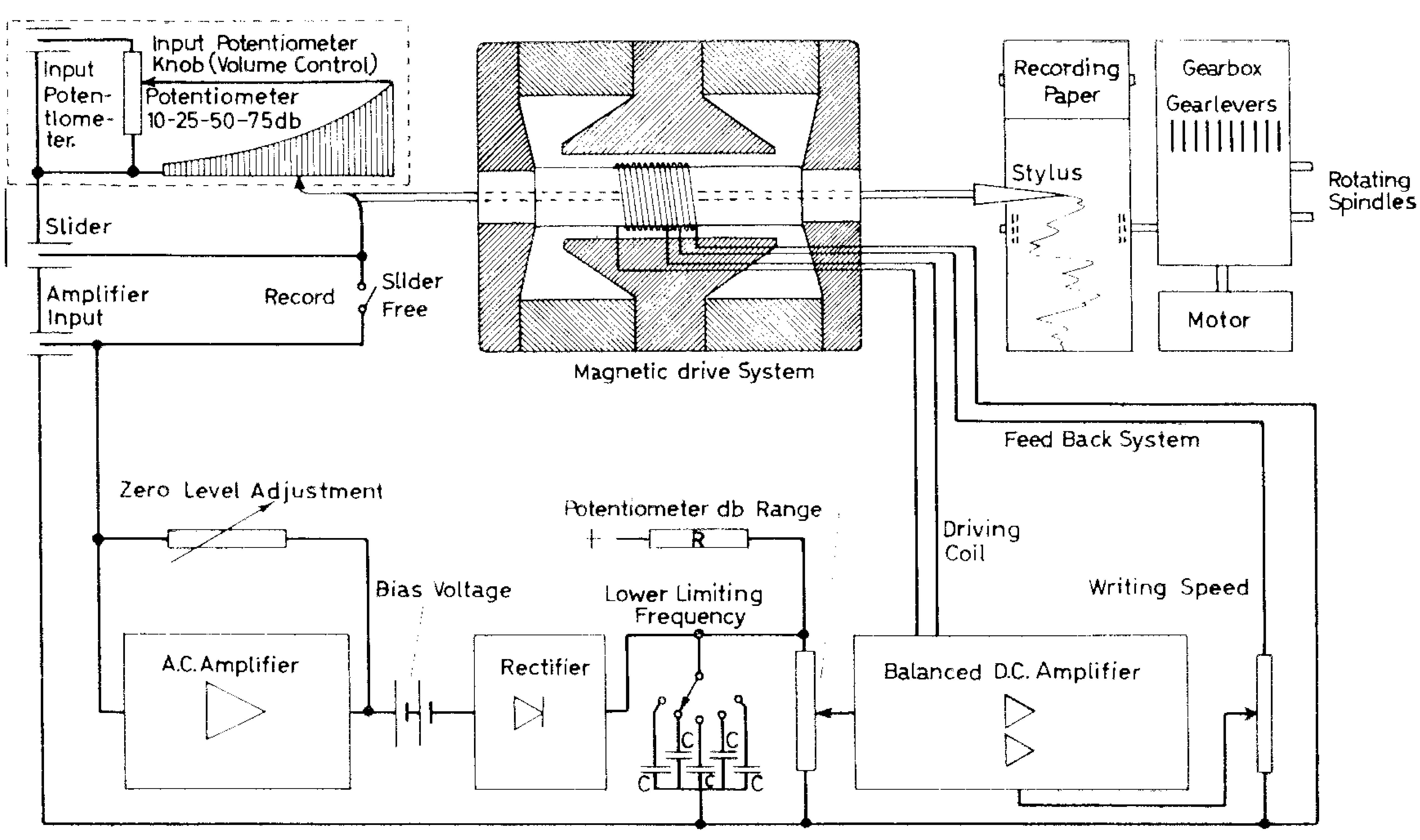


*Fig. 16. Sketch showing the principle of operation of the High Speed Level Recorder.*

Some extension filters, extending the normal selective frequency range of the analyzer down to 14 c/s were also used, and the speed of the magnetic tape was transformed 10 times up, i.e. the tape was played back at a speed 10 times greater than the one used for recording the strain signal

The frequency sweep of the analyzer can, as previously mentioned, be driven from the motor in the level recorder, and synchronized with the calibrated recording paper.

The level recorder is of the interchangeable input potentiometer type, which is a great advantage because it is often desired in strain recording of the type dealt with in this paper, to shift from one amplitude scale to another (logarithmic to linear, or to logarithmic scales with higher resolution) to

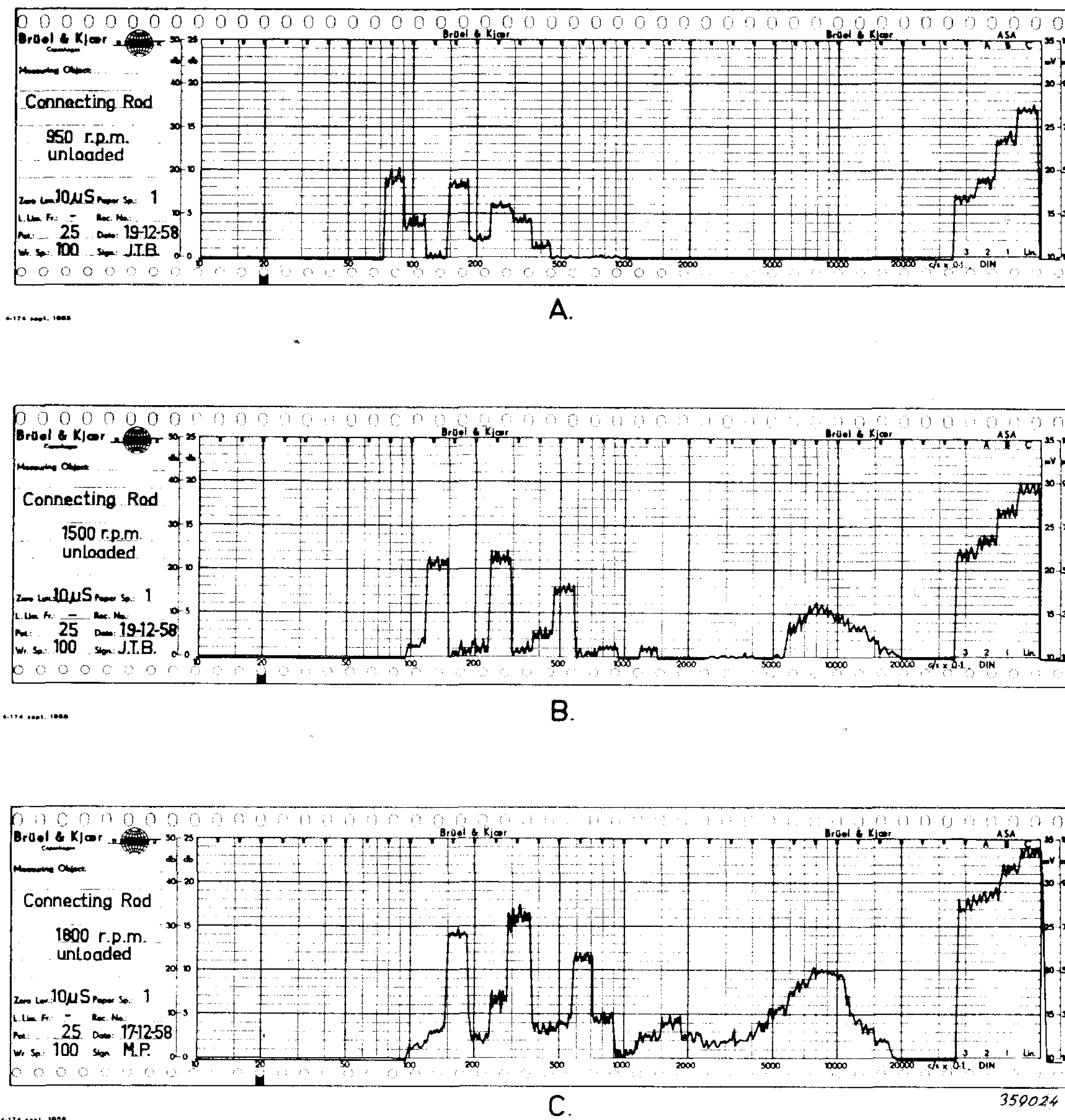


*Fig. 17. Automatically recorded spectrograms of the strain signal. Note the influence of the engine speed upon the excitation of the main resonance.*

study special parts of the strain signal which are of particular interest. Its principle of operation can be explained on the basis of Fig. 16.

As can be seen from the figure the operation is based upon the servo principle, making an accurate and stable indication of the input signal level possible. When indicating any particular level no current will flow in the driving coil of the magnetic drive system. If the magnitude of the voltage applied to the input potentiometer is changed, however, a current will start to flow in the driving coil, thus moving the writing stylus, which is mechanically coupled to the input potentiometer. By the movement of the stylus the voltage delivered from the potentiometer to the AC amplifier is changed until a position is found when, once again no current flows in the driving coil.

Fig. 17 shows a series of spectrograms recorded automatically by means of the set-up shown in Fig. 15. A 25 db potentiometer was used on the level recorder.

The spectrograms were taken of measurements carried out on the connecting rod of the engine under different operating conditions. A shows the spectrum of the strain when the engine was run at relatively low speed (950 r.p.m.) without load. It can be seen from the spectrogram that at this speed the main resonance of the rod was not excited.

The spectrogram shown in B. was taken for an engine speed of approx. 1500 r.p.m., and at this speed the resonance was slightly excited. However, comparing this spectrogram with the one obtained from the resonance measurements it is seen that a much greater damping of the resonance is present under actual operating conditions than under "simulated" conditions. At the same time the resonance is moved slightly upwards in frequency which means that the actual clamping of the rod must differ from the one used during the resonance measurements.

C. shows the spectrogram of the strain with the engine running at a speed of around 1800 r.p.m. The excitation of the resonance is clearly seen.

Another interesting fact which can be seen from the spectrograms is the shift in frequency of the main excitation signal with engine speed. Furthermore, when the engine is speeded up also the magnitude of the different strain

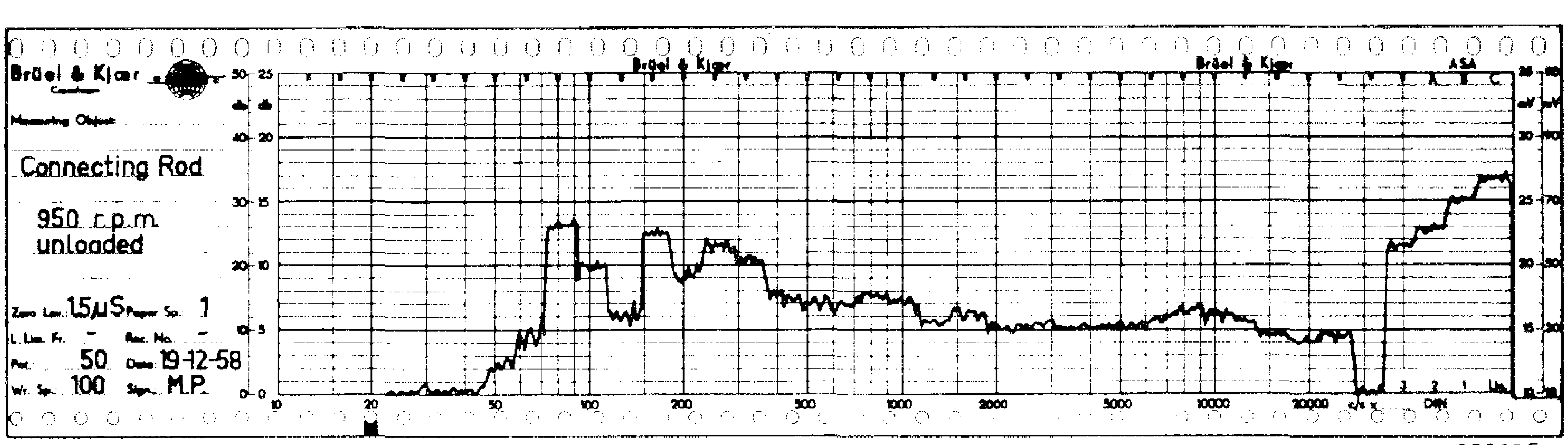


*Fig. 18. Spectrogram of the strain signal using a 50 db potentiometer on the Level Recorder.*

components are increased, which is quite natural because of the greater accelerations present.

In Fig. 18 the spectrogram of the measurements at an engine speed of 950 r.p.m. is shown once again. This time, however, a 50 db input potentiometer was used on the recorder. A much greater dynamic range is then obtained, on the expense of smaller resolution of the details.

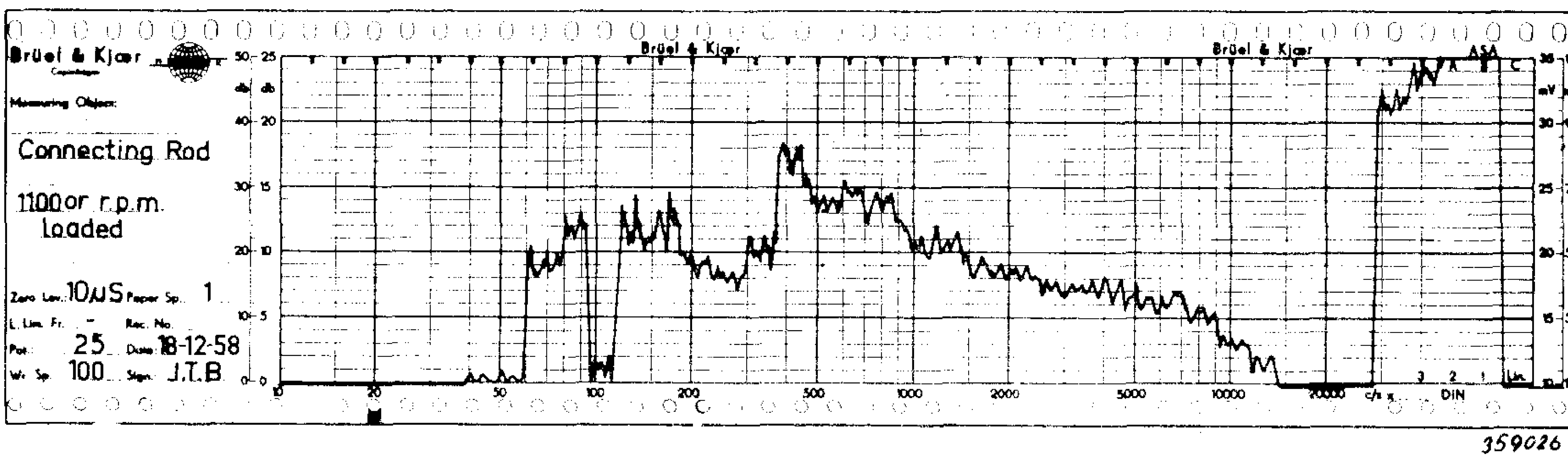


*Fig. 19. Spectrogram of the strain with the engine running at 1100 r.p.m. with load.*

Finally Fig. 19 shows a spectrogram of measurements taken with the engine running at around 1100 r.p.m., loaded. The load was produced by simply

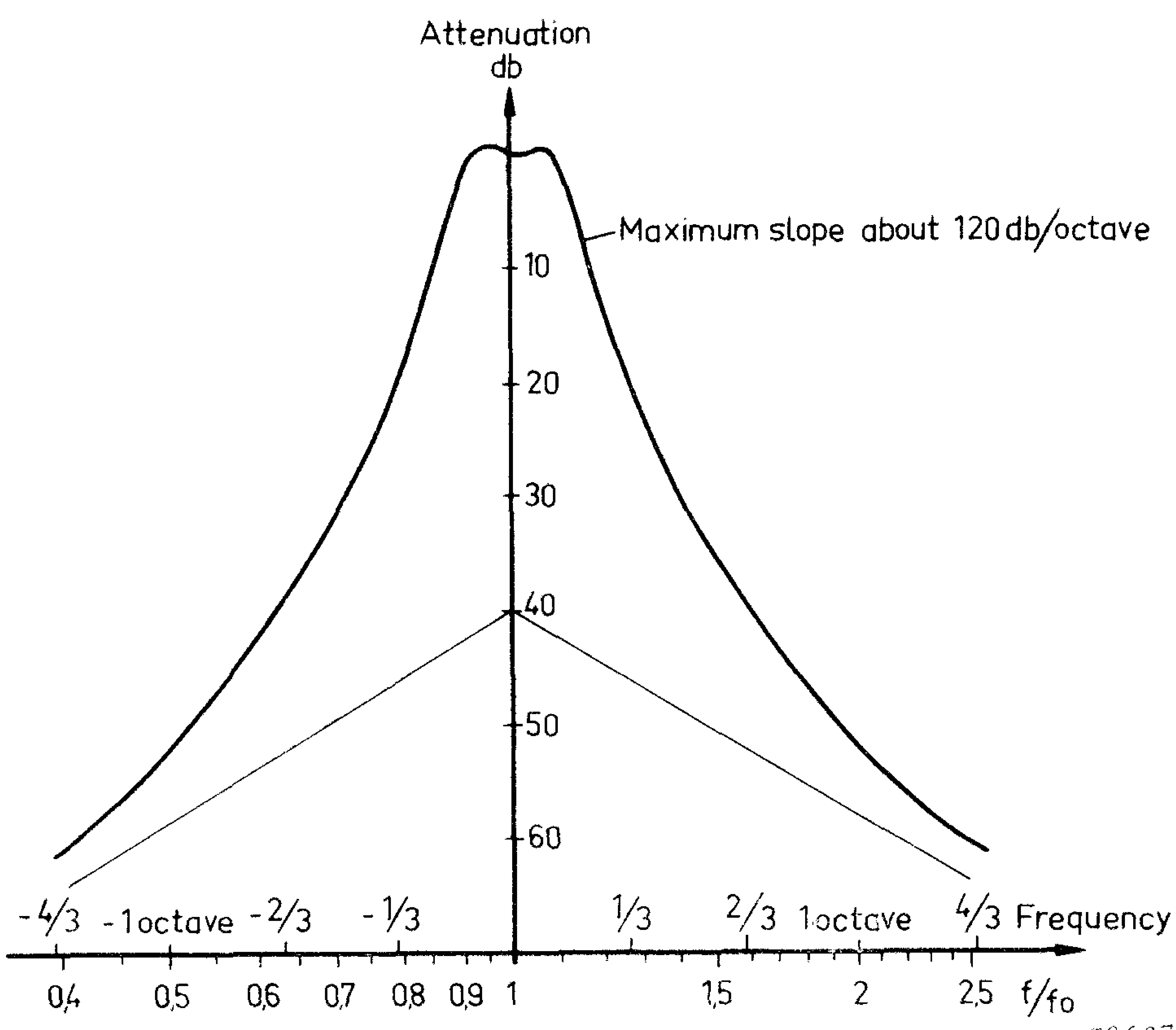


*Fig. 20. Typical frequency characteristic for the filter units used in the Spectrometer (frequency analyzer).*

braking the engine. A gear was inserted between the engine and the load, and the difference in spectrum type between the unloaded and loaded engine can be seen by comparing Fig. 17 and 19. The loaded engine shows a pronounced peak at the second harmonic of the speed of rotation.

The "subharmonic" of the rotation frequency seen in the figures corresponds to the ignition cycle of the engine (the engine was of the four stroke type).

The effect of the analyzer band-width is clearly noticed from the spectrograms and Fig. 20 shows the filter characteristic of one separate filter unit.

The analysis by means of bands of 1/3 octave width has several advantages: First of all, if the engine speed changes slightly up or down during measurement this will not be of very great importance because of the width of the band. Second, a band width of 1/3 octave will allow a relatively great frequency sweep to be used during analyses, because the ringing time of the filters is small (greatest for the low frequency end of the frequency range). Finally, the bandwidth of 1/3 octave is small enough to obtain a good picture of the frequency distribution of the signal being analysed, and clearly indicates the frequency region which might cause the equipment under test to mal-function.

In the region above 30 kc/s in the spectrograms of Figs. 17, 18, and 19 the magnitude of the total stress signal is recorded as measured with a linear frequency characteristic as well as when passed through some specially designed filters which depress the low frequency and high frequency end of the spectrum. These filters are originally included in the analyzer for use in sound level measurements, but might be of considerable interest also for other types of measurements, because it shows very clearly the influence of the high-frequencies.

It can, for example, be seen that the frequency spectrum of the strain signal from the connecting rod contains mostly low frequency components, as the total signal level is considerably higher when measured with a linear frequency characteristic than when passed through the filters.

The strain values indicated on the spectrograms are peak values, the rectifier circuit in the level recorder giving half-wave, peak type rectification.

Measurements were also taken using the carrier frequency system, and the

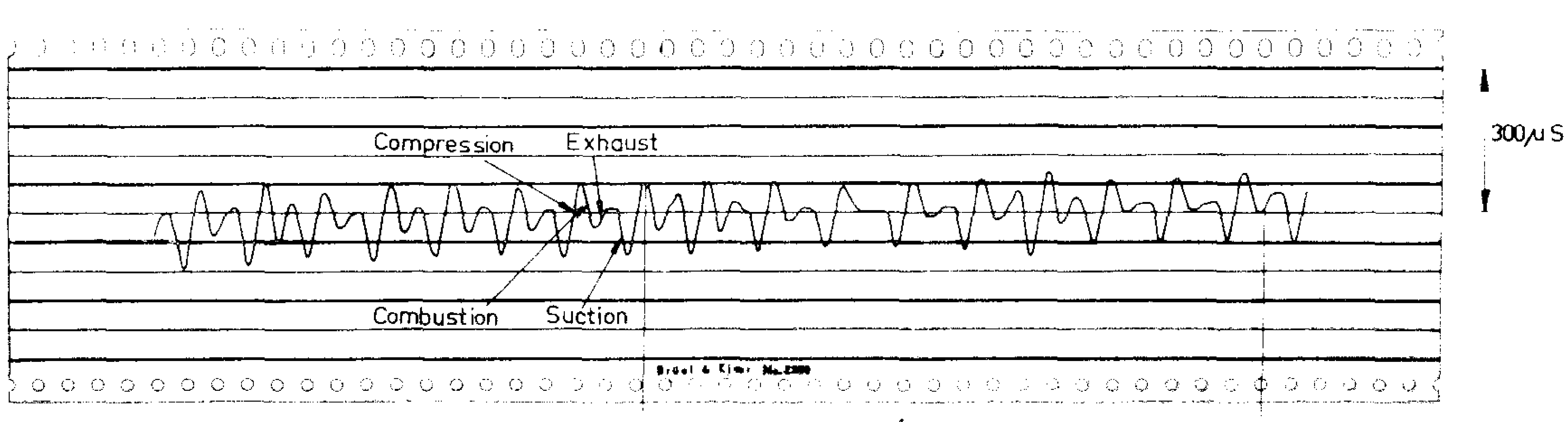


*Fig. 21. Amplitude-time recording of the strain signal.*

results are shown in Fig. 21. Also in this case direct frequency amplitude analysis can be carried out, by demodulating the carrier signal and analysing the result. This should be done when very low frequency components are present in the strain signal, using a second tape recording for frequency transformation. However, since alle frequency components of interest in the case investigated could be found by means of the already described method of analysis the results obtained from measurements with carrier signal were not frequency-amplitude analysed. In Fig. 21 the complete instantaneous variation of the strain is shown. To obtain a linear amplitude scale the level recorder was supplied with a linear input potentiometer.

The four strokes of the engine are indicated on the figure.

The great simplicity of frequency-amplitude analyses of complicated strain signals, compared with the often great mathematical calculation work involved in evaluating the strain-time curves makes this method suitable for a number of industrial development applications, not only in the "field", as in the case of the measurements described, but also in simulated vibration tests in the laboratory, where the use of magnetic tape recording may be avoided, and the measurements analyzed directly.

The method has also been succesfully applied for the location of excitation sources causing excessive stresses to occur at certain frequencies. At a shipyard in Germany, for example, damaging stress amplitudes caused by torsional vibrations were measured on the propeller drive shaft of a turbine ship.

A careful analysis of the strain spectrogram showed that the frequency of the dangerous vibrations coincided with the tooth frequency of the transmission gear from the engine to the drive shaft. When proper changes in the transmission system were made the vibrations ceased and the danger of a broken drive shaft was thus eliminated.

# News from the Factory

**New Accelerometer Program.**

Two new accelerometers have been developed for use at elevated temperatures and the "old" accelerometer contained in the Accelerometer Set Type 4308 and the Accelerometer Package Type 4348 has been modified. The B & K accelerometer program now consists of the following types:

| Accelerometer Sets | Accelerometer Packages |
|---|---|
| 4308 | 4348 |
| 4309 | 4349 |
| 4310 | 4350 |
| 4311 | 4351 |

**The Accelerometer Sets** contain one accelerometer, individually calibrated and supplied with its specific frequency response curve and calibration chart, as well as the following accessories: One screened low noise cable 1.2 m long supplied with a microplug and a JP 0018, two probes (3 and 10 m long), one screwdriver (Allen Key), ten screws for mounting the accelerometer and one screwtap.

**The Accelerometer Packages** are simple cardboard containers with 5 accelerometers and 5 low-noise cables of 1.2 m provided with microplug in one end and open in the other.
Some typical data for the accelerometers are given below.

| Accelerometer contained in | 4308 (4348) | 4309 (4349) | 4310 (4350) | 4311 (4351) |
|---|---|---|---|---|
| Sensitivity in mV/G | 35—70 | 6—12 | 35—70 | 6—12 |
| Principal resonance frequency kc/s | 18—25 | 40—50 | 18—25 | 40—50 |
| Max. ambient temperature °C | 100*) | 100*) | 260**) | 260**) |
| Capacity in pF (including cable) | 400 | 400 | 1000 | 1000 |
| Smallest leakage resistance in MΩ | 200 | 200 | 200 | 200 |

*) Sensitivity independent upon temperature.
**) Sensitivity dependent upon temperature.

Each accelerometer is separately calibrated and supplied with its own calibration chart upon delivery.

**Accelerometer Cables.**

The cables normally supplied with all the accelerometers are of the low noise type (AO 0021 and AO 0022). This cable can, however, only be used at ambient temperatures up to 80° C.

If it is desired to use the accelerometers at higher temperatures, teflon isolated cables AO 0025 and AO 0026 can be supplied on request.

**Cable AO 0025:** Similar to AO 0021, but teflon insulated to withstand temperatures up to 260° C.

**Cables AO 0026:** Similar to AO 0022, but teflon isolated to withstand temperatures up to 260° C.

**Audio Frequency Spectrometer Type 2111.**

The Audio Frequency Spectrometer Type 2110 has been extensively modified, whereby the typenumber has been changed to 2111.

*The automatic switching is now carried out electrically,* and a mechanical connection between the level recorder and the spectrometer is, by automatic recording of spectrograms, no longer necessary.

Instead of using the Flexible Shaft UB 3003 and the Speed Multiplier UG 3004 the automatic switching is carried out by mounting a special switch UG 3006 on the Level Recorder and connecting the contacts of this switch electrically to the "Remote Control" terminals on the back of the Spectrometer.

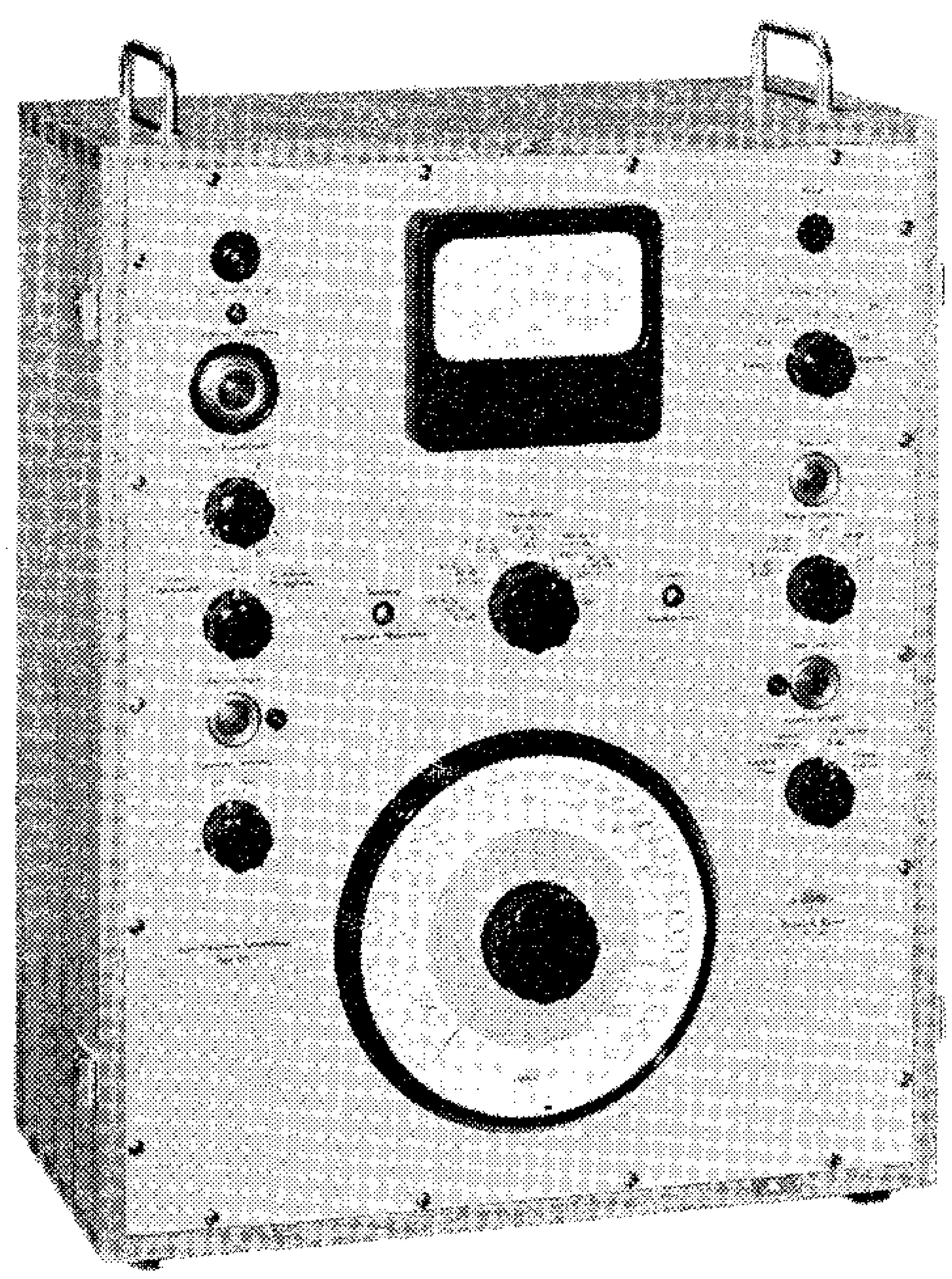

*Photo of Audio Frequency Spectrometer Type 2111.*

This also enables complete synchronization between the preprinted frequency scale on the recording paper and the "sweep" of the Spectrometer to be carried out in a very simple way.

The "Function Selector" switch has furthermore been modified and does now include a position for *full octave band measurements.* Frequency analyses can thus be made *either in third octave bands or in full octave bands,* depending upon the setting of the switch.

than previously. In addition to these modifications also a blocking capacitor has been mounted in the input probe.

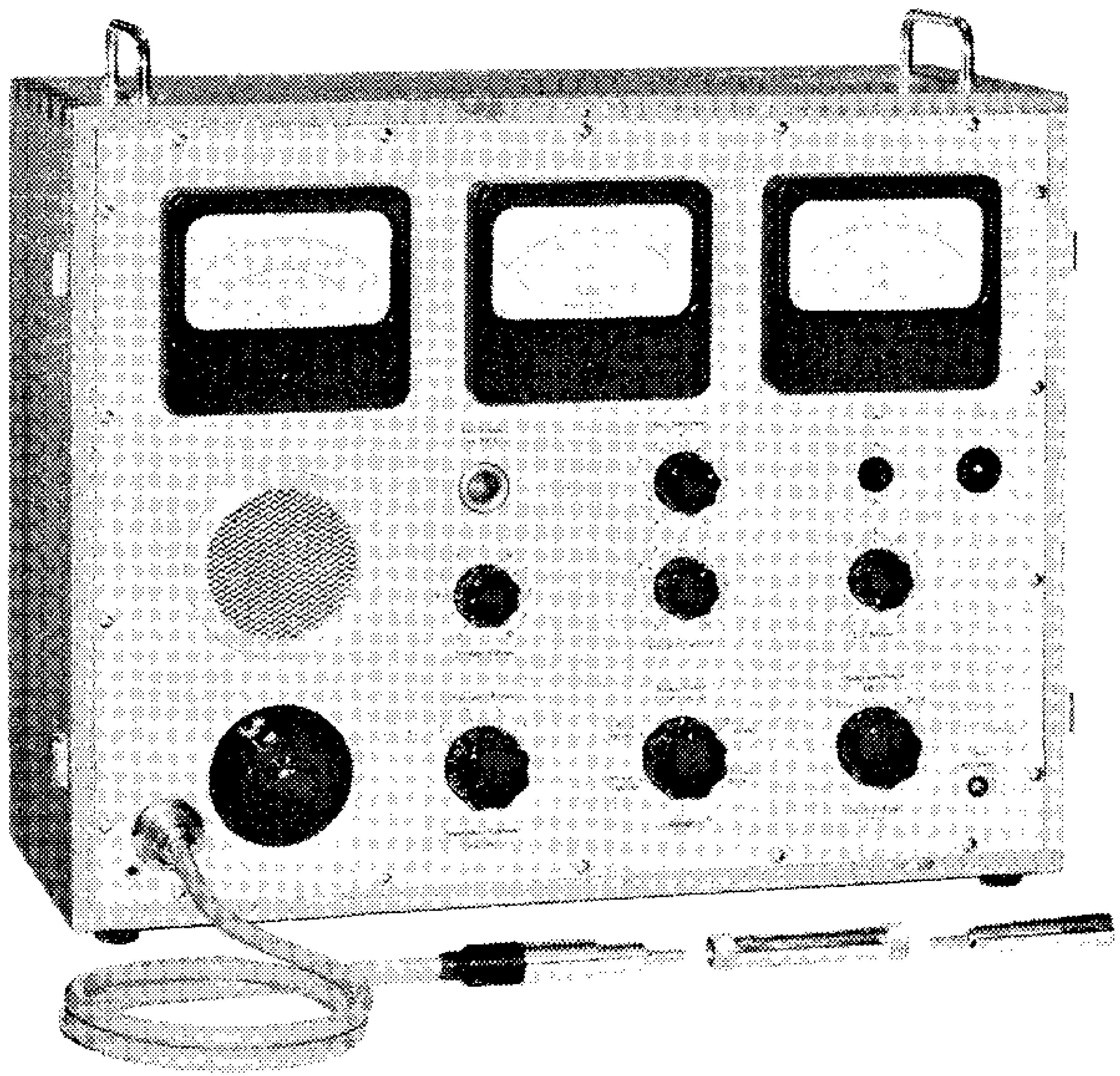

*Photo of Heterodyne Voltmeter Type 2005.*

The input impedance of the probe is now: 4 M$\Omega$ at 100 kc/s and 90 k$\Omega$ at 30 Mc/s paralleled by a capacitance of 5 $\mu\mu$F.
Due to the modification of the instrument its type-number has been changed to Heterodyne Voltmeter Type 2005.
Mechanical dimensions of the new input probe and accessories:

| | Total Length | Max. Width (Diameter) |
|---|---|---|
| Input Probe | 90 mm | 19.5 mm |
| 40 db Attenuator | 85 mm | 16 mm |

The length of the cable connecting the probe to the voltmeter is now 1 m (previously 0.6 m).

**Beat Frequency Oscillator Type 1017.**
The low frequency B.F.O. Type 1015 has been superseded by the new B.F.O. Type 1017 which covers the frequency range 2—2000 c/s.
This oscillator is supplied with an incremental scale allowing exact frequency selection in the range +5 to —5 c/s for any setting of the main frequency scale.
A mechanical switch arrangement on the tuning capacitor spindle, controlled from the front panel of the instrument, allows if desired the output voltage to be available in the upper or lower part of the frequency range only. This is an advantage when measurements are to be taken only in a part of the

full frequency range of the oscillator (for example when it is used for vibration tests).
The capacitors in the compressor rectifier circuit are precharged, whereby the "Compressor Speed" switch can be switched during operation of the instrumentation without upsetting the control, and unwanted regulation transients are avoided.
A second marking on the "Compressor Speed" switch indicates the lowest operating frequency at which a specific compressor speed should be used to avoid severe harmonic distortion. The markings are set for a distortion limit of approximately 1 % (the actual distortion will to a certain extent also depend upon the amount of compression used).
When the oscillator is used in production control arrangements it is sometimes desired during the initial setting up to check the output voltage from the test object at a higher frequency while the oscillator itself is fixed in

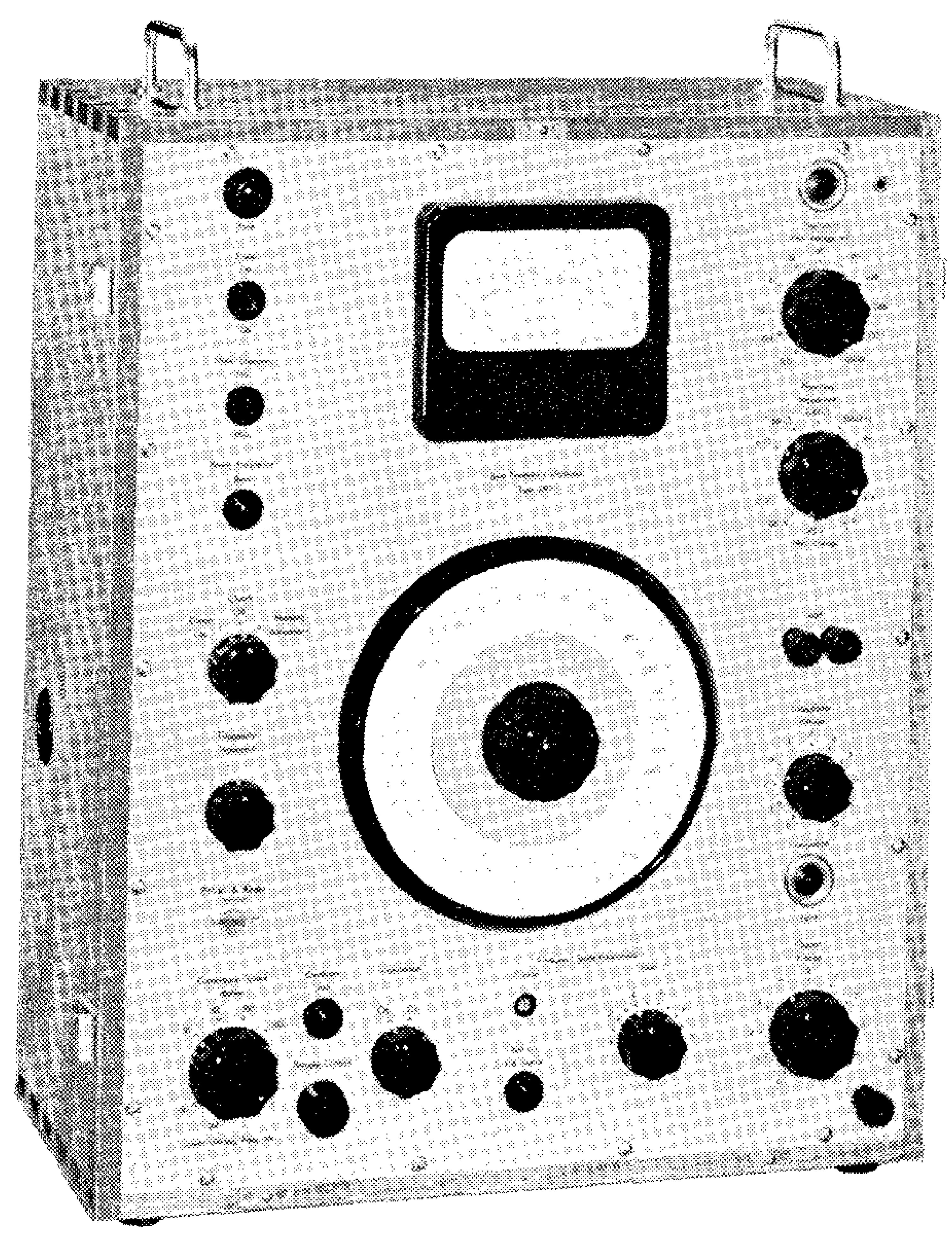

*Photo of Beat Frequency Oscillator Type 1017.*

its lower frequency limit position (2 c/s). This can now be done by means of a press button system without moving the scale pointer of the B.F.O.
When the oscillator is set to 2 c/s and the button marked "100 c/s, Ref. Signal" is pressed a 100 c/s signal will be present at the output terminals.
Both frequency and distortion characteristics of Type 1017 have been considerably improved with respect to the "older" Type 1015.
The "additional" frequency range 2002—4000 c/s of the previous oscillator has, however, been omitted in the 1017.

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Printed in Copenhagen, Denmark