Brüel & Kjær

Technical Review

To Advance Techniques in Acoustical, Electrical, and Mechanical Measurement

Noise from pulse jets

No. 4

1967

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TECHNICAL REVIEW

No. 4 – 1967

Contents

Changing the Noise Spectrum of Pulse Jet Engines

By

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ABSTRACT

After a brief description of the principle of operation of the pulse jet engine some acoustic experiments carried out in 1961 are discussed. These experiments were carried out by means of a siren simulating the noise from the conventional pulse jet engine. It then showed that by continuously changing the frequency of the air pulses produced by the siren the characteristic "combustion" note of the system disappeared resulting in a much less annoying noise.

Further experiments were carried out in 1965 on an actual pulse jet engine specially designed for the purpose. Measurements of the acoustic noise from the engine show that, in principle, the same decrease in "annoyance factor" as was observed during the siren experiments can be obtained. Some theoretical and practical considerations with regard to the design of less annoying pulse jet engines are given.

RÉSUMÉ

Après une brève description du principe de fonctionnement d'une machine à jet pulsé, on discute de quelques expériences acoustiques auxquelles il fut procédé en 1961. Ces expériences étaient menées au moyen d'une sirène simulant le bruit d'un jet pulsé conventionnel. On montra alors qu'en modifiant de manière continue la fréquence des impulsions d'air produites par la sirène, la note caractéristique de combustion du système disparaissait, avec comme résultat un bruit beaucoup moins gênant.

En 1965, il fut procédé à de nouvelles expériences sur des machines à jet pulsé spécialement conçues à cet effet. Les mesures du bruit acoustique du moteur montrent qu'en principe on peut obtenir la même réduction du «facteur de gêne» que celle observée pendant les expériences avec sirène. On donne quelques considérations théoriques et practiques concernant l'étude de machines à jet pulsé d'un fonctionnement moins gênant.

ZUSAMMENFASSUNG

Nach einer kurzen Beschreibung des Arbeitsprinzips von intermittierenden Strahltriebwerken werden einige akustische Experimente aus dem Jahre 1961 diskutiert. Diese Experimente wurden mit Hilfe einer Sirene ausgeführt, die das Geräusch eines herkömmlichen intermittierenden Strahltriebswerks simulierte. Dabei zeigte sich, daß durch ständige Frequenzänderung der von der Sirene erzeugten Luftpulsationen der characteristische »Verbrennungs«-Klang des Systems verschwand, woraus ein sehr viel weniger lästiges Geräusch resultierte. Weitere Versuche wurden 1965 an einem wirklichen, speziell für diesen Zweck konstruierten intermittierenden Strahltriebwerk durchgeführt. Lärmmessungen an diesen Aggregat ergaben, daß man prinzipiell die gleiche Abnahme des »Lästigkeitsfaktors« erzielen kann, wie es bei den Sirenenexperimenten zu beobachten war. Einige theoretische und praktische Überlegungen im Hinblick auf die Entwicklung von weniger störenden Strahltriebwerken werden angestellt.

Introduction

Aircraft and noise have always been regarded as closely connected subjects, but only in the most recent years has the noise from aircraft become an accepted threat to aircraft and aircraft engine development. Already the noise restrictions at several airports hinders the take-off of large aircraft with full loads and thereby the economy of the airlines is threathened. As aircraft size and aircraft speed is steadily increasing this problem will demand a never-ending research to be maintained. For the generally used jet engines the work on noise control is not very old but it is growing very rapidly.

The first, and probably still the only, jet engine type that has been completely abandoned mainly due to noise considerations is the pulse jet which will be remembered as the engine of the German flying bomb, V 1, of the Second World War. In the 1950's it was being developed in several countries for helicopter propulsion, but all projects stopped due to a number of reasons, one of which was always the high noise level.

The present article describes an attempt to prove that it is possible to build a pulse jet with a much decreased annoyance factor, so that this simple, inexpensive and reliable prime mover can still be considered for use in future helicopter and aircraft projects.

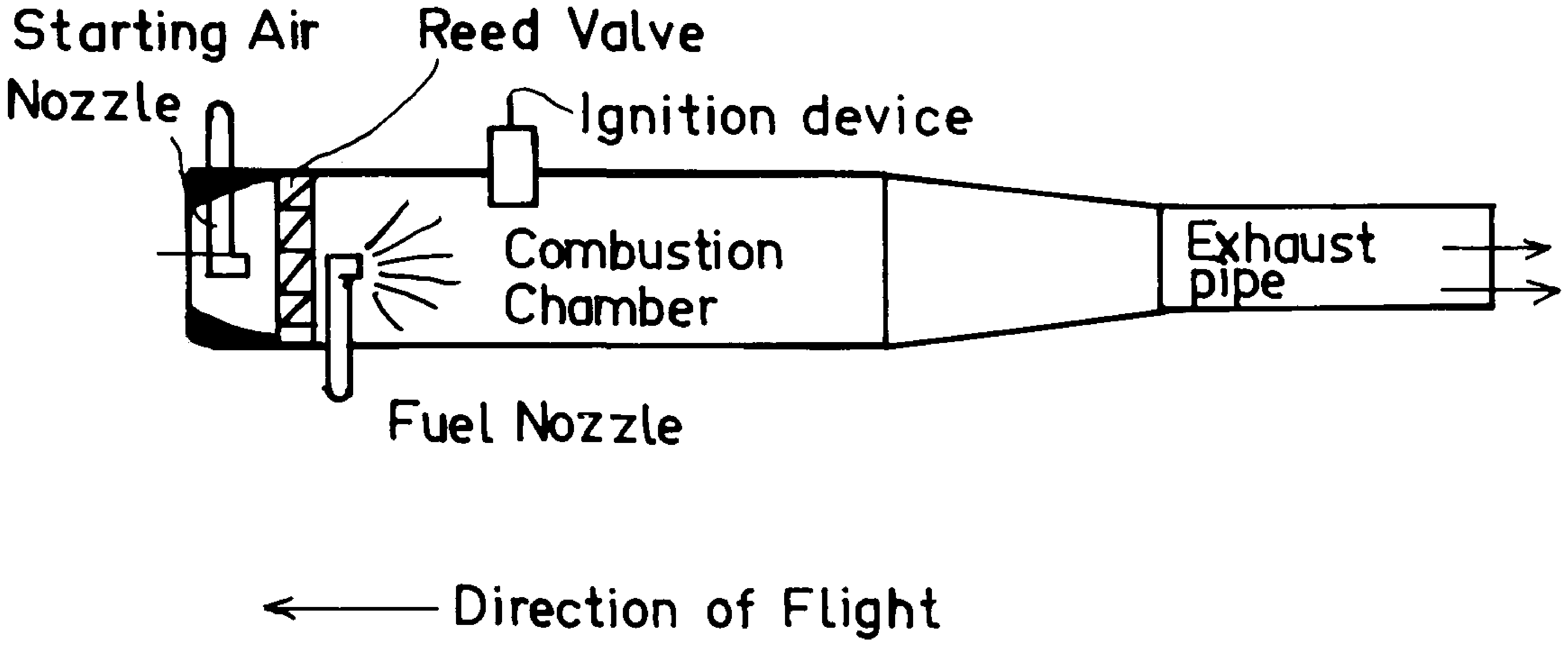

Fig. 1. Principle of operation of the pulse jet engine.

Construction

A typical pulse jet engine is constructed as shown in Fig. 1. It consists of a cylindrical combustion chamber, the forward end of which is closed by a reed type non return valve that will permit air to enter the combustion chamber when the pressure there is below the pressure on the front side of the non return valve. The combustion chamber is in free connection with the surroundings through an exhaust pipe at the rear.

The combustion chamber is continuously supplied with atomized fuel by a fuel nozzle, and the mixture in the combustion chamber can be ignited by a glow plug or similar device. Air can be blown through the engine by an air nozzle in the front.
Normally the air nozzle and ignition device are only used for starting the engine.

Operation
The combustion of a pulse jet is intermittent and a simplified typical working cycle is as follows (ref. 1):

1. Air enters the combustion chamber through a reed type inlet valve and is mixed with fuel, which is injected continuously, to provide a suitable air/fuel ratio. The air within the chamber should now be considered as consisting of two components:
   a. A fuel-enriched charge near the valve.
   b. A column of air or exhaust gas in the exhaust pipe.
2. Upon ignition, rapid combustion of the charge occurs near the valve, but expansion of the gases is resisted by the column of air in the exhaust pipe. Thus the increasing pressure closes the valve and forcibly ejects the column of gases out of the tail pipe.
3. As the ejected gases gain momentum the pressure in the chamber falls below the atmospheric pressure thereby inducing a fresh charge of air through the inlet valve in the form of a rapidly diffusing central core. During its passage into the chamber the air is enriched with fuel which vaporizes on mixing with hot gases in the chamber.
4. The exhaust gases flowing through the tail pipe, now reduced in momentum due to the atmospheric back pressure, reverse their direction of flow and return to the chamber where the arresting of the new momentum produces a slight pre-compression which closes the valve.
5. The combination of pre-compression and mean mixture temperature of the gases permits spontaneous ignition to occur and the whole combustion cycle recommences.

Most known pulse jets have a combustion frequency of 45–200 Hz depending on the following factors:

A. The acoustic properties of the combustion chamber and exhaust pipe, e.g. an elongation of the tail pipe will cause a reduced frequency so that a long engine will normally work slower than a short one.
B. The amount of fuel supplied to each combustion. An increase in the fuel supply will result in an instantaneously decreased frequency as each combustion will give more combustion gas that has to be expanded out through the exhaust pipe where the gas speed is already sonic.
C. The flow and temperature conditions in the combustion chamber, as ignition will not take place before the air-fuel charge has been brought in contact with a heat source of sufficient capacity.

The periodic combustion of the pulse jet creates a strong noise, and frequency analysis shows that it is mainly composed of high-frequency eddy noise (above 2,000 Hz) from the gas flow through the pulse jet plus a note corresponding to the combustion frequency and its harmonics. This note is the major cause of the great disturbance caused by the pulse jet as it has a great intensity and its low frequency "roar" makes it easy to distinguish from other noise.

In all the experiments for the development of better pulse jets that have previously been made, noise improvement has been sought by improving combustion as this would reduce the eddy noise, but the low frequency note still remained.

An Early Experiment

In an experiment made in 1961 by the author as a guest at the Department of Machine Design headed by prof. E. Frederiksen of the Technical University of Denmark it was found that air pressure pulses with fixed frequency from a siren gave a noise exactly the same as the one described above. However, if the pressure air pulses had a continuously changing frequency within a 30 % interval around the fixed frequency used before, the noise changed character as shown in Fig. 2. The noise spectrum above 1,000 Hz was unchanged, but below 1,000 Hz where the energy had been concentrated in high peaks around the air pulse frequency and its harmonics, there was now found a continuous frequency spectrum with nearly constant power spectral density from the lowest air pulse frequency used up to 1,000 Hz.

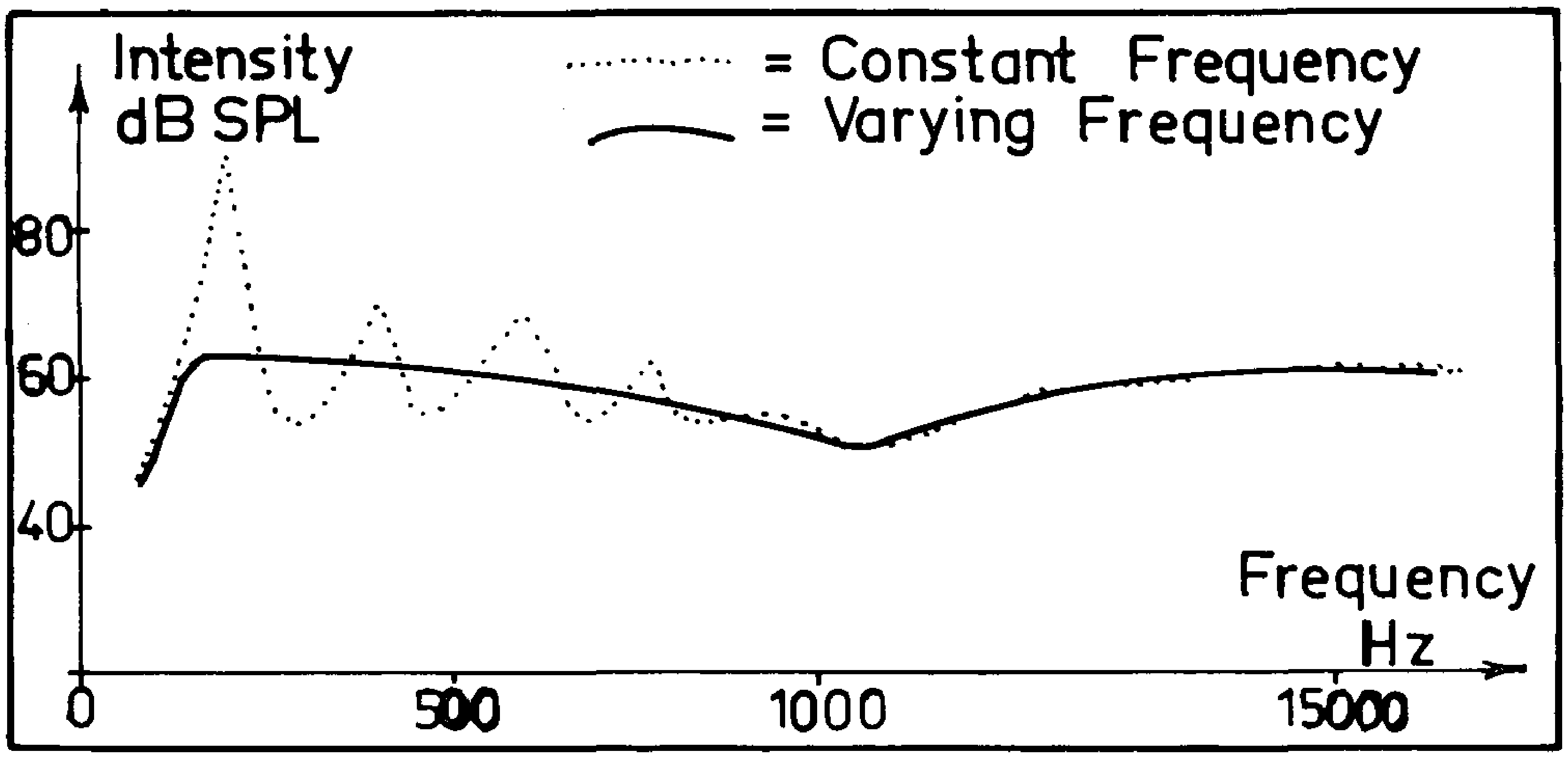

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Fig. 2. Typical frequency spectrum of the acoustic noise produced during the siren experiments.

This interval is made up by interference between the different air pulse frequencies and their harmonics.

The change from fixed to randomly varying frequency caused the maximum intensity in the noise spectrum to decrease by as much as 20 dB, whereas the total intensity was unaltered, indicating that the released energy was the same in both cases.

This changed noise spectrum has the following major advantages:

a. The maximum intensity is lowered considerably.
b. The characteristic note from the combustion has disappeared completely giving way to a noise spectrum that largely follows the sensitivity curves of the ear whereby it is heard as a noise that more easily blends into "natural" background noise and which is much less disturbing (ref. 4.).

This caused the author to work on the idea that if it was possible to build a pulse jet in which the exhaust gas was expelled with a continuously changing frequency it would give an improved noise spectrum and thereby be much less disturbing than the pulse jets known at present.

Short Introduction to the Oscillations of the Pulse Jet

To explain the possibilities of constructing a pulse jet with a varying exhaust frequency a simplified account of some of the processes taking place in a pulse jet will be given.

The interest will naturally be directed towards the pressure oscillations that guide the whole operation cycle as it is there that the limits for the obtainable variations must be found.

We will first look at a simplified model of the pressure oscillation caused by a single combustion in the combustion chamber of a pulse jet. See Fig. 3 (ref. 3).

A-B-C represents the pressure during the combustion where A is the point where ignition takes place.

C-D-E represents the suction that follows the combustion and which is used for drawing fresh air into the combustion chamber.

E-F-G and H-I-K is the decaying oscillation. The frequency is dependent on the acoustic properties of the combustion chamber. E-F-G is a positive pressure

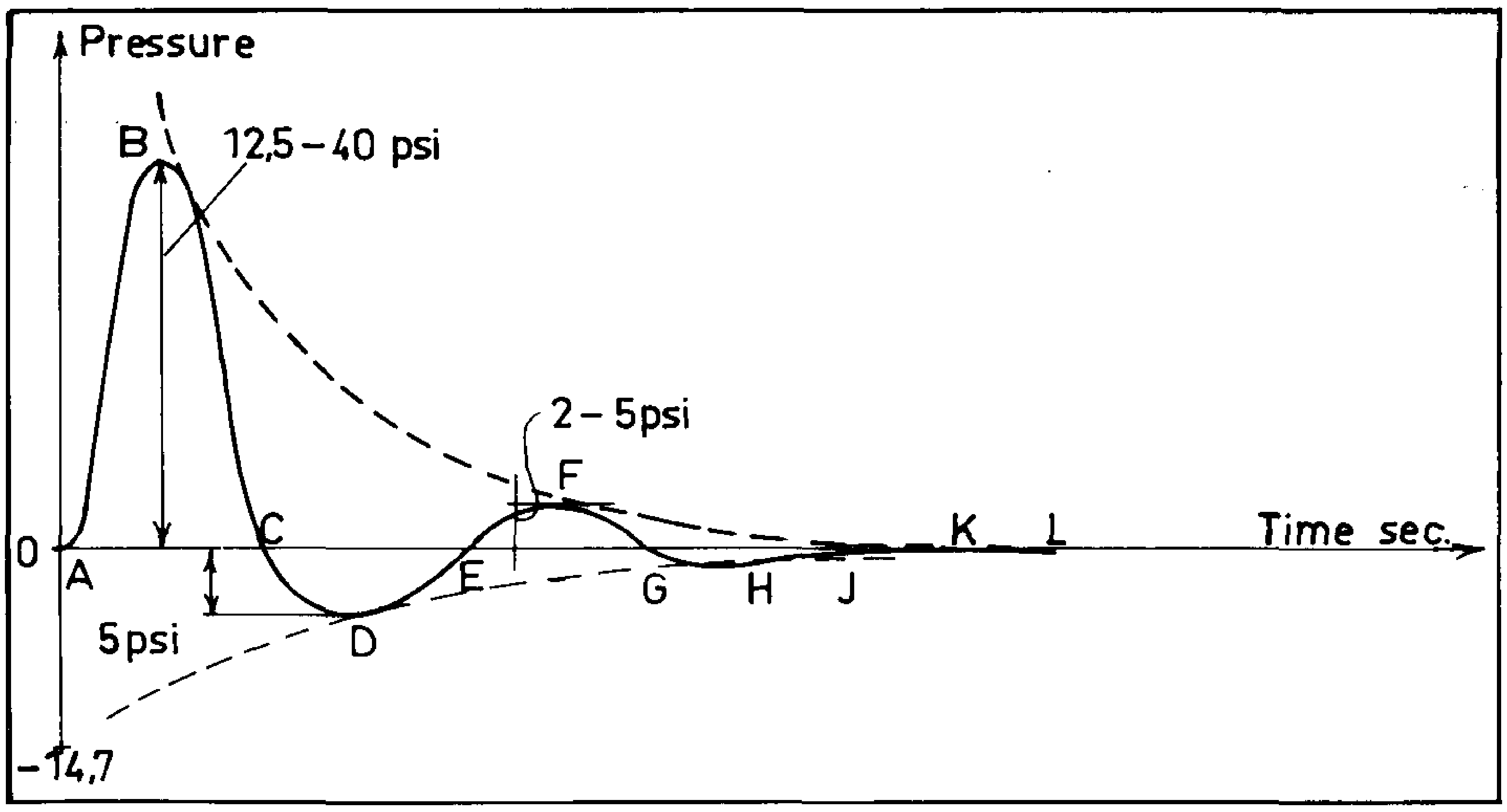


Fig. 3. Basic pressure versus time characteristic of a pulse jet engine (single burst).

and can be used for initiating a new combustion. It is therefore known as the pre-compression pulse.

Provided the gas temperature in the combustion chamber becomes equal to or above the spontaneous ignition temperature of the air/fuel mixture during the presence of the pre-compression pulse a new combustion will start. This will cause a new pressure oscillation which will be superimposed upon the rapidly decaying oscillation from the first combustion. The new oscillation will after a suction cycle give a pre-compression pulse and in this way combustion will follow combustion as long as a suitable amount of fuel is supplied.

For the pressure oscillation the distance B-F is equal to 1 period and to obtain resonance in the oscillating system, i.e. the column of gas in combustion chamber and exhaust pipe, the new combustion must be made so that it will give maximum pressure at F.

Hereby the forced frequency n_f (the combustion frequency) becomes equal to the natural frequency n (the frequency of the gas column). To obtain this with the given oscillation A-B-C the ignition must take place at E. See Fig. 4.

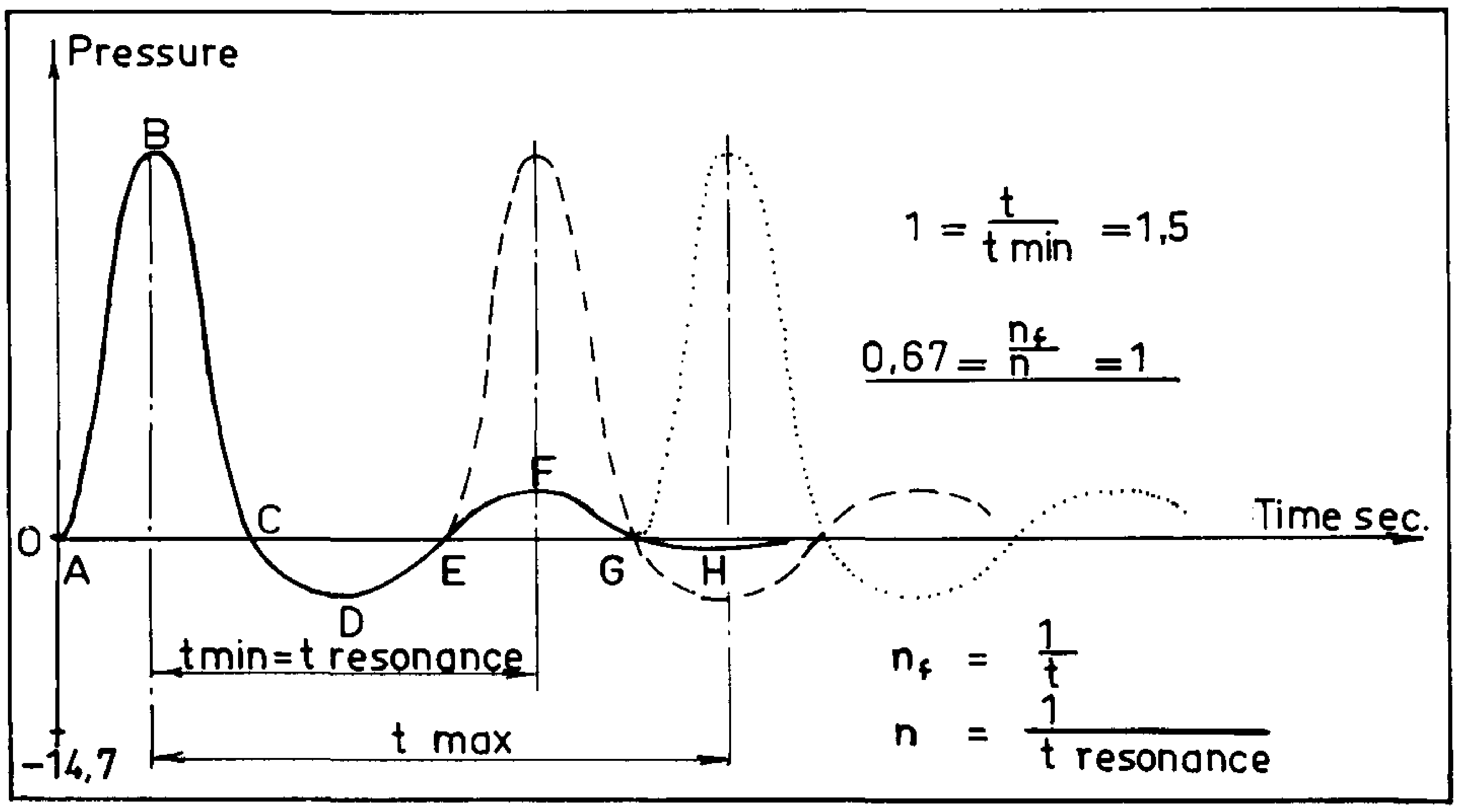


Fig. 4. Typical pressure versus time characteristic of a continuously running pulse jet engine.

However, an ignition at E means that the pre-compression pulse is not used to raise the pressure of the air-fuel charge before ignition and as this is the only compression it will get prior to combustion it is of some value even though rather small. Actual pulse jets therefore have ignition between E and G so the maximum pressure is reached between F and H. From Fig. 4 it can be seen that the following relation can be found between the combustion frequency n_f and the gas column frequency n

$$0.67\,n < n_f < n.$$

From Fig. 3 where the values, based on actual pulse jet engines, of maximum combustion pressure $p_{f,m}$ and maximum pre-combustion pressure $p_{k,m}$ are indicated, the logarithmic decrement δ for the oscillation can be found:

$$\frac{p_{f,m}}{p_{k,m}} = e^{\delta} \text{ (where } e \text{ is the base of natural logarithm)}$$

With the maximum values this gives

$$\frac{40}{5} = 8{,}00 = e$$

$$\delta = 2{,}08 \simeq 2{,}1$$

With the minimum values this gives:

$$\frac{12{,}5}{2} = 6{,}07 = e^{\delta}$$

$$\delta = 1{,}82 \simeq 1{,}8$$

These high values of δ indicate a very high damping of the oscillating system. This is caused by 3 factors:

1. The pressure ratio necessary to give sonic velocity through the exhaust pipe.
2. The reduction of suction caused by air entering the combustion chamber.
3. By friction losses in valves and combustion chamber.

The consequence of this damping is made clear by Figs. 5 and 6.

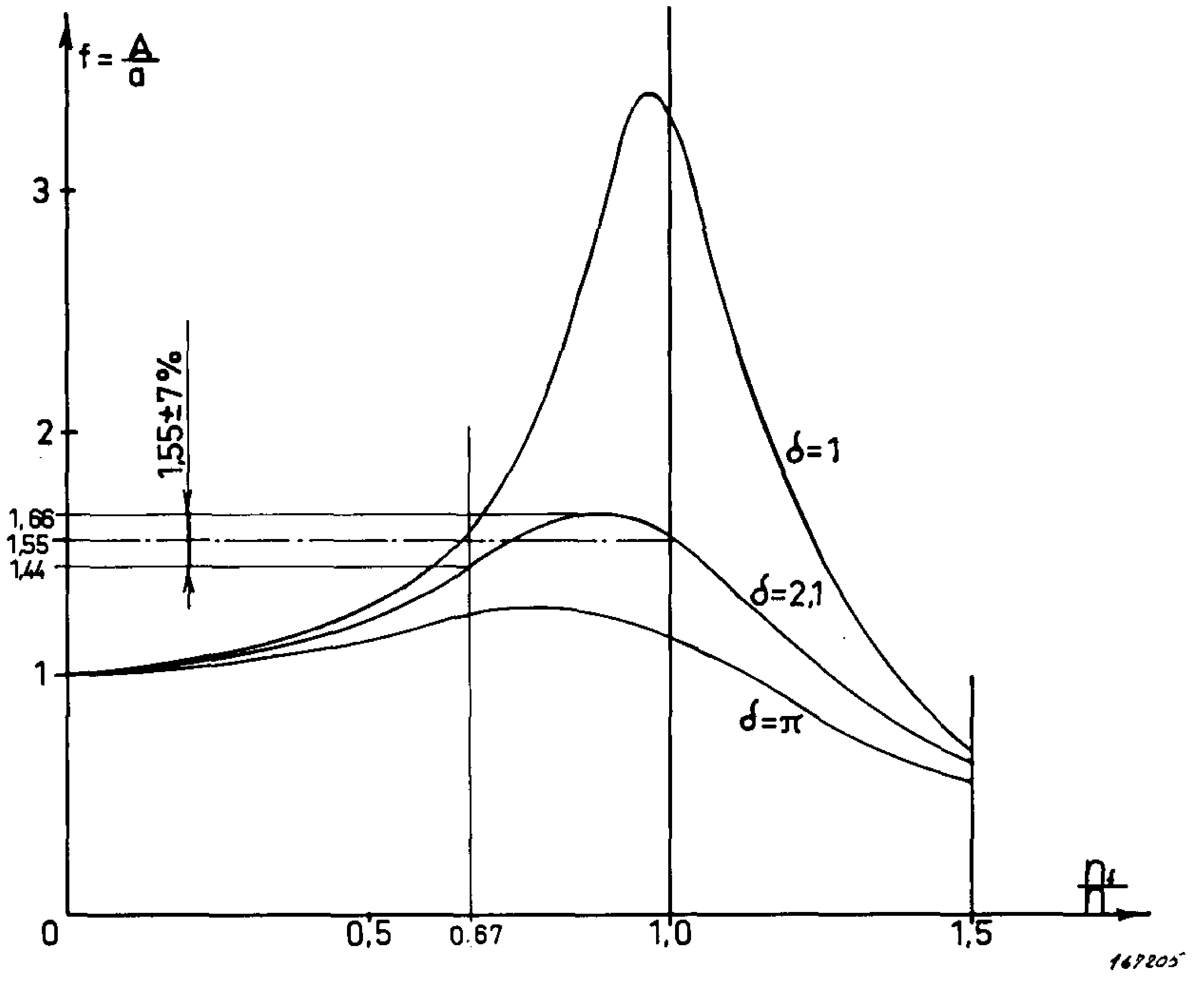


Fig. 5. The dynamical amplification $f = \frac{A}{a}$ *as a function of* n_f/n *and* δ

A = actual oscillation amplitude.
a = amplitude for statically applied force.

From the figures it can be seen that for $0{,}67 < \frac{n_f}{n} < 1$ and $\delta = 2.1$, which are

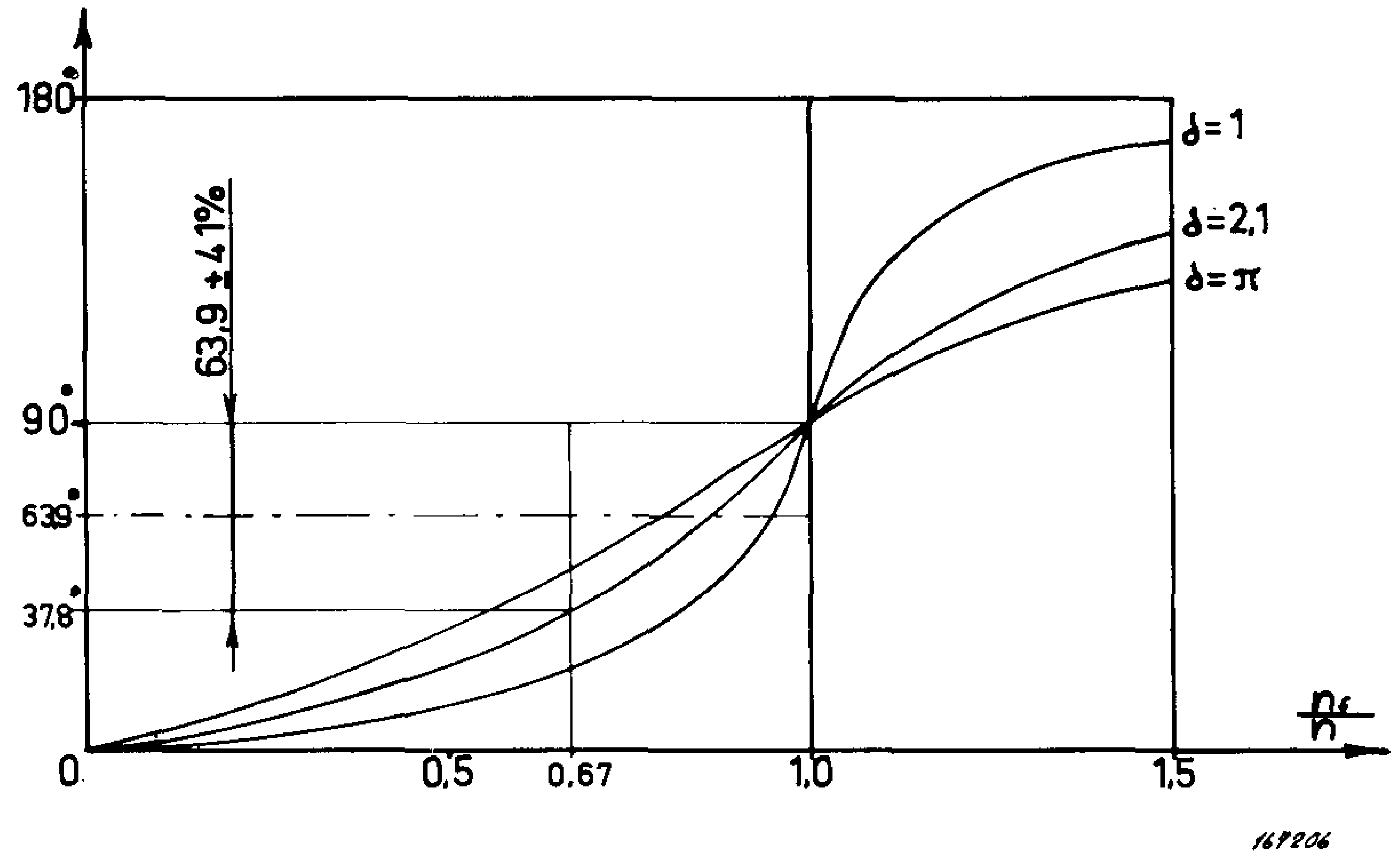


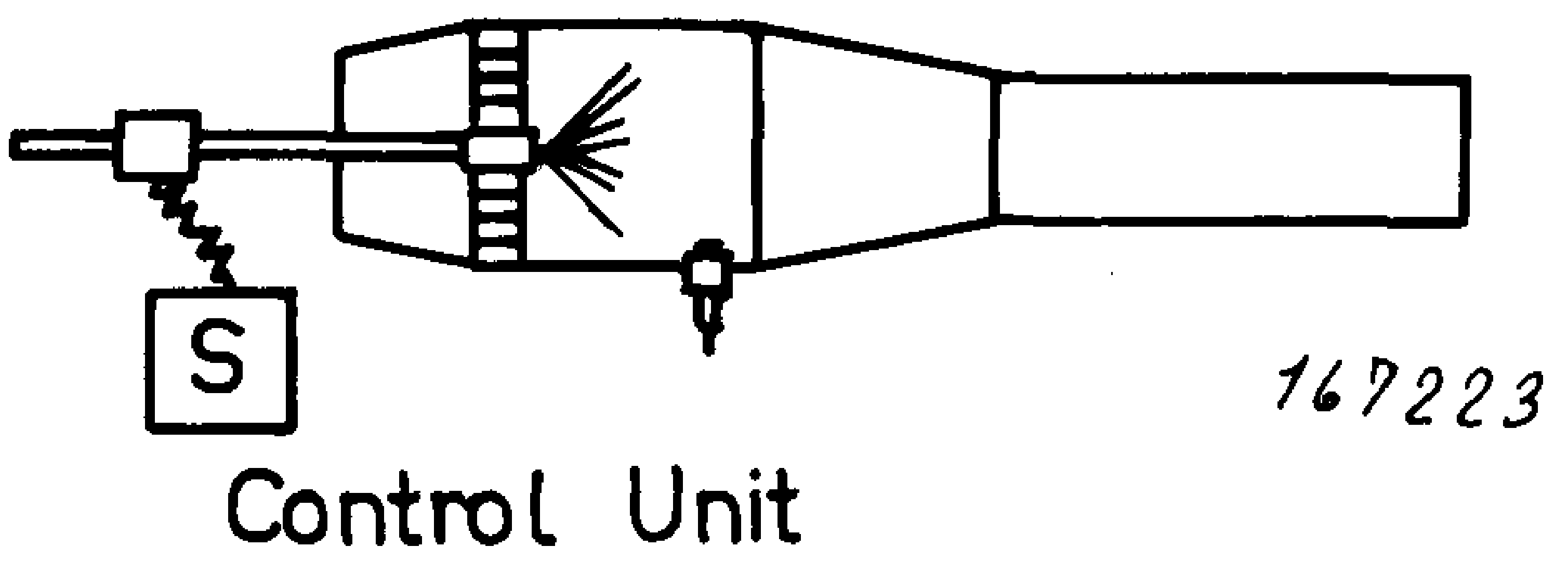
Fig. 6. The phase difference Φ between force (combustion) and oscillating system (gas column in pulse jet).

values from known pulse jets, *f* will only vary approximately ± 7 % of its mean value in the interval while the phase difference will vary approximately ± 40 % of its mean value.

From this it can be concluded that if combustions are made in a pulse jet with a continuously varying frequency n_f which is kept in or near the interval $0.67\ n \leq n_f \leq n$ the oscillations of the gas column can be controlled by the combustion pressure and have an almost constant amplitude. Similarly the variation in phase difference between the combustion pressure and the gas column oscillation will be small.

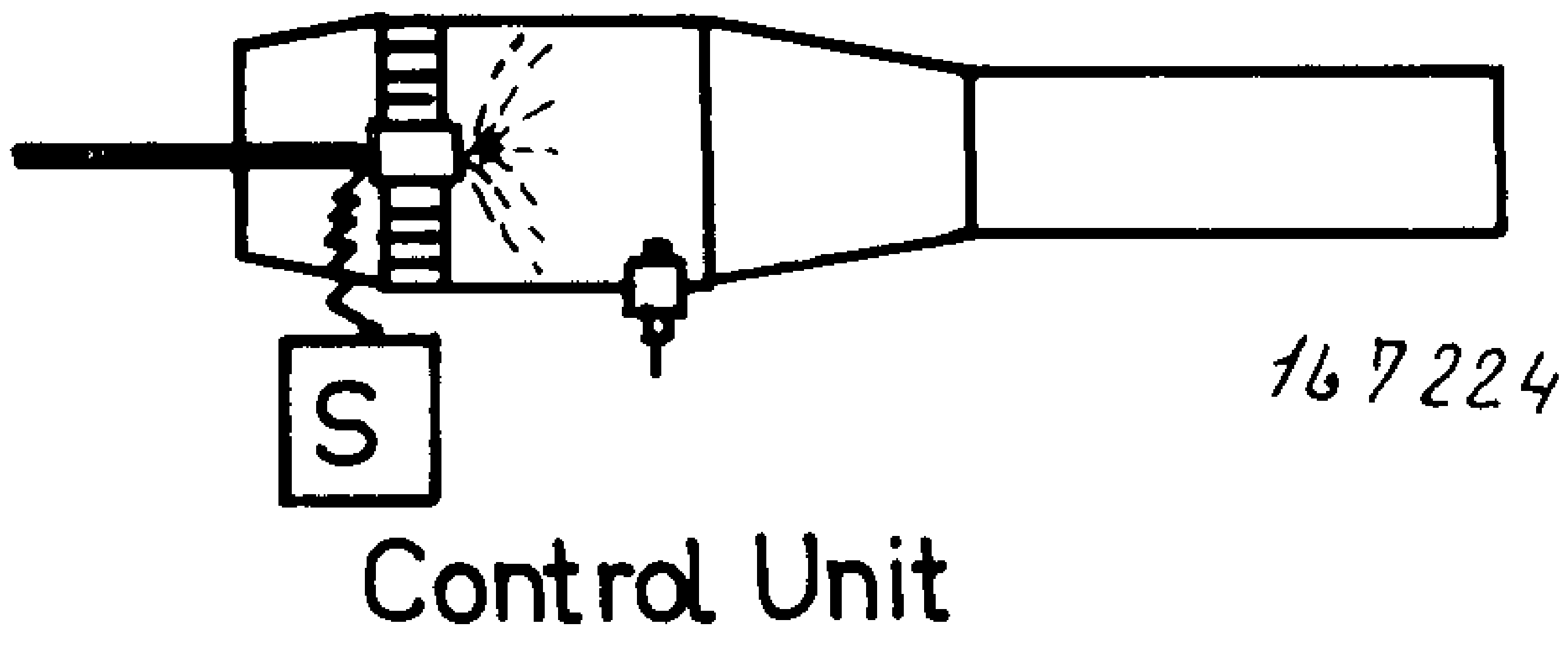
A variation in combustion frequency will give a variation in exhaust frequency, and as the combustion frequency is dependent mainly on the time of ignition it is possible to build a pulse jet with varying exhaust frequency if it is shaped so that it is possible to continuously vary one or more of the factors that governs the time of ignition and combustion. This can be done in the following ways:

1. By continuously varying the amount of fuel supplied to the engine by a valve in the supply line, as the combustion frequency is lowered by increased and raised by decreased fuel supply. This method is simple and will only demand minor controlling forces, but the variations obtainable will be small (ref. 1. p. 51).

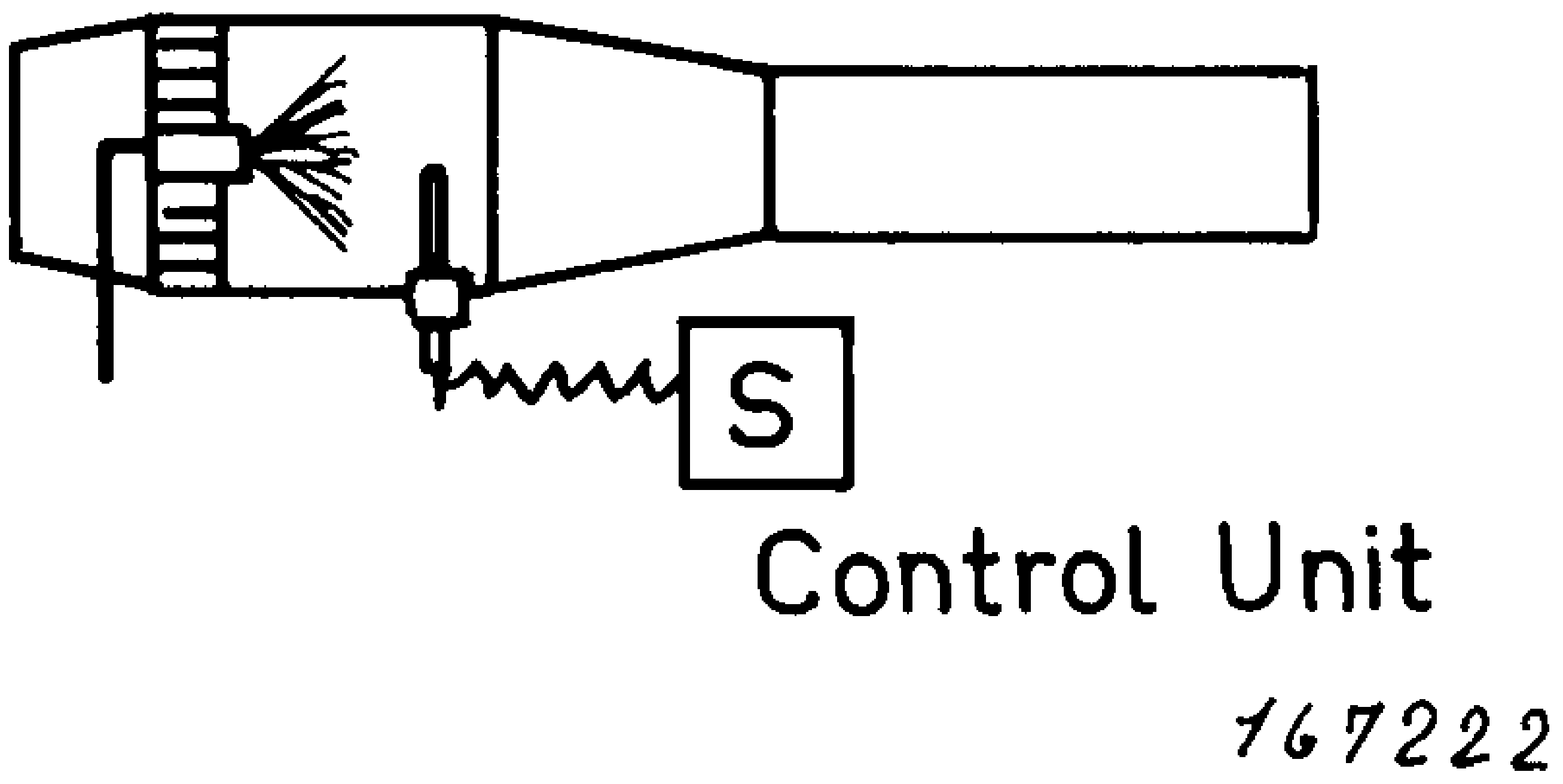


2. By using intermittent fuel injection with a continuously changing time of injection as ignition and combustion cannot take place before sufficient fuel has been supplied in each cycle.

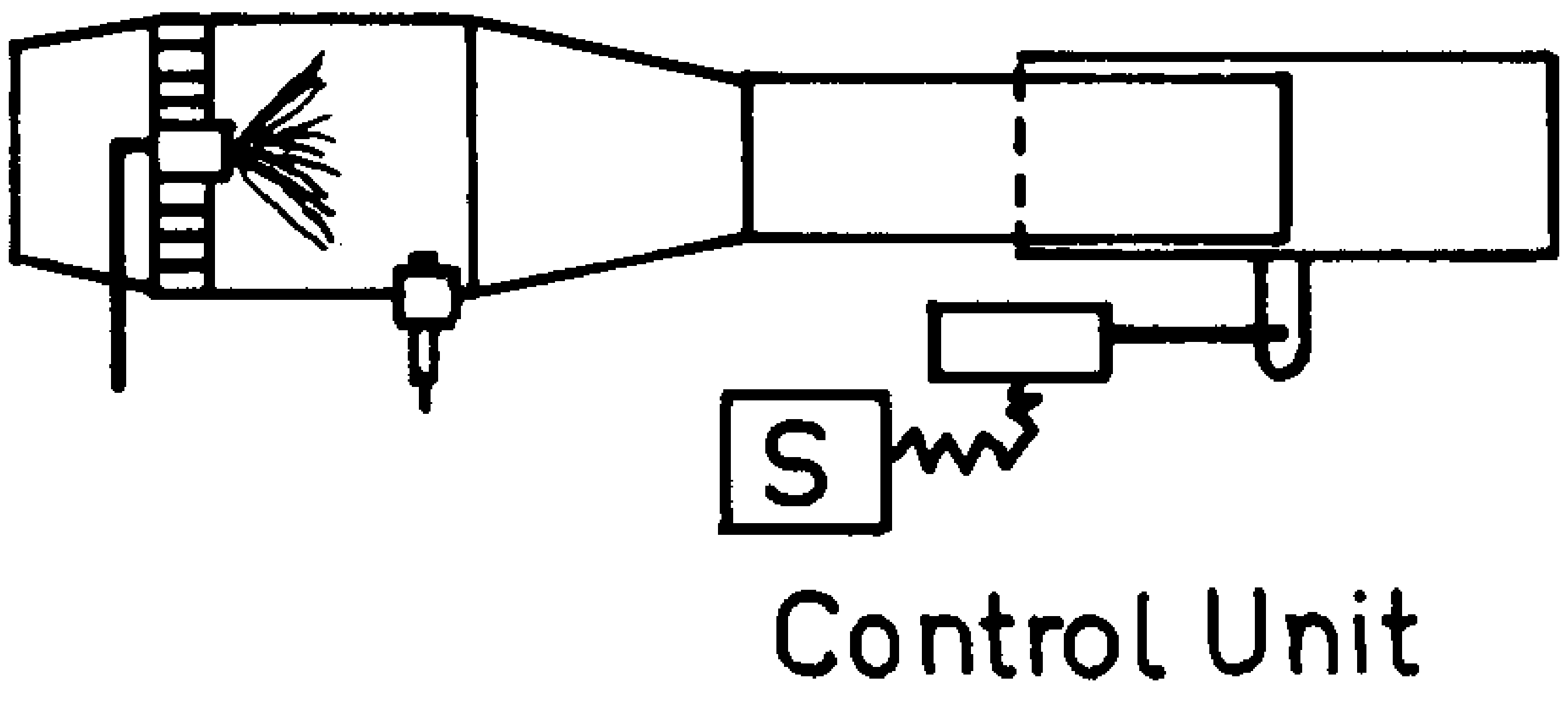
The injection system may be rather complicated, but it will only demand small controlling forces and the obtainable variations should here be rather high.



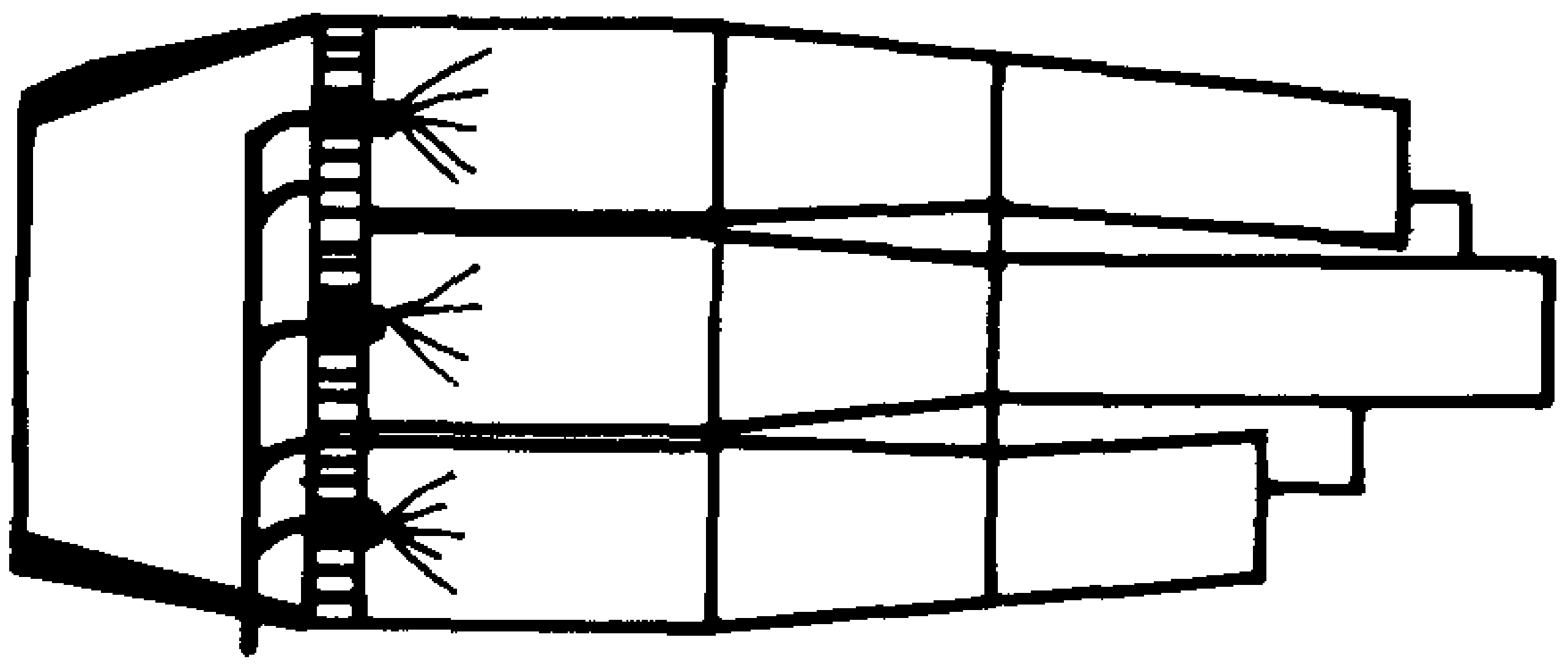
3. By controlling the ignition by a spark plug with a varying interval between ignitions.
   In this construction spontaneous ignition must be avoided by giving the air/fuel mixture a small area of contact with hot areas of the engine or a high velocity at these places so that heating is reduced sufficiently.
   The ignition system may be of a very simple construction and it will only demand small controlling forces and even when the unknown factors around spontaneous ignition are taken into account the obtainable variations can be expected to be high. Common to the above mentioned constructions is that the exhaust frequency is varied by changing the combustion frequency n_f while the natural frequency of the oscillating system is constant, i.e. $\frac{n_f}{n}$ is varied while n is constant.

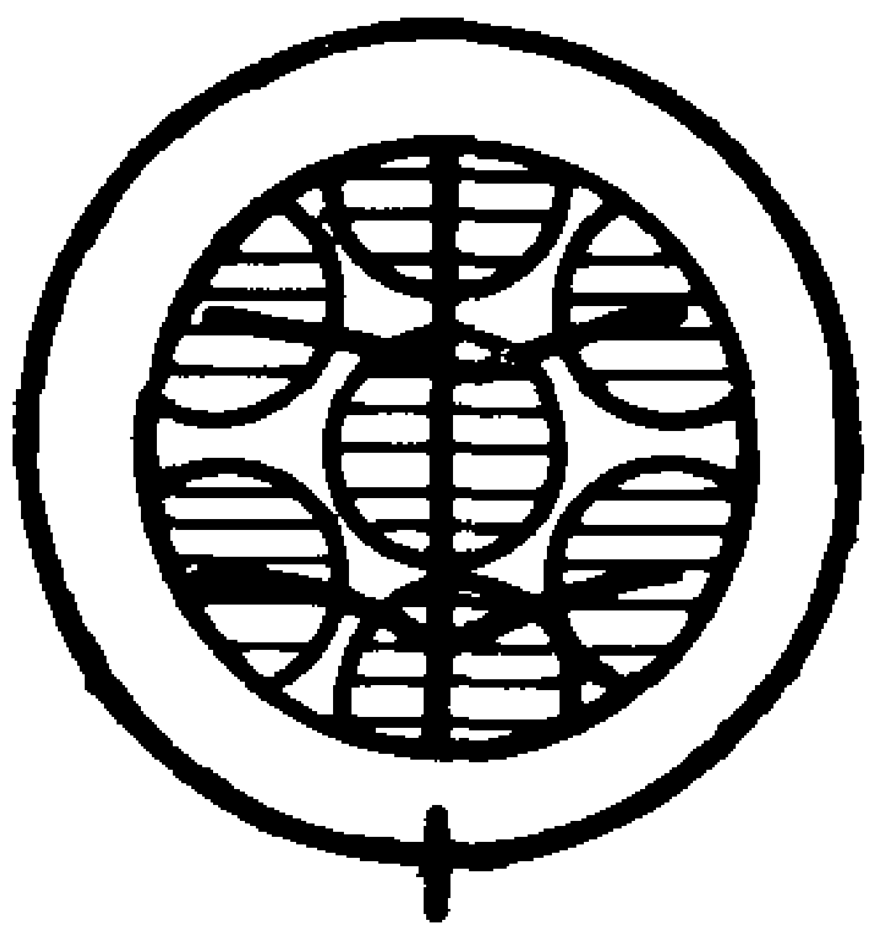


4. A construction where $\frac{n_f}{n}$ is almost constant and n is varied can be made by changing the length of the oscillating gas column by a moveable cylinder sliding on the exhaust nozzle. As this is the only interference that is made, ignition should take place in the same part of the cycle so that $\frac{n_f}{n}$ is constant.
   To move the cylinder with sufficient speed will demand large controlling forces and the system will be quite heavy. The obtainable changes in frequency can, however, be large.



5. Finally a pulse jet with varying exhaust frequency but $\frac{n_f}{n}$ and n constant can be made by matching a number of small pulse jets with different combustion frequencies. The method is simple but the pressure cycles of the different pulse jets may interfere to such an extent that the power is reduced appreciably.





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New Experiments

As his final University project in 1965, the author chose to construct and test a pulse jet engine according to the combined principles of 1 and 2 out-

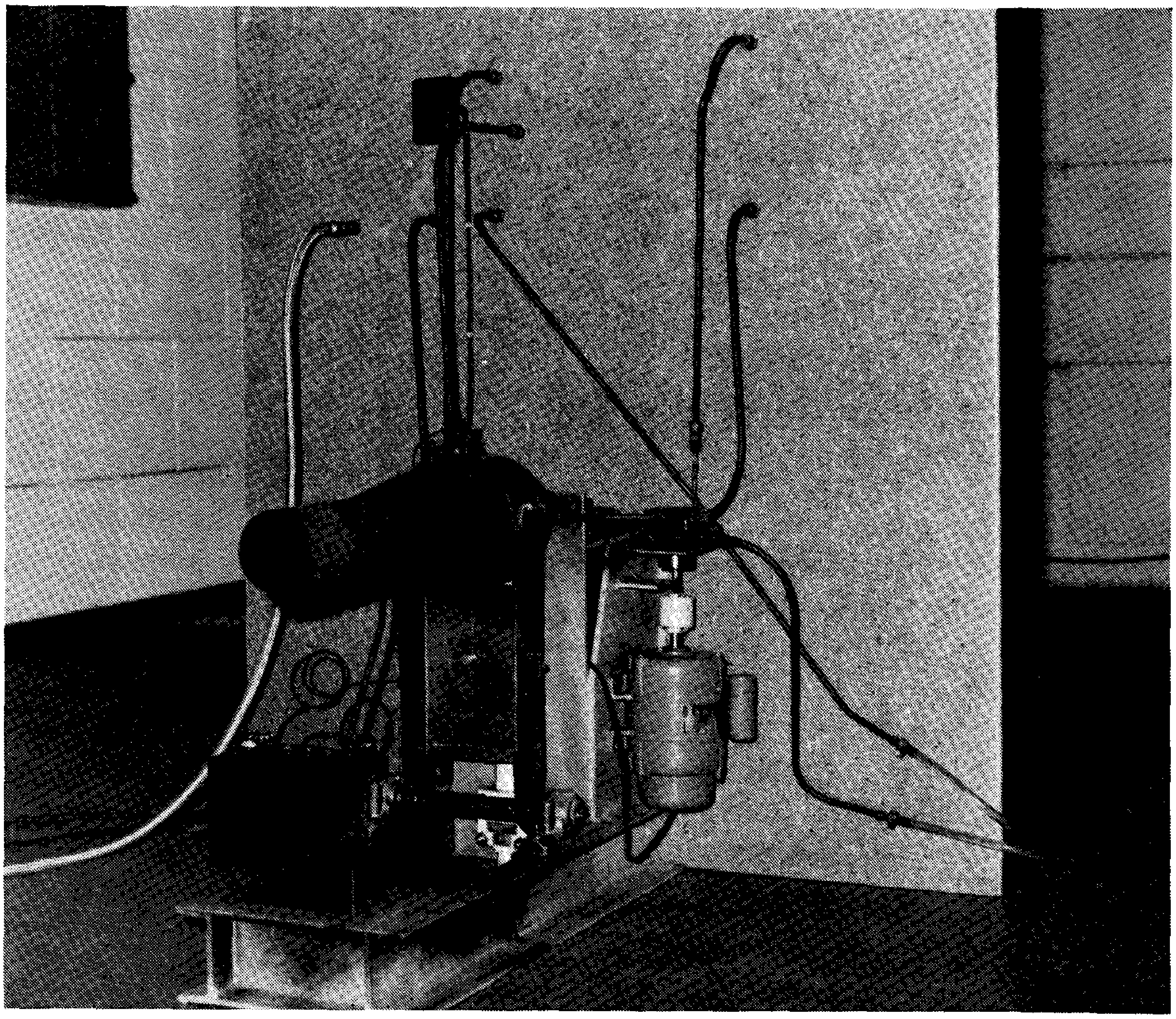


Fig. 7. Photograph of the experimental set-up.

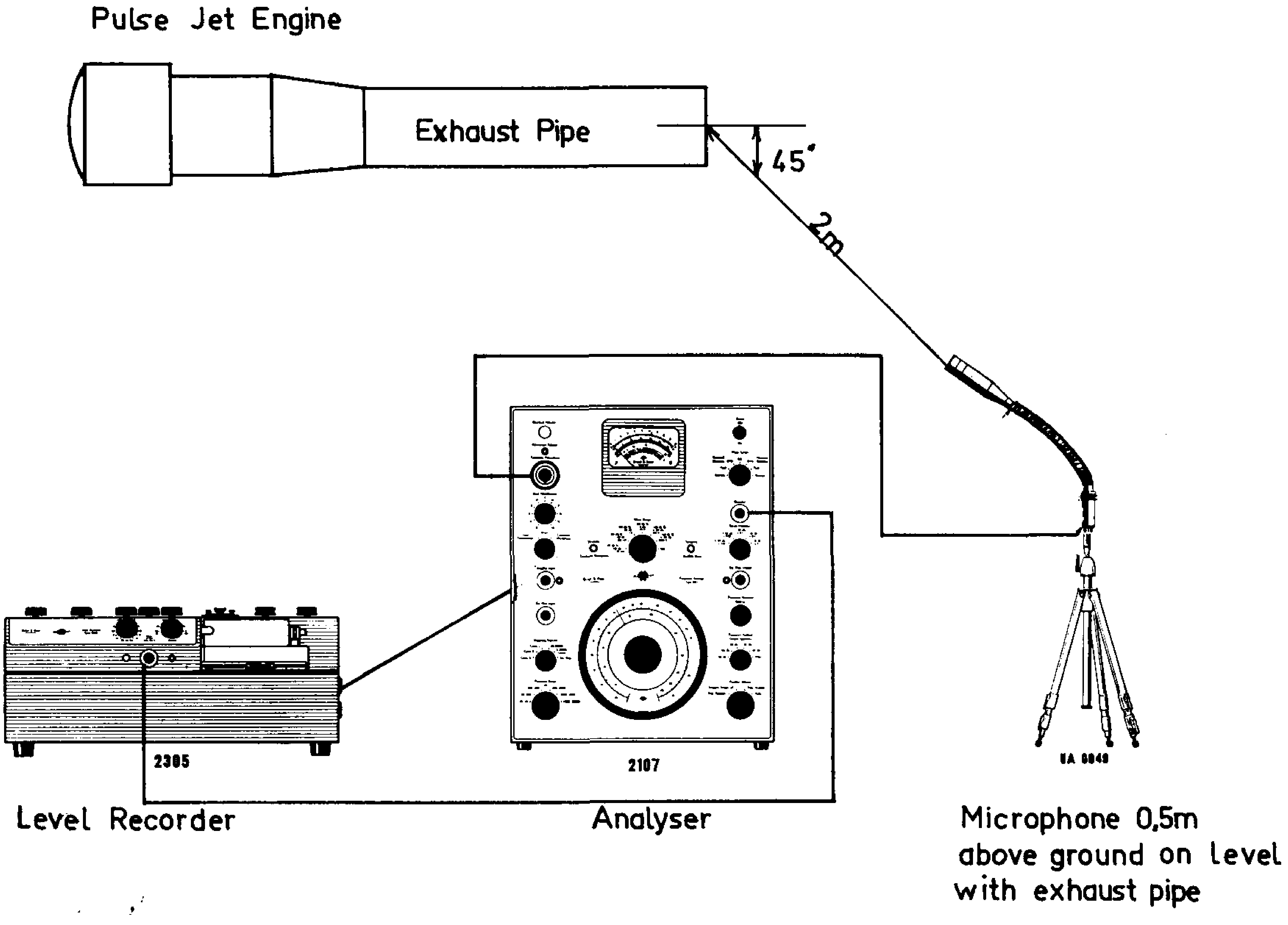


Fig. 8. Noise measurement arrangement.

lined above, that would also function as a normal pulse jet engine when the control system was disconnected. The design work was started in September 1965, construction started in December 1965, test running began in February and the whole work had to be completed by April 1966.
The development of the test stand and the development of the new pulse jet type was very time consuming and was actually far from finished in the short time available but certain important results were found.

a. The engine could function both as a normal pulse jet and as a pulse jet with continuously changing combustion frequencies, the fuel consumption being approx. 40 % lower in the latter case when fuel was injected discontinuously (the actual figure was 1.4 lb/lb thrust/hour).
b. The engine gave quite a few problems with instable combustion but as this was found both when the engine worked as a normal pulse jet and when the pulset jet had continuously varying combustion frequencies, the problems were attributed to the generally under-developed design and not to the variation system.
c. The engine gave a clear indication of being able to produce the desired noise spectrum, see Fig. 9.

A comparison between A and B gives the following results:

I. The maximum intensity of the noise spectrum is decreased 18 dB in B whereas the total intensities are practically identical.

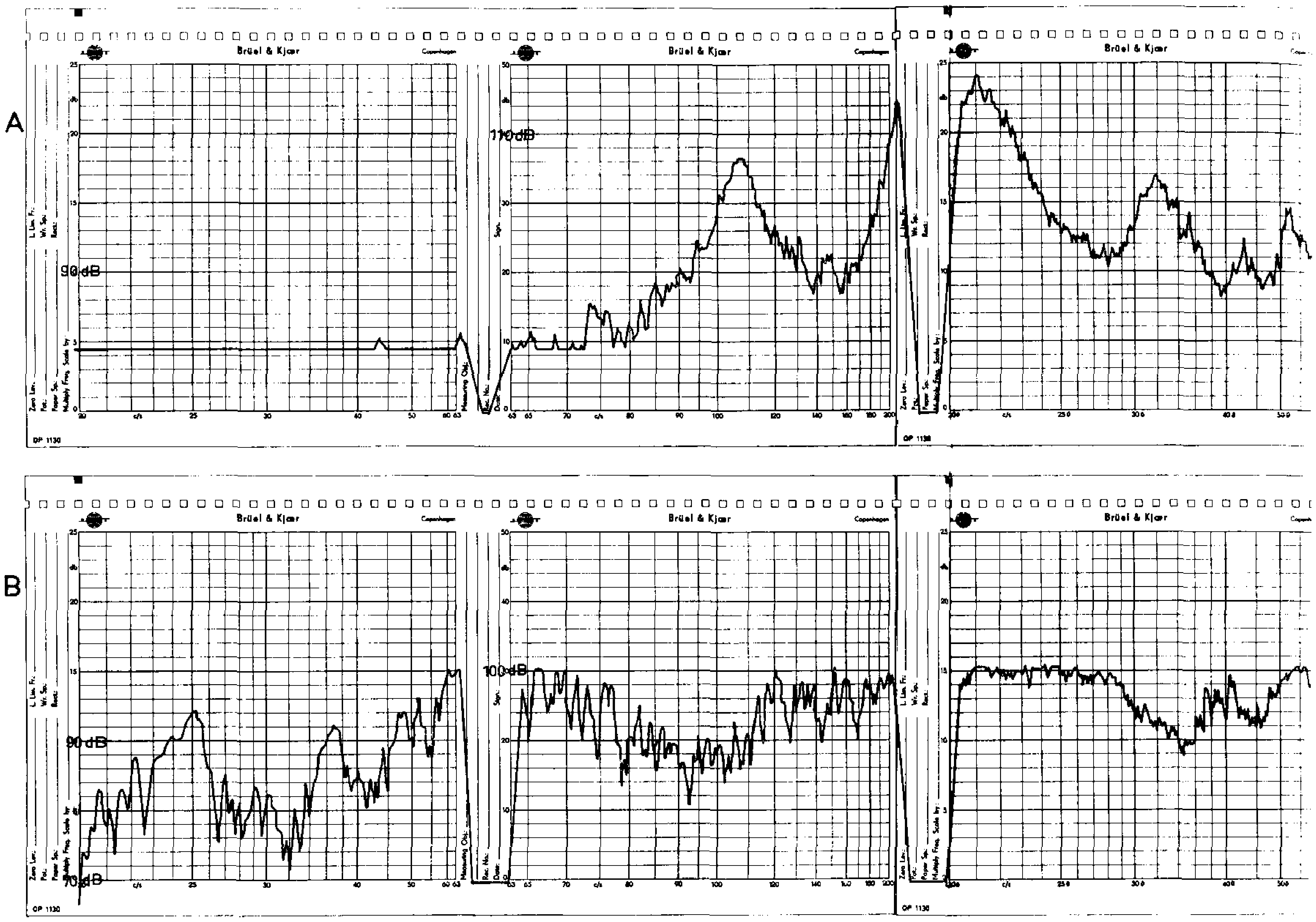


Fig. 9. Noise spectrum of experimental pulse jet. A = working as a normal pulse jet with continuous fuel injection. Total intensity 105 dB Lin. B = Working with intermittent fuel injection, the combustion frequency being changed continuously in the interval 150–270 Hz. Total intensity 109 db Lin.

II. At low frequencies (below 85 Hz) an increased noise level in B is caused partly by interference and partly by mechanical imperfections in the control system. Improvements in this area must be made to level out peaks.

III. Between 80 and 2,000 Hz the levelling of the noise spectrum B is clearly noticeable although further improvement should be sought.

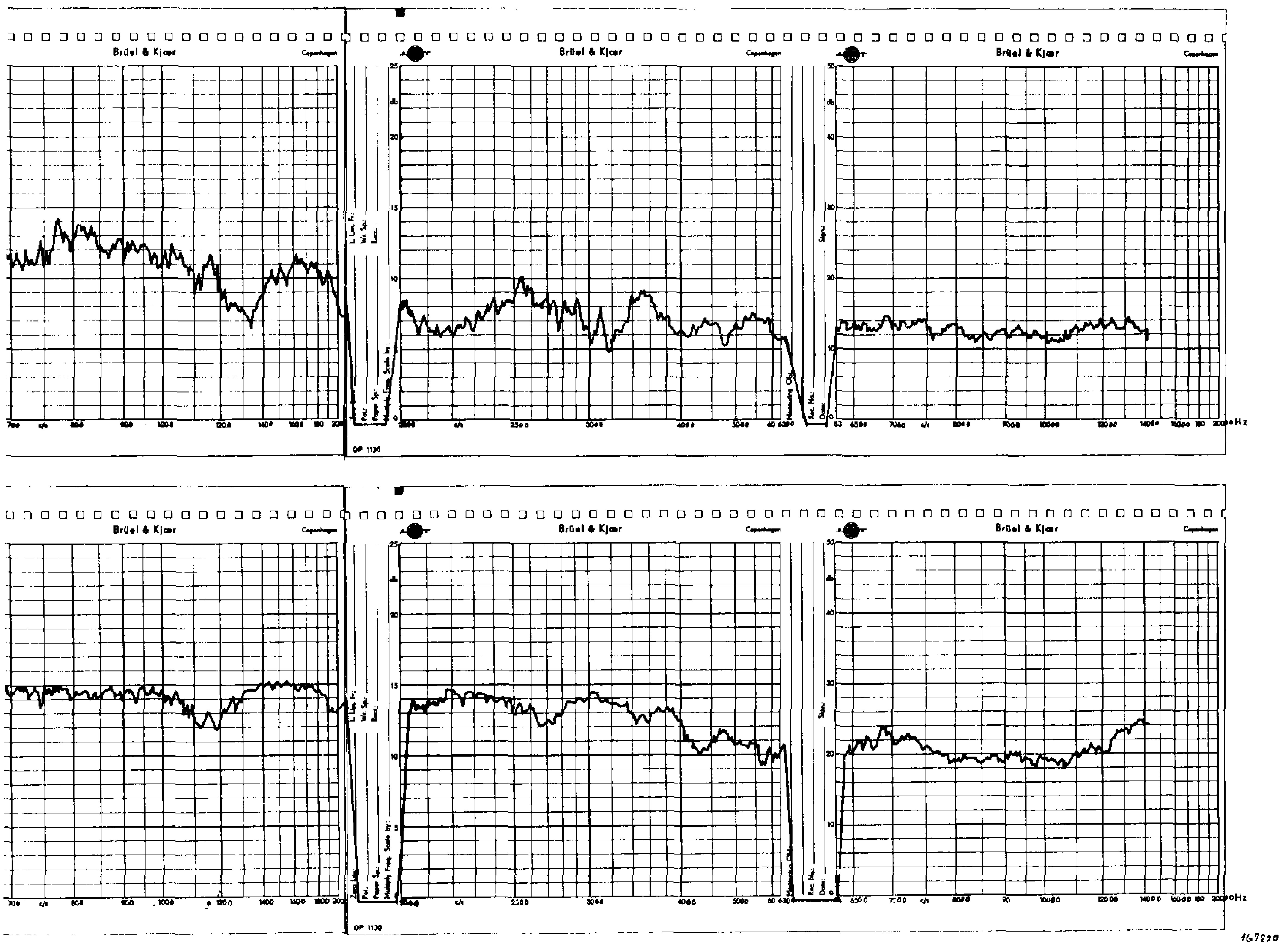
IV. For the higher frequencies, above 2,000 Hz, noise spectrum B is 10 dB above A indicating higher gas velocities and thereby higher thrust with the intermittent fuel injection.

Conclusion

From the above theoretical considerations and practical experiments it seems possible to build a pulse jet with continuously varying combustion frequencies. By improved design and adjustments of the jet the noise spectrum found in the present test (Fig. 9 B) could be further equalized and brought very close to the spectrum mentioned on page 5 whereby the disturbance reduction that was sought would be achieved.

Acknowledgement

The author would like at this point to express his deep appreciation to the



many people that through the years have helped keep this project alive, among which are: Mr. F. R. Drew who caused the start, Mr. C. E. Tharratt who provided the analysis of the basic principles of pulse jets, professor E. Frederiksen, and Mr. A. Andersen of the Technical University of Denmark who at different times made possible the experiments mentioned in this article.

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On the Averaging Time of Level Recorders

by

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and

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ABSTRACT

This article revises and extends the investigations of the effective averaging time of the Level Recorder Type 2305 originally described in the B & K Technical Review no. 1-1961.

After a brief discussion of the concept of effective averaging time two methods used to determine the averaging time of the Level Recorder are described. One of the methods is especially useful in the range of low Recorder writing speeds and utilizes a Statistical Distribution Analyzer Type 4420, while the second method is the same as the one used in the 1961 investigation and results in a direct measure of the standard deviation of the level fluctuations. The latter method is most efficient in the range of high Recorder writing speeds. As both methods can be used with advantage within a certain range of writing speeds double checking of some of the results is possible.

Finally a comparison between the effective averaging time of a standard Precision Sound Level Meter and that resulting from some specific settings of the Level Recorder is made. The main results of the investigation are given in Fig. 5 and in Tables 1 and 2.

SOMMAIRE

Cet article reprend et étend les investigations sur le temps d'intégration efficace de l'enregistreur de niveau type 2305 publiées dans la Technical Review n° 1 de 1961.

Après une brève discussion de la notion de temps d'intégration efficace, on décrit deux méthodes utilisées pour déterminer quel il est pour l'enregistreur de niveau. L'une d'elles est particulièrement utile dans la gamme des faibles vitesses d'inscription et fait appel à l'analyseur de distribution statistique type 4420 tandis que l'autre méthode est celle utilisée lors de l'étude de 1961 et aboutit à la mesure directe de la déviation normale des fluctuations de niveau. La dernière méthode est la plus efficace dans la gamme de vitesses d'inscription élevées. Comme les deux méthodes peuvent être utilisées avec avantage dans une gamme commune de vitesses d'inscription, il est possible d'effectuer un pointage comparatif de certains résultats. Finalement une comparaison entre le temps d'intégration efficace d'un sonomètre de précision normal et celui résultant de certains réglages particuliers de l'enregistreur de niveau est possible. Les résultats principaux de cette étude sont donnés à la figure 5 et aux tables 1 et 2.

ZUSAMMENFASSUNG

Dieser Artikel revidiert und erweitert die Untersuchungsergebnisse über die effektive Integrationszeit des Pegelschreibers Typ 2305, die erstmalig in der Ausgabe Nr. 1/1961 dieser Zeitschrift veröffentlicht wurden.

Nach einer kurzen Diskussion des Begriffes effektive Integrationszeit werden 2 Methoden zur Bestimmung der Integrationszeit von Pegelschreibern beschrieben. Eine dieser Methoden ist besonders für den Bereich niedriger Schreibgeschwindigkeiten geeignet, wobei der Pegelhäufigkeitszähler Typ 4420 verwendet wird. Die andere Methode ist dieselbe wie bei den früheren Untersuchungen. Sie läuft auf eine Direktmessung der Standardabweichung der schwankenden Pegelanzeige hinaus und ist besonders brauchbar für den Bereich hoher Schreibgeschwindigkeiten. Da die Anwendungsbereiche beider Methoden sich bei gewissen Schreibgeschwindigkeiten überschneiden, lassen sich einige Meßergebnsse zweifach überprüfen.

Schließlich werden die effektiven Integrationszeiten eines genormten Schallpegelmessers und eines Pegelschreibers bei einigen bestimmten Einstellungen miteinander verglichen. Die wichtigsten Ergebnisse der Untersuchungen sind in Abb. 5 und in den Tabellen 1 und 2 zusammengestellt.

Introduction.

The effective averaging time of the Level Recorder Type 2305 was discussed in the B & K Technical Review No. 1-1961 and was found to be dependent not only on the settings of the knobs marked WRITING SPEED and LOWER LIMITING FREQUENCY but also on the recording resolution (POTENTIOMETER RANGE) and the amount of pen fluctuations.

Since 1961, however, the Level Recorder has been subject to several improvements and modifications which mainly concern the electronic section. These modifications have slightly altered the performance of the Recorder when recording random phenomena where it is especially desirable to know the value of the effective averaging time in order to be able to calculate the statistical uncertainty of the measurement. Also, all the measurements described in the 1961 investigation were carried out with a 10 dB range potentiometer on the Recorder only.

Due to the above mentioned modifications and the desire to investigate the influence of the range potentiometer upon the averaging time some of the results of the 1961 investigations have been revised and the effective averaging time has been determined as a function of the writing speed of the Level Recorder using three different range potentiometers.

The Concept of Effective Averaging Time.

When measuring a randomly varying signal with gaussian instantaneous amplitude distribution which is stationary, at least during the time of measurement, and the power spectrum of which is flat within a certain frequency band and zero elsewhere it can be shown that the RMS value (standard deviation) of the *energy* level fluctuations relative to the mean value is given by:

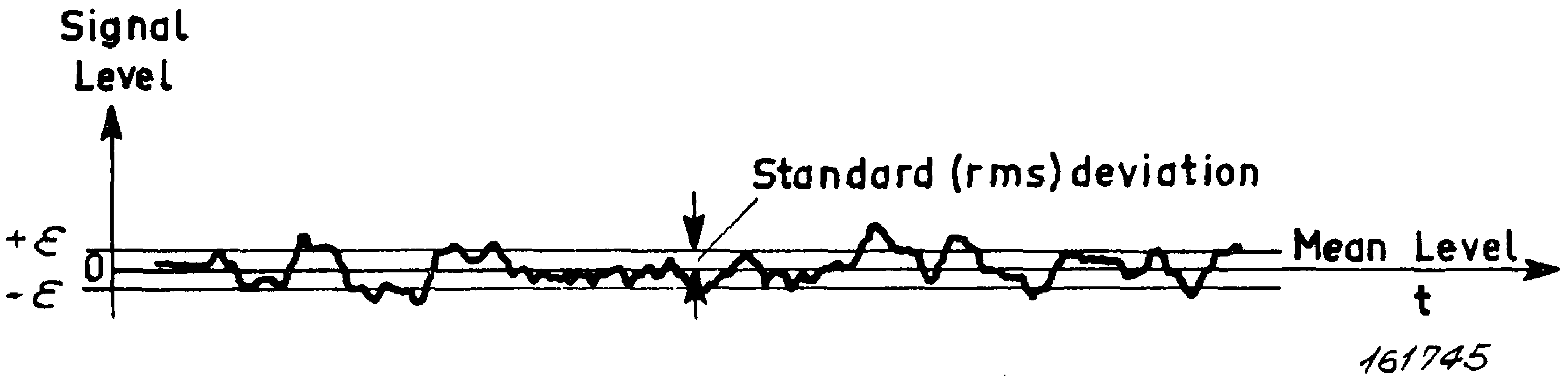

Fig. 1. Typical fluctuations of the RMS-values of a band of random noise around the true RMS value. The relative standard deviation (ε_A) of the fluctuations are also indicated.

$$\varepsilon_E = \frac{1}{\sqrt{BT}} \qquad (1)$$

where B is the bandwidth of the signal and T is the exact mathematical averaging time which should be chosen so that $BT \gg 1$.

If the exact mathematical averaging process is substituted by a continuous averaging process, as is the case when for instance an RC-filter is used in the rectifier circuit for averaging, the relative *energy* level fluctuations will be given by:

$$\varepsilon_E = \frac{1}{\sqrt{2\ BRC}} \tag{2}$$

where RC is the time constant of the averaging circuit.

By comparing (1) and (2) it is seen that in this case the effective averaging time $T = 2\ RC$. The relative *amplitude* level fluctuations are, for small values of ε_E, given by their RMS value as

$$\varepsilon_A \approx \frac{1}{2}\,\varepsilon_E \tag{3}$$

and from (1) it is then found that

$$T_a = \frac{1}{B\ \varepsilon_E^2} \approx \frac{1}{4\ B\ \varepsilon_A^2} \tag{4}$$

When the RMS value of the relative *amplitude* level fluctuations, ε_A, and the effective bandwidth, B*), of the signal are known it is therefore possible to find T_a for different averaging circuits.

Measurement of the Effective Averaging Time of the Level Recorder Type 2305.
In investigating the effective averaging time of the Level Recorder Type 2305 two methods of measurement have been employed, one at writing speeds below 250 mm/sec and one at writing speeds above 100 mm/sec so that a part of the entire range 2–1ooo mm/sec (50 mm paper width) has been double-checked. The three different range potentiometers used on the Level Recorder were: a logarithmic 10 dB, a linear 10–110 mV and a logarithmic 50 dB potentiometer. The corresponding settings of the POTENTIOMETER RANGE control knob (recording resolution) were "10", "32", and "50", i.e. the positions recommended for normal use of the Recorder with the three potentiometers inserted. (Actually the position "32" for the linear potentiometer is slightly higher than the recommended value but was chosen in order to ensure stable operation of the Recorder even at the highest writing speeds). The LOWER LIMITING FREQUENCY control knob was set for stable operating of the Recorder at each writing speed according to the Instruction Book (see Fig. 5), and the RECTIFIER RESPONSE was set to "RMS".

During all measurements the signal level was adjusted so that the mean value of the fluctuations was held at approximately half the paper width (25 mm). Fig. 2 shows the set-up used for measurements of ε_A at writing speeds below 250 mm/sec. White gaussian noise (20–20ooo Hz) from a Noise Generator was filtered by means of 1/3 octave filters in a Spectrometer and fed to the Level Recorder.

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*) The effective bandwidth of a filter can be found as $B = \frac{\int_0^\infty A^2(f)\,df}{A_{max}^2}$ where A (f) is the frequency response and A_{max} the maximum voltage gain of the filter. For a Spectrometer Type 2112 the effective bandwidth $B \sim 1.1\ B_{\div 3\,dB}$.

Mounted on the writing arm of the Recorder is a special slider which effects contact to a set of 12 level channels. This arrangement is then connected to a Statistical Distribution Analyzer containing 12 digital display channels with adjustable count rate. Each channel will register counts as long as the slider on the Recorder remains in contact with the corresponding channel contact. After a certain length of time, the number of counts displayed in the different channels will show the average instantaneous level distribution of the signal.

To be able to easily determine the mean value and the RMS value of the pen deflections from the number of counts, probability graph-paper was used (Fig. 3), plotting the number of counts cumulatively from the 12 counters. If the Level distribution is gaussian a straight line will be plotted and the relative amplitude fluctuation ε_A is determined as the ratio between the two.

During all measurements the count rate was held at maximum (10 counts per second) which has shown to be sufficient for writing speeds up to 250 mm/sec. The total number of counts was 10^4 per measurement.

In order to obtain a detailed impression of the level distribution both at large and small values of ε_A the spacing of the 12 level contacts was made variable in three steps: 4 mm, 1 mm and 0.5 mm pen deflection per contact. In this way all the counters were utilized even at the smallest values of ε_A. The 1 mm and 0.5 mm spacings were obtained by using a set of lamellae from a Level Recorder potentiometer, connecting 4 and 2 contacts, respectively, in parallel per counter channel.

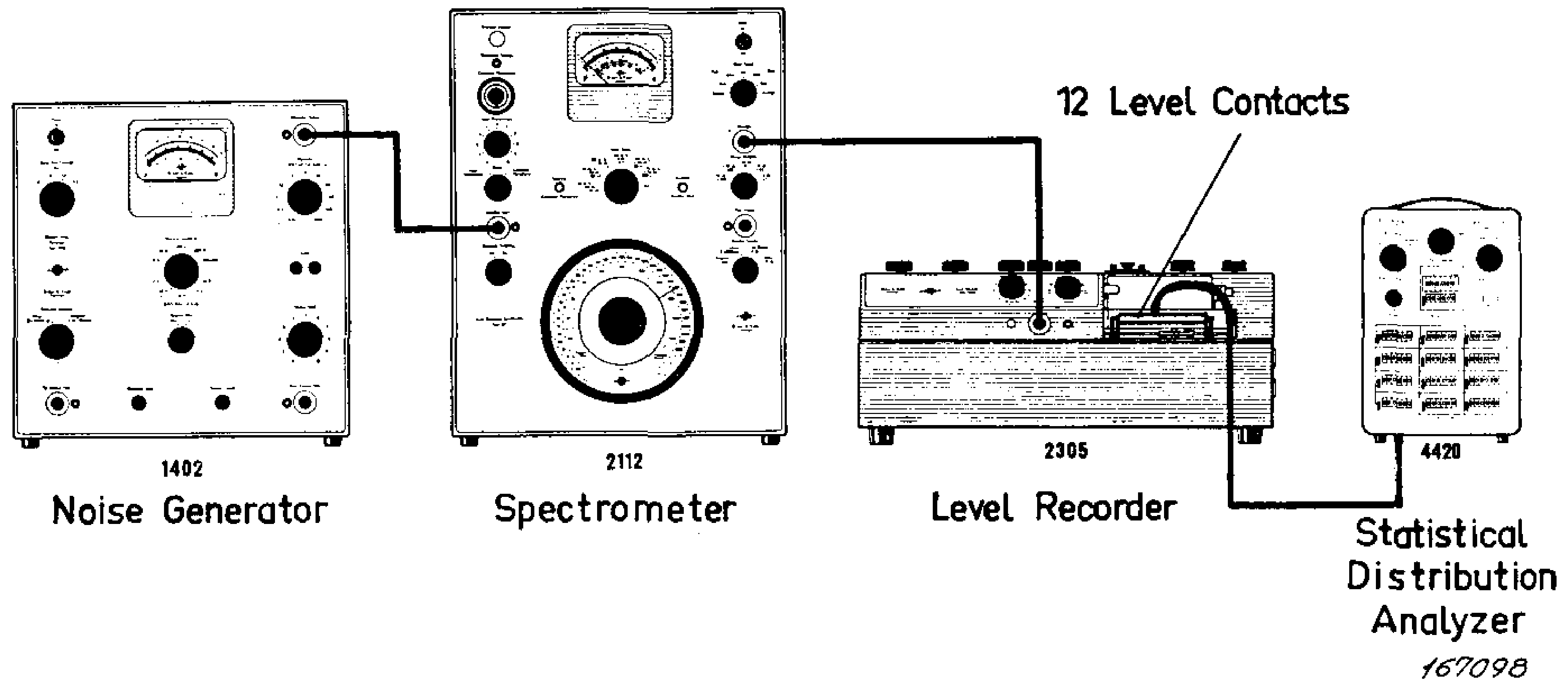
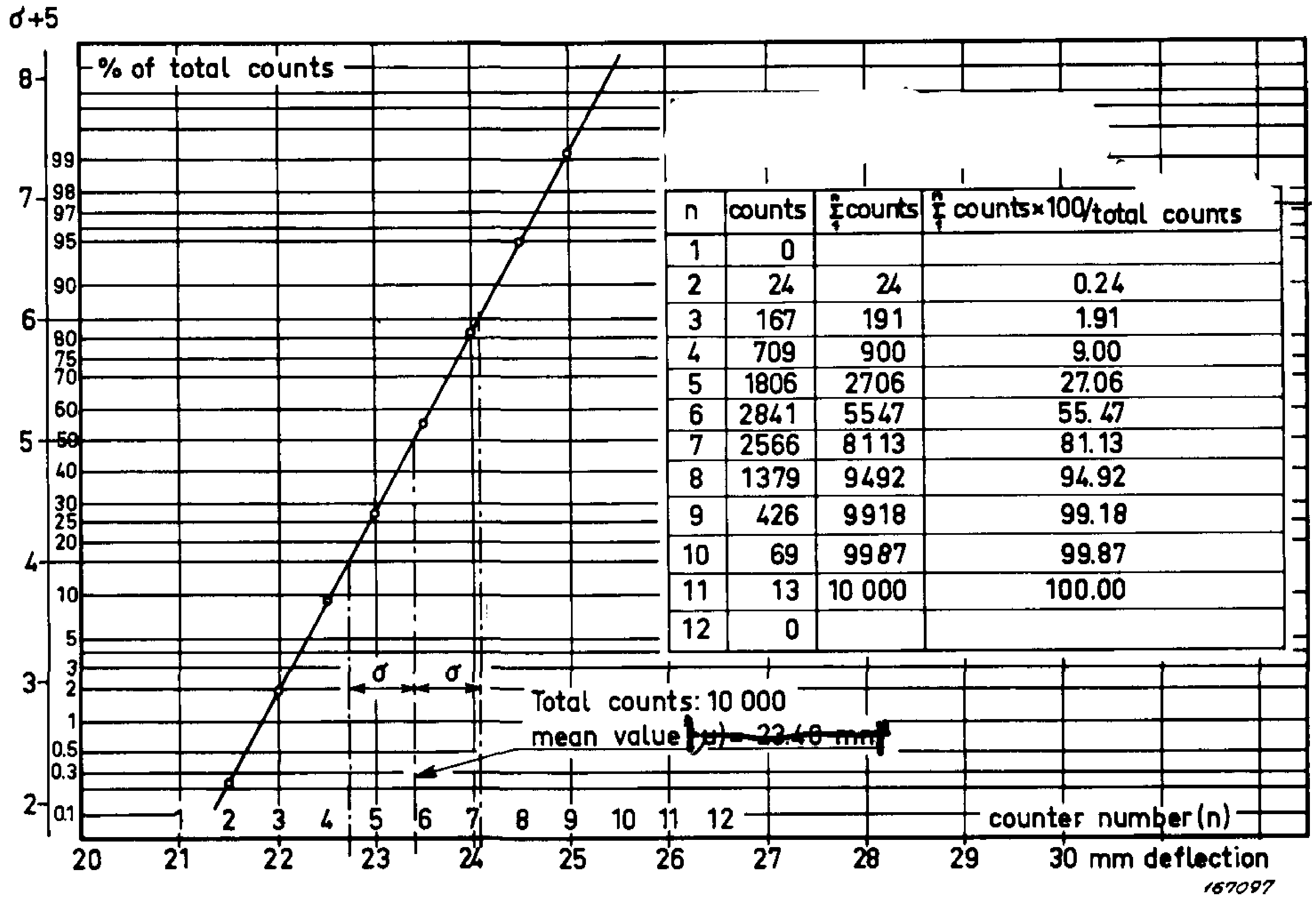


Fig. 2. Set-up for fluctuation measurements at writing speeds below 250 mm/sec.

Fig. 4 shows the set-up used for measurements of ε_A at writing speeds above 100 mm/sec. It differs from Fig. 2 in the determination of the fluctuations, the measuring device this time being an Analog Voltage Readout unit that is simply a wirewound linear potentiometer, the track of which is mounted to the Level Recorder's writing arm.

If a DC voltage is supplied to this potentiometer the output from the moving arm will be a certain DC voltage expressing the mean value of the pen deflections plus an AC voltage, the RMS value of which indicates the RMS value of the fluctuations. The AC voltage is monitored by means of a Random Noise



n	counts	$\sum_1^n$ counts	$\sum_1^n$ counts×100/total counts
1	0		
2	24	24	0.24
3	167	191	1.91
4	709	900	9.00
5	1806	2706	27.06
6	2841	5547	55.47
7	2566	8113	81.13
8	1379	9492	94.92
9	426	9918	99.18
10	69	9987	99.87
11	13	10 000	100.00
12	0		

Fig. 3. Example of determination of mean and standard deviation from probability graph-paper.

Voltmeter, i.e. an RMS voltmeter having a very large time-constant, and ε_A is found as the ratio between the AC and DC voltages.

Fig. 5 gives the results of the measurements. The effective averaging time is here determined as a function of the writing speed and for two values of ε_A: 2.5 % which is typically used in practice and 7.5 %. The corresponding RMS values of the relative energy fluctuations are 5 % and 15 % respectively.

As can be seen from Fig. 5 the effective averaging time increases with increasing fluctuation for constant writing speed (decreasing signal bandwidth B). This tendency is most pronounced at the lower writing speeds where it may be partly reduced by using higher recording resolution of the Level Recorder. The very often employed 50 dB potentiometer shows, however, no such tendency.

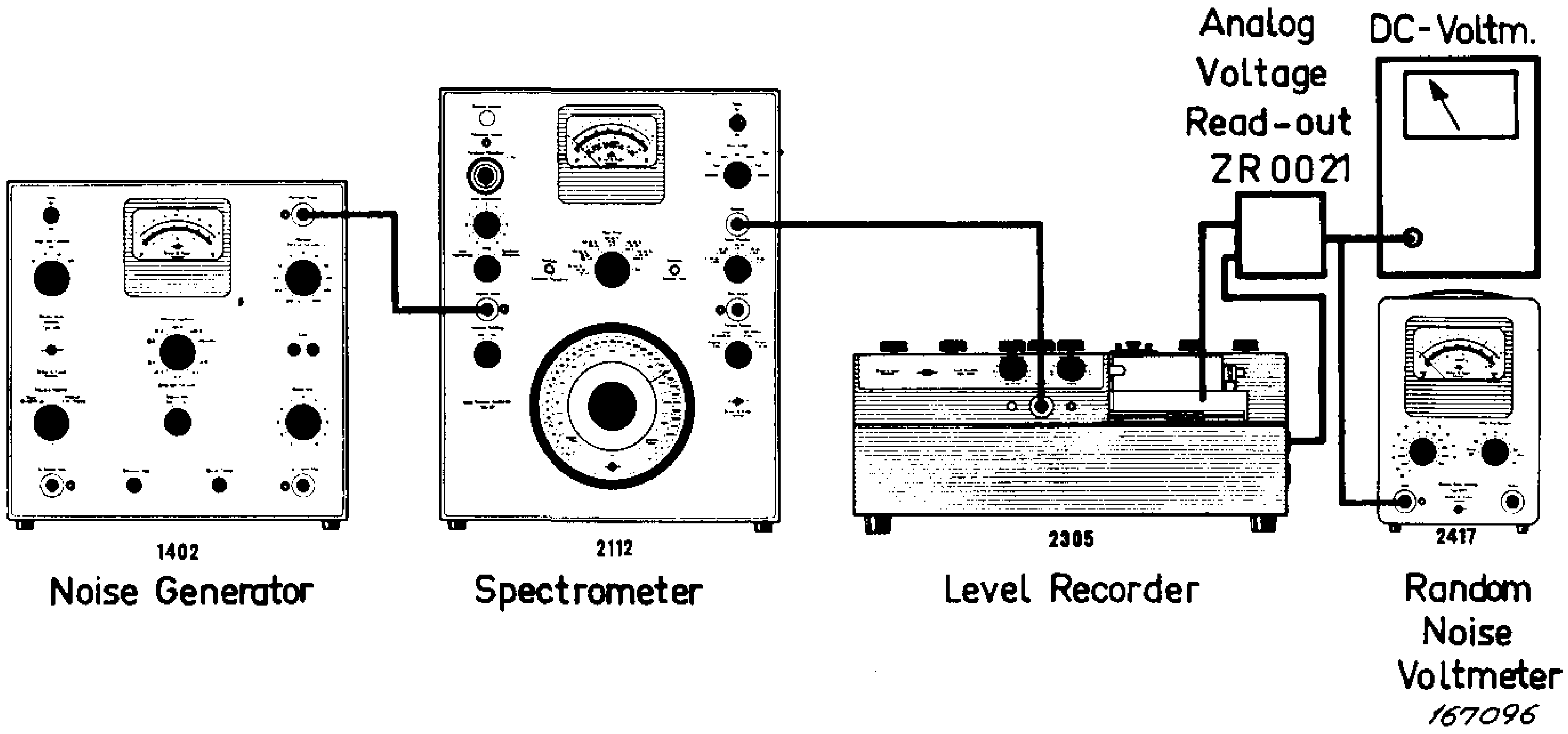


Fig. 4. Set-up for fluctuation measurements at writing speeds above 100 mm/sec.

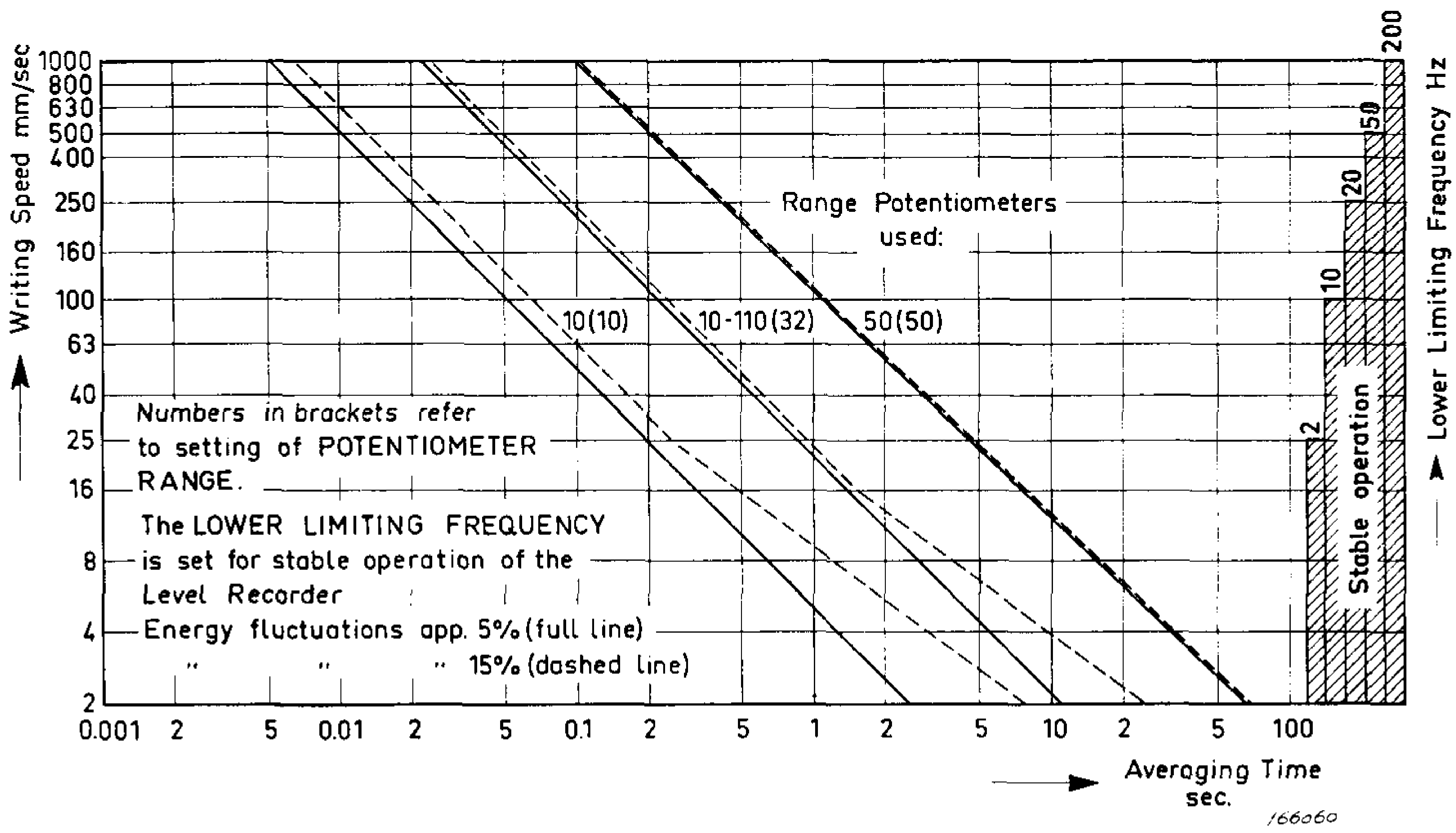


Fig. 5. The effective averaging time of the Level Recorder as a function of the writing speed.
Potentiometers used:
10 dB logarithmic,
10–110 mV linear and
50 dB logarithmic.
The lines drawn in the graph represent average values.

Comparison Between the Level Recorder and the Precision Sound Level Meter. In order to allow comparisons to be made between the effective averaging time of the Level Recorder and that required by the I.E.C. for sound level measurements, the averaging times of the Precision Sound Level Meter Type 2203, both when switched to position "Fast" and to position "Slow" have also been measured.

This was made by means of the set-up shown in Fig. 6 where a 10 kHz amplitude-modulated signal was fed to the instrument under test. The modulation signal was taken from a low frequency sine-wave generator, the frequency of which was variable, and the peak to peak meter pointer fluctuation was measured as a function of the modulation frequency. Curves were then obtained as illustrated by the examples shown in Fig. 7. In Fig. 7a two of the most common types of responses are shown, one being equal to the response of an integrating RC-circuit (− 6 dB/oct. end slope) and the other equal to the response of a critically damped LRC-circuit (− 12 dB/oct. end slope). By comparing equations (1) and (2) on p. 17/18 it is seen that the effective averaging time for an RC-type meter circuit is:

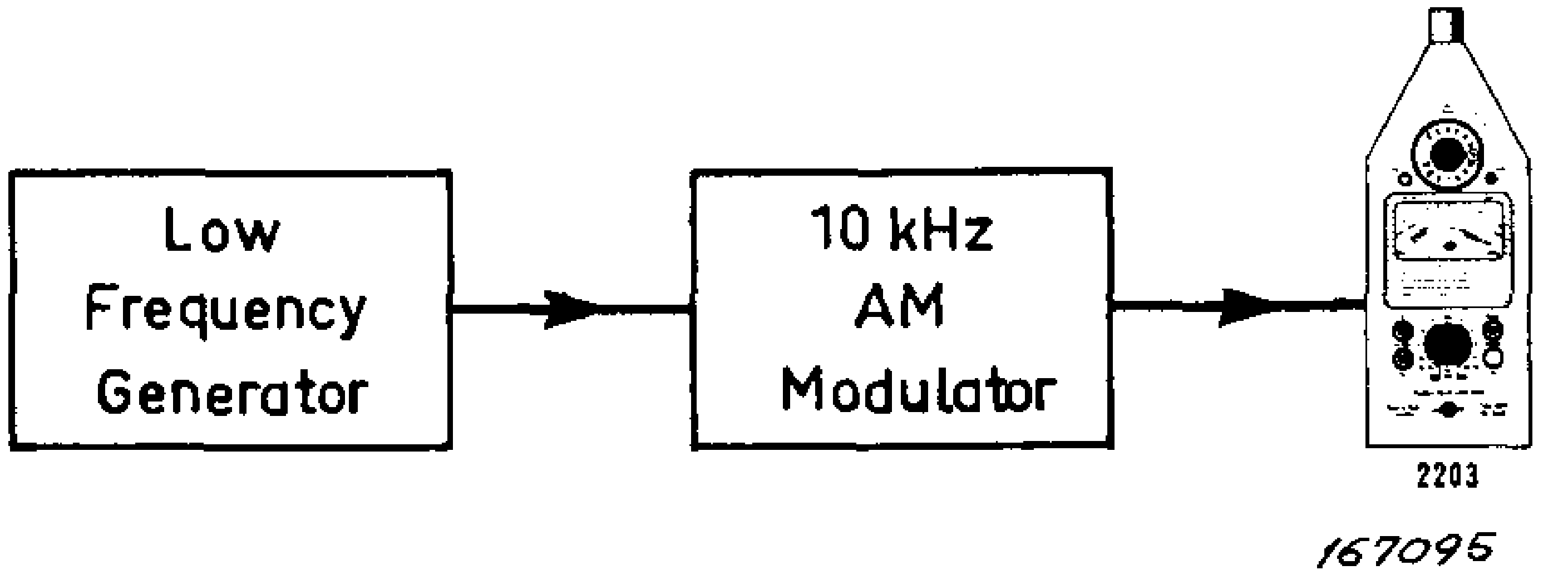


Fig. 6. Measuring arrangement used to determine the frequency response of the instrument meter of the Precision Sound Level Meter Type 2203.

$$T_a = 2\,RC = \frac{1}{\pi f_{\div 3\,dB}} \qquad (5)$$

i.e. T_a can in such cases be calculated from the 3 dB upper limiting frequency of the RC response curve of Fig. 7a.

In a similar way it can be found that for the LRC-type meter circuit

$$T_a = \frac{2}{\pi f_{\div 6\,dB}} \qquad (6)$$

where $f_{\div 6\,dB}$ is the 6 dB upper limiting frequency.

The averaging times of the Precision Sound Level Meter were found to be (Fig. 7b and formula (6)):

Table 1.

	Type 2203	
	Fast	Slow
T_a sec	0.27	1.03

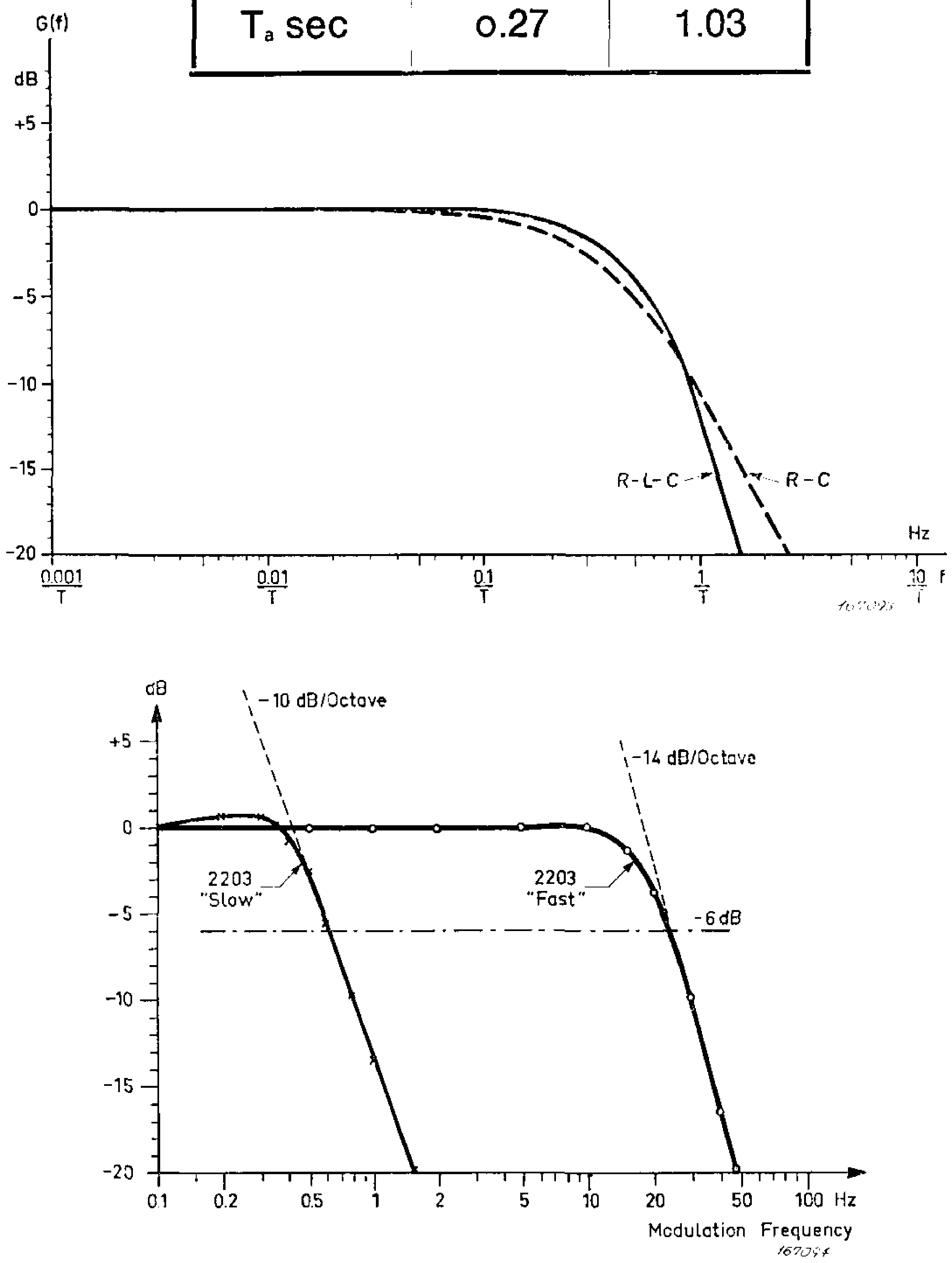


Fig. 7. Typical frequency responses of instrument meters.

a) Theoretical responses for R–C (or R–L) and critically damped R–L–C averaging systems.

b) Measured responses of the instrument meter in Type 2203 both for position "Fast" and for position "Slow".

By comparing these values with the curves given in Fig. 5 the following table can be constructed:

Table 2.

Potentiometer used	2203 Fast	Slow	Writing speed in mm/sec and Lower Limiting Frequency in Hz:
50 dB	400	100	W.S.
logarithmic	50	10	L.L.F.
10–110 mV	100	25	W.S.
linear	10	2	L.L.F.

To check whether these results were consistent with the practical measurement of a randomly fluctuating signal bands of random noise were supplied both to the Precision Sound Level Meter and to the Level Recorder. A comparison was then made between the visually determined relative peak-to-peak deflections of the Sound Level Meter pointer and the pen fluctuations on the paper-recording obtained by means of the Level Recorder.

As the dynamics of the indicating mechanisms are very different for the two instruments some differences were to be expected. However, generally speaking the correlation was quite good, see Table 3.

Table 3.

Potentiometer used	2203 Fast	Slow	Max. rel. peak to peak deflection of meter and Level Recorder pen
50 dB	12 %	16.8 %	Meter
logarithmic*)	11.2 %	19.2 %	Pen
10–110 mV	7.2 %	13.2 %	Meter
linear	7 %	13.7 %	Pen

Finally, the Level Recorder was subjected to the test specified by the I E C for standard sound level meters. This test requires that:

"The sound level meter as a whole shall possess the following dynamic characteristic, which shall be designated as *Fast.*

If a pulse of sinusoidal signal having a frequency of 1000 Hz (c/s) and duration of 0.2 s. is applied, the maximum reading shall be ± 1 dB less than the reading for a steady signal of the same frequency and amplitude.

If a sinusoidal signal at any frequency between 100 and 12500 Hz (c/s) is suddenly applied and thereafter held constant, the maximum reading shall exceed the final steady reading by 0.6 ± 0.5 dB.

The sound level meter may also be provided with the following dynamic characteristic, which may be designated as *Slow.*

If a pulse of sinusoidal signal having a frequency 1000 Hz (c/s) and duration of 0.5 s. is applied the maximum reading shall be 4 ± 1 dB less than the reading for a steady signal of the same frequency and amplitude.

If a sinusoidal signal at any frequency between 100 and 12500 Hz (c/s), is suddenly applied and thereafter held constant, the maximum reading shall exceed the final steady reading by $0.6^{+1}_{-0.5}$ dB."

From the tests it was found that the "standard" settings of the Level Recorder which produced the same averaging time with regard to random noise measurements as those measured on the Precision Sound Level Meter Type 2203 did *not* fulfill the above requirements with regard to suddenly applied signals and pulses. Again this is not surprising considering the difference in indicating mechanism between the Level Recorder and the Sound Level Meter.

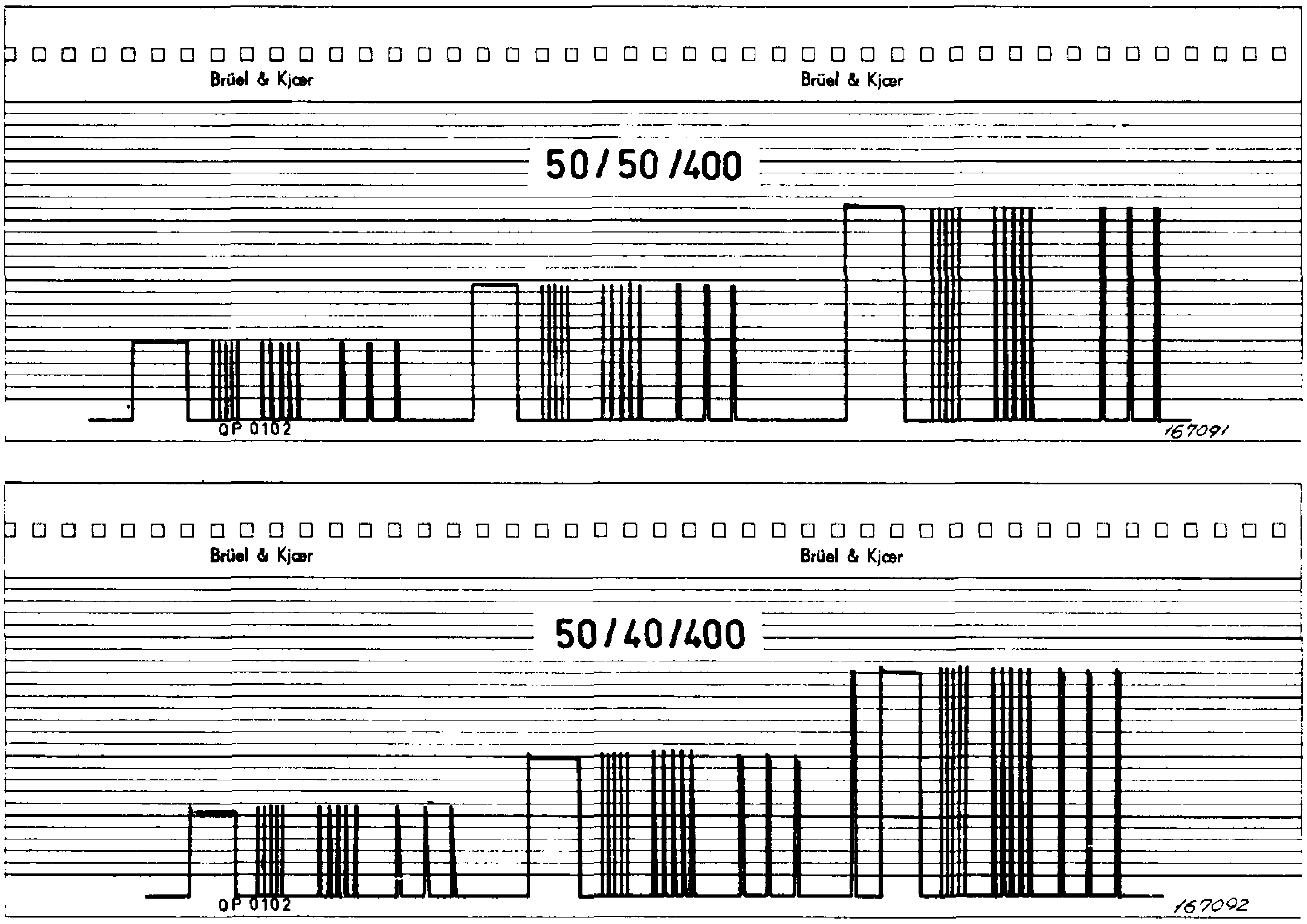


Fig. 8. Examples of the responses of the Level Recorder to suddenly applied signals and tone pulses of different amplitudes.

On the other hand, it was found that when the Recorder is supplied with a 50 dB range potentiometer the requirements laid down by the IEC with respect to the *Fast* characteristic could be fulfilled by reducing the setting of the POTENTIOMETER RANGE switch to "40" instead of the originally stated value of "50", this making the Recorder slightly "unstable". Fig. 8 shows some results of the measurements indicating the response of the Recorder to suddenly applied signals and pulses under the above described conditions.

The reduction in the setting of the POTENTIOMETER RANGE switch corresponds to a decrease in effective averaging time for random noise signals of around 35 %.

Now, other settings of the Recorder control knobs can also be found which give the writing system dynamic properties fulfilling the *Fast* requirements of the IEC, see Fig. 9. A number of these knob settings have therefore been further investigated in order to find a setting which fulfills both the IEC requirements to *Fast and* gives the same effective averaging time for random noise signals as does a "normal" sound level meter. As a result of these investigations an example of such settings is:

WRITING SPEED: 250 mm/sec
POTENTIOMETER RANGE: 32
LOWER LIMITING FREQUENCY: 20 Hz
(50 dB range potentiometer)

In Fig. 10 the three settings of the Recorder control knobs, a, b, c (see Table 4) have been compared both with respect to the Recorder response to steady signals, to 200 msec. pulse (IEC), and to random noise measurements.

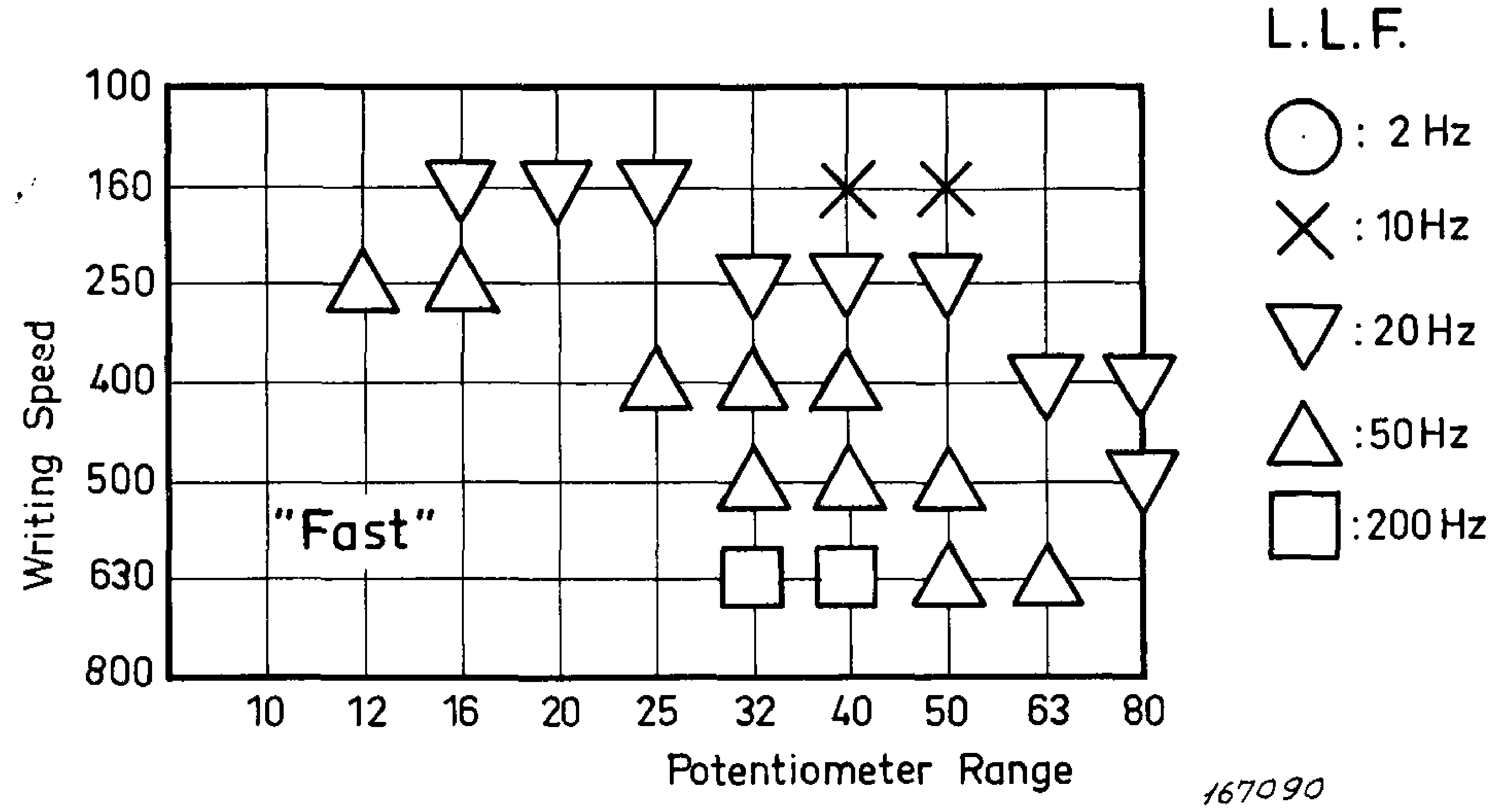


Fig. 9. Chart showing different settings of the Level Recorder control knobs which produce dynamic responses in accordance with the requirements laid down by the IEC ("Fast").

It should also be mentioned that the recording paper width used also slightly influences the dynamic properties of the Recorder, especially with respect to pulses. This is due partly to the mechanical "gearing" introduced in changing from 50 mm recording width to 100 mm recording width, and partly to a change in friction effect between the writing pen and the paper. Also a change from ink recording to wax-paper recording has some effect, although both of the effects mentioned are of little practical significance.

In trying to relate the IEC requirements to *Slow* with some settings of the Level Recorder control knobs no setting could in this case be found which covered the complete dynamic range of the 50 dB range potentiometer.

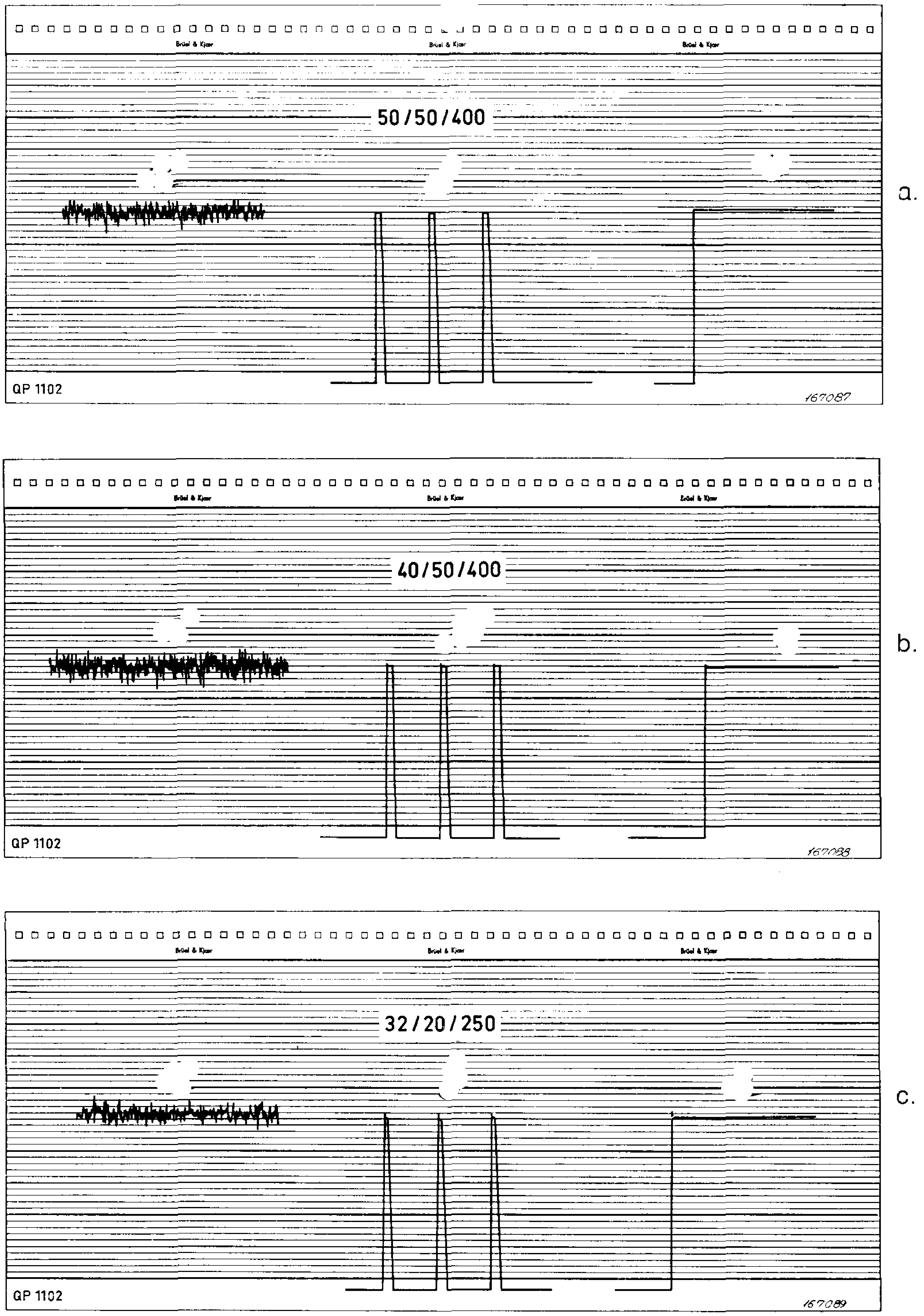


Fig. 10. Comparison of the responses of three different settings of the Recorder control knobs.

a) Response to a band of random noise.

b) Response to a 200 msec pulse.

c) Response to a suddenly applied steady signal of the same magnitude as that used to produce b).

On the other hand, it is felt that in most noise measurement situations the effective averaging time, as defined in the beginning of this article, is of considerably more practical interest than the response of the dynamic system in question to suddenly applied signals and pulses. It is therefore, in general recommended to adjust the Level Recorder according to the curves shown in Fig. 5 (or to the figures given in Table 2) rather than trying to relate its transient response to some given impulse criteria, especially if the two requirements give conflicting settings.

Table 4.

	1	2	3
WRITING SPEED	400	400	250
POTENTIOMETER RANGE	50	40	32
LOWER LIMITING FREQUENCY	50	50	20

Reference.

BROCH, J. T. and WAHRMAN, C. G.:	Effective Averaging Time of the Level Recorder Type 2305. Brüel & Kjær Technical Review No. 1-1961.

Brief Communications

Noise Measurements on Household Appliances

By

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In the following a measurement method is proposed by means of which comparison measurements can be made of the noise produced by household appliances and similar devices.

General

The total audible sound radiated from a noise source may be described by a single number which in general will depend upon the sound power produced by the source.

When such a number is to be determined from measurements carried out with the noise source placed in an acoustically free field the sound radiated in each direction has to be measured and added on an energy level basis. Acoustically free field conditions can be obtained in a socalled "anechoic" chamber. However, the construction of such a chamber requires considerable capital investment, and the large number of measurements and computations necessary to produce the desired single "noise number" makes the method very time consuming and expensive.

If, on the other hand, a reverberation room is used for the measurements instead of an anechoic chamber, the desired "noise number" can be obtained in a much simpler way. In a good reverberation room the average noise intensity will depend only upon the difference between the sound energy radiated by the source and that absorbed by the room boundaries. The sound absorption of the boundaries may, furthermore, be described by means of an equivalent 100 % absorbing area. Thus, by comparing the different equivalent 100 % absorbing areas, A, of different rooms it is possible to estimate the level difference in sound intensity which one and the same noise source will produce in these rooms:

$$\Delta L = 10 \log_{10}\left(\frac{A}{A_0}\right)$$

Unfortunately this level difference is often strongly dependent upon frequency, even when the rooms have been designed especially as reverberation rooms. From the above can be seen that the same average sound intensity, and thus also the same measuring results, may be expected if the equivalent 100 % absorbing area is the same in two different measuring rooms. As the natural sound absorption in a room can be increased artificially by simple means a large number of rooms can be adjusted to have the same equivalent sound absorbing area.

In rooms with well defined absorbing areas the flow of sound energy will be directed towards these areas. When the most prominent absorbing areas in a room are concentrated at one point the sound energy flow is therefore directed towards this point. For the case of single frequency radiation the overall sound "picture" in the room consists of standing waves with local maxima and minima while the sound field close to the absorbing area will approach the character of free progressive sound waves arriving from various directions. Only a small part of the total sound energy will travel directly from the sound source to the absorption area while the rest will have been reflected a number of times at the various room boundaries before it arrives at the absorbing "termination".

Which part of the sound absorption area that will be the most effective one depends upon the geometry of the arrangement, sound source-reflecting areas-absorbing area. An irregularly shaped room with highly reflecting walls produces the most uniform distribution of sound "rays".

In an ideal combination of a reverberation room and sound absorption area the sound power produced by the noise source is absorbed with an equal amount of energy per unit area of sound absorption, i.e. a uniform distribution of sound energy is produced over the entire absorbing area. If the sound pressure level is measured at a single point immediately in front of the sound absorption area information is thus obtained on the total sound energy radiated from the sound source. This information is again closely related to other possible idealized "noise numbers", such as for instance the sound pressure level at a distance of 1 m from the source.

Also in the practical realization of the above proposed measurement arrangement it is possible to obtain quite satisfactory results from measurements at a single point.

Many different rooms with different volumes and quite different dimensions but with approximately the same absorbing area can be used and will give good agreement in measuring results. The measurement method can be used for noise checks on all household appliances and similar devices which are intended for use in closed rooms, and may be carried out as linear sound pressure level measurements or measurements of weighted sound levels. It is also possible to utilize the arrangement when measurements are made in terms of one or third octave band sound pressure levels. However, when the measurement bandwidth becomes narrower the expected measurement errors increase.

In the ideal case, on the other hand, a fixed ratio exists between measurement values obtained by the suggested method and those obtained from space averaging in an acoustically free field.

Measurement Accuracy

When weighted sound level measurements are carried out on a particular device the influence of different measurement rooms may, by using the method outlined above, be reduced to some ± 2 dB. If the sound source produces a continuous frequency spectrum this uncertainty can be even further reduced to the order of ± 1 dB. These estimates do not include instrumentation errors. Experimental tests on a particular household appliance showing a continuous noise frequency spectrum in two superficially treated, very different rooms of 27 m^3 and 64 m^3 resulted in an average difference of 2 dB. The difference obtained when the rooms were not treated at all was 5 dB.

When the same tests were performed on a vacuum cleaner, which may be considered a sound source with a high degree of directivity, a difference of 3.5 dB remained after treatment of the rooms. The sound absorbtion area consisted in this case of 8 m^2 of glasswool placed on one wall only.

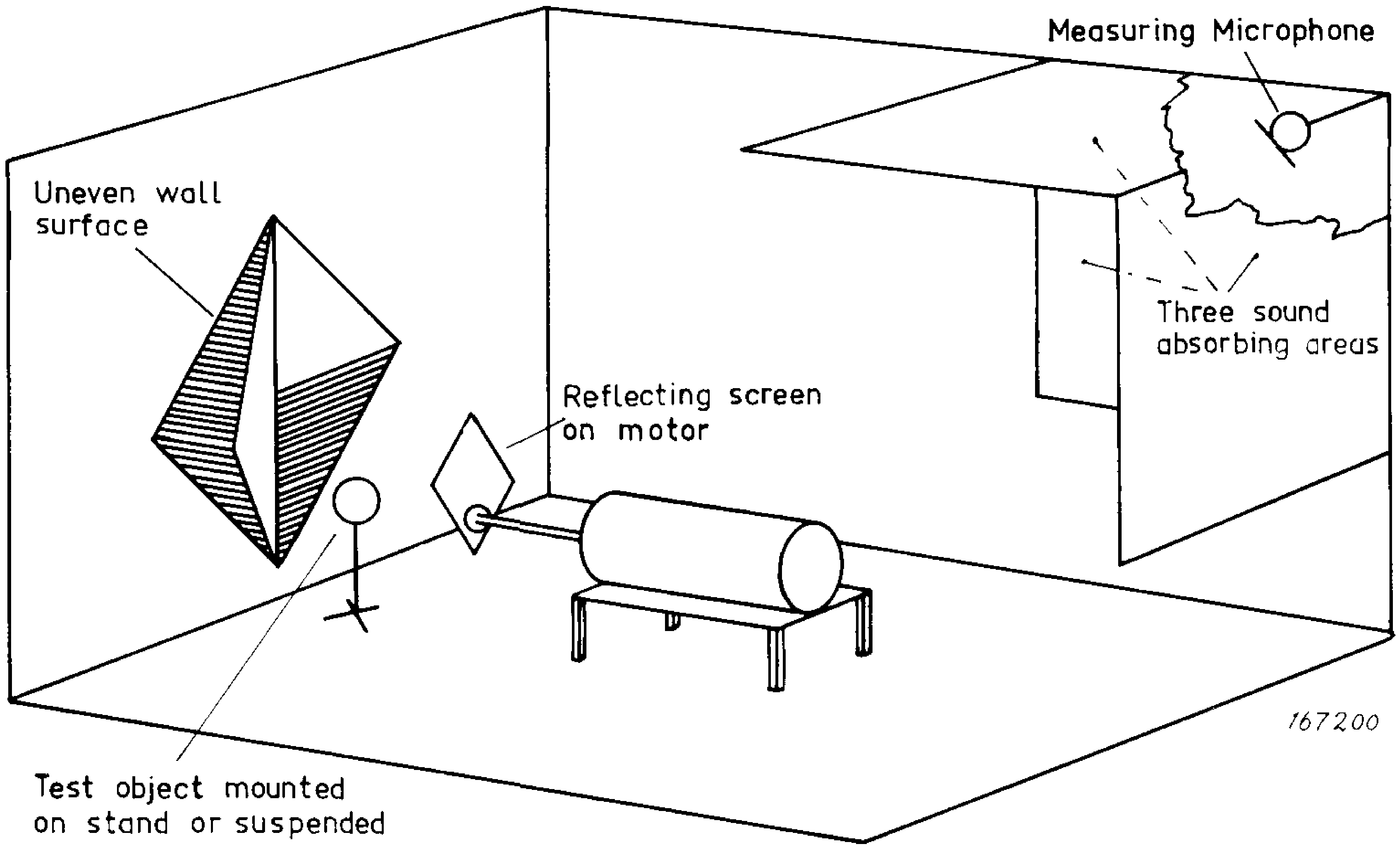

Fig. 1.

Proposed Measurement Arrangement

a) The measurement room should be situated in quiet surroundings and have highly sound reflecting walls (hard walls). There should be no windows in the room and the volume should be at least 25 m^3. (Preferably the volume of the room should be of the same order of magnitude as the room in which the device is intended to operate in practice.)

b) Three equally sized pieces of sound absorbing material, totalling an area of 12 m^2, should be mounted in the test room so that they meet in a corner see Fig. 1. The measuring microphone should be placed in the corner close to the absorption material and pointed at the interior of the room.

c) The test object should be placed at the opposite end of the room. Between it and the microphone a reflecting surface, plane or vaulted, should be mounted in such a way that a minimum of direct sound from the sound source reaches the microphone.

d) The spread in measured results is estimated by comparing the weighted sound level measured for different positions of the test object in the room. A final "noise number" is obtained as the mean value of at least three measurement configurations with the sound source situated in one place, but turned successively three times 120° around its vertical axis.

e) In the case of noise checks on series produced items a single measurement configuration may be sufficient. This does, however, presuppose a preliminary investigation showing that the mean value discussed in d) above is obtained when exactly this specific configuration is used.

f) The measurement errors resulting from an arrangement of the type discussed are caused partly by the fact that some sound absorption takes place in the room itself and not only at the deliberately introduced "absorbing area". These errors should be minimized by a slight reduction in the "absorbing area". Check measurements can be made by means of a typical, well defined (calibrated) sound source.

g) The efficiency of the reflector (item C above) can be increased by rotating it so that a hypothetical line vertical to the reflector surface and directed at an angle towards the specimen, would describe a circle around the specimen. The speed of rotation, or the velocity of the motion, should be chosen so as to facilitate a mean value reading on the measuring instrument. In the case of frequency analysis of the noise the reflector should perform at least two cycles of rotation during the period of time that the Analyzer stays within one bandwidth.

   A further increase in reflector efficiency is obtained by giving the wall opposite to the reflector an irregular shape (Fig. 1).

The rotation of the reflector can be replaced or supplemented by moving or rotating the test object itself.

Transconductance of Field Effect Transistors (FET)

By

V. Neble Jensen, M.Sc.

In many of the electrical circuits where FET is used today it is of great importance to know the value of the transconductance more exactly than it is normally specified by the manufacturer. The difference between the maximum and the minimum values of the transconductance given in datasheets can be up to 5–10 times, which is too much when a reasonable accuracy in circuit design is required. This applies especially to balanced amplifier circuits where it will be necessary to select FET-elements with similar data (transconductance).

To aid such a selection exact comparison measurements of transconductance data can be carried out on a B & K Deviation Bridge Type 1504 which consists of a Wheatstone Bridge with fixed resistors in two arms and terminals for connecting an external standard and the unknown component in the other two arms respectively. The bridge is operated from a built-in generator working at a frequency of 1,000 Hz.*)

The Bridge diagonal voltage is fed to a phase-sensitive demodulator via a two-stage amplifier and the output voltage measured on a moving coil instrument with large interchangeable scales reading the positive and the negative deviation between the standard and the unknown component. There are, however, two things which must be considered when the apparatus is used for measurements on active elements such as FET's.

Firstly, problems with hum originating from the power supply can arise as none of the external terminals of the apparatus can be grounded.

Secondly the signal-voltage from the generator is too large for a direct measurement on FET's. This voltage therefore must be reduced (RANGE ADJUSTMENT) and an amplifier introduced in the measuring circuit to obtain reasonable sensitivity.

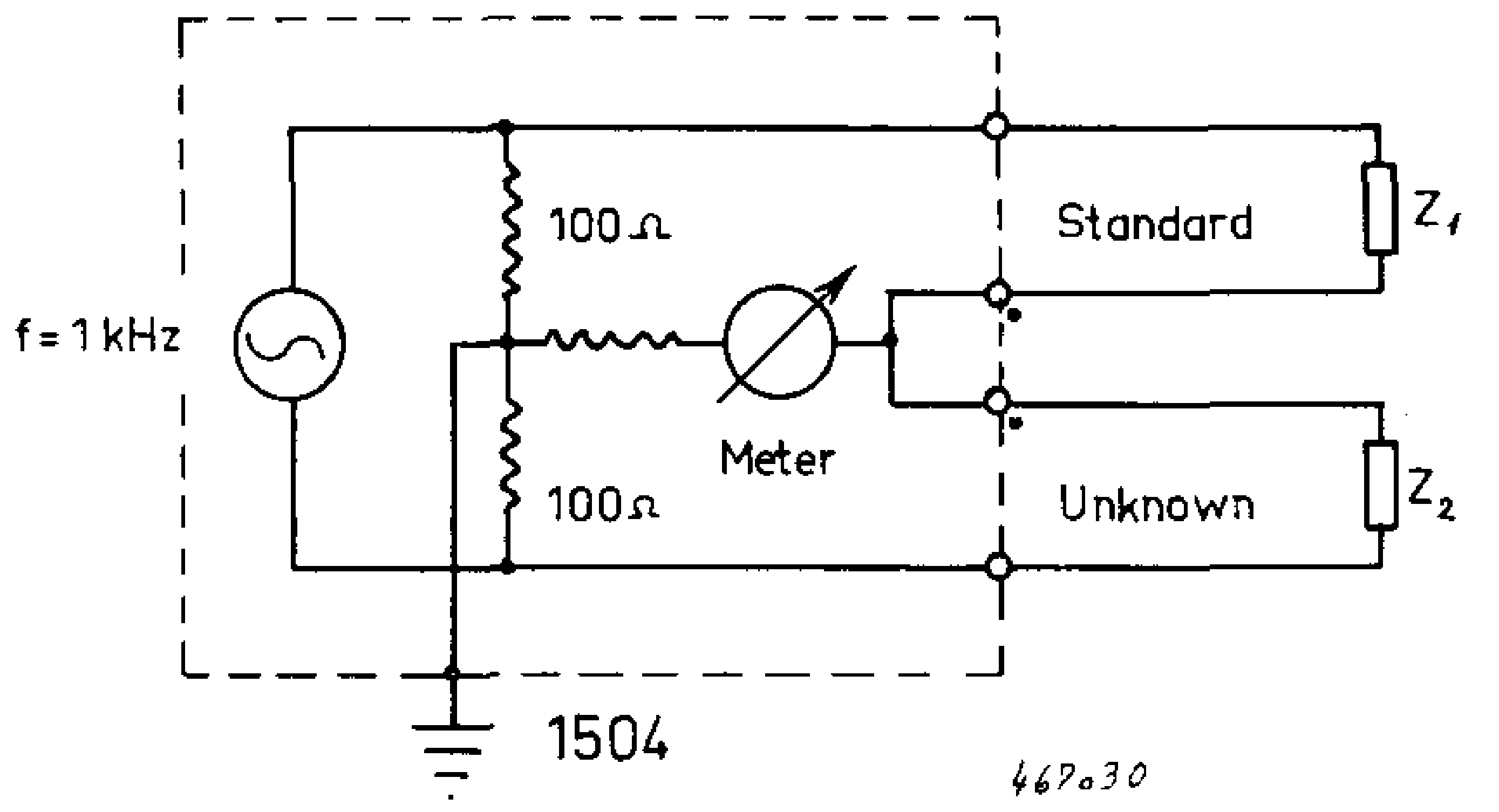

Fig. 1.

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*) 1,000 Hz is the frequency at which the transconductance is normally measured by the manufacturer.

In the following some measurement possibilities will be described which have been investigated at Brüel & Kjær. Fig. 1 shows the principle of operation of the Deviation Bridge Type 1504. As shown, the mutual connection between the two fixed resistors is grounded (internal connection in the apparatus) whereby no ground connection can be made of the terminals for "Standard" or "Unknown". When Z_1 and Z_2 include active elements which require the use of an external power supply a serious hum component is introduced. There are, however, several methods whereby the hum component may be reduced to negligible proportions. One such method is shown in Fig. 2. In this arrangement the external DC power supply is effectively connected in series with the two 100 Ω resistors shown in Fig. 1. As the power handling capacity of these resistors is more than 1 W the small extra DC current will not affect the measurements.

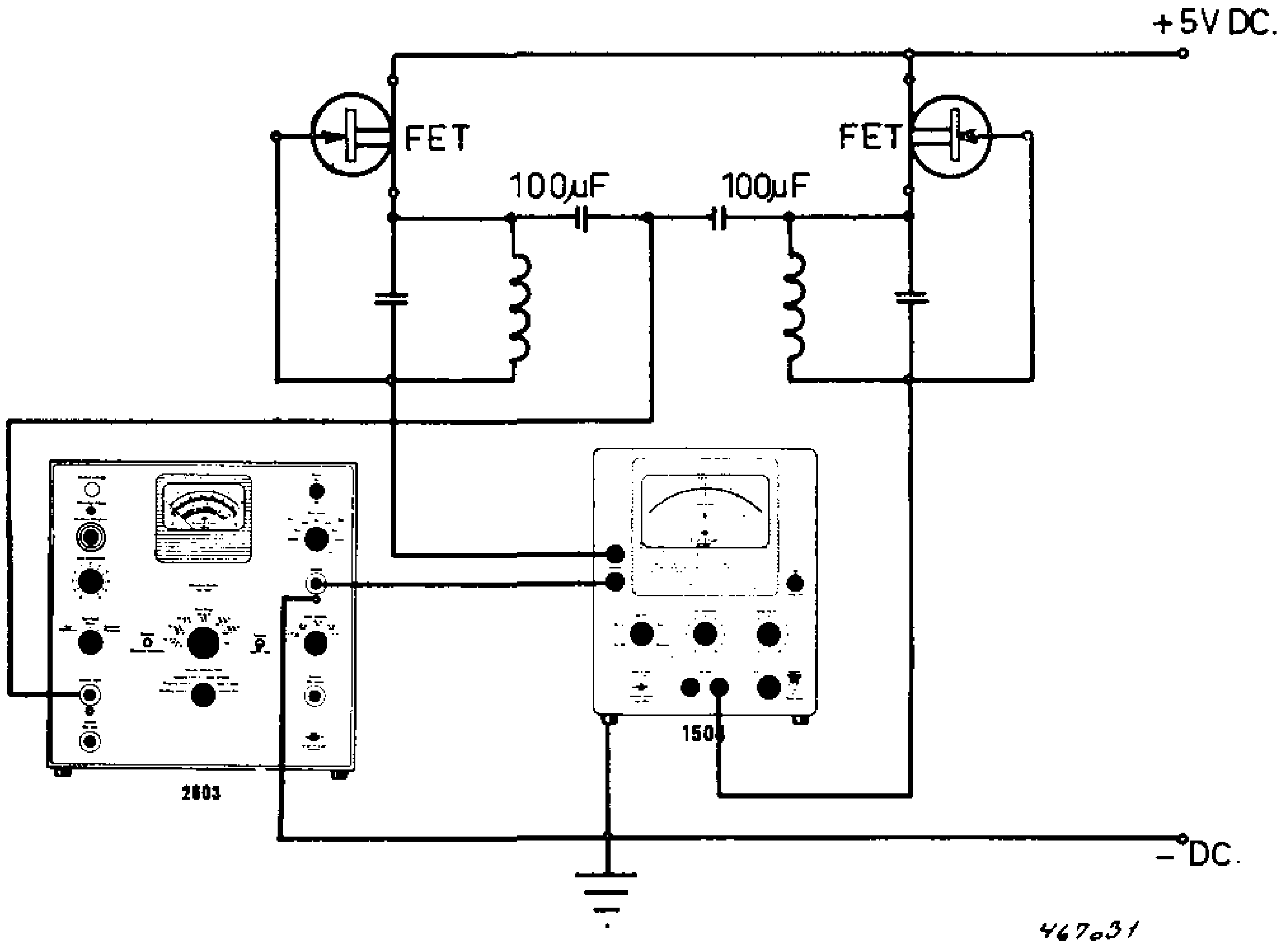

Fig. 2.

From the figure it is seen that a parallel resonance circuit has been introduced in the source lead of the FET. This ensures an effectively high AC impedance of the circuit without affecting the DC functioning of the transistor. (From an AC point of view the internal resistance of the transistor parallels the resonance circuit.) The Q-value of the circuit must be high in order not to interfere with the measurements and the circuit must be tuned to resonance at $f_0 = 1{,}000$ Hz.

To further reduce the possible influence of hum and extreneous noise upon the measurements the Type 2603 amplifier shown in Fig. 2 may be substituted by the Audio Frequency Spectrometer Type 2112 set for third octave operation and switched to 1,000 Hz center frequency. If it is found undesirable to pass the DC through the 100 Ω resistors, such as indicated in Fig. 2, the necessary return path can be established via two chokes which must have a high impedance (e.g. $Z > 10\,\text{k}\Omega$ at 100 Hz) and a DC resistance $< 100\ \Omega$. The necessary circuit is shown in Fig. 3. (A suitable inductance for these chokes will be $L = 2$ Henry).

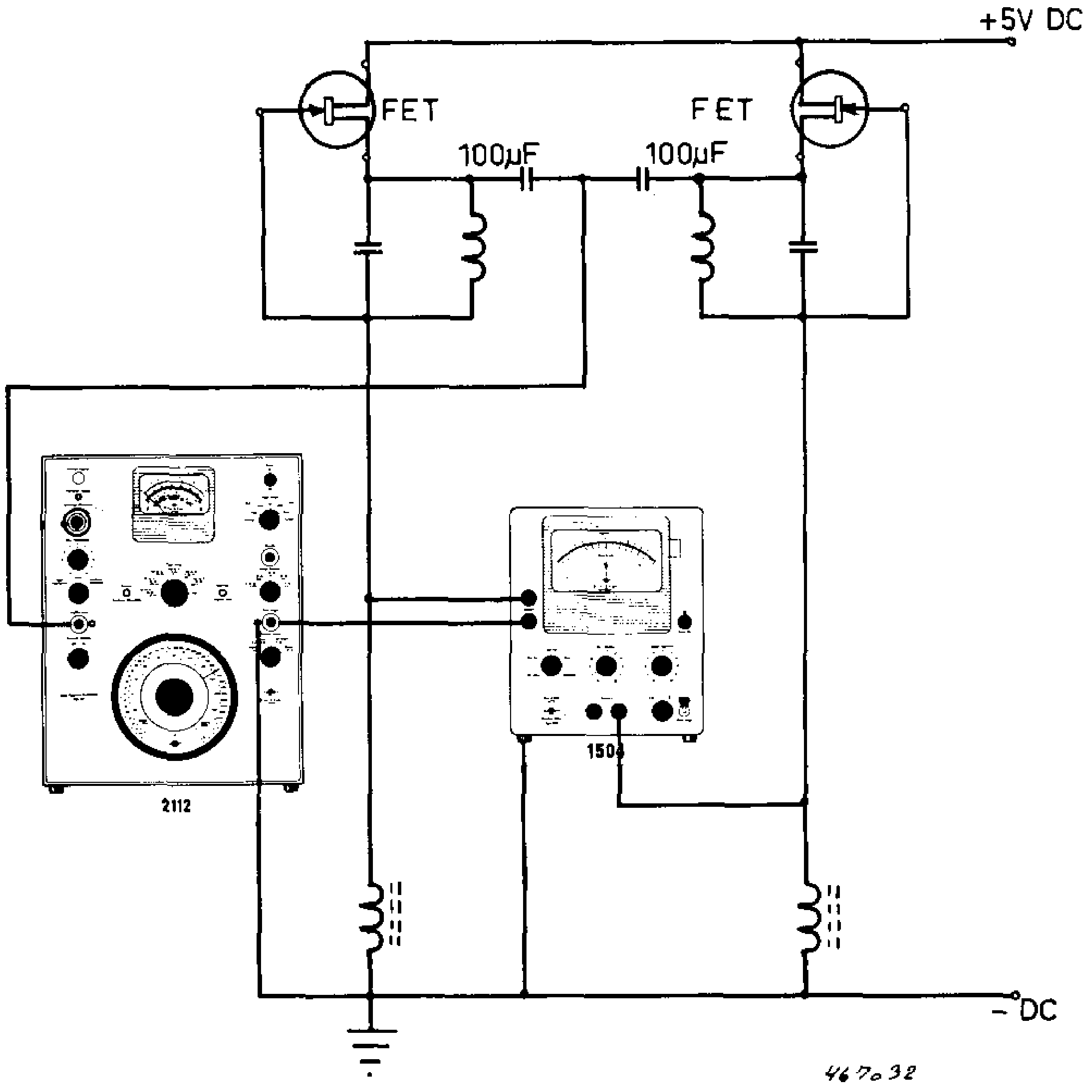

Fig. 3.

As mentioned above the AC signal voltage to be applied to the FET's during measurement is smaller than that normally supplied to the component being tested by the Deviation Bridge. To make use of the calibrated scales supplied with the Bridge it is then necessary to adjust the amplification of the external amplifier (Type 2603, Type 2112) to exactly the same value as the AC voltage to the FET is attenuated. This does, however, in practice not pose any difficulty.

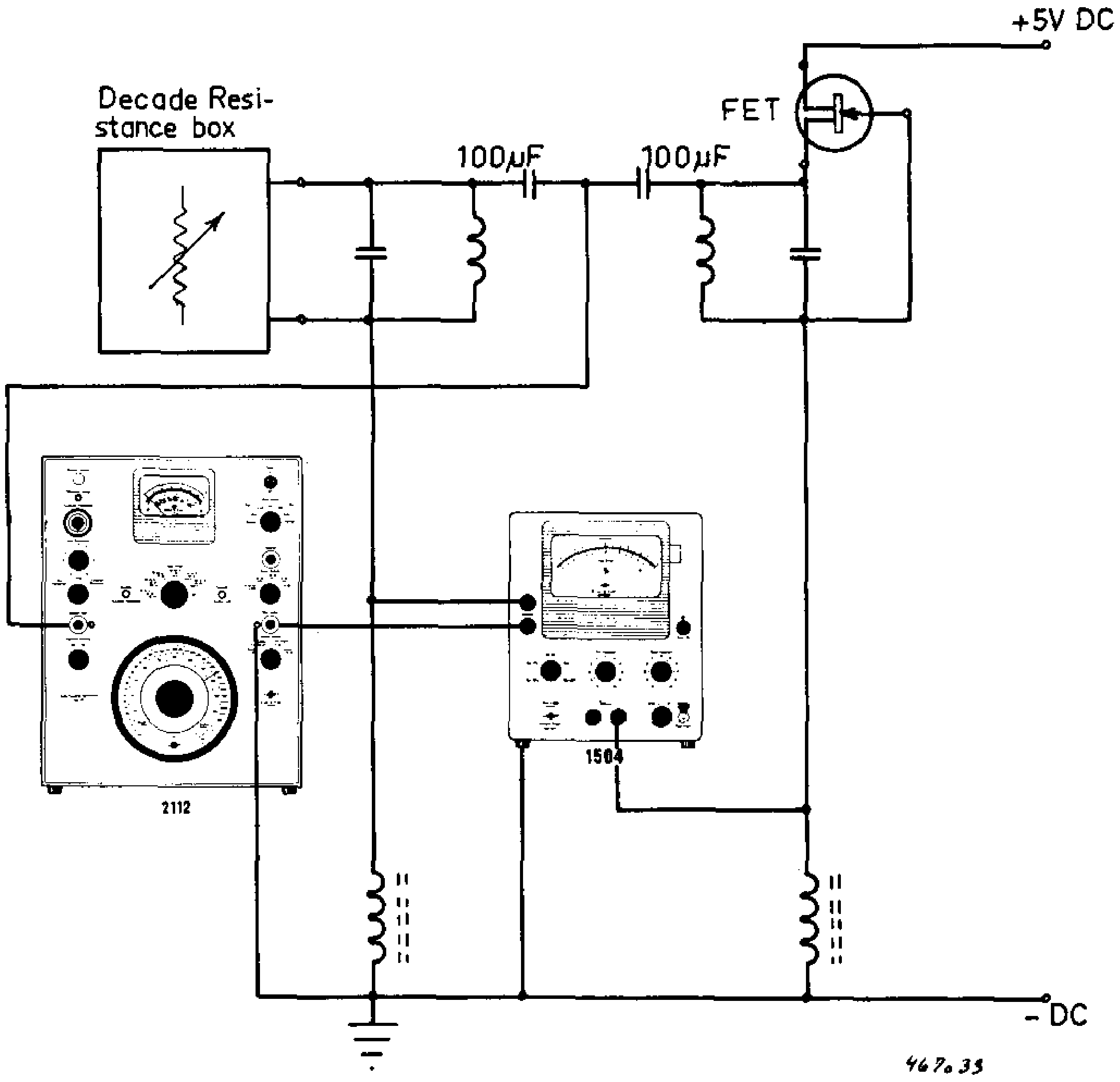

Fig. 4.

Finally, by substituting the FET in the circuit connected to the "Standard" terminals by a decade resistance box as shown in Fig. 4 the transconductance of the FET connected to the "Unknown" terminals can be determined directly as

$$g_m = \frac{1}{R} \text{ mhos}$$

Here R is the resistance of the resistance box when adjusted to obtain zero meter deflection on the Deviation Bridge.

Measurement methods of the kind described here are, of course, not limited to transconductance measurements on FET's. Similar measuring arrangements may well be used for measurements on other active elements.

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PRINTED IN DENMARK K. LARSEN & SØN - LYNGBY