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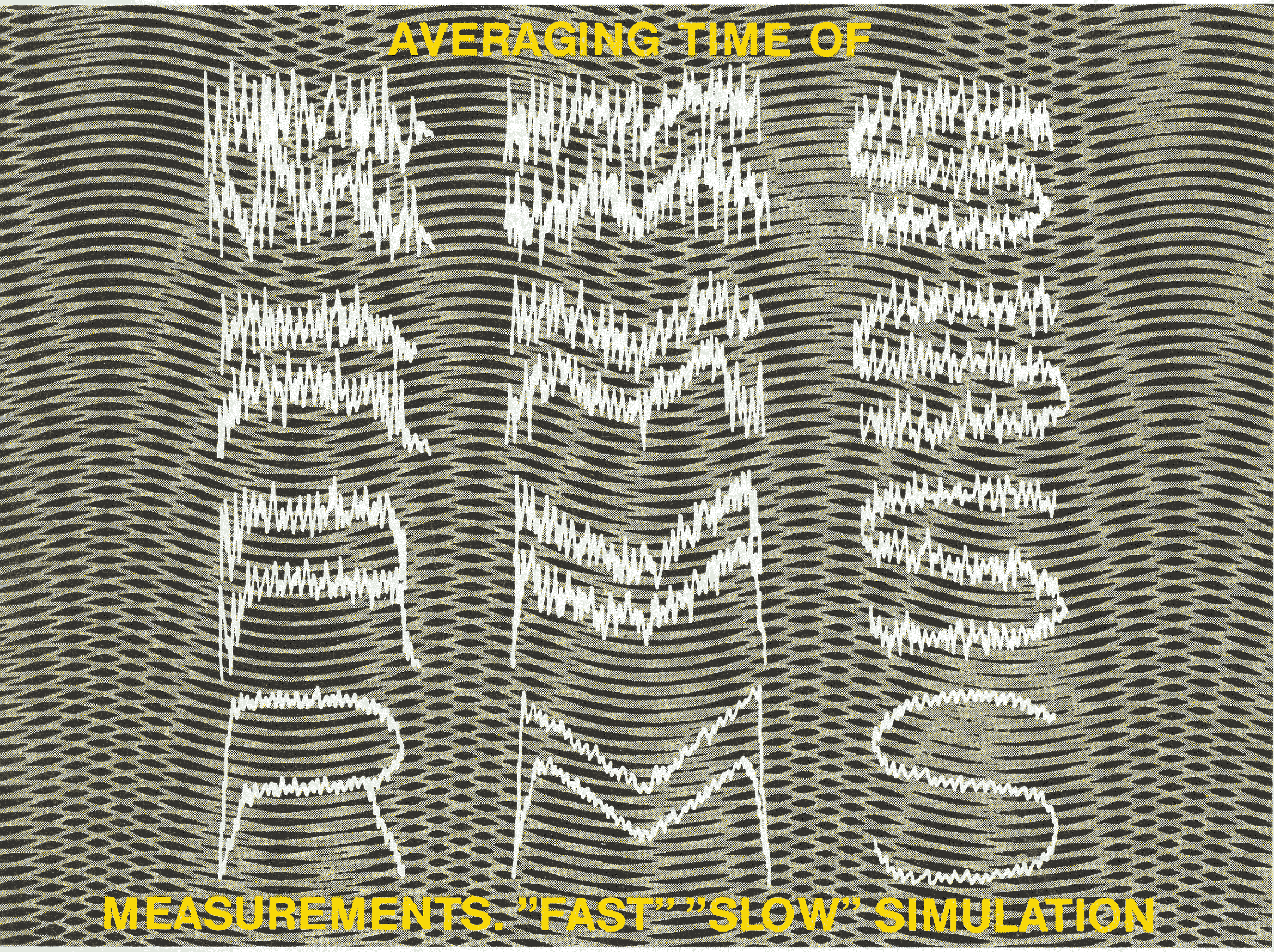

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TECHNICAL REVIEW

No. 2 — 1975

Contents

On the Averaging Time of RMS Measurements

by

C. G. Wahrmann and J. T. Broch

ABSTRACT

Time averaging and/or weighting are some of the most important processes in data reduction measurement systems.

This paper deals with these processes as applied to RMS (Or MS) measurements. After introducing various kinds of time averaging techniques, the time and frequency domain descriptions of averaging processes are briefly outlined, particularly with regard to the most important practical averaging systems: The running integration technique and the RC-weighting technique. Comparing the use of these two techniques in the measurement of stationary random signals the important "equivalence criterion" T = 2 RC is derived.

This result is then applied to the measurement of stationary periodic signals, and it is shown that also in these cases T = 2 RC is a satisfactory practical "equivalence criterion".

The paper will be extended in the next issue of the B & K Technical Review, where the different kinds of integration/averaging techniques are applied to transient and impulsive signals, and some general conclusions are formulated.

SOMMAIRE

L'intégration et (ou) la pondération temporelles sont parmi les processus les plus importants pour la réduction des résultats dans les systèmes de mesure.

Cet article traite de ces processus appliqués aux mesures de valeur efficace (ou de moyenne quadratique). Après l'introduction de différentes techniques d'intégration temporelle, les descriptions, dans les domaines du temps et des fréquences, des procédures d'intégration sont rapidements étudiées, en prenant particulièrement en considération les plus importants des systèmes pratiques: l'intégration continue et la pondération RC. En comparant l'emploi de ces deux techniques pour les mesures sur des signaux aléatoires stationnaires, on abouti à l'important "critère d'équivalence" T = 2 RC.

Ce résultat est ensuite appliqué à la mesure de signaux périodiques stationnaires, et l'on montre que, dans ce cas, la relation T = 2 RC est aussi un "critère d'équivalence" pratique satisfaisant.

Cet article sera complété dans la prochaine édition de la Revue Technique B & K, où les différentes techniques d'intégration et de pondération seront appliquées aux signaux transitoires et impulsionnels et où certaines conclusions générales seront tirées.

ZUSAMMENFASSUNG

Die zeitliche Mittelung mit und ohne zeitabhängige Bewertung ist einer der wichtigsten Prozesse in datenreduzierenden Meßsystemen.

Dieser Beitrag beschreibt solche Prozesse, angewandt auf den Effektivwert (oder quadratischen Mittelwert). Nach einer Einführung in verschiedene Arten von Zeitmittlungs — Techniken wird die Darstellung von Mittlungsprozessen im Zeit — wie im Frequenzraum kurz aufgezeigt, insbesondere im Hinblick auf die praktisch bedeutsamsten Mittlungsarten: die Technik der gleitenden Integration und der RC-Mittlung. Durch Vergleich dieser beiden Techniken in Anwendung auf die Messung stationärer stochastischer Signale wird das wichtige "Äquivalenskriterium" T = 2 RC hergeleitet.

Dies Ergebnis wird dann angewandt auf die Messung stationärer periodischer Signale, und es zeigt sich, daß auch in diesem Fall T = 2 RC ein für die Praxis zufriedenstellendes Kriterium darstellt.

Der Artikel wird in der nächsten Ausgabe der B & K Technical Review fortgesetzt, wobei die verschiedenen Arten von Integrations-/Mittlungstechniken auf flüchtige und impulsartige Signale angewandt und einige allgemeine Schlußfolgerungen formuliert werden.

1. Introduction

The most complete description of a signal is obtained by recording its entire time history. This is, however, not only impractical and time-consuming but very often also unnecessary, as only certain typical characteristics of the signal are normally important to the practicing engineer. One such characteristic is the so-called *RMS* (root mean square) value of the signal, defined mathematically as:

$$X_{RMS} = \sqrt{\frac{1}{T}\int_0^T x^2(t)\, dt}$$

The particular importance of the *RMS*-value may be found in the facts that it is "directly" related to the signal energy content, and that it does, to a certain extent, take the signal time history into account.

As can be seen from the mathematical definition of the *RMS*-value, its determination requires *time averaging*, and it is the intention in this paper to discuss, in some details, the practical implications involved in the averaging process.

There are, basically, several ways in which the time averaging can be performed experimentally:

1. Long-time integration/averaging.
2. Step-wise integration/averaging.
3. Running integration/averaging.
4. Weighted integration/averaging.

In the case of *long-time integration*/averaging the averaging time *T* is chosen to equal the total time of observation of the signal.

A more practical method of integration/averaging is the *step-wise integration* mentioned above. Here the signal is integrated and averaged over a time *T*, whereafter a new averaging takes place over another period of time *T* starting at the end of the first period, etc. The result of the averaging is indicated at the end of each period *T*.

The third method is here called "*running integration*" and consists in a true, continuous averaging over the last *T* seconds of the signal i.e. the integrating memory continuously "throws away" signal values which occurred before $t - T$.

In comparing step-wise integration with running integration the results must always equal each other at the end of each (and the beginning of the next) stepped interval of *T*. When running integration is used the averaged value vary continuously while in the case of step-wise integration the result obtained in one integration period, *T*, remains indicated until the next average is completed, see Fig. 1.

The fourth method mentioned above, i.e. the weighted integration/averaging, is the most commonly used type of averaging to date. In

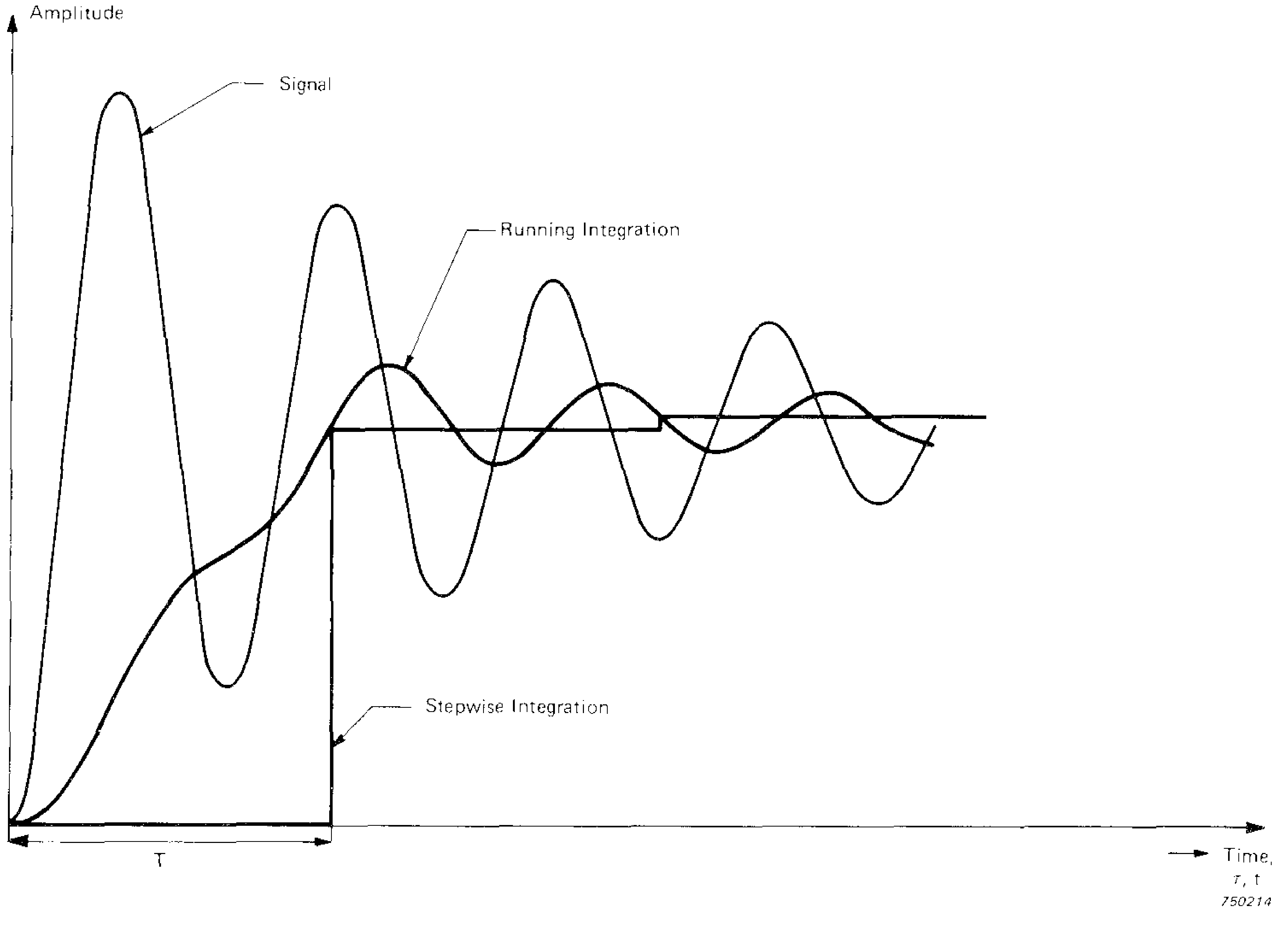

Fig. 1. Illustration of the concepts of running integration and stepwise integration.

analog type measuring instruments the weighting is normally exponential and is derived from R-C averaging circuits.

While the running integration/averaging weight each instantaneous value of the signal within T equally, the weighted averaging may give greater weight to signal values occurring at the instant of measurement than to signal values occurring, say T seconds earlier.

The main purpose of this article is, under different measurement conditions, to compare the different types of averaging techniques. Such a comparison should then enable the practicing engineer to better judge the limitations imposed upon the measurement by the averaging system, and to choose the parameters involved so as to obtain optimum results. *This is of particular importance when the measured results are to be converted into digital form for further data processing.*

2. Time and Frequency Domain Descriptions of the Averaging Process

As time and frequency are dual quantities, it is possible to study the time averaging process either in the *time domain* or in the *frequency domain*. Conversion from one domain to the other is, in this case, based on the so-called Fourier-transformation and the principle of superposition.

The Fourier transformation theorem states that:

$$F(\omega) = \int_{-\infty}^{\infty} f(t)\exp(-j\omega t)\,dt$$

and

$$f(t) = \int_{-\infty}^{\infty} F(\omega)\exp(j\omega t)\,df$$

where $\omega = 2\pi f$, while the principle of superposition states that: *In linear systems the effect of simultaneously superimposed actions is equal to the sum of the effects of each individual action.*

Utilization of the superposition principle can be made for instance by considering the function $f(t)$ as consisting of an infinite number of impulses each with an infinitesimal width, $\Delta\tau$, and a height $f(\tau)$, and superimposing the responses produced by the action of each of these impulses, see Fig. 2. Mathematically this can be written:

$$x(t) = \int_{-\infty}^{t} f(\tau)h(t-\tau)\,d\tau$$

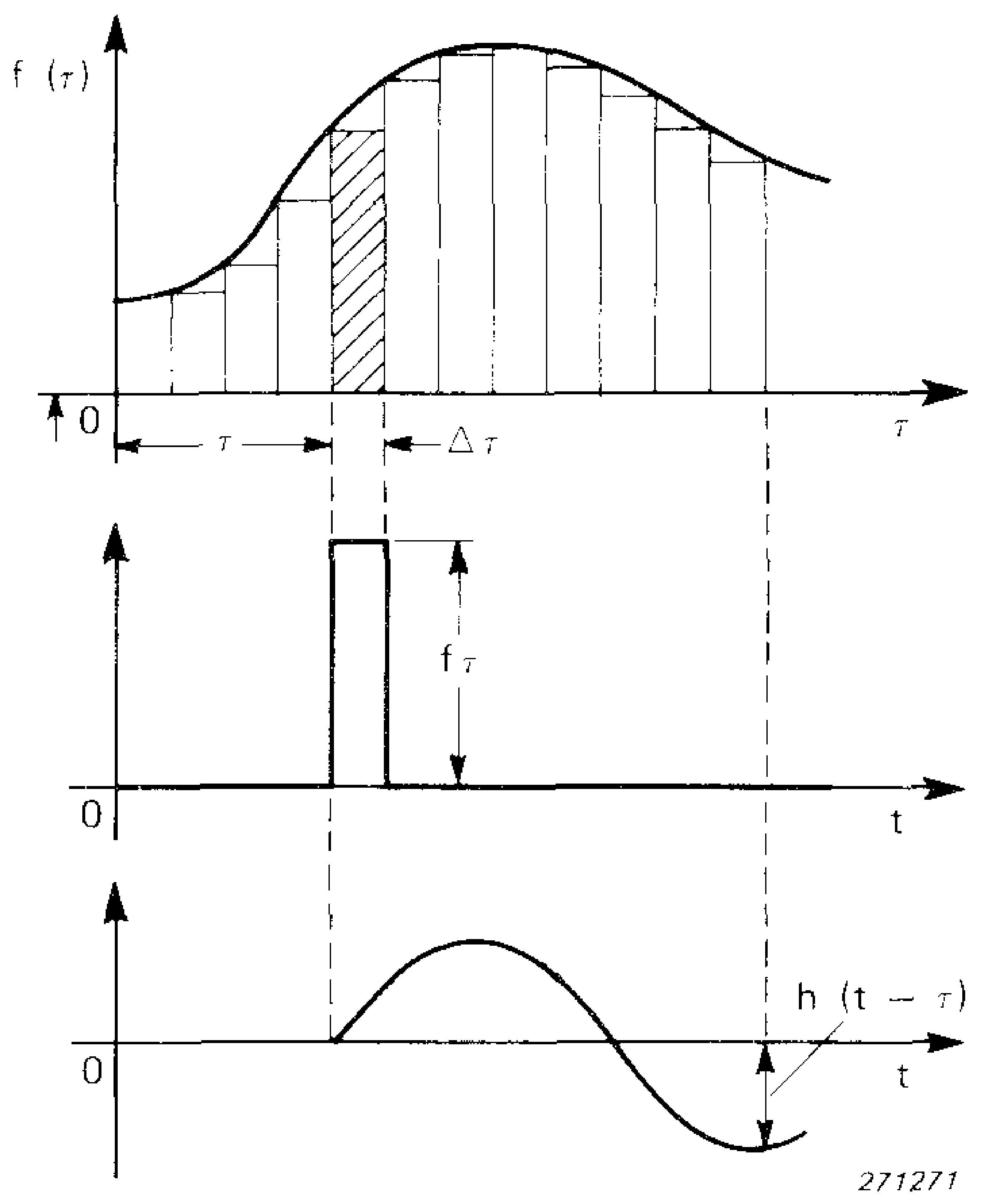

Fig. 2. Illustration of the concepts involved in time domain superposition.

where $h(t - \tau)$ is the response of the system at the time t to a unit impulse excitation acting at time τ. A unit impulse (Dirac δ-function) excitation is characterized by the fact that it is zero, except at $t = \tau$ where it is infinite, and encloses unit area:

$$\lim_{\varepsilon \to 0} \int_{-\varepsilon}^{\varepsilon} \delta(\tau)\, d\tau = 1$$

By applying the Fourier transformation theorem to the function $x(t)$ above it can be readily shown that:

$$X(\omega) = H(\omega) \cdot F(\omega)$$

Here $X(\omega)$ is the Fourier transform of $x(t)$, $F(\omega)$ is the (complex) frequency spectrum of the time function to be averaged and $H(\omega)$ is the (complex) frequency response function of the averaging network.

An important fact, which can be seen directly from the above expressions is that a convolution (folding) in the time domain corresponds to a straight forward multiplication in the frequency domain. Similarly, a multiplication in the time domain would result in a convolution in the frequency domain.

Two simple, but practically important cases of averaging are treated below, namely the originally defined averaging:

$$X_{RMS}{}^2 = \frac{1}{T} \int_0^T f^2(t)\, dt$$

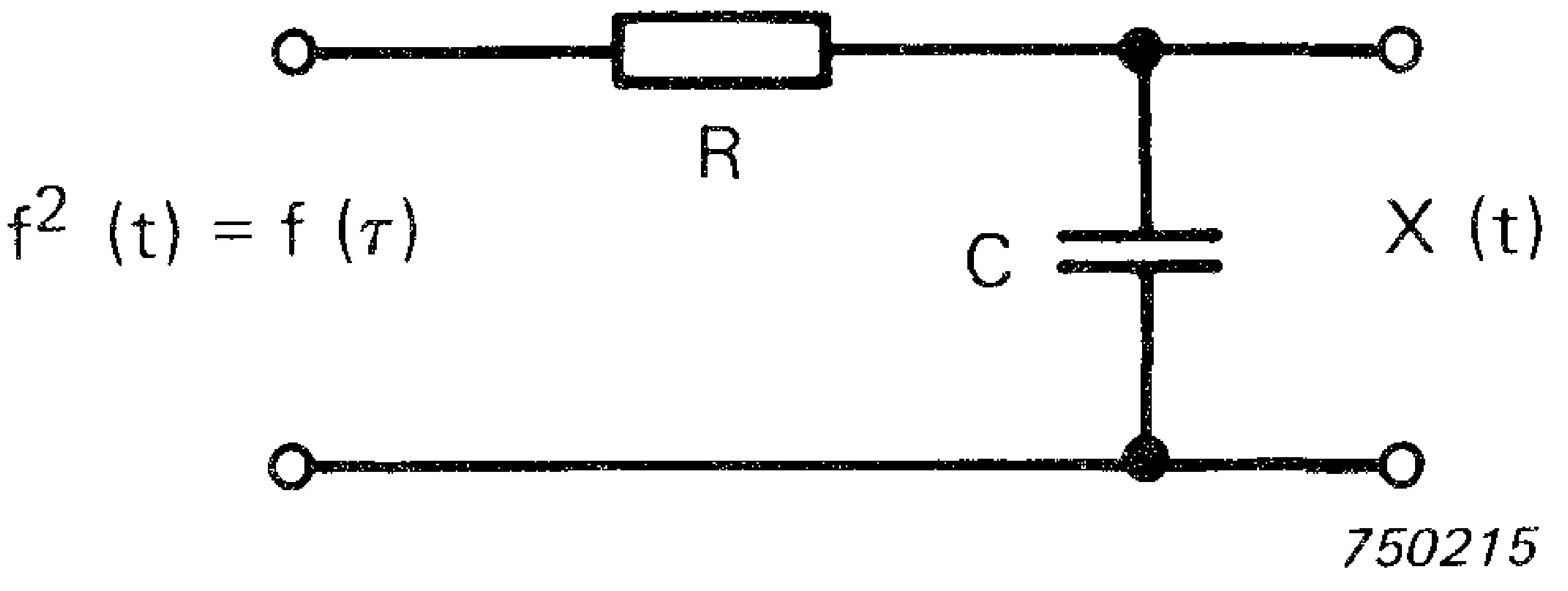

Fig. 3. Typical RC-averaging (weighting) network.

and the weighted averaging using a simple RC-circuit as weighting device, Fig. 3.

For the sake of convenience set $f^2(t) = f(\tau)$, so that

$$X_{RMS}^2 = \frac{1}{T}\int_0^T f(\tau)\, d\tau$$

This integral can also be written:

$$X_{RMS}^2 = \int_0^T f(\tau)\,\frac{1}{T}\, d\tau = \int_{-\infty}^{\infty} f(\tau) h_1(t-\tau)\, d\tau$$

The upper limit of integration is ∞ because the integral is finite and:

$$h_1(\tau) = \begin{cases} \frac{1}{T} & \text{when} \qquad 0 < \tau < T \\ 0 & \text{elsewhere} \end{cases}$$

The Fourier transform of the impulse response function is:

$$H_1(\omega) = \int_{-\infty}^{\infty} h_1(\tau)\exp(-j\omega\tau)\, d\tau$$

$$= \int_0^T \frac{1}{T}\exp(-j\omega\tau)\, d\tau$$

Thus:

$$H_1(\omega) = \frac{\sin(\omega T/2)}{(\omega T/2)}\exp(-j\omega T/2)$$

Fig. 4a) shows $|H_1(\omega)|$ and indicates clearly that the integration and averaging process in the frequency domain acts as a low-pass filter with a $|\sin(x)/x|$-characteristic.

In the case of RC-weighted averaging the result of the averaging in the time domain can be written:

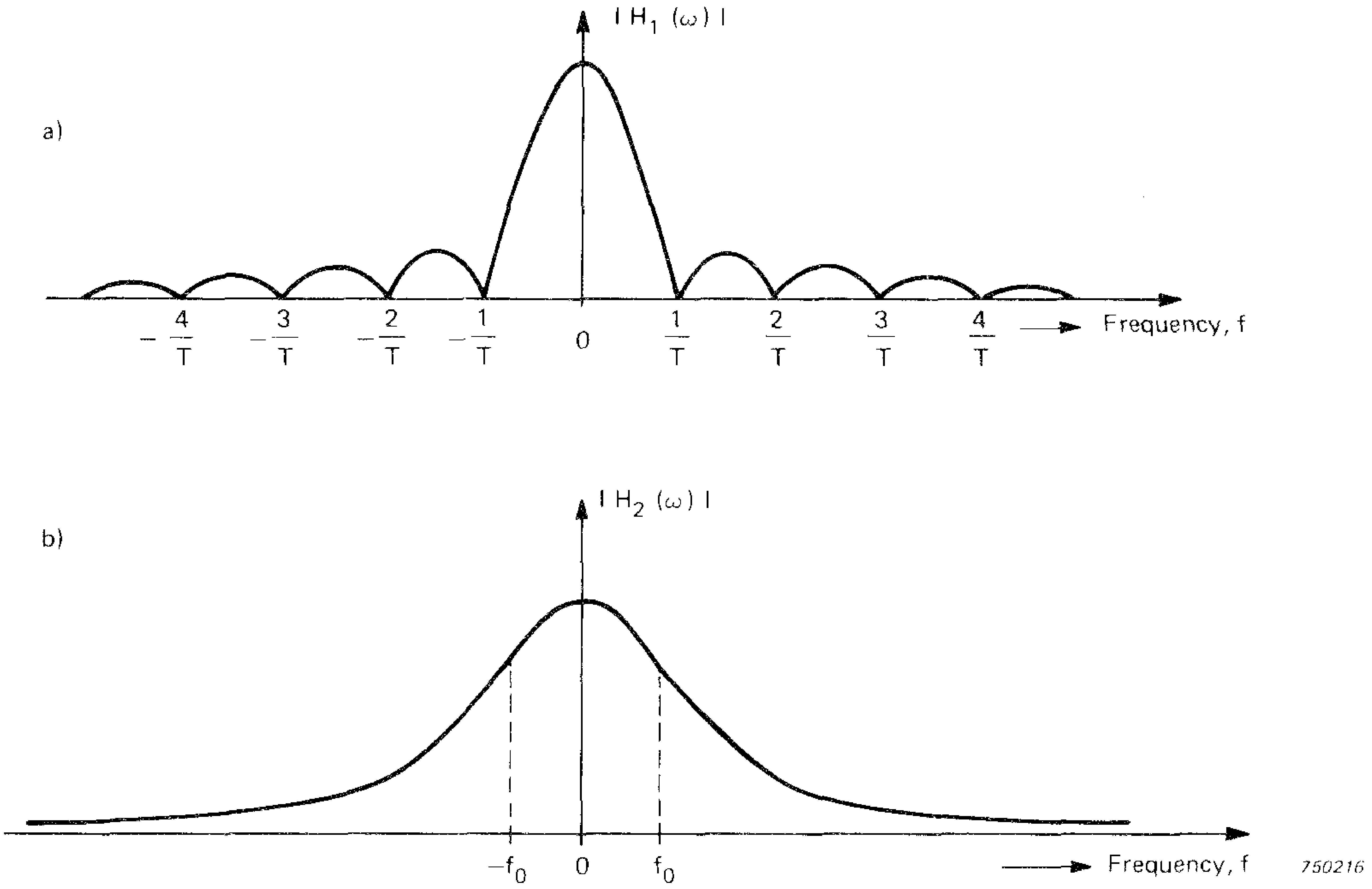

Fig. 4. Response characteristics in the frequency domain for
a) True integration/averaging
b) RC-weighted integration/averaging

$$X_{RMS}{}^2(t) = \int_{-\infty}^{t} f(\tau)h_2(t-\tau)\,d\tau$$

$$= \frac{1}{RC}\int_{-\infty}^{t} f(\tau)\exp[-(t-\tau)/RC]\,d\tau$$

as the impulse response function for the RC-weighting is:

$$h_2(\tau) = \frac{1}{RC}\exp(-\tau/RC) \qquad \tau > 0$$

Here the Fourier transform of the impulse response function is:

$$H_2(\omega) = \int_0^{\infty} \frac{1}{RC}\exp(-\tau/RC)\exp(-j\omega\tau)\,d\tau$$

$$H_2(\omega) = \frac{1}{1 + j\omega RC}$$

The function $|H_2(\omega)|$ is plotted in Fig. 4b) and shows the well known frequency response of an R-C-network.

3. Averaging of Random Signals

When statistically fluctuating signals such as narrow band random noise are measured the output signal from the detector will also fluctuate. These output signal fluctuations are then reduced by means of the averaging process.

One method of comparing different types of averaging processes is, consequently, to choose the averaging parameters in such a manner that the relative energy fluctuations in the averaged signal are the same, independently of the type of averaging system used. This method has been utilized by the authors in some earlier work, see Ref. (1), and is therefore only briefly outlined below.

It was found in Ref. (1) that the simplest way of dealing with the averaging process in connection with random signals was to use frequency domain descriptions of the phenomena. This was, due to the character of the signal, done in terms of mean square (power) spectral densities and squared frequency response functions. Fig. 5a) indicates an "ideal" (rectangular) frequency band of random noise with a power spectral density, w_B, and bandwidth B. When this band of noise is squared and applied to the input of the averaging circuit the spectrum of Fig. 5a) is transformed into the one shown in Fig. 5b). Here linear scales are used in the graph †).

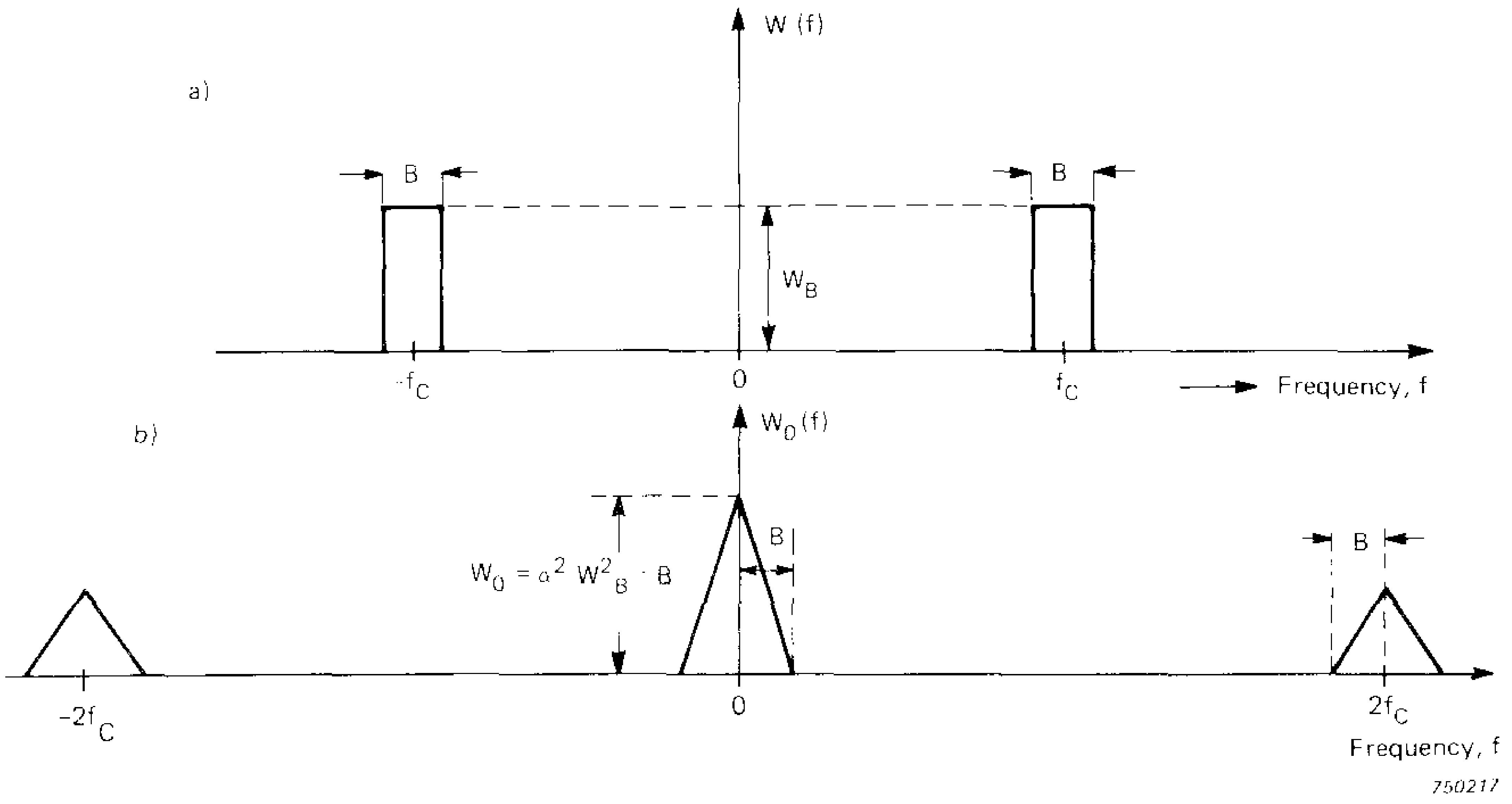

Fig. 5. Sketches illustrating the effect of squaring a narrow frequency band of random noise.
a) The noise frequency spectrum before squaring
b) The output spectrum from the squaring device

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† The triangular shape of the spectrum is due to the fact that the squaring process in the time-domain transforms into a convolution process in the frequency domain.

By redrawing the low frequency part of the spectrum with expanded frequency scale the result will be as indicated in Fig. 6. Fig. 6 also illustrates the effect of passing the signal through an averaging filter with a cut-off frequency which is much smaller than the bandwidth, B, of the (narrow) noise band being measured.

It is clearly seen that the resulting spectral density function can be assumed constant over the operating range of the averaging filter. The (approximately constant) spectral density, w_0, in Fig. 6 can be shown to have the value:

$$w_0 = \alpha^2 w_B{}^2 B$$

where α is an instrumentation constant.

a) If the averaging process is of the type:

$$\frac{1}{T}\int_0^T f(\tau)\, d\tau$$

its corresponding squared frequency response function would be:

$$|H_1(\omega)|^2 = \left(\frac{\sin(\omega T/2)}{\omega T/2}\right)^2$$

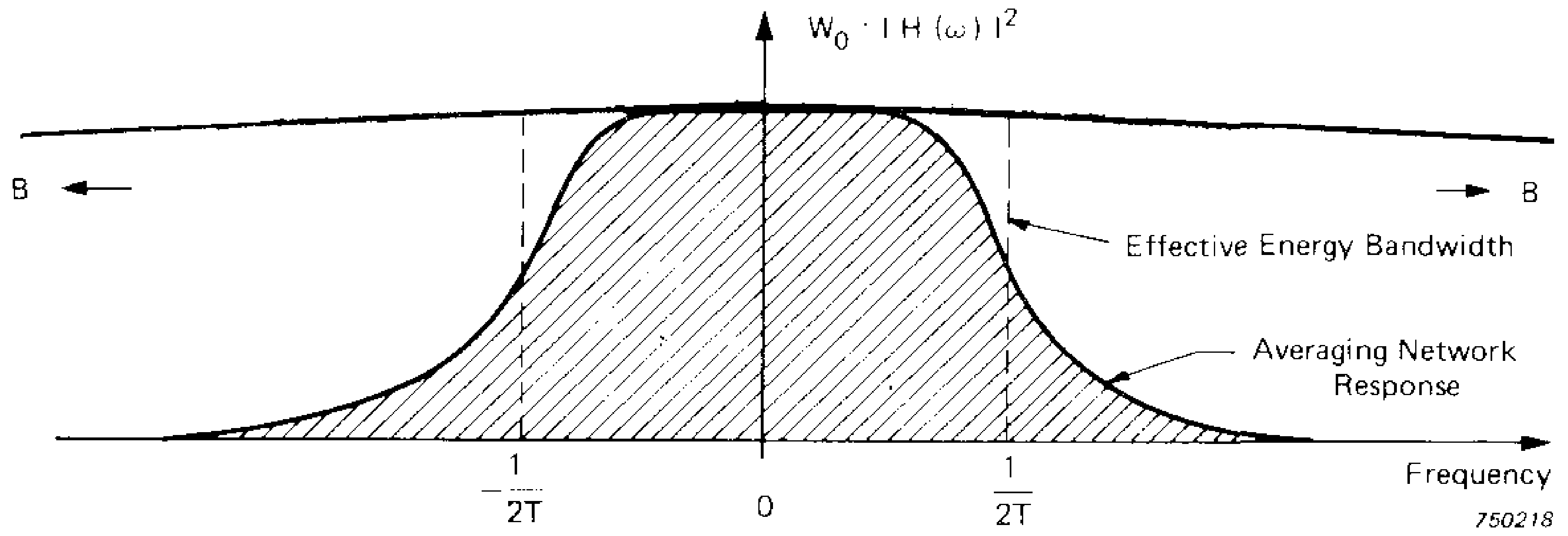

Fig. 6. The low-frequency portion of the squared signal spectrum shown with expanded frequency scale, together with the effect of passing the spectrum through an averaging network.

The squared *RMS*-value of the *fluctuations* at the output of the averaging circuit, or in statistical terms: the variance of the mean square fluctuations after averaging, will be:

$$\sigma_1{}^2 = \int_{-\infty}^{\infty} w_0 \cdot |H_1(\omega)|^2\, df = \int_{-\infty}^{\infty} \alpha^2 w_B{}^2 B \left(\frac{\sin(\pi f T)}{\pi f T}\right)^2 df$$

as $\omega = 2\pi f$.

Thus

$$\sigma_1{}^2 = a^2 w_B{}^2 \frac{B}{T}$$

or:

$$\sigma_1 = a w_B \sqrt{\frac{B}{T}}$$

Now, the mean square value of an "ideal" band of random noise with constant spectral density is:

$$E' = w_B B$$

and, taking the instrumentation constant, a, into account:

$$E = a w_B B$$

The *relative energy* fluctuations at the output of the averager is thus:

$$\frac{\sigma_1}{E} = \frac{a w_B \sqrt{B/T}}{a w_B B}$$

or:

$$\boxed{\frac{\sigma_1}{E} = \frac{1}{\sqrt{BT}}}$$

b) If the averaging process is of the RC-weighted type then the squared frequency response function would be:

$$|H_2(\omega)|^2 = \frac{1}{1 + \omega^2 R^2 C^2} = \frac{1}{1 + (f/f_0)^2}$$

where $f_0 = \frac{1}{2\pi RC}$.

Substituting this kind of averaging for the one treated above results in a variance of the mean square fluctuations after averaging of:

$$\sigma_2{}^2 = \int_{-\infty}^{\infty} a^2 w_B{}^2 B \frac{df}{1 + (f/f_0)^2} = a^2 w_B{}^2 B \pi f_0$$

and:

$$\sigma_2 = a w_B \sqrt{B \pi f_0}$$

whereby the relative energy fluctuations at the output of the averager becomes:

$$\frac{\sigma_2}{E} = \frac{a w_B \sqrt{B \pi f_0}}{a w_B B}$$

or:

$$\boxed{\frac{\sigma_2}{E} = \sqrt{\frac{\pi f_0}{B}} = \frac{1}{\sqrt{2BRC}}}$$

Equating the relative energy fluctuations at the output of the two kinds of averagers one obtains:

$$\frac{1}{\sqrt{BT}} = \sqrt{\frac{\pi f_0}{B}} = \frac{1}{\sqrt{2BRC}}$$

or:

$$\boxed{T = \frac{1}{\pi f_0} = 2RC}$$

where f_0 is the 3 dB upper limiting frequency of the RC-network (Fig. 4b). Another fact, which is worth noting in connection with the above derivations is that because the comparison has been based on *energy* considerations also *the energy* (*or noise*) *bandwidths of the two averagers are the same.*

4. Averaging of Periodic Signals

Two important types of periodic signals are considered in the following because they represent "limiting" cases. The first type of signal is the simple (harmonic) sine-wave, while the second type consists of an "infinite" train of periodically repeated δ-functions.

In the case of *the simple sine wave signal* the use of frequency domain descriptions may again prove to be the most straight forward method of dealing with the problem.

Considering the signal to be measured to be given by:

$$x(t) = X_0 \sin(\omega t)$$

where $\omega = 2\pi f$, the "energy" signal at the input to the averager would be:

$$f(\tau) = a x^2(t) = a X_0^2 \sin^2(\omega\tau) = \frac{a X_0^2}{2}(1 - \cos(2\omega\tau))$$

where, once again, a is an instrumentation constant. Fig. 7 shows this signal both in the time domain and in the frequency domain, and it is readily seen that it consists of a DC-component, $(a/2)X_0^2$,

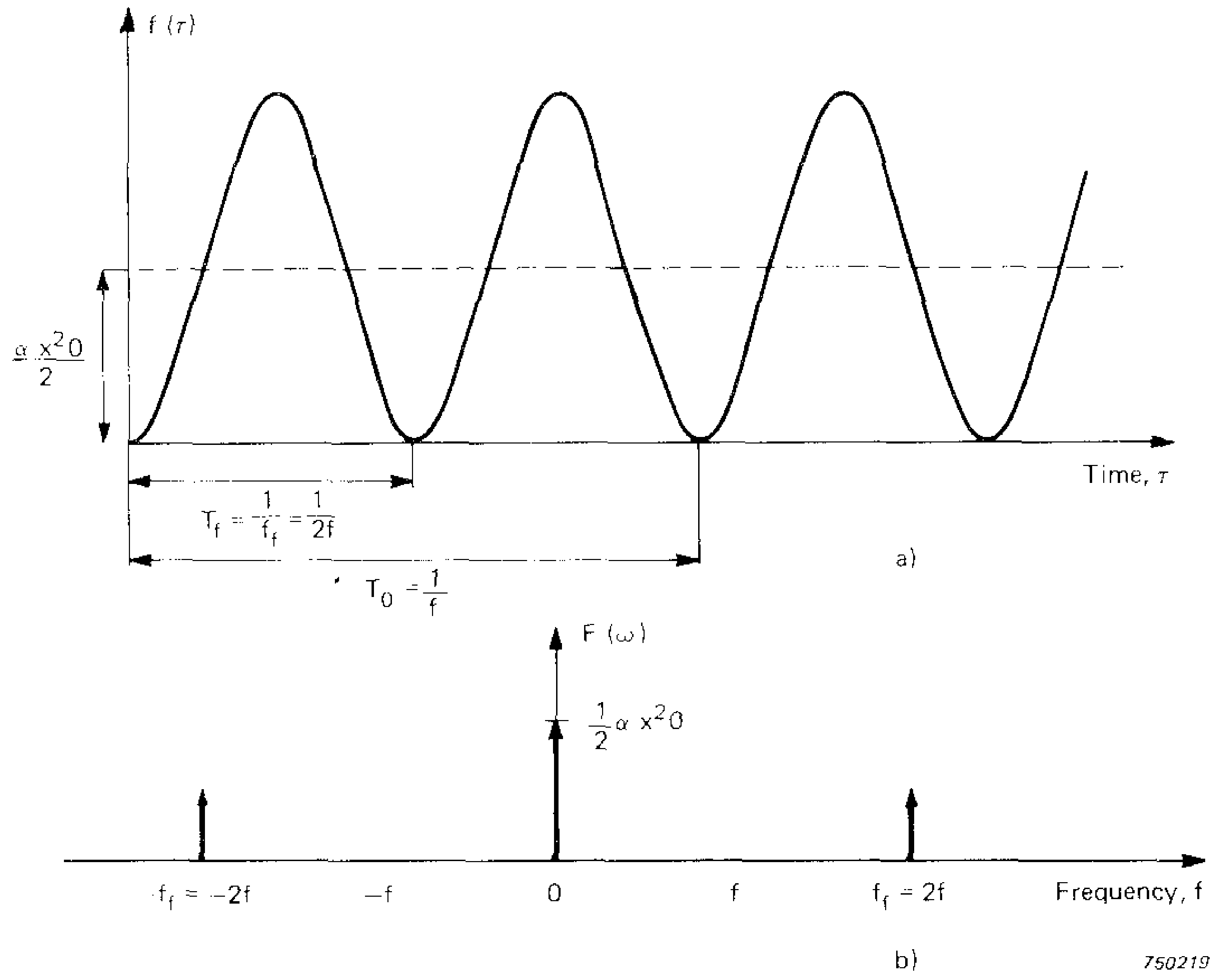

Fig. 7. The input signal to the averaging network when the signal to be measured consists of a pure harmonic (sine wave) signal.
a) Time domain description
b) Frequency domain description

and a fluctuating component, $(a/2)X_0{}^2$, fluctuating with a frequency $f_f = (2\omega/2\pi) = 2f$.

When this signal is passed through an averaging network the DC-component remains the same (the "true" value of the signal) while the fluctuating component is attenuated in accordance with the frequency response function of the network.

If the averaging process is of the type:

$$\frac{1}{T}\int_0^T f(\tau)\, d\tau$$

i.e. its corresponding frequency response function is:

$$|H_1(\omega)| = \frac{\sin(\omega_f T/2)}{\omega_f T/2}$$

the maximum relative energy fluctuations at the output of the averager are given by:

$$\frac{\varepsilon_1}{E} = \frac{\frac{1}{2}aX_0{}^2\left(1 \pm \dfrac{\sin(\omega_f T/2)}{\omega_f T/2}\right)}{\frac{1}{2}aX_0{}^2}$$

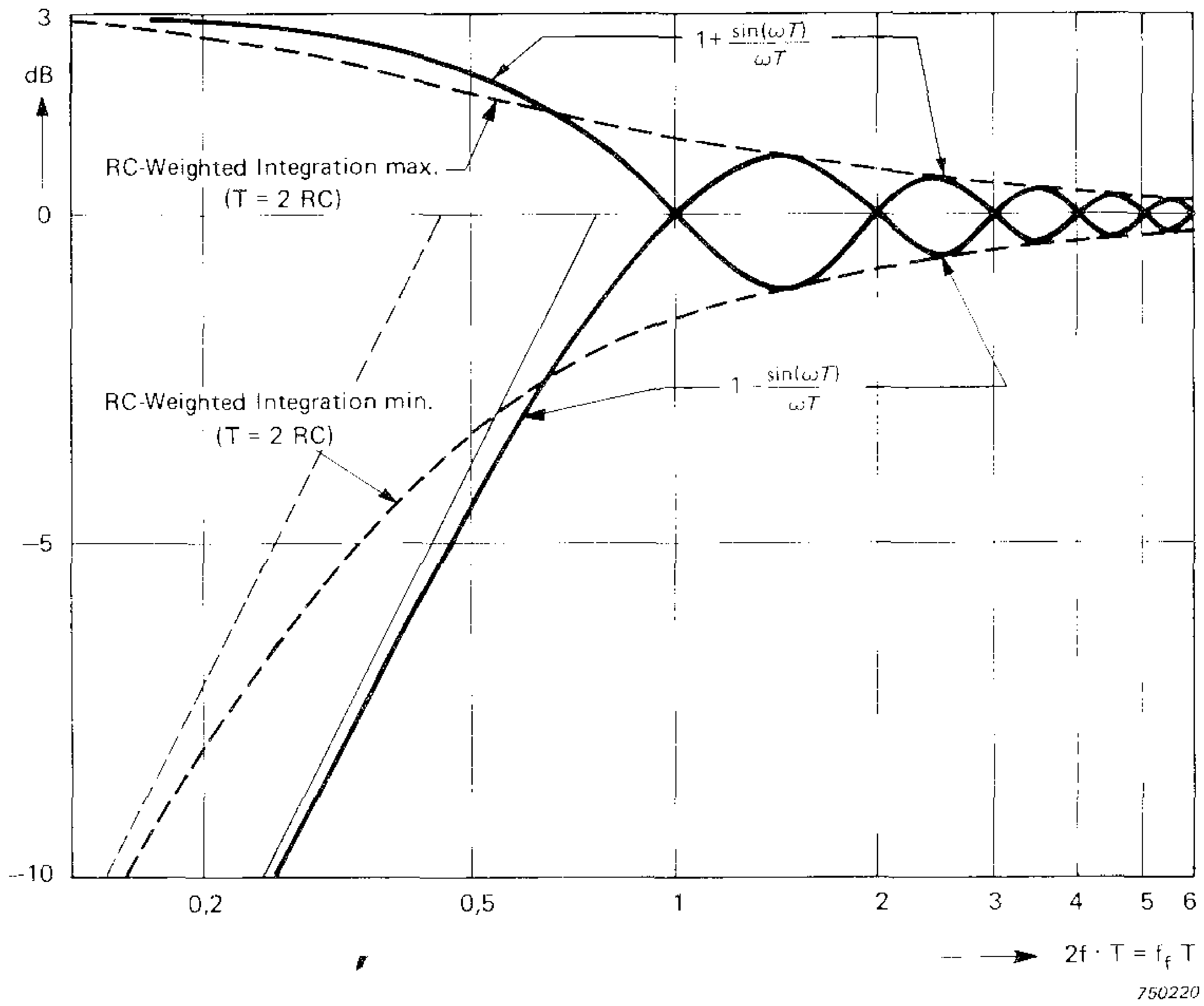

Fig. 8. Maximum "energy" fluctuations of sine-wave signals after averaging.

or

$$\boxed{\frac{\varepsilon_1}{E} = 1 \pm \frac{\sin(\omega T)}{\omega T}}$$

as $\omega = 2\pi f = \pi f_f$.

The function ε_1/E is shown graphically to logarithmic scales in Fig. 8 (fully drawn curves). Actually the shape of the curves is intuitively understood by considering the physical process of integration. Wherever the integration time T equals an even number of half periods of the fluctuation frequency ($f_f = 2f$) then the "net"-fluctuation will be zero.

In fact, the curves represent the maximum and minimum deflections of an "ideal" logarithmic (dB) instrument meter.

Considering next an averaging process of the RC-weighted type with a frequency response function of the kind

$$|H_2(\omega)| = \frac{1}{\sqrt{1 + (\omega_f RC)^2}}$$

Then

$$\frac{\varepsilon_2}{E} = \frac{\frac{1}{2}aX_0{}^2(1 \pm 1/\sqrt{1 + (\omega_f RC)^2})}{\frac{1}{2}aX_0{}^2}$$

or:

$$\frac{\varepsilon_2}{E} = 1 \pm \frac{1}{\sqrt{1 + (2\omega RC)^2}}$$

as again $\omega = 2\pi f = \pi f_f = \omega_f/2$.

Setting $T = 2RC$ gives:

$$\boxed{\frac{\varepsilon_2}{E} = 1 \pm \frac{1}{\sqrt{1 + (\omega T)^2}}}$$

The function ε_2/E is also plotted in Fig. 8 (dotted curves) and shows that when T is chosen to equal 2 RC, as postulated for narrow band random noise, then, in the case of harmonic signals, the *maximum* fluctuations at the output of the averager are the same for the two kinds of averagers†.

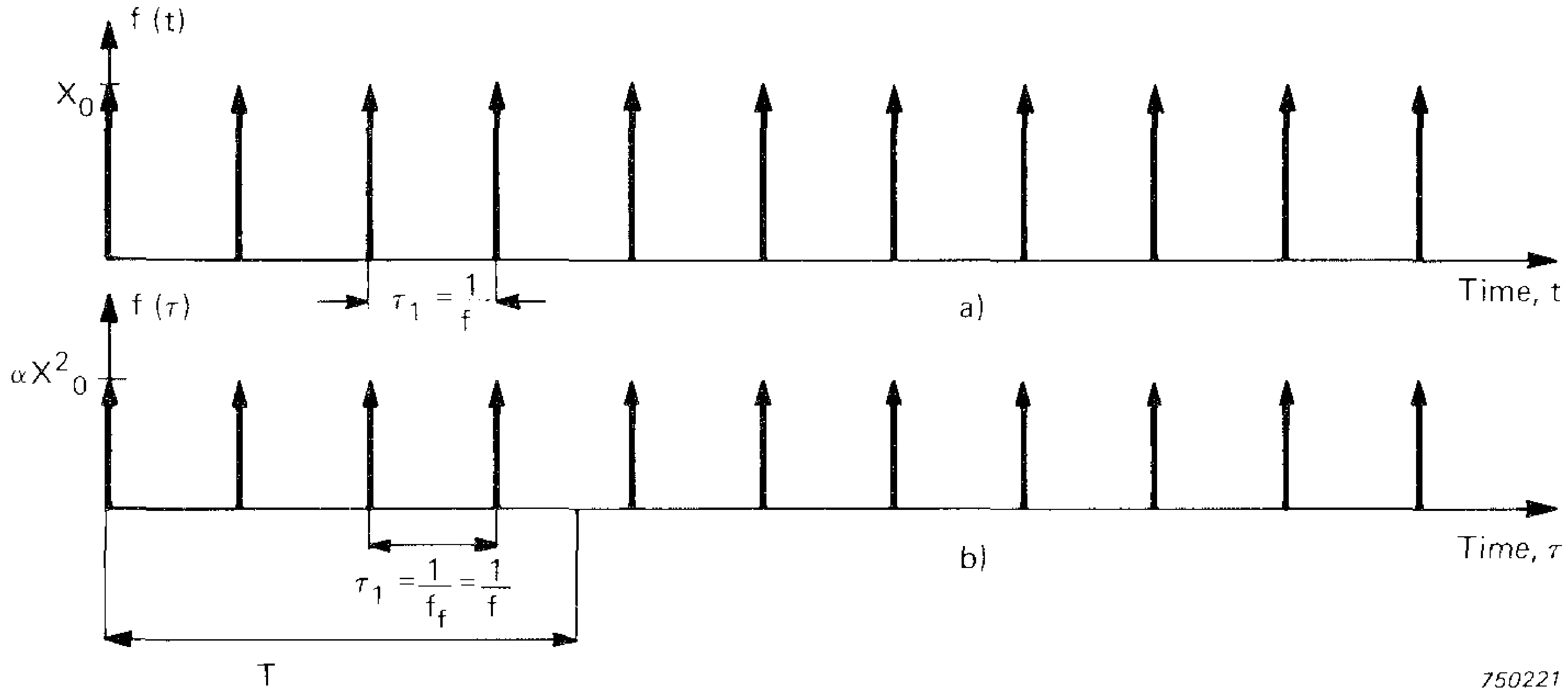

Fig. 9. Illustration of a time-train of impulse functions.
a) Input signal to be measured
b) Input to the averager (squared signal)

In the case of periodically repeated δ-functions, Fig. 9, the averaging process may be more advantageously treated by means of time-domain methods than by means of frequency domain methods, see Appendix A.

Actually, the signal shown in Fig. 9b), i.e. the "energy" signal at the input to the averager, can in this case be mathematically described by the function:

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† This is, however, only strictly true when the product fT is larger than, say 1.5.

$$f(\tau) = aX_0^2 \sum_n \delta(\tau - n\tau_1)$$

where τ_1, is the repetition period, and $\delta(\tau - n\tau_1)$ describes δ-functions (unit impulse functions) occurring at times $\tau = n\tau_1$.

If the averager is the type

$$\frac{1}{T}\int_0^T f(\tau)\, d\tau$$

the relative "energy"-fluctuations, η_1/E, can be expressed as:

$$\boxed{\left(\frac{\eta_1}{E}\right)_{\max} = \frac{n+1}{fT}} \quad \text{and} \quad \boxed{\left(\frac{\eta_1}{E}\right)_{\min} = \frac{n}{fT}}$$

where $f = 1/\tau_1$, and $T = n\tau_1 + \tau_x$ (Fig. 9b)). $n = 0, 1, 2, 3$, etc.

These fluctuations are plotted (fully drawn curves), again to logarithmic scales, in Fig. 10.

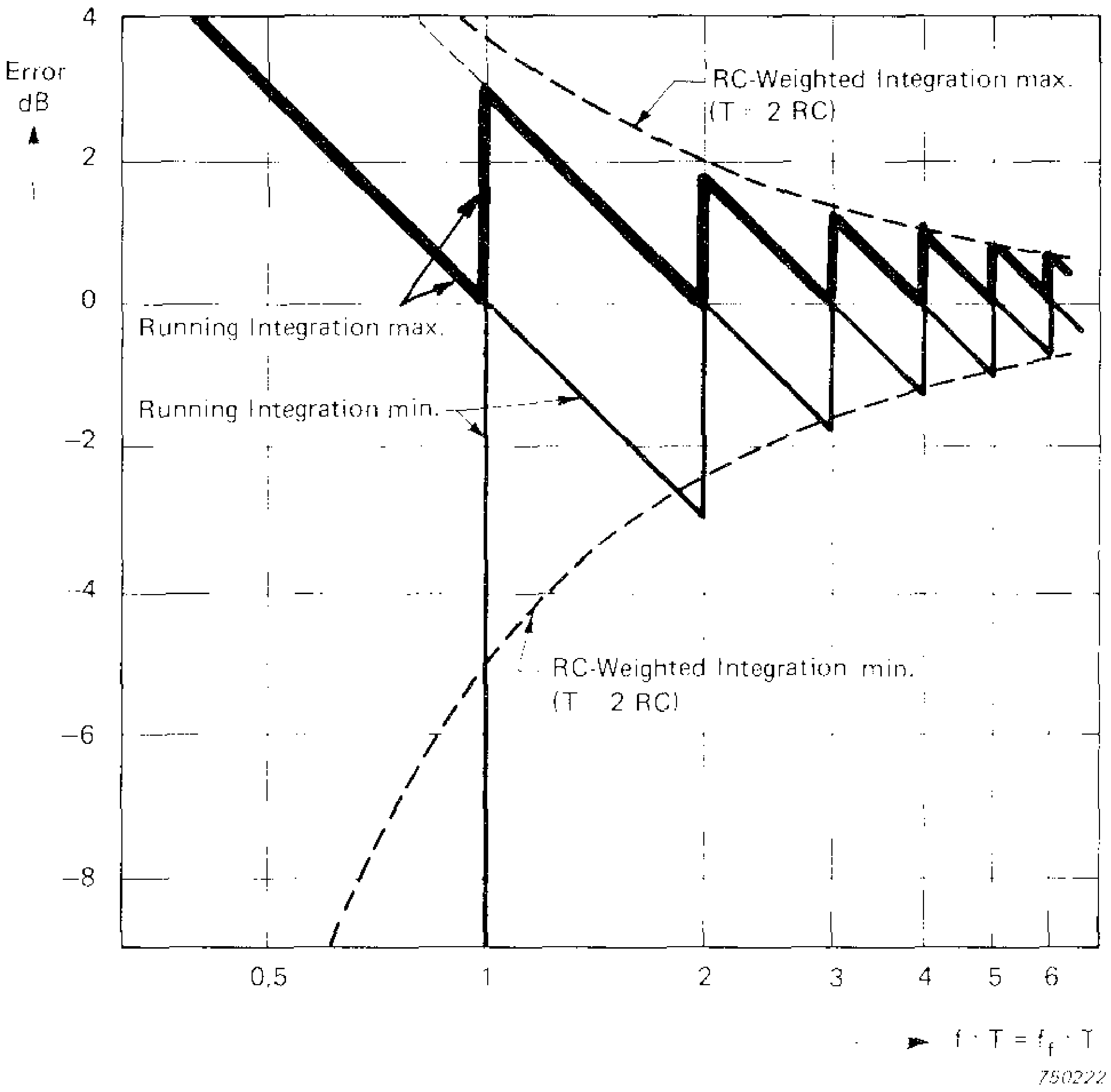

Fig. 10. Maximum "energy" fluctuations of a time train of δ-impulses after averaging.

If the averager is of the RC-weighted type the time function output from the averaging process can be mathematically formulated in terms of the convolution signal and the relative "energy"-fluctuations, η_2/E, become:

$$\boxed{\left(\frac{\eta_2}{E}\right)_{\max} = \frac{2}{fT(1-\exp(-2/fT))}}$$

and

$$\boxed{\left(\frac{\eta_2}{E}\right)_{\min} = \frac{2}{fT(\exp(2/fT)-1)}}$$

Also these functions are plotted in Fig. 10 (dotted curves), and again $f = 1/\tau_1$ and $T = 2\ RC$.

Note that even in this case the relative fluctuations in the RC-weighted averaging practically envelopes the fluctuations in the running integration type of averaging.

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APPENDIX A

Averaging of Periodically Repeated δ-Functions

As stated in the main text of this paper the averaging of periodically repeated δ-function is best studied in terms of time-domain methods.

Considering first the case of running integration the output from the averager would have the form:

$$\eta_1 = \frac{aX_0^2}{T}\int_0^T \sum_n \delta(\tau - n\tau_1)\, d\tau$$

or

$$\eta_1 = \frac{aX_0^2}{T}\sum_n \int_0^T \delta(\tau - n\tau_1)\, d\tau$$

The evaluation of this expression depends upon the relationship between τ, T and $n\tau_1$, and may be best understood by the following reasoning:

The summation of the δ-function integral, i.e.:

$$\sum_n \int_0^T \delta(\tau - n\tau_1)\, d\tau$$

actually expresses how many unit impulses are within the integration interval T. If, for instance, $0 \leqq T \leqq \tau_1$, only one impulse (or none) is inside the integration interval. The output from the averager will therefore fluctuate between 0 and a maximum value of $a \cdot (X_0^2/T)$. It is readily seen that this maximum value decreases hyperbolically as T increases.

When T becomes larger than τ_1, then either one or two impulses are included in the averaging process. In general, therefore, when T is larger than τ_1 the maximum value of the fluctuations can be mathematically described in the form:

$$(\eta_1)_{\max} = \frac{aX_0^2}{T} \sum_{n+1} \int_0^T \delta(\tau - n\tau_1)\, d\tau$$

$$= \frac{aX_0^2(n+1)}{n\tau_1 + \tau_x}$$

where $n\tau_1 + \tau_x = T$ and $0 \leqq \tau_x \leqq \tau_1$

Similarly the minimum value of the fluctuations is given by:

$$(\eta_1)_{\min} = \frac{aX_0^2 n}{n\tau_1 + \tau_x}$$

The "true" average of the signal is:

$$E = \frac{aX_0^2}{\tau_1}$$

and introducing $f = 1/\tau_1$, the relative "energy" fluctuations, η_1/E become:

$$\underline{\left(\frac{\eta_1}{E}\right)_{\max} = \frac{n+1}{fT}} \quad \text{and} \quad \underline{\left(\frac{\eta_1}{E}\right)_{\min} = \frac{n}{fT}}$$

In the case of RC-weighted averaging the output from the averager is again obtained by means of time domain convolution and takes the form:

$$\eta_2 = \frac{\alpha X_0^2}{RC} \int_0^t \sum_n \delta(\tau - n\tau_1)\exp[-\,(t-\tau)/RC]\; d\tau$$

or

$$\eta_2 = \frac{\alpha X_0^2}{RC} \sum_n \int_0^t \delta(\tau - n\tau_1)\exp[-\,(t-\tau)/RC]\; d\tau$$

Physically this means that every time an impulse occurs the averager will respond in terms of its impulse response function, and at any instant of time, t, the total response is equal to the sum of all the impulse responses up to that instant. This is illustrated in Fig. A.1 for a particular instant of time, t_1.

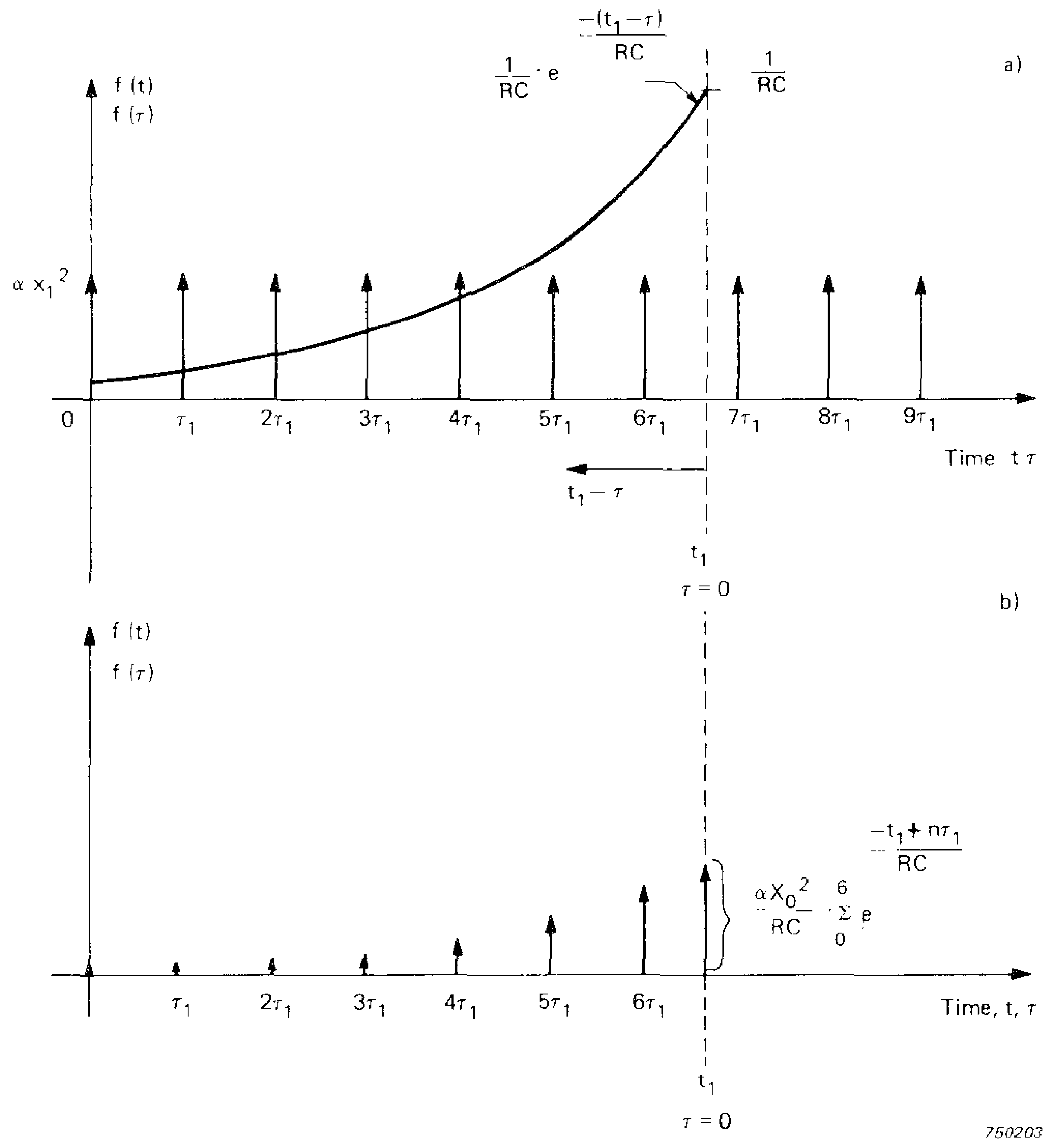

Fig. A.1. Illustration of RC-weighting of a train of impulses (convolution technique).

From the figure it can also be deduced that the response must have a maximum immediately after an instant where $t = n\tau_1$, and then decay according to the exponential function until immediately before $t = (n+1)\tau_1$.

The maximum value is obviously

$$(\eta_2)_{\max} = \frac{\alpha X_0^2}{RC} \sum_0^n \exp(-n\tau_1/RC)$$

and the minimum value:

$$(\eta_2)_{\min} = \frac{\alpha X_0^2}{RC} \sum_0^n \exp(-(n+1)\tau_1/RC) = (\eta_2)_{\max} \exp(-\tau_1/RC)$$

The absolute maximum is (theoretically) reached when $n \to \infty$ and the sum then represents an infinite geometric progression:

$$\sum_{n=0}^{\infty} (\exp(-\tau_1/RC))^n$$

and as $\exp(-\tau_1/RC) < 1$ then:

$$\sum_{n=0}^{\infty} (\exp(-\tau_1/RC))^n = \frac{1}{1-\exp(-\tau_1/RC)}$$

Again the "true" average of the signal is:

$$E = \frac{\alpha X_0^2}{\tau_1}$$

whereby

$$\left(\frac{\eta_2}{E}\right)_{\max} = \frac{(\tau_1/RC)}{1-\exp(-\tau_1/RC)}$$

The minimum value of the relative fluctuations can now be obtained from:

$$\left(\frac{\eta_2}{E}\right)_{\min} = \left(\frac{\eta_2}{E}\right)_{\max} \exp(-\tau_1/RC) = \frac{(\tau_1/RC)}{\exp(\tau_1/RC)-1}$$

Introducing $T = 2RC$ and $f = 1/\tau_1$, the results can be written:

$$\underline{\left(\frac{\eta_2}{E}\right)_{\max} = \frac{2}{fT(1-\exp(-2/fT))}}$$

and

$$\underline{\left(\frac{\eta_2}{E}\right)_{\min} = \frac{2}{fT(\exp(2/fT)-1)}}$$

Averaging Time of Level Recorder Type 2306 and "Fast" and "Slow" Response of Level Recorders 2305/06/07

by

K. Zaveri, M. Phil.

ABSTRACT

The averaging time of Level Recorder Type 2306 was determined for its various writing speeds. Investigations were also carried out to determine the most suitable writing speeds that would simulate pen fluctuations of a Level Recorder with the meter needle deflections of a Sound Level Meter. For small pen fluctuations writing speeds of Level Recorders Types 2305/06/07 are suggested for AC and DC recording that will yield the best correlation.

SOMMAIRE

Le temps d'intégration de l'Enregistreur de Niveau Type 2306 a été déterminé pour les différentes vitesses d'écriture de l'appareil. On a également cherché à déterminer les vitesses d'écriture qui permettent d'obtenir des fluctuations du système d'écriture simulant les déflexions de l'aiguille d'un sonomètre. Pour de petites fluctuations, on suggère les vitesses d'écriture des Enregistreurs de Niveau Types 2305/06/07 donnant, pour les enregistrements en alternatif et en continu, la meilleure corrélation.

ZUSAMMENFASSUNG

Die Mittlungszeit des Pegelschreibers Typ 2306 wurde in Abhängigkeit von der einstellbaren Schreibgeschwindigkeit bestimmt. Auch wurden Untersuchungen angestellt, um diejenigen Schreibgeschwindigkeiten herauszufinden, bei denen die Schreibstiftschwankungen eines Pegelschreibers mit den Zeigerausschlägen eines Schallpegelmessers bestmöglich korrespondieren. Für Gleich- und Wechselspannungsaufzeichnung mit den Pegelschreibern 2305/06/07 werden Einstellungen vorgeschlagen, für die bei kleinen Ausschlägen die beste Übereinstimmung erzielt wird.

Introduction

Since the publication of Technical Review No. 1 1974, describing the measurement of Averaging Times of Level Recorders Types 2305 and 2307, Brüel & Kjær have developed a transportable Level Recorder Type 2306. The Averaging Time of this Level Recorder is determined and the results presented as a function of its writing speed in Part I of this article.

Furthermore, the desire to try to correlate the meter response of conventional Sound Level Meters with level recorder pen fluctuations, has lead to the investigations described in Part II of this article. However, the task of simulation of meter needle deflections with pen fluctuations on the Level Recorder paper is not as simple and direct as one might expect at first sight. The main reason for this is that the modes of operation and thus the dynamics of the Sound Level Meter and the Level Recorder are basically different. While the definition of "Fast" and "Slow" response, primarily intended for Sound Level Meter, is based on tone burst response, such a definition, as will be shown by the results, is not suitable for a Level Recorder as its response is dependent on the amplitude levels of tone bursts.

The following three types of experiments were carried out:

a) Direct comparison of Meter Needle deflections of a Sound Level Meter with pen fluctuations of a Level Recorder at different writing speeds for a narrow band random noise input.

b) Measuring the frequency response characteristic of the Sound Level Meter and the Level Recorder for a 10 kHz carrier frequency signal input, amplitude modulated by a low frequency sinusoid.

c) Determining Level Recorder response to tone burst signals (cfr. IEC 179).

Part 1

Averaging Time of Level Recorder Type 2306

The measurement of Averaging Time of Level Recorder Type 2306 was carried out in identically the same manner as described in Technical Review No. 1, 1974, (Ref. 1) for Level Recorders Types 2305 and 2307. A band-limited white noise signal was fed to the Level Recorder (fitted with a 50 dB pot.) and the resulting pen fluctuations were transformed proportionally to an electrical signal with the aid of a specially prepared transducer and an Analog Voltage Readout Type ZR 0021. (24 V DC for ZR 0021 was supplied from a Level Recorder Type 2305). The electrical signal was amplified by an experimental AC preamplifier with a very low lower limiting frequency and RMS detected by a modified Measuring Amplifier Type 2607 which allowed measurements to very low frequencies, see Fig. 1.

For a logarithmic potentiometer the measured RMS value of the fluctuations can be considered to be a measure of the relative amplitude error

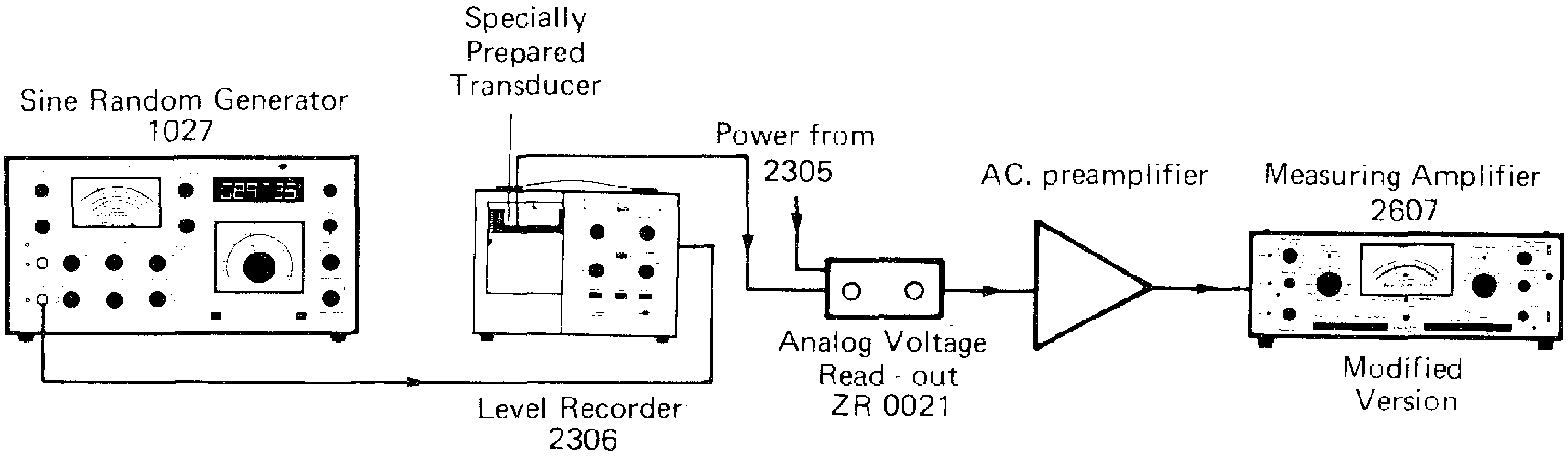

Fig. 1. Measurement Arrangement for averaging times

ϵ_2. For small fluctuations the amplitude error equals half the energy error ϵ_1 and can be expressed in terms of bandwidth and averaging time as derived in Ref. (2) and (3).

$$\epsilon_2 = \frac{\epsilon_1}{2} = \frac{1}{2\sqrt{BT}} \qquad \text{i. e. } T = \frac{1}{4B\epsilon_2^2}$$

where B is the noise bandwidth,
and T is the averaging time.

A numerical example of the calibration procedure and of the calculation is given below. The output voltage from ZR 0021 was adjusted to change 2V DC for a change of 10dB in position (50dB potentiometer and 50mm paper). For a noise signal input of 31,6Hz bandwidth at 1000Hz centre frequency to the Level Recorder set at a writing speed of 100mm/s, the measured RMS value at the ZR 0021 output was 380mV. This voltage corresponds to 1,9 dB_{RMS} or a ratio of R = antilog (1,9/20) = 1,2445. The relative error ϵ_2 = 0,2445 thus obtained, can be used to calculate the averaging time from the equation

$$T = \frac{1}{4B\epsilon_2^2} = \frac{1}{4 \times 31{,}6 \times 0{,}2445^2} = 0{,}132\,\text{s}$$

In order to determine ϵ_2 accurately enough, it is necessary to measure the very low frequency components of the pen fluctuations which is particularly important at low writing speeds. The measurement system was therefore extended down to 0,002Hz the RC lower limiting frequency of the AC preamplifier while the detection time constant of 300s of the meter circuit of a Measuring Amplifier Type 2607 was used. The meter circuit alone, has virtually DC response when the capacitor C 1212 (0,68μF) on circuit board ZL 0027 is short circuited as

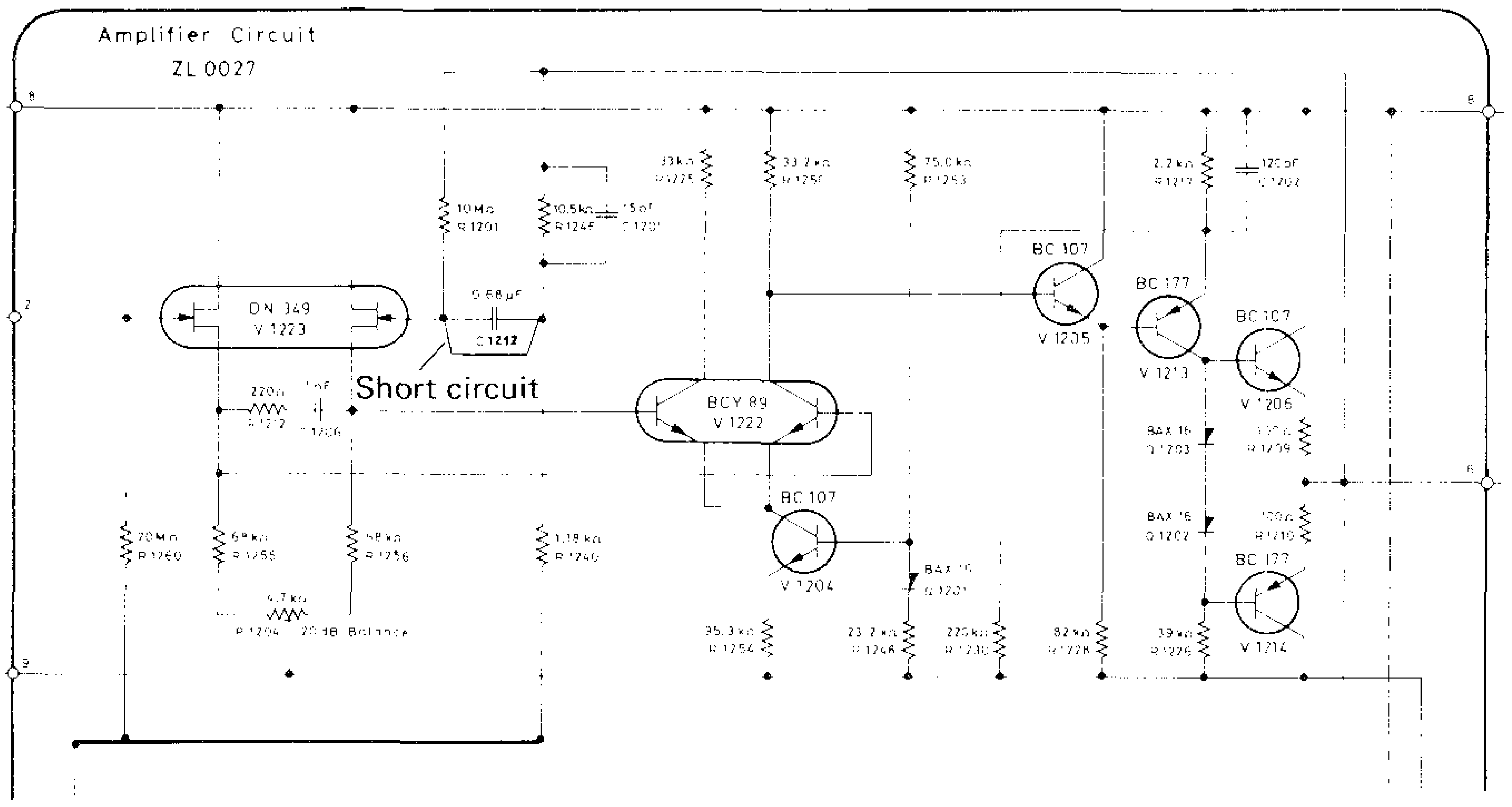

Fig.2a. The short circuit over the capacitor C 1212 in ZL 0027

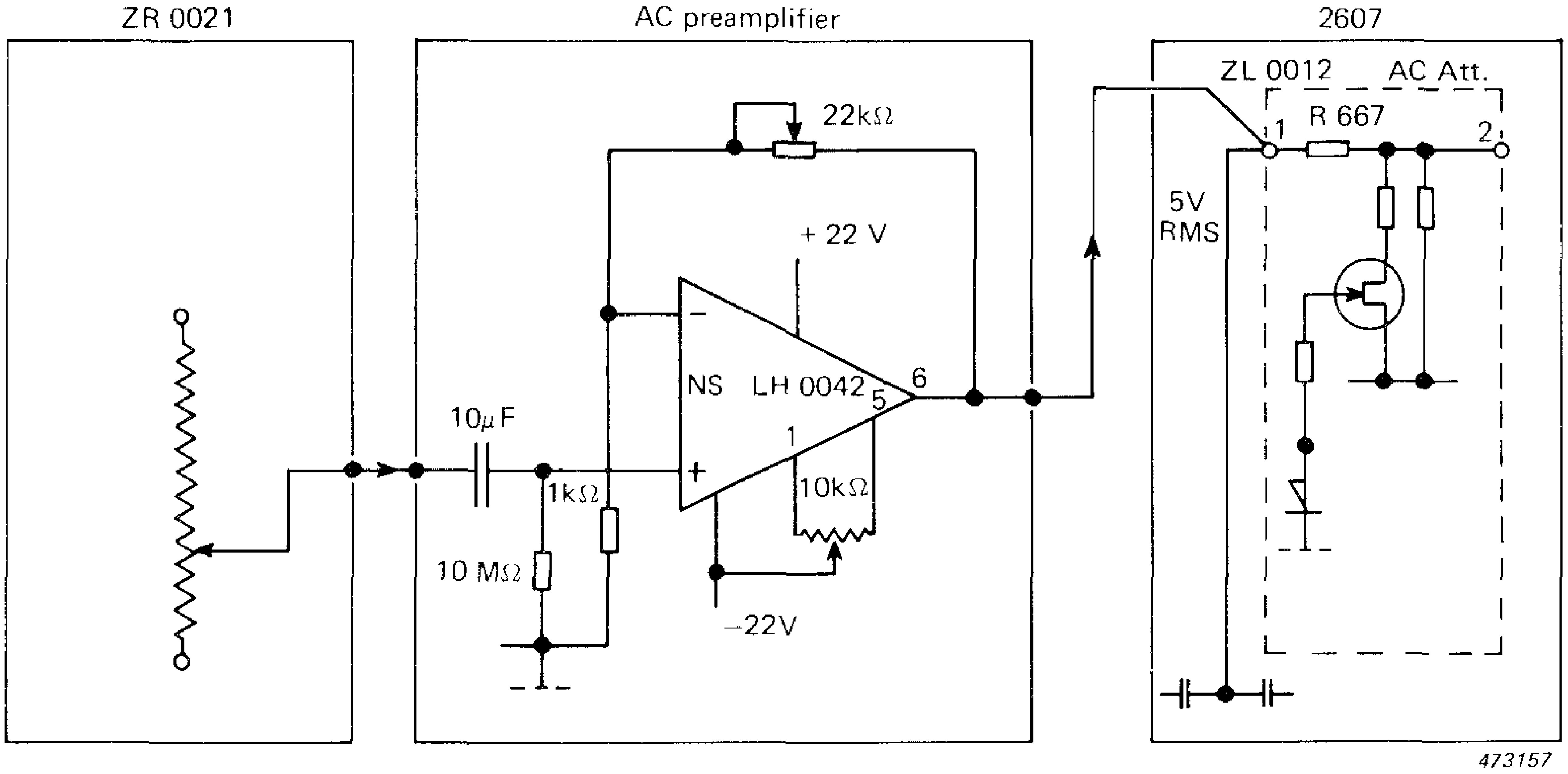

Fig.2b. The AC-preamplifier connected to ZR 0021 and 2607

shown in Fig.2a and provides full meter deflection for an input voltage of 10V_{RMS}. The need for gain in a separate amplifier can thus be seen and is provided by the AC preamplifier. The output from the AC preamplifier is connected to pin 1 of circuit board ZL 0012 of the Measuring Amplifier Type 2607. Care should, however, be taken as no overload protection is provided at this point. A diagram of the preamplifier is given in Fig.2b together with its connection to the meter section of 2607.

The band limited noise signal was supplied from the Sine Random Generator Type 1027 where the bandwidths quoted are the effective noise bandwidths.

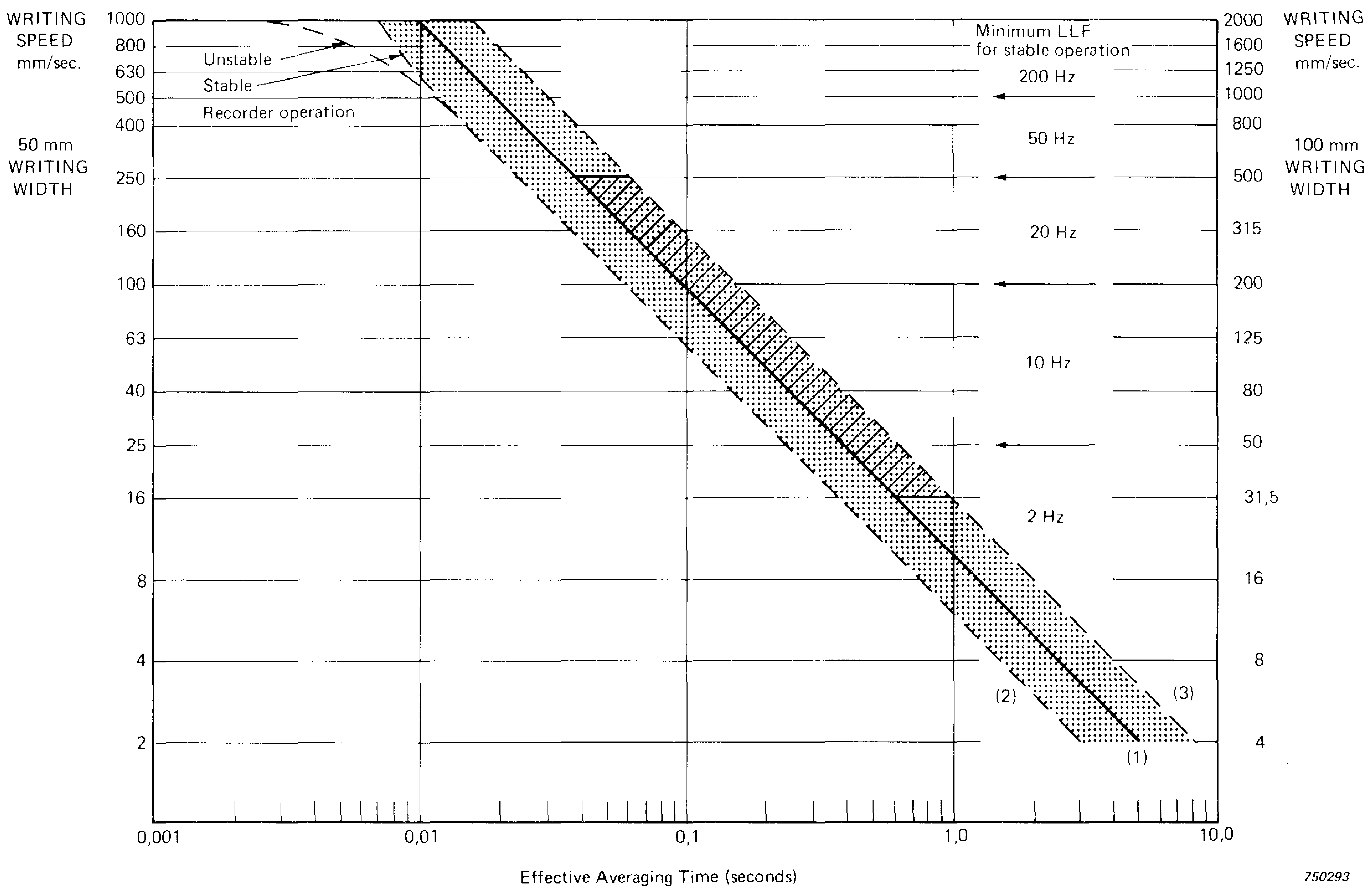

Fig. 3. Averaging Time with tolerance limits against writing speed

Measurement Results

Experiments were carried out by applying different noise bandwidths to the Level Recorder and measuring the resultant various levels of pen fluctuations. Fig.3 shows a plot of averaging time against writing speed where the spread of results obtained for the Level Recorder Type 2306 is shown by the double shaded area lying between curves 1 and 3 for the four writing speeds of 16, 40, 100 and 250 mm/s. Curves 1, 2 and 3, reproduced from Ref. (1), refer to the averaging times for Level Recorders Types 2305 and 2307. Curve 2 also given in Ref. (2), gives the limiting curve for zero pen fluctuations; curve 1 represents the averaging time of Level Recorders 2305 and 2307 for normal Recorder Settings (described in Ref. 1), while curve 3 is considered as the limiting curve for maximum allowed pen fluctuations. As can be seen, the averaging time of Level Recorder Type 2306 agrees reasonably well with those of Level Recorders 2305 and 2307 and curve 1 is suggested to be the nominal curve also for Level Recorder Type 2306.

Part 2

Simulation of "Fast" and "Slow" Meter Time Constants on Level Recorders

Fluctuating sound pressure levels when measured with sound level meters are averaged on the Meter according to Internationally accepted Time Constants "Fast" or "Slow". However, the frequent desire to obtain permanent records on Level Recorder paper of the sound pressure level requires determination of the most suitable writing speed that simulates meter needle deflections as closely as possible. In the following, three methods are described for determining appropriate writing speeds.

a) Direct comparison of Meter Needle deflections with pen fluctuations

i) Fast Response

In this method band limited noise was fed to a Sound Level Meter Type 2209 (Set on "Fast") while its DC output was fed to the Level Recorder Type 2306, see Fig.4. For a fixed noise bandwidth input to the Sound Level Meter, the meter deflections were observed and the DC output from the Sound Level Meter was recorded at different writing speeds. A set of recordings were now obtained for different noise bandwidth inputs. Fig.5a shows DC recording at writing speeds 40, 100 and 250 mm/s for noise bandwidth inputs of 100 Hz and 31,6 Hz to the Sound Level Meter. For 100 Hz and 31,6 Hz the Meter deflections were approximately 3 dB and 7 dB peak-to-peak respectively. Comparison of Meter needle deflections and pen fluctuations (for amplitude

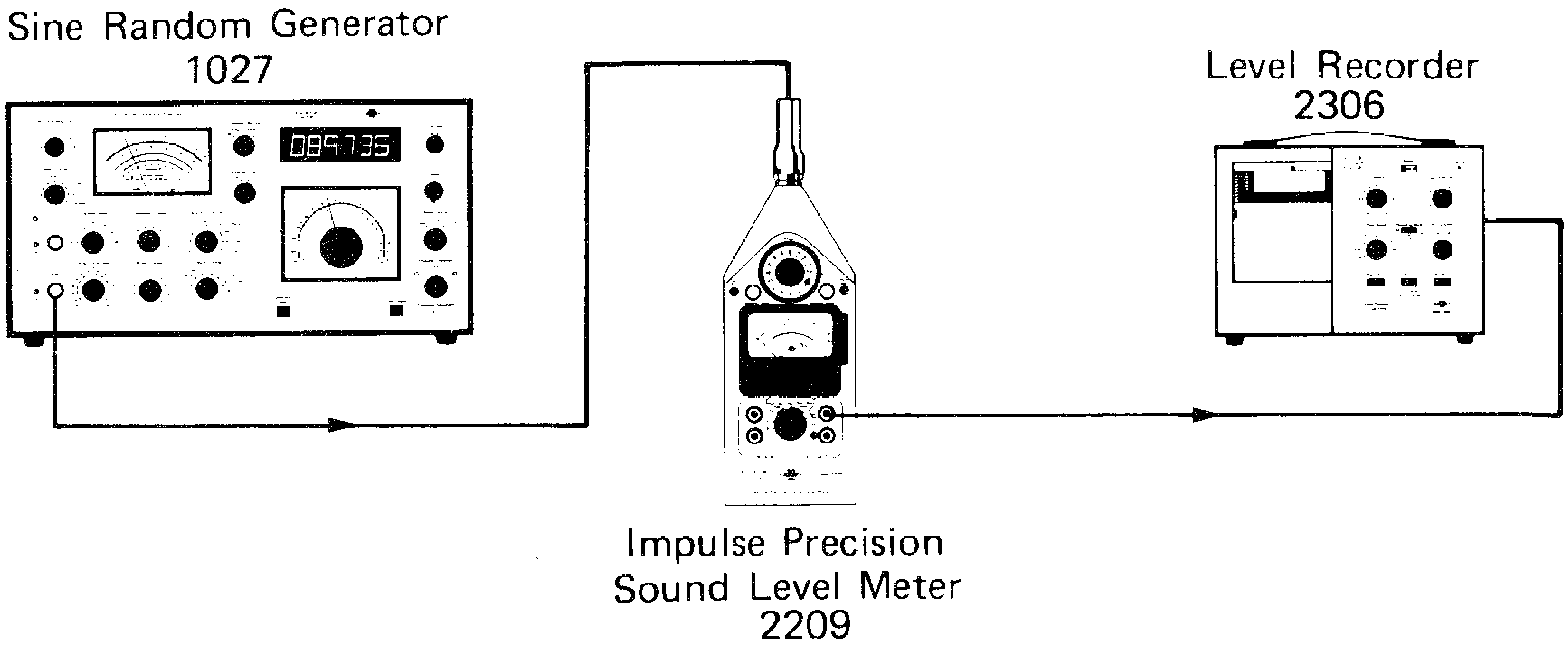

Fig. 4. Measurement Arrangement for deflection comparison tests

and frequency*) showed that the simulation at 100 mm/s for DC recording was most representative.

The AC output of the Sound Level Meter was now fed to the Level Recorder and AC recordings shown in Fig.5b were obtained at 40 and 100 mm/s for the same noise bandwidth inputs. It should be noted that for DC recording the averaging will be carried out by the RC network of the Sound Level Meter and that the Level Recorder pen and the meter needle will respond to the same DC voltage on the capacitor of the Sound Level Meter averaging circuit. The difficulty in simulation occurs after this stage, as the meter and the Level Recorder writing system dynamics come into play. For AC recording, however, an additional factor plays a role, namely that the averaging is now carried out only by the Level Recorder averaging circuit.

The AC recordings were therefore compared with meter needle deflections as well as DC recording at 100 mm/s. In this case writing speed of 40 mm/s for AC recording for small fluctuations was most suitable while 100 mm/s for large deflections.

ii) Slow Response
With the Sound Level Meter set on "Slow" response, effective noise bandwidths of 31,6 Hz and 10 Hz were supplied in turn to the Sound Level Meter and DC and AC recordings were taken at 16 and 40 mm/s

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* A frequent expression used for this kind of comparison estimation is "eyeballed" measurements.

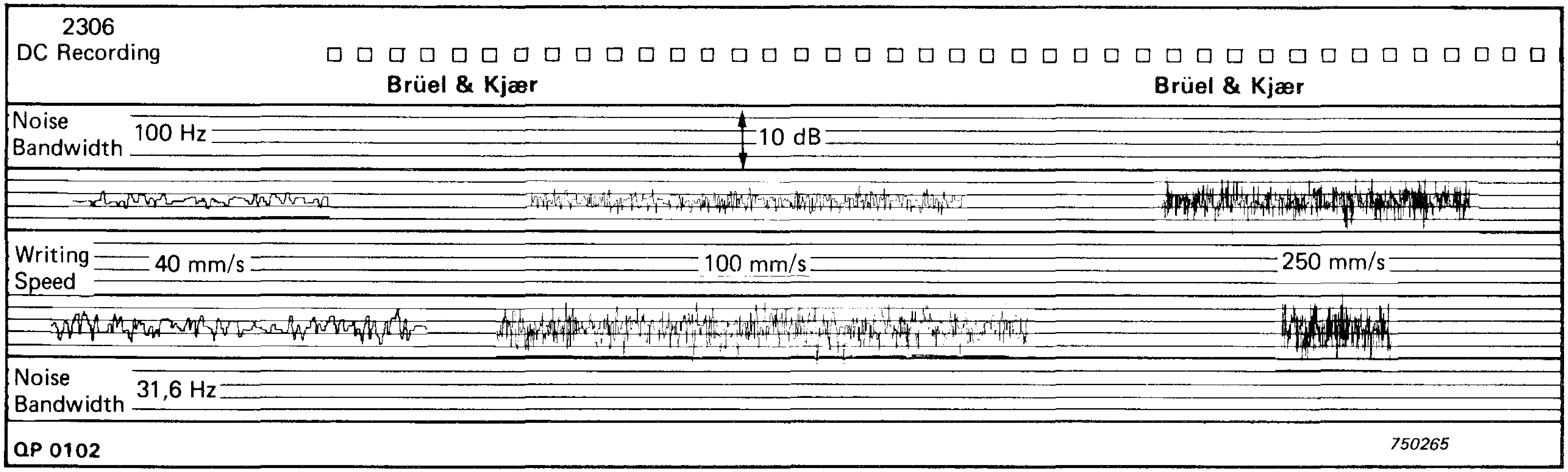

Fig.5a. 2306, DC recordings of narrow-band noise for simulation of "Fast" response

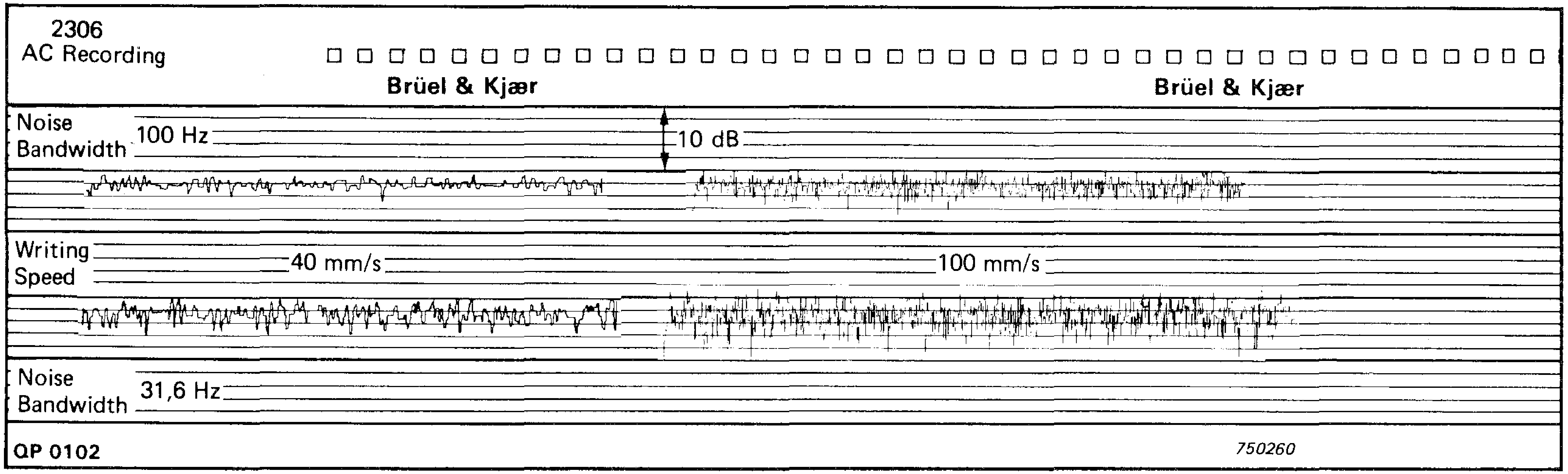

Fig.5b. 2306, AC recordings of narrow-band noise for simulation of "Fast" response

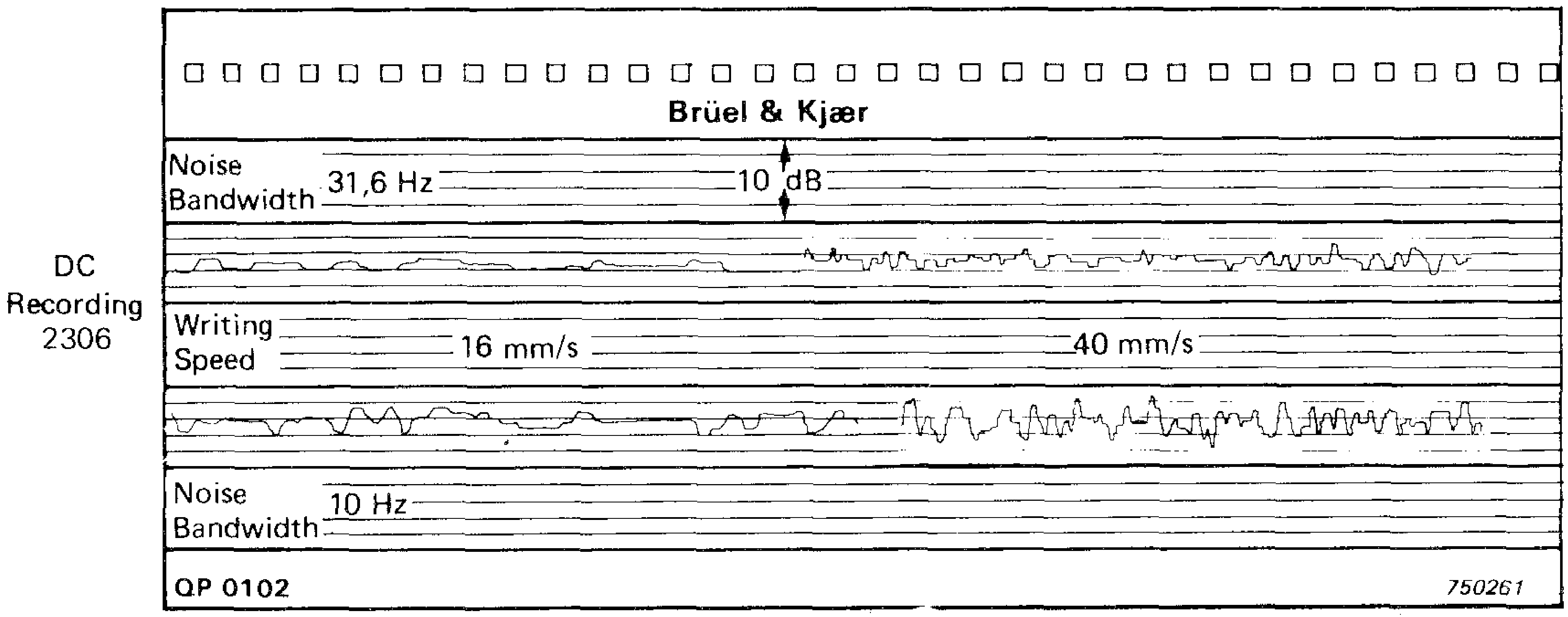

Fig.6a. 2306, DC recordings of narrow-band noise for simulation of "Slow" response

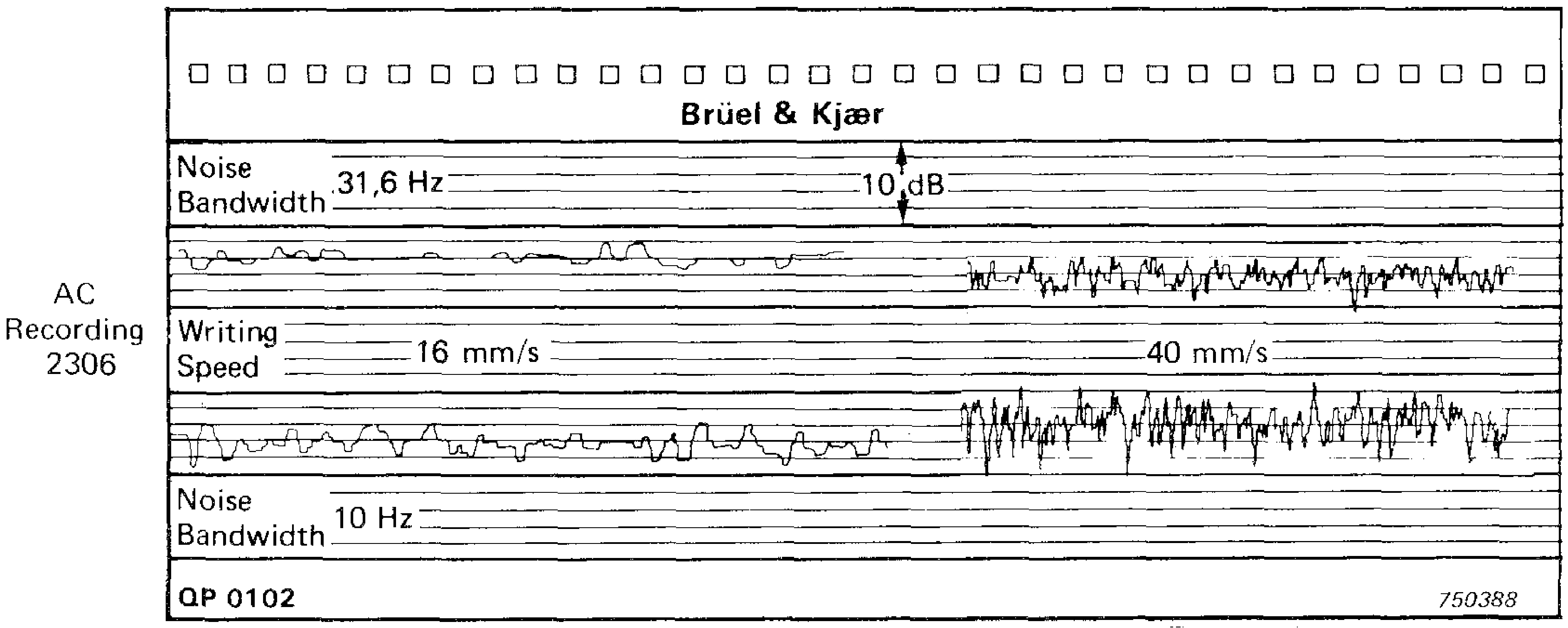

Fig.6b. 2306 AC recordings of narrow-band noise for simulation of "Slow" response

for Level Recorder Type 2306. The meter needle deflections were found to be 2 and 4 dB peak-to-peak for 31,6 Hz and 10 Hz respectively. The recordings are shown in Figs. 6a and 6b. For DC recording 40 mm/s was found to be most appropriate, while for AC recording 16 mm/s should be used.

b) Frequency Response Measurements

Fig.7 shows the arrangement used to measure the frequency response of the Sound Level Meter and the Level Recorder 2306. A 10 kHz carrier frequency was amplitude modulated by a low frequency sinusoidal signal and applied to the Sound Level Meter input.

The frequency response of the Sound Level Meter for "Fast" and "Slow" response were obtained and are shown in Fig.8. The AC output of the Sound Level Meter was now fed to the Level Recorder Type

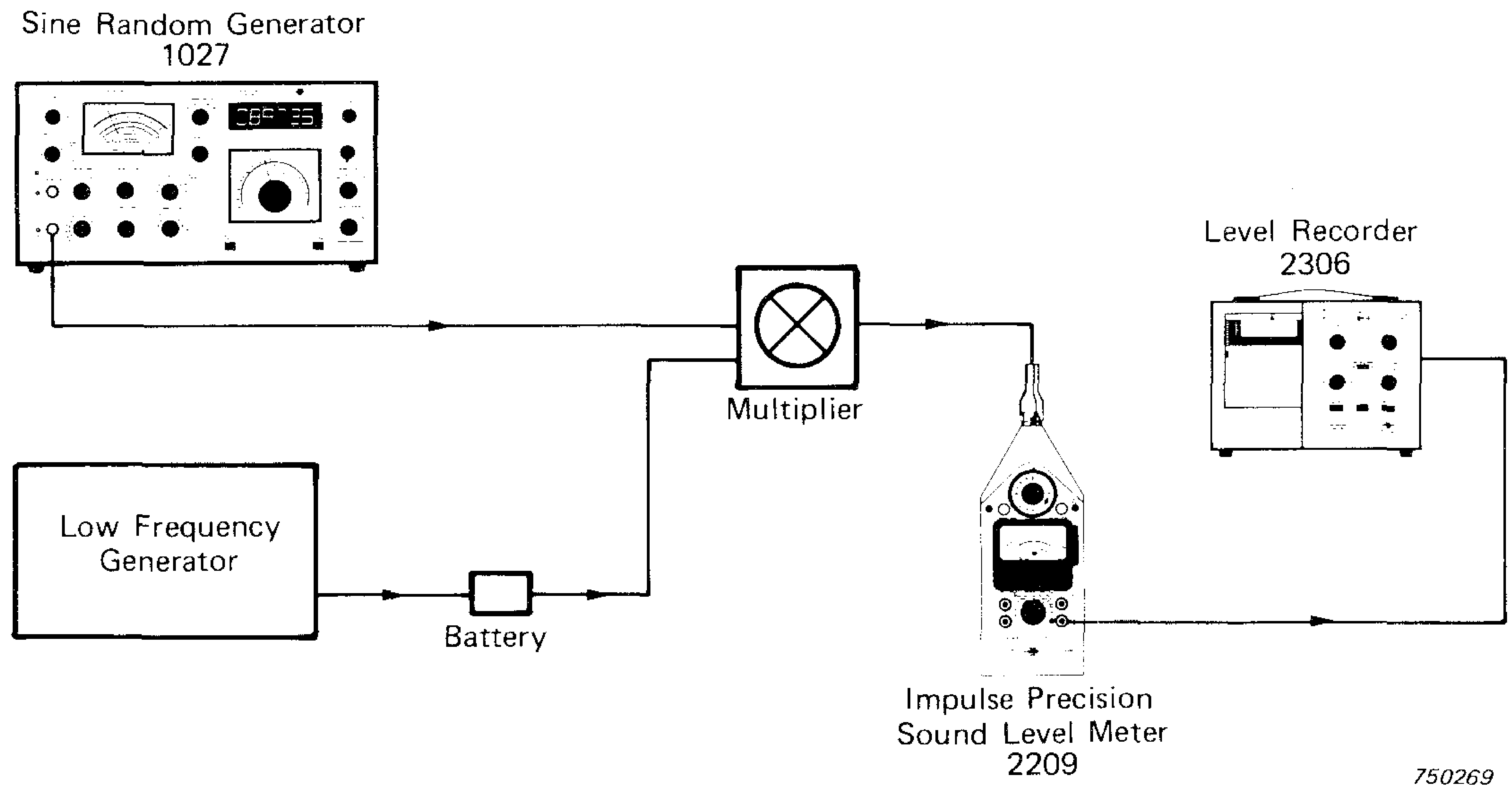

Fig. 7. Set-up used for frequency response measurements

2306 and its response was obtained at writing speeds of 16, 40 and 100 mm/s. The results obtained are again presented in Fig. 8.

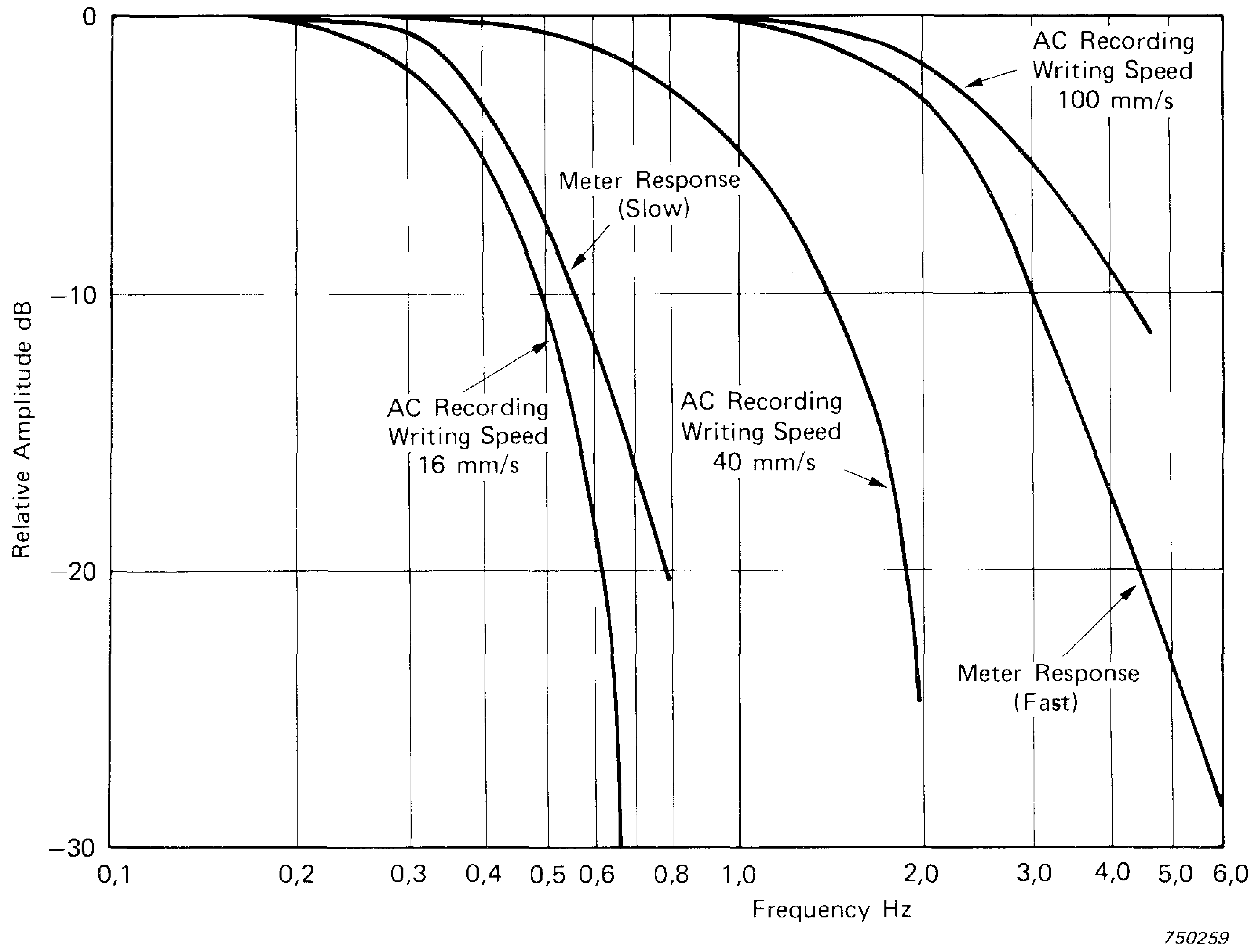

Fig. 8. Frequency Response of Sound Level Meter and Level Recorder 2306

It can be seen that the Meter Response for "Fast" lies in-between the response for 40 mm/s and 100 mm/s for AC recordings. Therefore for "Fast" response it is suggested that for small deflections 40 mm/s should be used while 100 mm/s should be used for large deflections. For "Slow" response 16 mm/s should be used.

c) Tone Burst Response Measurements

The definition of "Fast" response according to IEC 179 for a Sound Level Meter is that if a pulse of sinusoidal signal having a frequency of 1000 Hz and duration 0,2 s is applied, the maximum reading shall be 1 ± 1 dB less than the reading for a steady signal of the same frequency and amplitude.

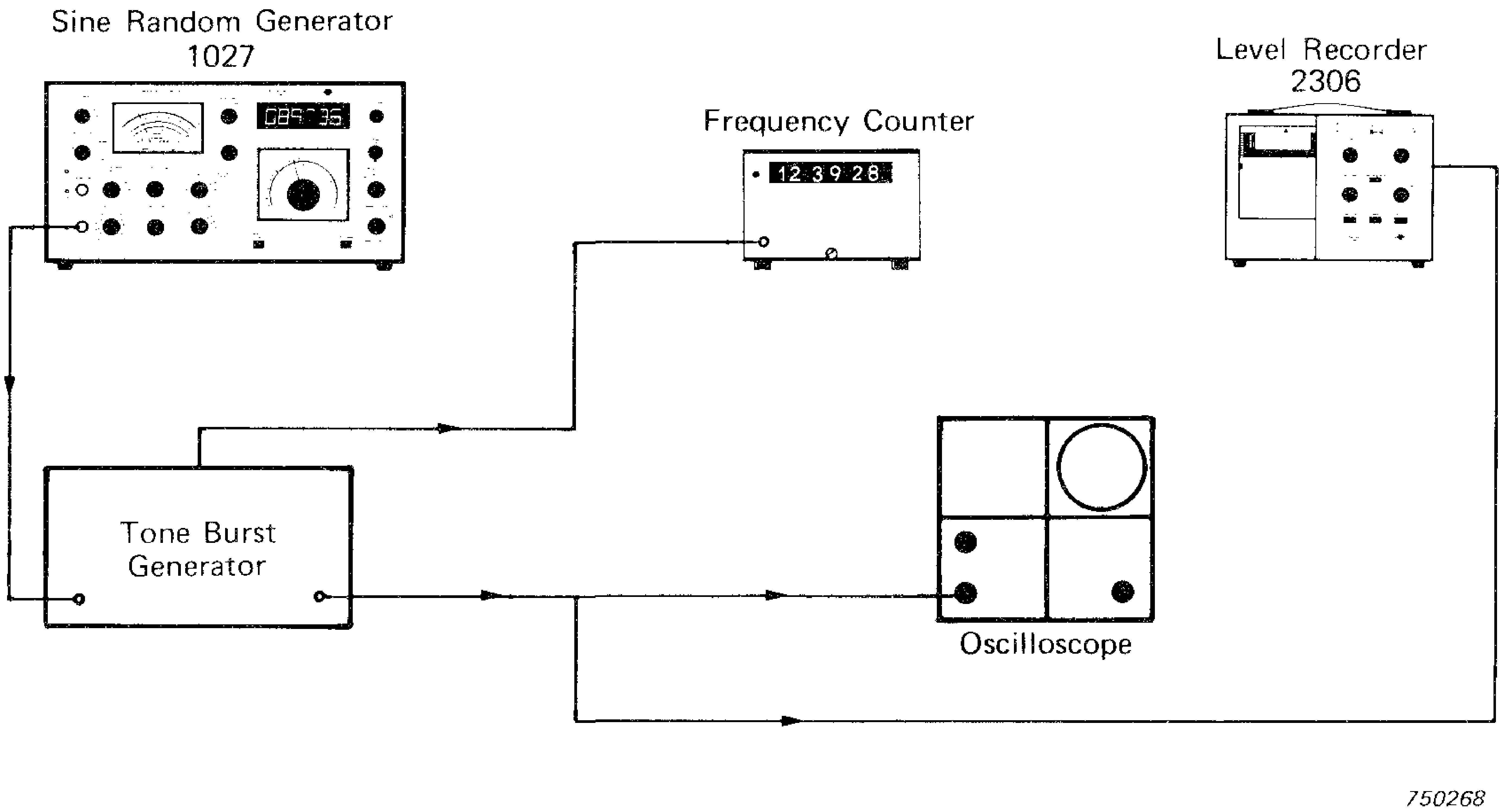

Fig.9. Set-up used for tone-burst response measurements

To examine the tone burst response of Level Recorders such a signal was applied to Level Recorder Type 2306 as shown by the measurement arrangement in Fig.9. The amplitude of the tone burst was chosen such that a steady signal of the same frequency and amplitude gave a deflection of 4 dB above the bottom-most position of the pen. The tone burst was recorded at 40 mm/s and 100 mm/s. The amplitude of the tone burst was now increased to 6, 10, 20, 30 and 40 dB in steps and recordings were taken at the same writing speeds and the same attenuator positions on the Level Recorder. The results are shown in Fig.10.*

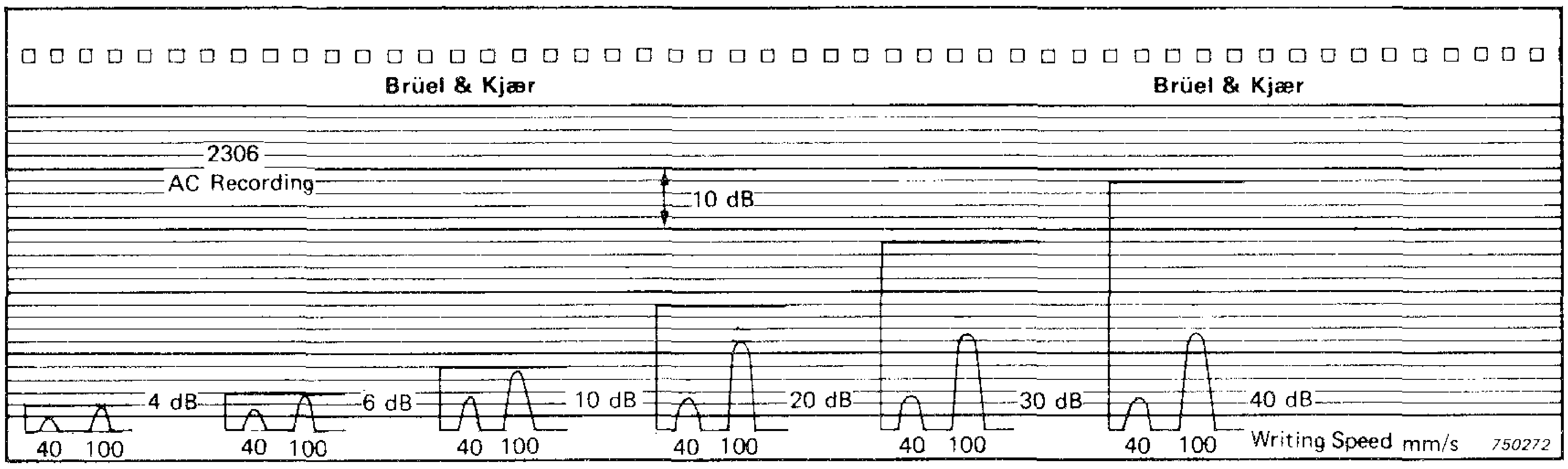

Fig.10. Tone-burst Response of Level Recorder 2306

From the results it can be seen that in order to fulfil the "Fast" requirements of IEC one would need to increase the writing speed for increasing levels of tone burst signals, a fact which can be theoretically verified by considering the design principle utilized in Level Recorders, Ref. (2).

Discussion of Results

In method (a) meter needle deflections were compared to pen fluctuations and the writing speeds were chosen which gave the best simulation amplitudewise and frequencywise. On account of the stepwise regulation in writing speeds the choice is sometimes made difficult and this is also illustrated by the frequency response method (b), see Fig.8.

It should be noted that whenever DC output facilities are available, such as on Sound Level Meter Type 2209 and Measuring Amplifier Types 2606 and 2607, DC recordings should be carried out as the pen and the meter needle will respond to the same DC voltage on the capacitor of the Sound Level Meter (or the Measuring Amplifiers) averaging circuit. Unfortunately, it is here where the simulation ends, as after this stage Meter and Level Recorder writing system dynamics come into play. This is further illustrated by the results obtained by method (c). While the definition of "Fast" and "Slow" response for Sound Level Meters is based on tone burst response, such a definition is not sui-

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* P.S. For investigation of the DC response of the Level Recorder to impulsive signals, tone bursts of the same amplitudes were applied to the Level Recorder via the DC output of the Sound Level Meter. The results showed that the DC recordings gave higher responses than AC recordings for the same writing speed. Also by increasing the writing speeds for increasing levels of tone bursts, the "Fast" requirements of IEC could be fulfilled, nevertheless the simulation of Meter Dynamics with Level Recorder writing system dynamics cannot still be achieved for the present generation of Sound Level Meters.

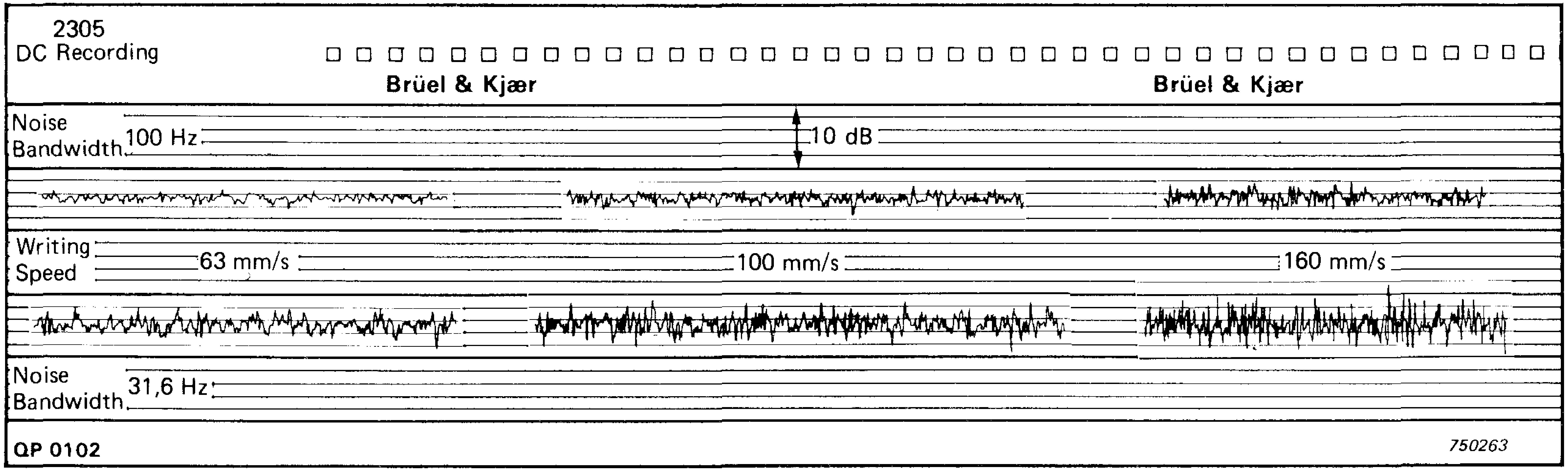

Fig. 11a. 2305 DC recordings of narrow-band noise for simulation of "Fast" response

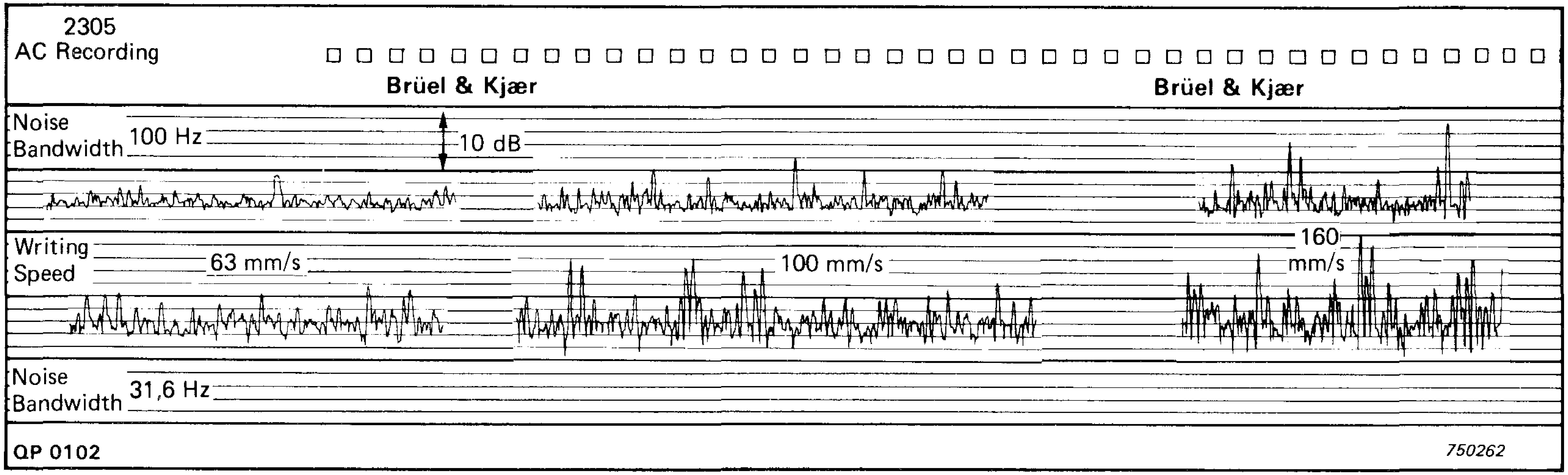

Fig. 11b. 2305 AC recordings of narrow-band noise for simulation of "Fast" response

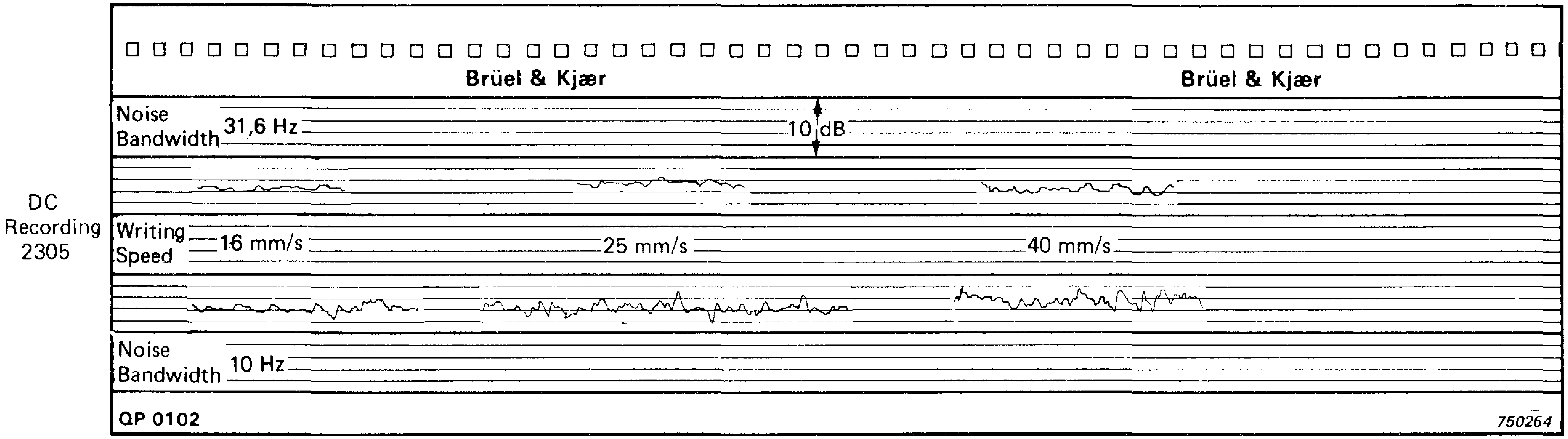

Fig. 12a. 2305 DC recordings of narrow-band noise for simulation of "Slow" response

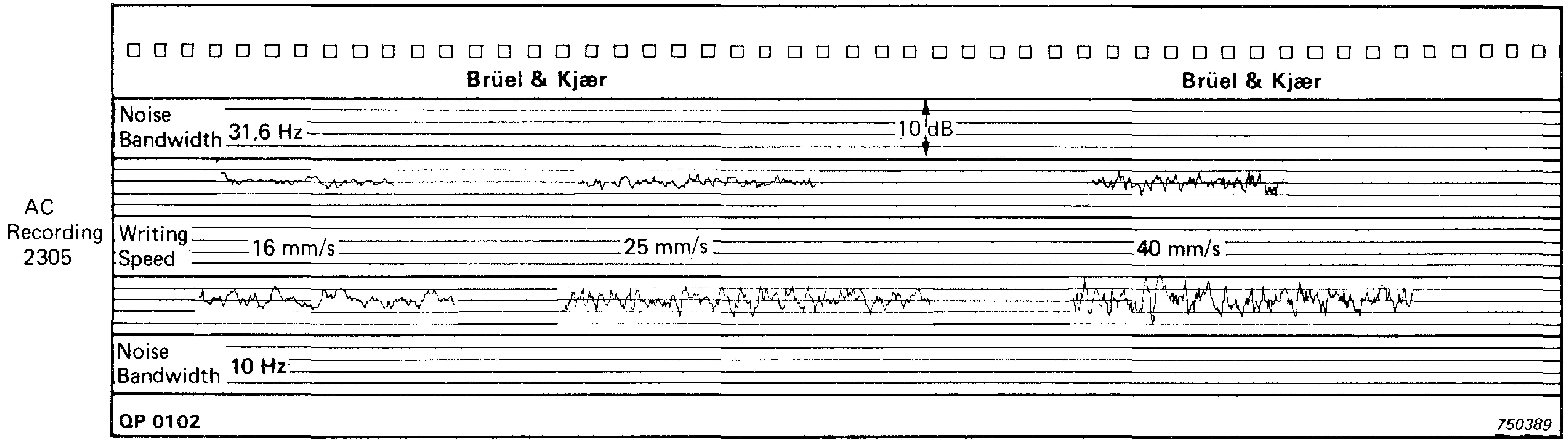

Fig. 12b. 2305 AC recordings of narrow-band noise for simulation of "Slow" response

table for Level Recorders as its response is dependent on the amplitude levels of tone bursts as shown in Figs. 10 and 13.

Experiments with Level Recorder Type 2305

Experiments were also carried out for Level Recorder Type 2305 (fitted with 50 dB Pot. and 50 mm paper) according to method (a). Figs. 11a and 11b show DC and AC recordings respectively at writing speeds 63, 100 and 160 mm/s for noise bandwidth inputs of 100 and 31,6 Hz. Sound Level Meter deflections of 3 and 7 dB for 100 Hz and 31,6 Hz respectively for "Fast" response were compared to AC and DC recordings. From the results it is suggested that a writing speed of 100 mm/s should be used for DC recording while for AC recording 63 mm/s for small fluctuations and 100 mm/s for larger ones.

Figs. 12a, and 12b show DC and AC recordings at writing speeds 16, 25 and 40 mm/s for noise bandwidth inputs of 31,6 Hz and 10 Hz. For these bandwidths the meter needle deflections were 2 and 4 dB peak-to-peak respectively for "Slow" response. For DC recordings 40 mm/s seems to be most appropriate while for AC recordings 16 mm/s is suggested for small fluctuations and 25 mm/s for larger ones.

The tone burst response of Level Recorder Type 2305 was also examined according to method (c), using the measurement arrangement of Fig. 9. Tone burst amplitudes of 4, 6, 10, 20, 30 and 40 dB above the bottom-most position of the pen were recorded at 40, 63, 100 and 160 mm/s. The recordings are shown in Fig. 13 and again it can be seen that the writing speeds must be increased for increasing levels of tone bursts to fulfil the "Fast" requirements of IEC.

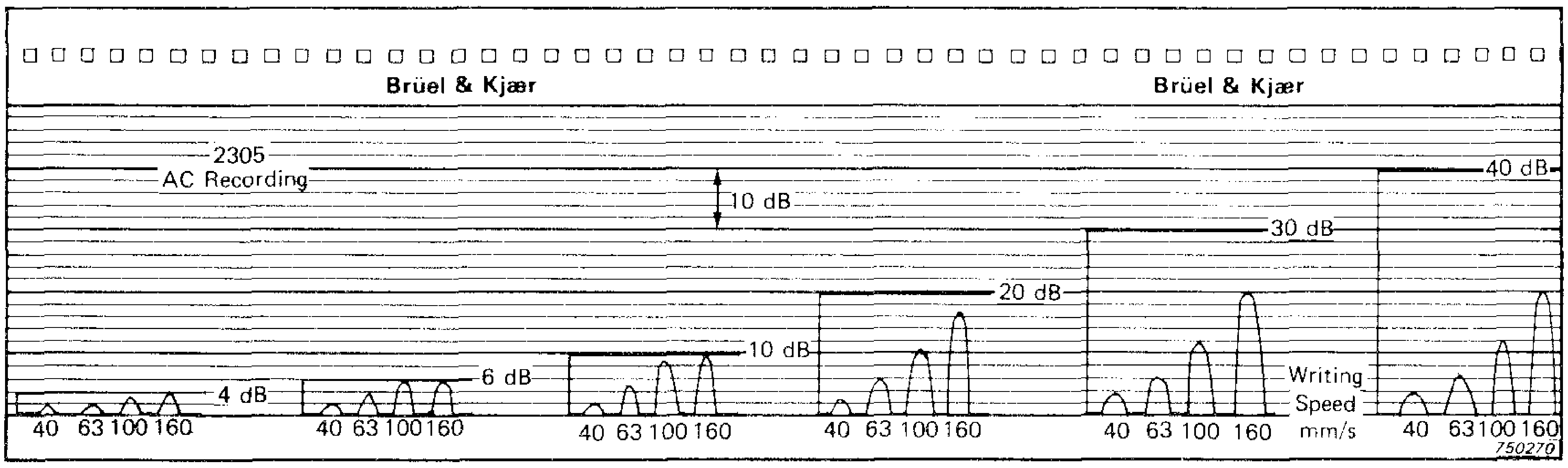

Fig. 13. Tone-burst Response of Level Recorder 2305

Conclusions

The averaging times of Level Recorder Type 2306 agree reasonably well with those of Level Recorders 2305 and 2307, and curve 1 in Fig.3 is suggested to be the nominal curve also for Level Recorder Type 2306.

For stationary random signals with **small fluctuations** equivalent writing speeds on Level Recorders can be found that would simulate pen fluctuations with meter needle deflections of the present generation of Sound Level Meters both amplitudewise and frequencywise.

In Table 1, are given writing speeds of Level Recorders 2305, 2306 and 2307 for "Fast" and "Slow" response measurements for AC and DC recordings when 50 mm paper is used. Whenever DC output facilities are available, DC recordings are preferable as in this case the deviation in simulation is only affected by the meter and level recorder writing system dynamics. Unfortunately, such facility is not always available and AC recordings then have to be carried out for which two writing speeds are given in the Table, the lower one for small fluctuations and the higher one for larger ones. The values quoted in the Table are slightly lower than those suggested in DIN Standard 45 633.

	FAST		SLOW	
	DC	AC	DC	AC
2306	100 mm/s	40 - 100 mm/s	40 mm/s	16 mm/s
2305, 2307	100 mm/s	63 - 100 mm/s	40 mm/s	16 - 25 mm/s

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Table 1.

In using the writing speeds given in the Table, care should be exercised as they are given only as guidelines.

Finally, it should be mentioned that all the results have been obtained using a 50 dB potentiometer, and that the Level Recorder Type 2307 is assumed to perform in the same manner as 2305 since their system dynamics are the same and their averaging times are of the same order of magnitude.

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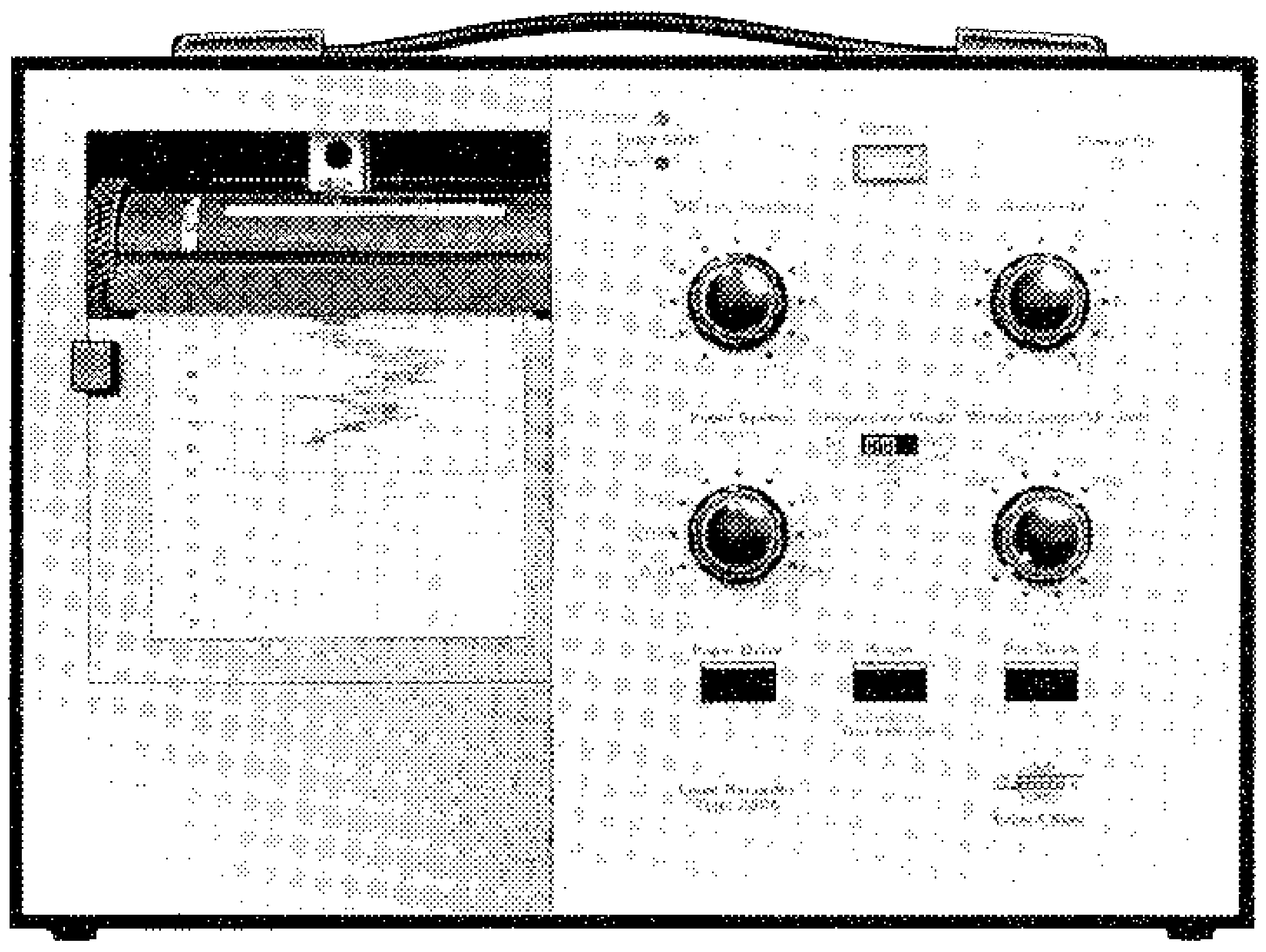
1. H. P. OLESEN and K. ZAVERI — Measurements of Averaging Times of Level Recorders Types 2305 and 2307. Brüel & Kjær Technical Review No. 1—1974.

2. JENS T. BROCH and CARL G. WAHRMANN — Effective Averaging Time of the Level Recorder Type 2305. Brüel & Kjær Technical Review No. 1—1961.

3. JULIUS S. BENDAT and ALLAN G. PIERSOL — Random Data: Analysis and Measurement Procedures, Wiley-Interscience 1971.

News from the Factory

Portable Graphic Level Recorder Type 2306

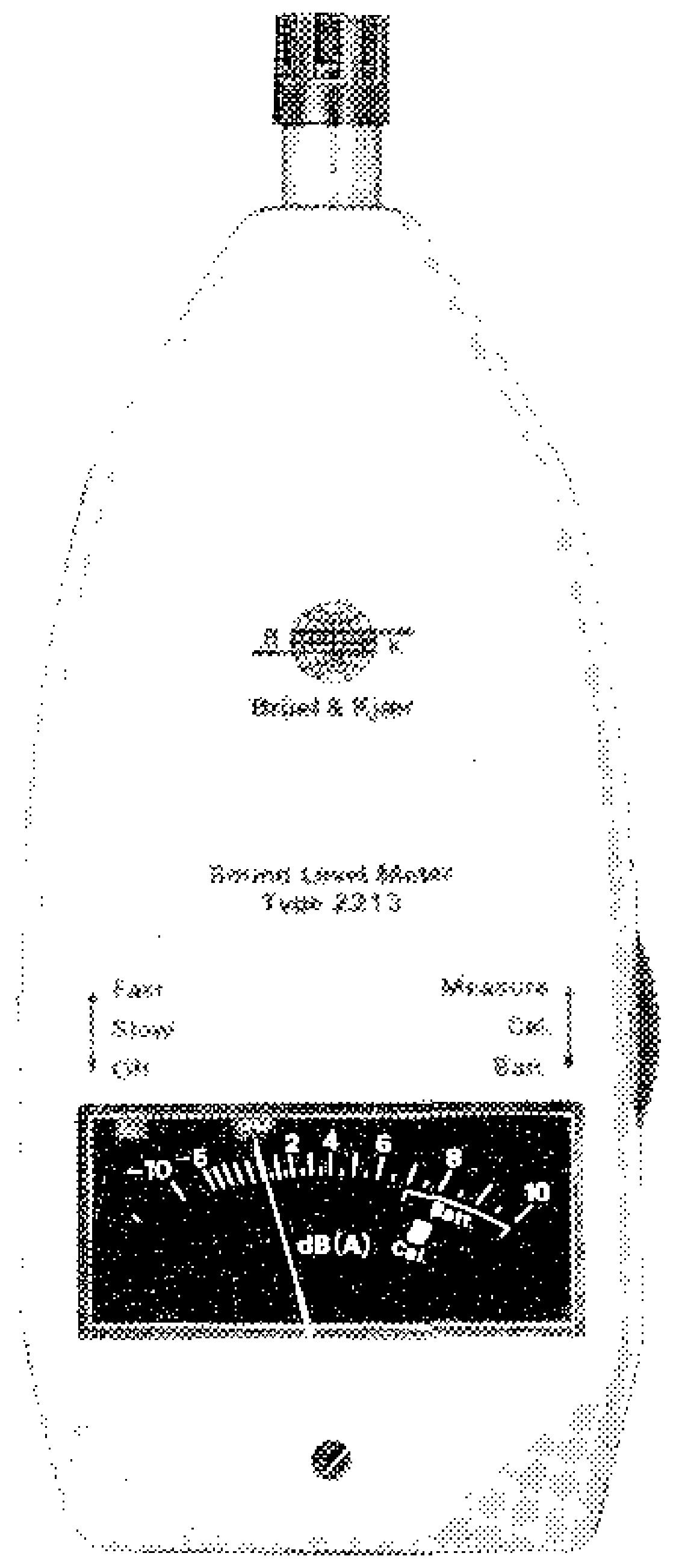


This portable Level Recorder, which has been developed for field and laboratory recording of DC and AC signals, has three recording modes, "AC Log.", "DC Log." and "DC Lin.". In the "AC Log." mode it records the RMS value of any waveform in the frequency range 1 Hz to 20 kHz within an accuracy of ± 0,5 dB for signals with crest factor up to 3. In the "DC Log." and "DC Lin." modes the signal from the range potentiometer is fed through a 500 Hz electronic chopper before it enters the RMS rectifier circuit. The dynamic range of the Level Recorder is determined by the interchangeable logarithmic potentiometers of 25 dB or 50 dB. These potentiometers are also used when the recorder is operated in its linear mode as an anti-logarithmic amplifier is inserted between the input amplifier and the range potentiometers.

The writing system of the recorder has four speeds, 16, 40, 100 and 250 mm/s and uses interchangeable fibre pens or sapphire stylii. The recordings are made on 50 mm wide preprinted frequency calibrated or lined paper either as a function of frequency or time. Eight fixed paper speeds can be selected between 0,01 mm/s and 30 mm/s and the start and stop of the paper drive can be remotely controlled. Facilities are also included for filter synchronization and external synchronization of the paper movement.

The power for driving the recorder can be supplied either from dry cells, rechargeable NiCd-batteries, from the mains via the plug-in Power Supply Type 2808 or from an ordinary 12 V automobile battery. A built-in miniature meter on the front panel is also provided for monitoring the supply voltage.

General Purpose Sound Level Meter Type 2213

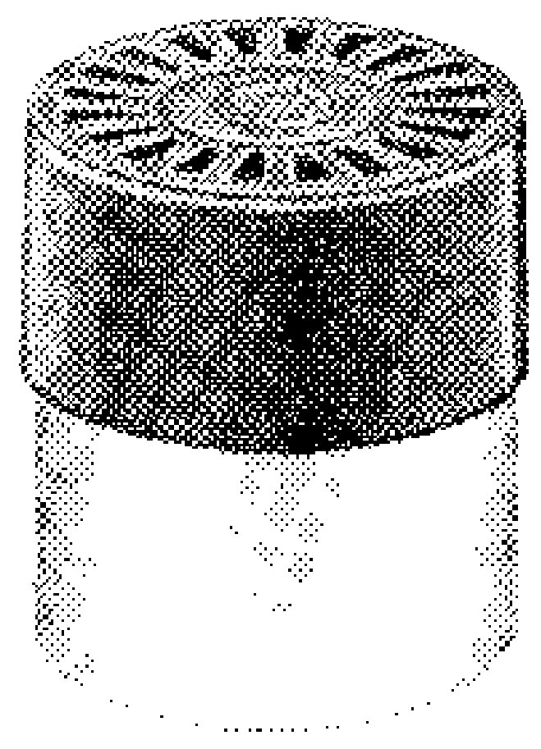


The Sound Level Meter Type 2213 has been designed to meet the internationally approved standards IEC 123 and ANSI S1.4-1971, Type 2 for less demanding sound and noise measurements in the range 50 dB — 130 dB(A). It is inexpensive and therefore well suited for noise abatement engineers, traffic police, industrial hygienists, and public health inspectors.

The Sound Level Meter is equipped with a 1/2" Condenser Microphone Type 4125 adjusted to have a linear free-field, 0° incidence, frequency response from 5 Hz to 12,5 kHz within ± 3 dB. The RMS rectifier circuit has an accuracy of 0,5 dB for signals with crest factors up to 3, while the meter has two damping characteristics "Fast" and "Slow" according to IEC and ANSI standards. A 1 kHz square wave generator is incorporated, whereby the complete system can be calibrated (electrically).

The power to the instrument is supplied from two 9 V batteries, IEC Type 6F22, or Neda Type 1604 allowing 80 hours of continuous operation. Facility for check on the battery condition is also provided via a reading on the meter.

1/2" Condenser Microphone Type 4125



This condenser microphone is a low cost quality microphone designed primarily for use with Noise Dose Meter Types 4424 and 4425 and Sound Level Meter Type 2213. Its rugged construction and wide temperature range makes it well suited for use in industrial environments. Due to the low polarization voltage used, it has good resistance to humidity as well as high stability normally associated with this type of condenser microphone.

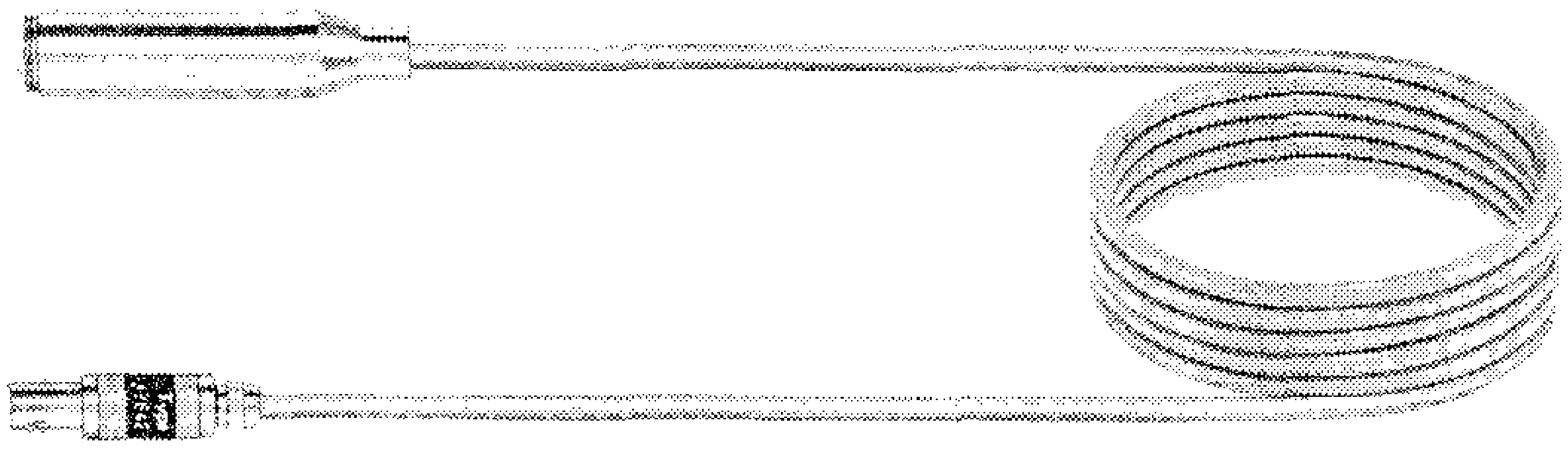
For polarization voltage of 28V DC the microphone has an open circuit sensitivity of —40dB re. 1 V/Pa and is adjusted to have a linear, free-field 0° incidence frequency response within

± 1 dB between 11 Hz to 3,15 kHz
± 2 dB between 7 Hz to 6,3 kHz
± 3 dB between 5 Hz to 12,5 kHz

However, the 3dB lower limiting frequency can vary between 0,5 Hz and 5 Hz. Although the microphone is designed for use with low polarization voltages, it can easily be used with voltages upto 140V DC.

For use of the microphone in dusty environments a Dust Cap DD 0139 is included which also improves the random incidence response of the microphone.

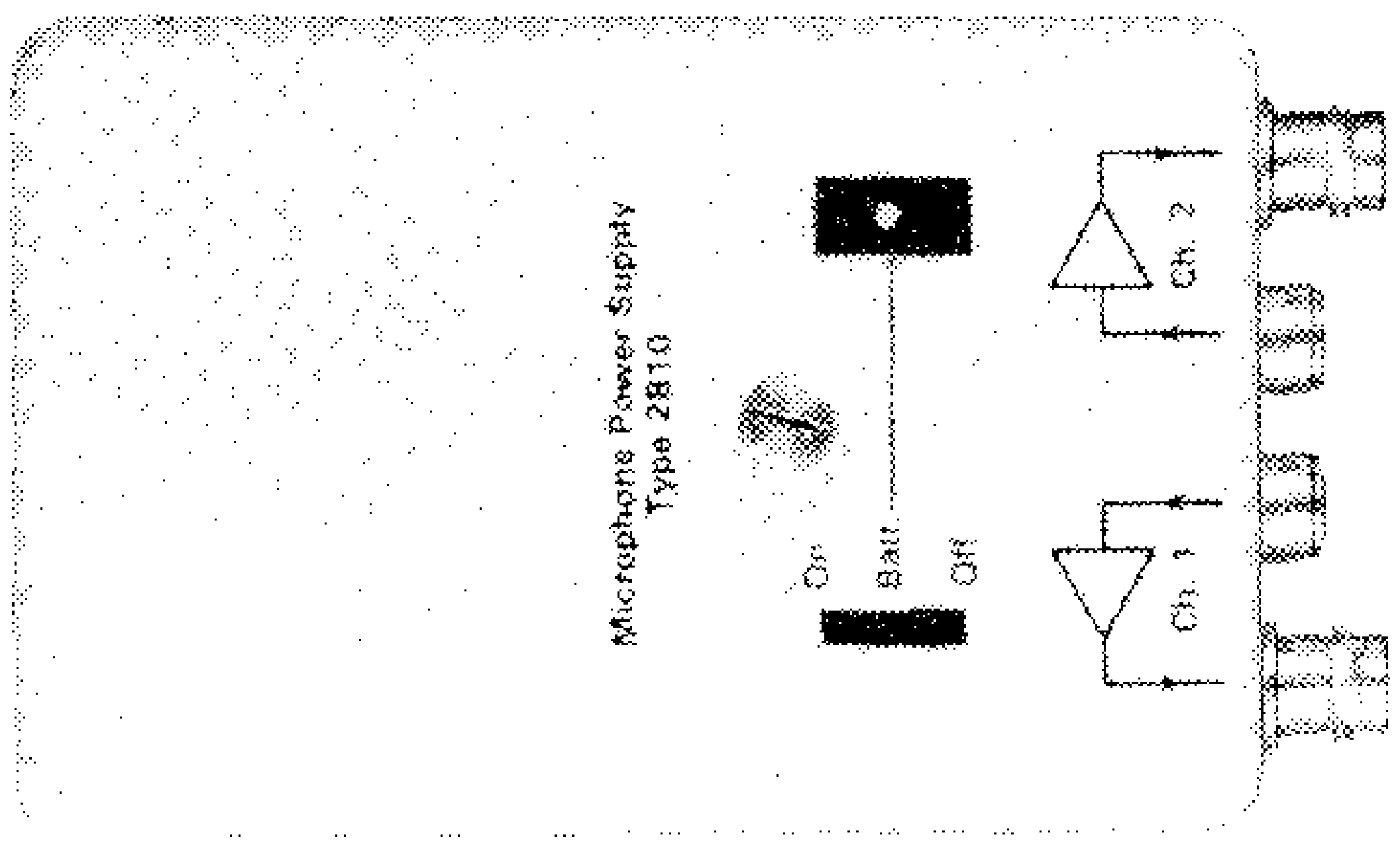
Microphone Preamplifier Type 2642



Microphone Preamplifier Type 2642 is a low cost preamplifier for use especially with the Microphone Type 4125. It can, however, be used with all other B & K 1/2" Condenser Microphones. The input impedance of the preamplifier is typically 1 GΩ//3 pF and the amplifier has a linear frequency response from 20 Hz to 20 kHz within ± 1 dB with a transducer capacitance of 15 pF connected to the input.

The power for the preamplifier and polarization voltage for the microphone can be supplied either from a Microphone Power Supply Type 2810 or from B & K Spectrometers, Analyzers, and Measuring Amplifiers via the adaptor JP 0708.

Microphone Power Supply Type 2810



The Microphone Power Supply Type 2810 is battery driven and has two channels with individual amplifiers. It supplies driving voltages for two microphone preamplifiers 2642 and polarization voltage for two microphones 4125. The built-in amplifiers have a linear frequency range from 10 Hz to 15 kHz within ± 1 dB with individual gain settings in the range 0 to 40 dB. The output impedance is < 100 Ω permitting use of long cables to the following measuring equipment.

When Microphones Types 4125 and 4148 are used with this microphone power supply, their nominal sensitivities are maintained as the polarization voltage supplied is 28 V. When other B & K 1/2" Condenser Microphones requiring 200 V polarization voltage are used their sensitivities drop by approximately 17 dB.

The Microphone Power Supply is powered either from four ordinary 9 V transistor radio batteries IEC 6F22, or NEDA Type 1604. The Microphone Power Supply when equipped with a set of these batteries will give continuous operation for approximately 200 hours with both channels in operation. An LED indicator for check of the supply voltages is also included.

Microphone Type 4125, Microphone Preamplifier Type 2642 and Microphone Power Supply Type 2810 constitute a low cost portable battery powered microphone system suitable for sound power measurements, sound insulation measurements, monitoring and quality control and general purpose sound measurements.

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