THE SYNCHRONOUS MAGNETIC RECORDER AND ITS APPLICATIONS—II: EXPERIMENTAL

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SUMMARY

The design considerations regarding the construction of a synchronous magnetic recorder for the extraction of weak signals in noise and the description of an actual devise are given. Striking photographs giving the input and output signals illustrate the practicability of the basic ideas. The signal to noise ratio in the output of the recorder has been discussed and rough criteria and methods for judging the same are given.

1. THE DESIGN OF A SYNCHRONOUS MAGNETIC RECORDER

In Part I[1] of this series the physical principles and the theory of the synchronous magnetic recorder have been given. In this paper the experimental realization of the ideas and their demonstration are presented.

In the design of a synchronous magnetic recorder suitable for application to the extraction of weak signals in noise occurring in the course of physical investigations, two things have to be borne in mind. Firstly, it must be capable of providing an integration time sufficiently long to suit the requirements of the problem. Secondly, it must reproduce the signal faithfully; particularly one must guard against the possible presence of false detail. The necessary integration time may be estimated from the theory given in Part I. One can then make a recorder of suitable dimensions. Regarding the second an examination of the results obtained with known signals will provide a criterion for judging the significance or otherwise of the details of the output signal. However, faithfulness of signal reproduction consists in allowing all the fourier components of the signal and achieving a flat frequency response curve. In doing so the fourier components of noise will also be admitted and it is necessary to increase the recording time. Thus the two requirements are rather interrelated.

There are various parameters which determine the over-all performance of the synchronous magnetic recorder. They are the periodicity of the signal, length and diameter of the drum, the magnetic properties of the material, the recording head gap width, the length and gap width of the reproducing head and the amplification to which the signals must be subjected to prior to recording. All these parameters have to be chosen to satisfy the two broad requirements set above. In doing so, we may make use of the knowledge available regarding the ordinary magnetic recording of sound a clear account of which may be found in a book by S. J. Begun on "Magnetic Recording". So we may pass on to discuss these parameters and set limits for the same without entering into any elaborate discussion on the principles of magnetic recording. A description of the apparatus constructed along these general lines is given followed by the experimental results of its application to the detection of signals in the presence of noise. The concluding section gives an estimate of the signal to noise ratio in the output from the synchronous magnetic recorder.

The Periodicity of the Signal.—The choice of the signal periodicity depends mainly on the physical problem to which the device has to be applied. Time effects may accompany the signal and a too rapid or too slow variation might be detrimental. For example the relaxation effects in nuclear magnetic resonance or the response time of power detectors such as those used in infra-red spectroscopy which may be large may be cited. Further the phenomenon occurring may itself be of short duration but the rapidity with which it may be repeated small. Where such time effects are not important, the use of a high frequency may be desirable in view of the ease of amplification, etc. But it is seen that repetition frequencies ordinarily range from 10 ~ to 200 ~. The choice of a fairly low frequency will cover most cases of interest though it might not be the optimum. 25 cycles/sec. seems to be desirable and the use of a subharmonic of the line frequency has some advantages. In the model described below 25 cycles has been chosen. The exact frequency is dependent on the motor used to revolve the drum.

The Dimensions of the Drum.—In choosing the diameter of the drum, two considerations prevail. They are the necessity for an adequate surface speed and suitable high frequency cut-off characteristics. In conventional magnetic recording the material is in the form of a wire or tape and its velocity determines the voltage induced in the reproducer head. Low velocities (2 ft./sec.) are preferred for conserving the medium. In the case of the synchronous magnetic recorder this is of no consequence as the material is used over and over and an adequate output points to the necessity of a large drum diameter. The surface speed in this case can be of the order of 25 to 50 ft./sec. However, even if the recording were done at low velocities, one can always play it back at a higher frequency of rotation thus ensuring a large output voltage. The drum diameter along with the gap width determines the high frequency cut-off. The first high frequency minimum occurs at a frequency given by $\nu = (4\pi r/g)\,\nu_0$, where r is the radius of the drum, g the gap width and ν_0 the frequency of rotation. So by making the gap large high frequency components which are not absolutely essential for the faithful reproduction of the signal can be cut-off. It is only correct to do so as the main object of using the instrument will be to study weak signals. It is ordinarily found that the presence of about 20 harmonics ensures a fair idea of the signal. In some of the systems currently in use for the detection of weak signals, the signal is usually scanned and the scanning introduces a smoothing effect due to the loss of the high frequency fourier components. It is found that even with large scanning intervals the signals are reproduced well. So assuming that 20 harmonics are enough, the circumference need not be more than 10 times the gap width of the recorder or reproducer head. In this matter of gap width the synchronous magnetic recorder differs markedly from the magnetic sound recorder where gap widths of the order of only a few thousandths of an inch are used. Thus a considerable latitude exists in the choice of the drum diameter and the final selection may be based on such practical considerations as availability, space, material, etc.

The Length of the Drum.—The length of the drum is determined by the recording time needed. With $\nu_0 = 25 \sim$ and a sharp recording head it is possible to cover the drum surface at about $\frac{1}{4}''$ per second and an integration time of one minute requires about 16″ length of the drum and hence is quite practicable.

The Material.—All the characteristics of a magnetic material like retentivity, coercivity and linear transfer characteristic desirable in the case of magnetic recording of sound are also necessary in the present case. As the recordings can be made at a high level of input and picked up at high levels minor non-uniformities in the medium can be tolerated. From the following description of an actual instrument, it will be seen that the choice of the material is not critical. However if materials specially suited for magnetic recording are available in suitable forms it will be an added advantage.

The Recording Head.—While it must be possible to make use of the conventional recording heads available commercially, it is simpler to make one which suits the specific needs of the present problem. It has already been pointed out that the gap width can be large of the order of a few millimeters. It is preferable to make the contacting region between the drum and the recording head such that too much overlap does not exist between the successive members of the spiral record. However, it is found that it does not very seriously hamper the recordings if there is a small amount of overlap. In fact there is some direct addition of magnetism when a few multiple recordings take place at the same point. The limit to this is set by the saturation of the medium on the one hand and the coercivity on the other. Several of the frills to be found in the commonly used recording heads such as a second gap, laminated construction, etc., need not be duplicated in view of the limited band of frequencies and the large gap width. A material of large low field strength permeability like mumetal or permalloy is suitable for the construction of the recording and reproducing heads.

The Reproducing Head.—The requirements regarding the length and the gap width of this have already been dealt with in connection with the dimensions of the drum. The gap width is chosen to provide a proper high frequency cut-off. About 5 mm. for drums of moderate dimensions is quite satisfactory.

The Signal Input and Output Levels.—The process of magnetizing by itself requires very little energy, most of the power being dissipated in the coils of the recording head. With coils of about a few hundred ohms resistance and a current of a few milliamperes the power required is only a few milliwatts and any ordinary amplifier will be able to deliver it. The voltage induced in the reproducing head is about 100 m.v. when the whole drum is covered. Ordinary amplifiers are enough to feed the output to a cathode-ray oscillograph.

Synchronization.—Perfect synchronization of the signal periodicity with the rotation of the drum is *essential* for the successful operation of the device. Such synchronization can be achieved by the use of synchronous motors or by the use of an alternating current generated simultaneously with the rotation of the drum. The latter method is to be preferred on account of its simplicity, perfect synchronization and the absence of indeterminate phase shifts. So it is always desirable to incorporate a small A.C. generator in the recording system to obtain the synchronization with the signal periodicity.

2. DESCRIPTION OF THE SYNCHRONOUS MAGNETIC RECORDER

Being simple both in theory and practice, a brief description of the instrument is sufficient. A drawing of it is given in Fig. 1.

(1) is the recorder drum made of steel 6″ O.D. and 10″ length. This was part of an aircraft and was used because it was easily available. It has given good results. The ends of the drum were blocked by soft iron plates (2) and a shaft (3) passed through and was mounted on ball bearings (4) and (5) in a rigid frame (6). This assembly was bolted on to a wooden base (7). One end of the shaft was coupled by means of a short length of thick rubber

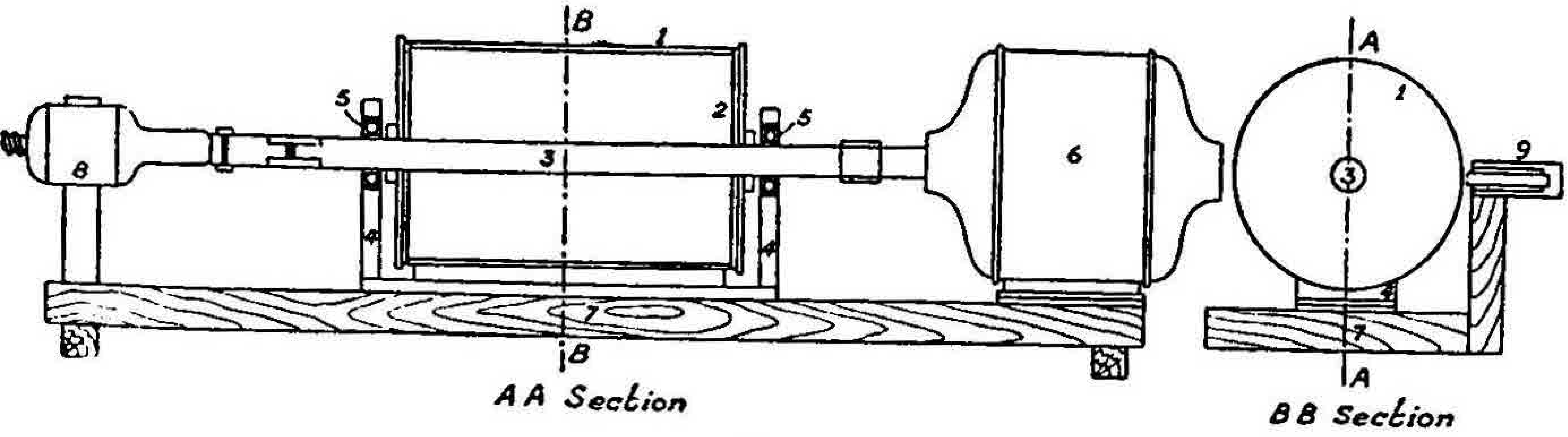

FIG. 1

tubing to the shaft of the motor (6). The other end was similarly attached to a small permanent magnet alternator (8).

The Recording Head.—Two types of recording heads have been illustrated in the accompanying Figs. 2 *a* and 2 *c*. The first one is very simple and gives quite satisfactory performance. It consists of a strip of *mu*-metal ½″ × 4″ × 1/64″ bent into the form of a narrow U. The ends of the metal strip are trimmed to a point and bent towards each other. On the limbs of the U two coils of 500 turns each of No. 40 enamelled copper wire are wound and connected in series. The resistance of the completed coil assembly is about 150 ohms.

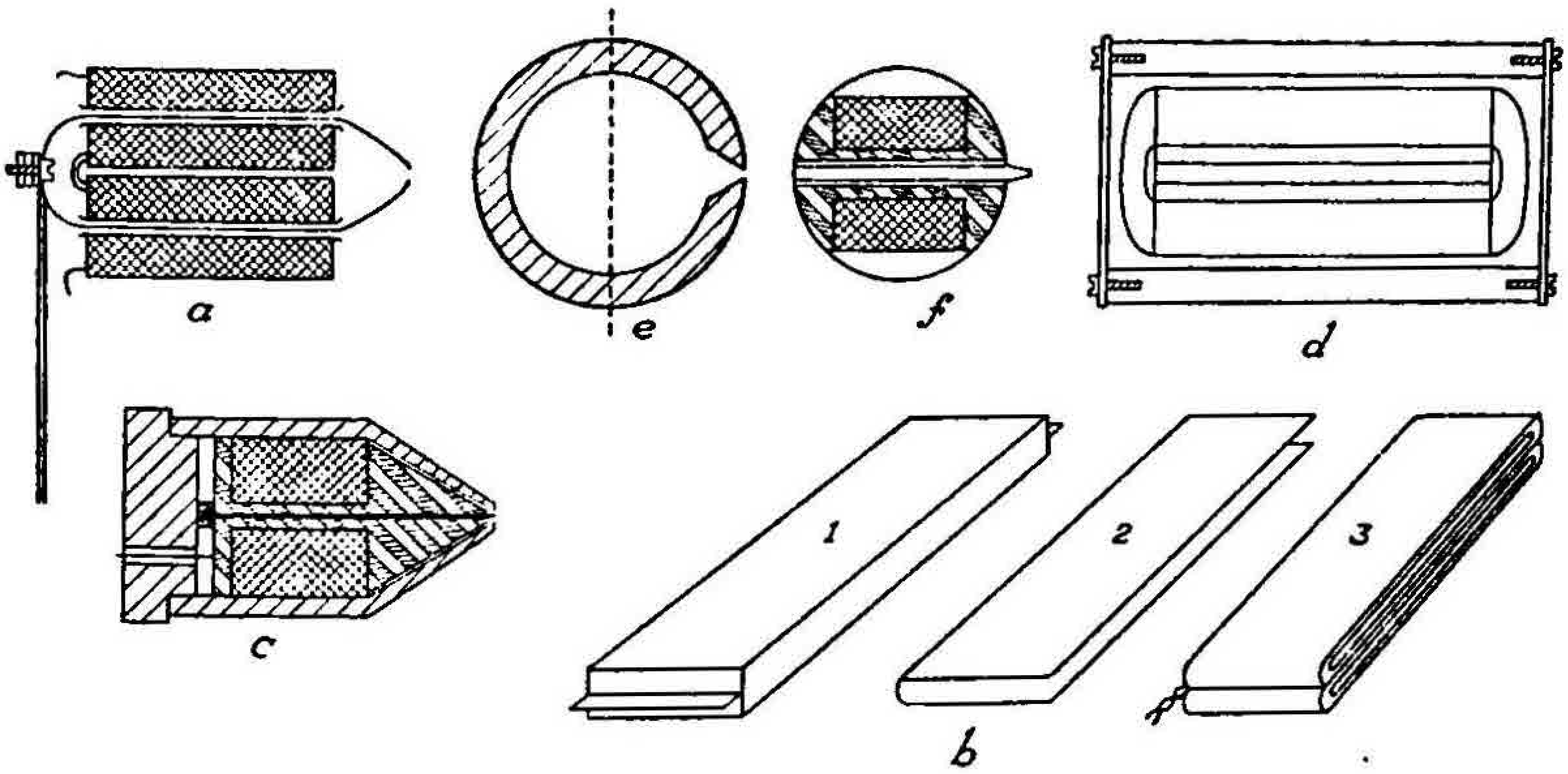

FIG. 2

The second type is of a more rigid construction and is necessary only when narrow gap widths are required. Its construction will be clear from the drawing Fig. 2 *c*.

The Reproducing Head.—There are two types of reproducing heads corresponding to the two recording heads described above. Fig. 2 *b* shows the first type. It consists of two long flat coils 2″ × 8″ of No. 40 wire, 500 turns each wound on thin forms of phenolic sheets (Fig. 2 *b*, 3). A *mu*-metal sheet 7″ × 6½″ × 1/64″ is bent at two right angles with ½″ separation between the limbs (Fig. 2 *b*, 2). The coils are slipped on the limbs and the ends of the *mu*-metal sheet are bent towards each other. The whole is enclosed in a sheet aluminium casing (Fig. 2 *b*, 1). The other type is illustrated in Fig. 2 (*d*, *e*, *f*). The former for the coil is made of two half cylinders with channels milled along their length (Fig. 2 *f*). A strip of *mu*-metal is inserted between the half cylinders. This assembly is enclosed in a soft iron tube with a lengthwise cut on its wall (Fig. 2 *e*). This type of construction is rigid and allows a small gap width suitable for use with drums of very small diameters.

Biasing and Erasing.—Any magnetic recording device must incorporate some form of erasing the record when necessary and also be able to apply a biasing magnetic field to achieve a linear transfer characteristic. The simplest means of erasing is to hold a permanent magnet near the drum. This has been used by the author.

There are two principal forms of biasing. One is the D.C. biasing got by applying a small magnetic field opposite in direction to the erasing field. The other is A.C. biasing got by mixing a high frequency current with the signal current. When the synchronous magnetic recorder is used for studying weak signals in the presence of noise it is found that the noise voltages themselves give A.C. biasing. On account of the random character of noise it is not easy to calculate the exact effect, but in practice it is found that it does take place on account of the distorsion-free signal reproductions observed. In most of work of the author with the synchronous magnetic recorder, the D.C. biasing has been used by holding the erasing magnet in a reverse direction at a distance of a few centimetres from the drum. This procedure has been found satisfactory.

Moving the Recording Head.—In order to cover the length of the drum the recording head has to be slowly and evenly moved. With a little practice this can be easily accomplished by hand preferably with a guide to keep the movement in a straight line. A gear and screw arrangement can be easily designed and incorporated if necessary. This has not been attempted in the present apparatus in order to keep the construction simple.

3. RESULTS OF PERFORMANCE

We may now present the results obtained in the use of the synchronous magnetic recorder. The accompanying oscillograph records of the input and output signals of the synchronous magnetic recorder give a striking demonstration of the general correctness of the basic ideas and their practicability. The record [Plate IV, (*a*)] gives a general idea of the possibilities of the instrument. It will be noticed that all the details of the original signal which are only barely visible are reproduced clearly and definitely without the masking effects of noise.

The second record [Plate IV, (*b*)] has been reproduced here to show that details not made visible due to photographic integration are also made clear. The noise-like signal shows one easily visible peak and another only just visible to the trained eye (arrow lines indicate the peaks). It is seen that the second peak is also reproduced very clearly by the synchronous magnetic recorder.

A rough estimate of their signal content in decibels is given along with the photographs. Each contains one pair of signals and have both contributed to the measured power level. Actually the signal level of either peak is smaller by half the indicated *db*. About $-6db$ is that an observer can just locate on seeing the signal on the CRO screen but some improvement is obtained when photographed with exposures of the order of a few seconds and the signal values illustrated are higher than the actual value of the signal processed by the instrument. A word regarding the test signals used in this investigation and in getting the accompanying photographs may not be out of place. All these are nuclear magnetic resonance signals due to a small amount of water in a Twin T bridge. By varying the quantity of water and the concentration of paramagnetic salt it contains, signals over large orders of magnitude can be obtained. A very quick method of increasing the noise content with respect to the signal is to detune the receiver. Another is to increase the power input to the bridge to cause saturation of the medium and thus decrease the signal. One or the other of these were used to get faint but known signals. The nulcear magnetic resonance signals were particularly useful in assessing the usefulness of the device, for during every rotation of the recorder drum *two* nuclear resonance signals are found and the ratio of their heights form a useful reference when comparing two different recordings of the same pair of signals. More about this will be mentioned in the next section. Another important point to be noted is the ease with which the signals may be switched off keeping everything else the same.

4. OUTPUT S/N RATIO

When one observes a periodic signal presented on a cathode-ray oscillograph a fair discrimination between noise and signal may be made when the observation extends over a few seconds. The eye smooths out the contribution of noise and this fact has now been well recognised. There is a threshold for this and is about $-3db$ to $-6\,db$ varying with observers and their training in locating signals. The capacity of the observer for integration does not extend beyond that. Thus even though some signals happen to be below noise level, within certain limits, it is possible to recognise its presence and form an estimate of its magnitude and get an idea of its true detail. How far is this practicable when using the magnetic recorder? How far are the details presented by a synchronous magnetic recorder reliable? It is not possible to observe the signal over a length of time and sift the true from false detail in the strict sense of the term for the reproduced output form is just single and no amount of looking at it can possibly reveal details as true or otherwise. For this it is necessary to compare distinct recordings of the same signal and find to what extent they agree with each other. A few say two or three recordings of the same signal will usually enable one to distinguish the true from the false detail. An examination of the accompanying photographs will show that the synchronous magnetic recorder can give a high discrimination from noise.

While looking at a series of recordings of the same signal is very instructive and useful it is possible to acquire a rough estimate of the output S/N ratio in some cases as follows. The total r.m.s. voltage or current output is measured for various integration intervals t. If the current signal output is measured then

$$\sqrt{\bar{i}^2_{\text{signal}}} \alpha t$$

and

$$\sqrt{\bar{i}^2_{\text{noise}}} \alpha \sqrt{t}$$

The total output may be written as

$$\bar{i}^2_{\text{out}} = \bar{i}_0{}^2_{\text{signal}} t^2 + \bar{i}_0{}^2_{\text{noise}} t$$

$$\frac{\bar{i}^2_{\text{out}}}{t} = \bar{i}_0{}^2_{\text{signal}} t + \bar{i}_0{}^2_{\text{noise}}$$

By drawing a graph of

$$\bar{i}^2/t \text{ vs } t$$

it is in principle possible to get an estimate of $(S/N)_{\text{out}}$. Such a graph is given in Fig. 3. The accuracy of the measurements is not enough to measure $\bar{i}_0{}^2$ accurately particularly as this happens to be very small. The figure, however, illustrates the linear dependence on t. In this case, the output S/N is about 50 but this is an under-estimate in view of the rough character of the measurement particularly at low values. The input signal was about -5 *db* and so the improvement is about 22 *db*. For comparison, if the high frequency cut-off is placed at 1,000 cycles the improvement to be expected on considerations of bandwidth and recording time is about

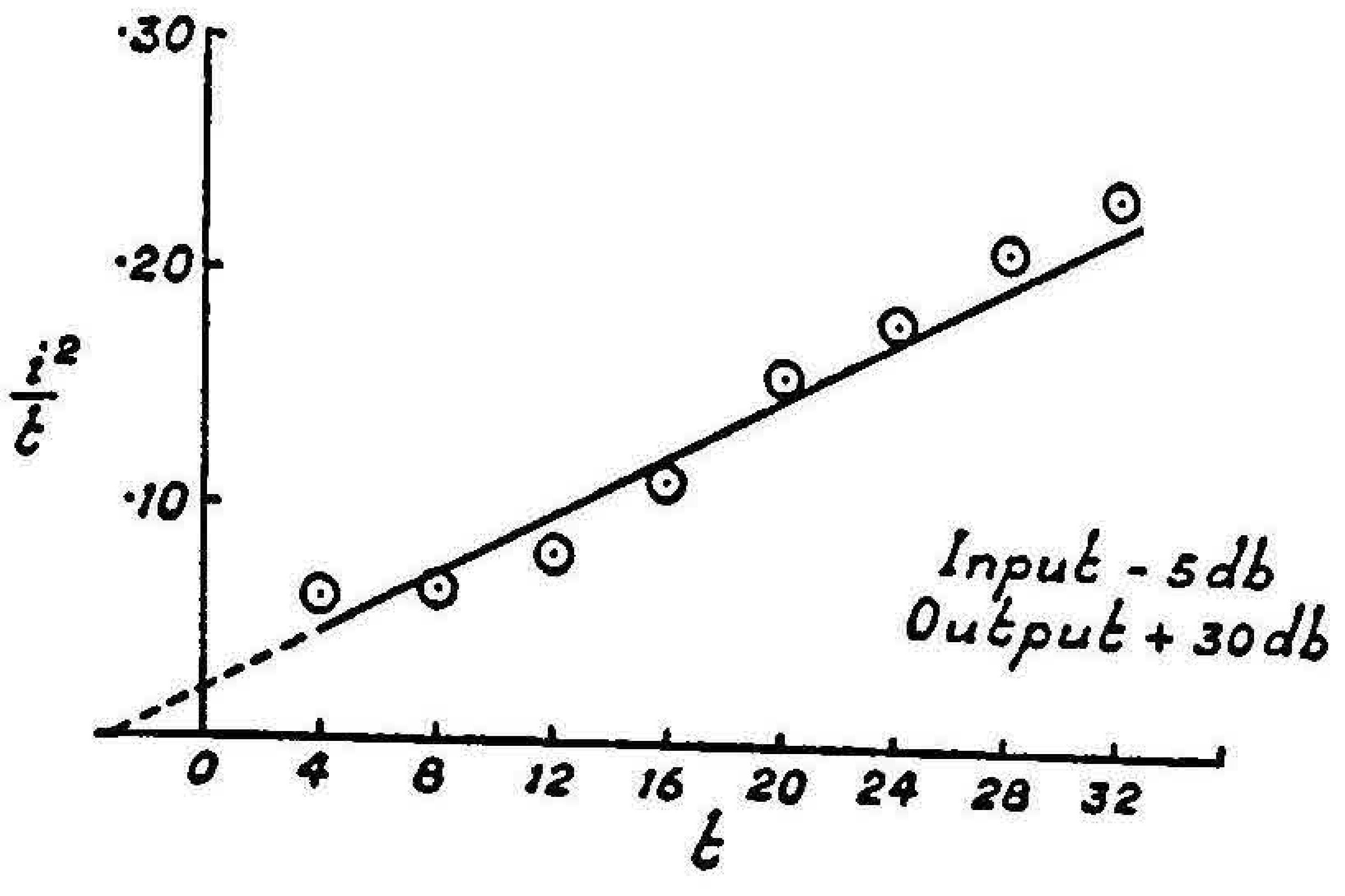

FIG. 3

+ 25 *db* (40 harmonics admitted in 1,000 cycles and recording time – 35 sec.). In view of the rough estimates the near agreement must be considered accidental. However, it is instructive to note that the orders of magnitude are preserved. It must be remembered here that the reference level chosen for the above quoted *db* figures is the noise level itself and that in all the cases of noise + signal, whether the input or the output, the corresponding reference level is that of the input or output respectively. While this method of choosing a separate reference level does not give a link between the input and output, it does represent the facts better. All sources of secondary noise produced in the recorder is also taken into account.

But for the effects of noise, the ratio of the heights of a pair of signals should be unaltered due to recording in the synchronous magnetic recorder and by observing this ratio in the amplitude for the corresponding points on a pair of similar signals an idea of the extent of admixture of noise can be found. The general idea will be clear on referring to Fig. 4 *a* and the graph 4 *b*. Fig. 4 (*a*) shows a pair of signals A and B recorded by means of a synchronous magnetic recorder over a short interval of time (10 seconds).

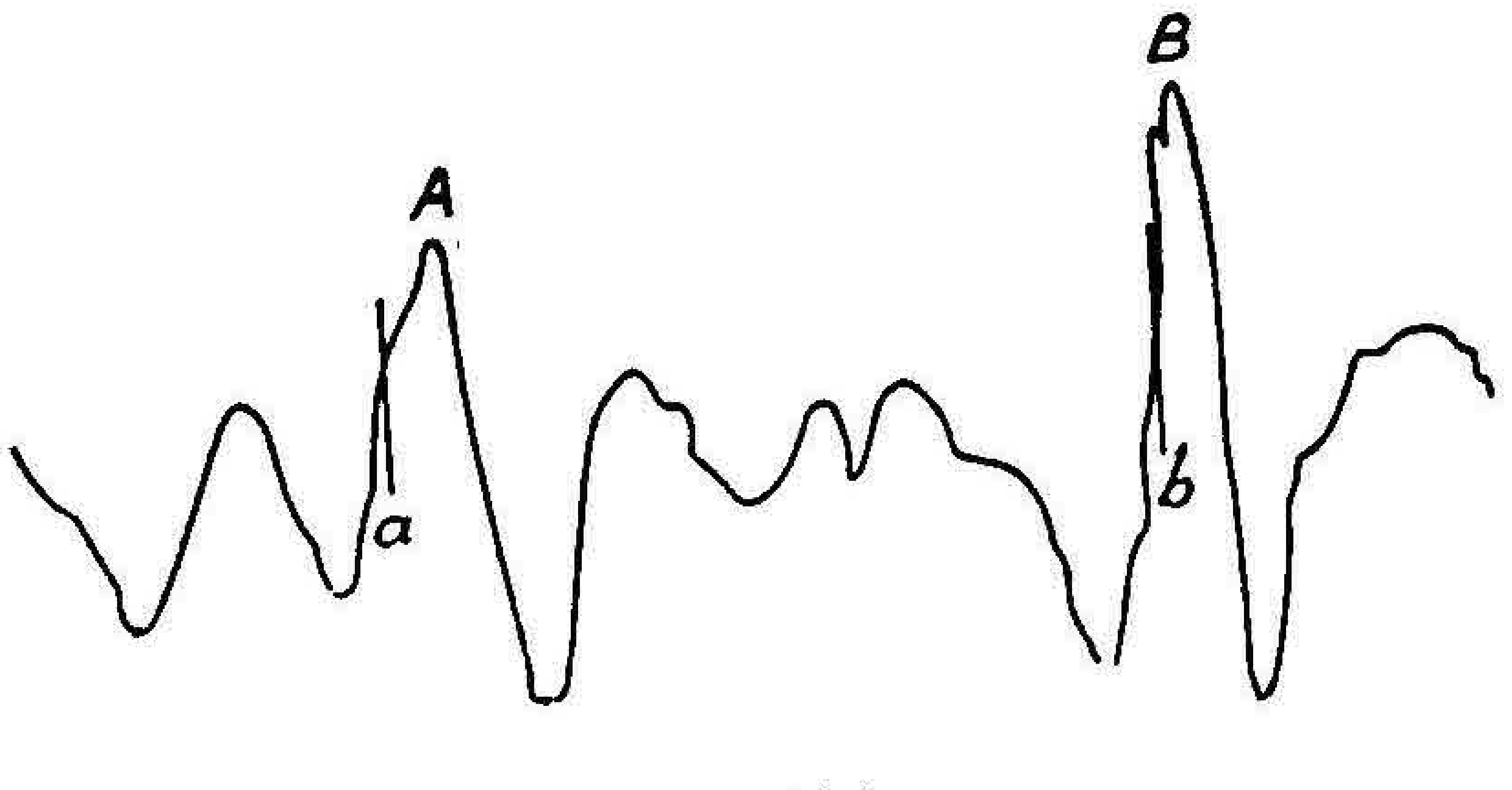

FIG. 4 (*a*)

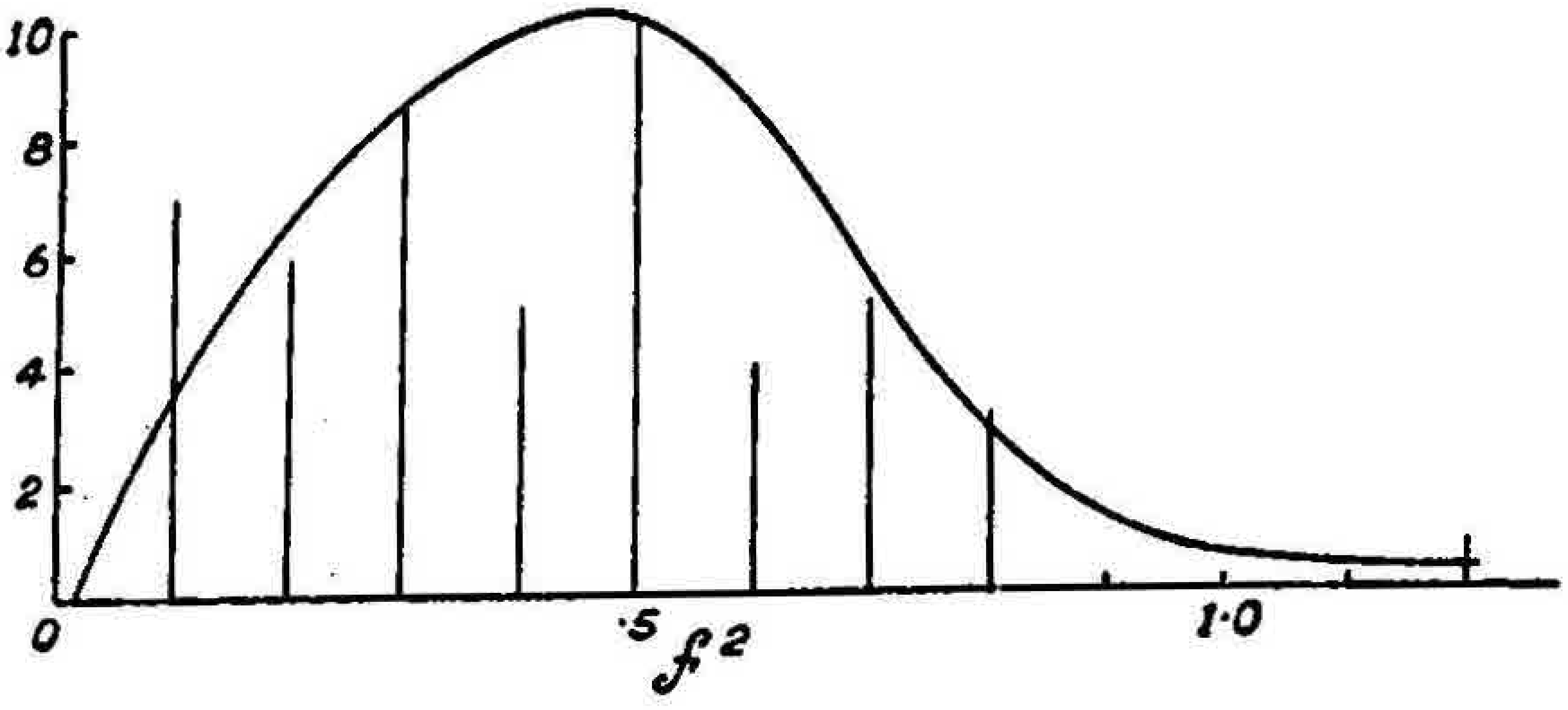

FIG. 4 (*b*)

The signal A is about 0·7 times B. If there were no distorsions and A and B were exactly alike, then the ratio of their ordinates at similar points *a* and *b* for example, must also be 0·7. This however is not the case. The extent of the deviation from the ratio 0·7 is seen in the graph [Fig. 4 (*b*)]. This graph was obained as follows. Each of the signals was divided into 70 parts and the squares (f^2) of the ratio of their ordinates ($A/B = f$) were calculated. They were grouped into intervals of 0·1 and the graph Fig. 4 (*b*) is a histogram. The group belonging to zero is omitted as large values are obtained when the signal A is very small. It is seen that a maximum occurs at $f^2 = 0 \cdot 5$. The general nature of the rise and fall indicates something similar to Maxwellian distribution. If there were no noise content there would have been only one sharp peak at $f^2 = 0 \cdot 5$. The presence of noise has broadened the peak. Exact expressions for the shape of a curve obtained in this way for varying noise contents and signal shapes can be calculated but it is outside the scope of the present investigation. From other considerations it may be remarked that the distribution represented in graph [Fig. 4 (*b*)] corresponds to a S/N ratio of about 5 and may form an empirical criterion for the signal to noise ratio in the output of a synchronous magnetic recorder. An extensive theoretical and experimental investigation in this direction is desirable to establish quantitative criteria for the S/N ratio in the output of a filter integrator like the magnetic recorder which is able to present the signal in a complete form. In a further part of this series, the method of applying the basic principles of the synchronous magnetic recorder for other purposes will be dealt with.

Author's thanks are due to Prof. R. S. Krishnan for his kind interest and continued support.

REFERENCE

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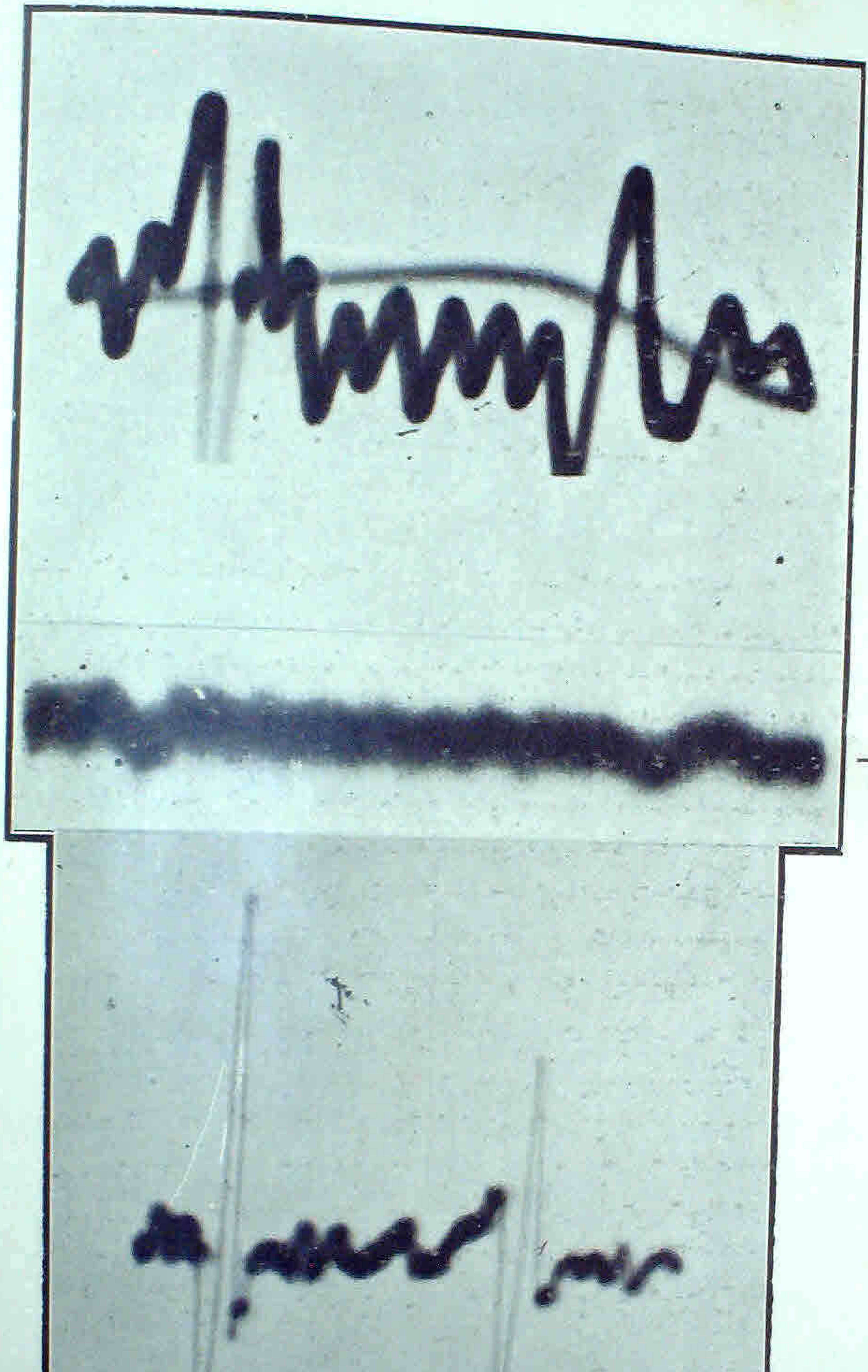
(a)
—6 db
(b)
LOVE
—10 db