JOURNAL OF
THE
INDIAN INSTITUTE OF SCIENCE
SECTION A

VOLUME 35 JULY 1953 NUMBER 3

THE SYNCHRONOUS MAGNETIC RECORDER AND ITS APPLICATIONS—PART I: THEORY

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SUMMARY

The theory and characteristics of the Synchronous Magnetic Recorder devised by the author for the extraction of weak signals from noise have been given. Matters pertaining to the design of the instrument have been dealt with in addition to giving a brief account of its general usefulness for post and pre-detector integration of weak signals.

1. INTRODUCTION

The rapid advances in the application of novel electronic methods to the study of various physical phenomena have brought to the forefront the problem of detecting weak electrical signals in the presence of noise. A partial list of subjects where such considerations are important may be given here to indicate their wide range. They are, microwave spectroscopy, nuclear and paramagnetic resonance, infra-red spectroscopy, radio astronomy, mass spectroscopy, etc. Again in the field of communication engineering, there has been an interest on the effects of noise in the reception of carrier-wave and pulsed signals. New ideas on the nature and extent of usefulness of the observer and his organs of reception in relation to weak signals have been advanced.

The problem of the masking effects of various forms of noise in electronic and electrical instruments is old and various limits are set by sound reason to the extent to which the effects of noise can be unmasked. Of these, the existence of thermal noise and the role of the band width of the detecting system are the important. In experimental work it has always been the aim to approach as close to the thermal noise limit as possible and to reduce the band width as much as possible. Various practical devices have been suggested and some have come into general use for attaining these desirable qualities. They are for example, the phase detector with galvanometer of large time constant, transmission line storage system, regenerative delay line, the mechanical signal extractor,[1] the use of photographic integration,[2] etc. Each of these and similar devices has its own sphere of usefulness and there are theoretical and practical limitations which limit their applicability. Several of the desirable qualities of these can be simultaneously found in a simple device called the " Synchronous Magnetic Recorder ".

The synchronous magnetic recorder was originally introduced by the author for the extraction of weak nuclear magnetic resonance signals from noise which accompanies them always. However, its unlimited usefulness for other fields of study and its interesting properties made a detailed investigation desirable and these papers give a theory of its operation, experimental realization and performance characteristics of the device and the extension of the basic principles for other related applications.

2. THE GENERAL PRINCIPLES OF THE EXTRACTION OF WEAK SIGNALS FROM NOISE

It is well known that the power transferred from a constant power source to a tuned circuit of time constant T depends upon the spectral-distribution of energy in the output of the power source. If the spectral distribution is monochromatic, the power transferred is proportional to T and hence the voltage across the circuit is proportional to $T^{\frac{1}{2}}$. On the other hand a source with a continuous spectral distribution of power in its output transfers power independent of the time constant T of the circuit into which it feeds. In practice a continuous distribution of power in the spectrum corresponds to that given by a noise source and the monochromatic spectrum refers to a signal of given frequency, amplitude and phase. Thus the difference in the behaviour of a tuned circuit with respect to monochromatic and continuous sources gives a means of isolating one from the other.

There are two ways of looking at the role of the tuned circuit. We may look upon it either as a filter of band width 1/T in which case we may qualitatively say that it admits almost all of the signal and only a small portion of noise or we may look upon it as an integrating device which goes to add up the signal all the time and the noise only much less so, on account of the infinitesimal power content in a very small frequency range. The concepts of bandwidth and integration time are conjugate to each other. One is reminded of the relationship existing between the steady state transmission characteristics and the transient behaviour of an amplifier, or the relation existing between the line width and life-time of an atom existing in an excited state.

Such a form of integration making use of the selective property of a tuned circuit or similar device is known as " pre-detector integration ". However, a limit exists as to the possible selectivity obtainable or the usefulness of a high selectivity if one such were obtainable. For, in practice, the signal sources are not strictly monochromatic in their output, and their power content is rather spread over though on a limited band of frequencies. Pre-detector integration is useful in so far as the selectivity of the integrator does not encroach on this domain. But when it does the signal frequencies also get affected and the process of integration instead of contributing to augment the signal actually mutilates it. In such a case the only available information regarding the signal is the power available from it and we cannot say anything regarding its amplitude or phase.

This does not mean however, that nothing more can be done to find the existence of a signal in noise and form an estimate of its magnitude. Still further integration is possible not of the type discussed above but depending on some prior knowledge of the signal. For instance, the signal might be repeated at regular known intervals and the problem may be just to estimate the magnitude of such a *periodic* signal. In such a case the carrier wave is said to be modulated and the modulation is dealt with by a rectifier or detector whose output when suitably integrated can be made to give useful information regarding the signal. In the majority of the physical investigations where it is necessary to detect a weak signal, means may be found to modulate the signal in a known way. Thus for example, in nuclear magnetic resonance, the magnetic field is varied periodically, in microwave spectroscopy the stark effect is made use of by employing a varying electric field, and in infra-red spectroscopy and radio-astronomy the modulation is effected by a periodic interruption of the source of the signal. As such a modulation can be performed at low frequencies (in fact it is practicable to do so only at fairly low frequencies) and a narrow band chosen about this frequency, it becomes possible to effect a second integration to discriminate against noise. This is called post-detector integration. In view of the now well-known fact that the process of detection causes some loss of information regarding the signal and that it makes the signal look noise like, post-detector integration is not as effective as pre-detector integration for equal integration intervals. However, the comparative ease with which post-detector integration can be performed makes it the favoured. As already mentioned, different schemes have been proposed and tested for performing such integrations. The qualitative considerations outlined above apply to all the systems and form a framework on which the design, the analysis of operation and evaluation of the performance can be based. These apply also to the synchronous magnetic recorder with which we will be concerned specifically in what follows.

3. THE SYNCHRONOUS MAGNETIC RECORDER

Before proceeding to discuss the theory of the synchronous magnetic recorder as an instrument for the extraction of weak signals from noise a brief description of the instrument in its simplest form may be included here to fix our ideas. The purely experimental material forms the subject-matter of another communication. The synchronous magnetic recorder consists of a small drum of permanent magnet material capable of being revolved about its axis at a suitable frequency depending upon the periodicity of the weak signal to be detected. The frequency of rotation may be chosen to be *equal to* or a small simple fraction of the periodicity of the signal and is synchronized with it. The signal along with its noise is fed to a small *recording head* similar to those used for the magnetic recording of sound. The recording head records the signal as a spiral pattern of magnetization on the surface of the drum while slowly travelling parallel to the axis of the drum—along the length of the drum. This pattern of magnetization is reproduced as a voltage while it rotates past a reproducing head. This reproducing head while working on principles to the ones used in magnetic recording of sound is dissimilar to them in many ways. It is made long and extends parallel to the drum mentioned above. The instantaneous voltage induced into it is proportional to the sum of all the magnetization existing along the length of the drum. When the recording has been carried over a sufficiently long interval of time T, the fourier components of the signal which are all in synchronism with the drum rotation give rise to an output which is proportional to T. The Fourier components of noise being of random amplitude and phase for each cycle of recording, give rise to an output proportional to $n^{\frac{1}{2}}$, where n is the number of cycles in time T. As n is proportional to T the output due to noise is proportional to $T^{\frac{1}{2}}$. Therefore, the net signal output is increased by a factor of $T^{\frac{1}{2}}$ with respect to noise. Thus the synchronously rotating drum, a recording head and long pick-up head form the basic components of the synchronous magnetic recorder.

In developing the following considerations, ideas which are in current use in the theory of the ordinary magnetic recording of sound have been taken and a clear account of magnetic recording can be found in a book by S. J. Begun.[3]

4. THEORY

In order not to lose sight of the extent of applicability of the theory and its limitations, we may briefly mention the important assumptions made in the course of the following. All non-linear effects are ignored and the simple mathematical analysis is intended to give a broad working basis than to treat all the problems in minute detail.

It is assumed that:

1. The magnetization is proportional to the instantaneous current signal in the recording head.

2. At constant angular velocity of the drum, the instantaneous reproduced voltage is proportional to the magnetization. It follows that the reproduced voltage is proportional to the original current signal or the sum of the original current signals if the reproducer extends along the length of the drum. Thus if a number of periodic signals of period τ are recorded for a time T and all of them are reproduced simultaneously, the output voltage is proportional to the sum of the instantaneous current signals at times say, $0, \tau, 2\tau, \ldots (T/\tau)\tau$ assuming that T/τ is an integer without much loss of generality (*i.e.*, if $T/\tau >> 1$). Remembering these we may now try to calculate the improvement in signal to noise-ratio due to the recorder. The mathematical representation of noise plus signal may be achieved by expressing them in a fourier series in the period τ. Noise is characterized by a random distribution of its fourier amplitudes and phases. All the fourier components of the signal are definite in amplitude and phase for all time. We may take a linear superposition of these two as the mathematical representation of noise + signal. Thus with every fourier component, $A_n \sin(n\omega t + \epsilon_n)$ of the signal, there is associated a term $A_n' \sin(n\omega t + \epsilon')$ due to noise. The quantities A_n and ϵ_n are independent of time and are given once for all for a given signal. The quantities A_n' and ϵ_n' are not independent of time and they form a two-dimensional normal distribution. The noise components go to produce random amplitude and phase modulation of the signal. However, we may assume that the noise and signal powers are additive, that is, the cross terms due to amplitude and phase modulation are all negligible. Then the available signal and noise powers are proportional to their mean square amplitudes. The mean square amplitudes of the reproduced signal are proportional to

$$\frac{\tau}{T}\left[\overline{\left(\frac{T}{\tau}\right)^2 A_n^2 \sin^2(n\omega t + \epsilon)}\right] = \frac{T}{\tau}\bar{A}_n^2$$

and of noise

$$\frac{\tau}{\mathrm{T}}\overline{\left[\sum_{m} \mathrm{A}_n'(m) \sin(n\omega t + \epsilon_m')\right]^2}$$

$$= \frac{\tau}{\mathrm{T}} \sum_{m}^{\mathrm{T}/\tau} (\mathrm{A}_n'(m))^2 = \bar{\mathrm{A}}_n'^2,$$

where $\bar{\mathrm{A}}_n'$ is the r.m.s. value of noise, because of the random character of A_n' and ϵ_m' and the cross terms take on both positive and negative values. The available signal + noise power $= \frac{\mathrm{T}}{\tau} \bar{\mathrm{A}}_n^2 + \bar{\mathrm{A}}_n'^2$

$$\therefore \quad \frac{\mathrm{S}+\mathrm{N}}{\mathrm{N}} - 1 = \frac{\mathrm{S}}{\mathrm{N}} = \frac{\mathrm{T}}{\tau}\left[\bar{\mathrm{A}}_n^{2}/\bar{\mathrm{A}}_n'^2\right]$$

Therefore the improvement in S/N (power) ratio is T/τ. This rather elementary derivation shows that the time of integration T is the deciding factor in the output signal to noise ratio. On the classical theory we may look upon the integrator as having a band width 1/T. This brings us to the discussion of the nature of the transmission characteristics of the synchronous magnetic recorder.

5. TRANSMISSION CHARACTERISTICS OF THE SYNCHRONOUS MAGNETIC RECORDER

We can regard the synchronous magnetic recorder as a four or three terminal circuit element and speak of its frequency response. Besides exhibiting fairly sharp high and low frequency cut-offs, it exhibits peculiar band pass characteristics. It will be seen that signal frequencies which are octaves of the fundamental frequency of rotation of the drum will also be reproduced because of their exact synchronism. So there will be maximum of transmission at frequencies ν_0, $2\nu_0$, $3\nu_0 \ldots$, etc., till the high frequency cut off is reached. Sub-harmonics of the fundamental will also be admitted, but, output due to them falls off much more rapidly than that of the harmonics of the fundamental. All even sub-harmonics will not at all be reproduced. The output of the odd sub-harmonics falls of as $2n + 1$, where n is an integer. There is a small region of pass around each of both the harmonics and subharmonic frequencies. This width is determined by the time of integration T. Thus the entire pass band is something like a comb shown qualitatively in Fig. 1. The over-all comb or spiked structure does not continue indefinitely on both sides of the fundamental frequency ν_0. Superposed is the high and low frequency cut-off characteristics due to the mechanical specifications of the recorder.

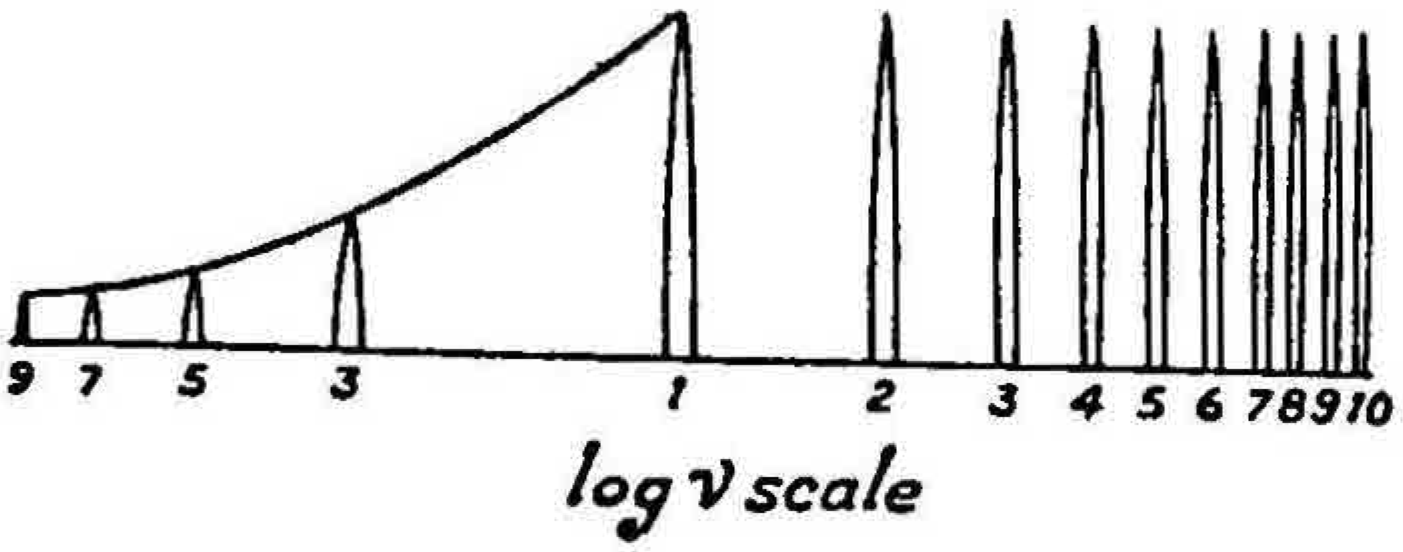

FIG. 1. Comb-like transmission characteristics of the synchronous magnetic recorder

The High Frequency Cut-Off.—The high frequency cut-off is determined by:—

1. Speed of revolution and dimensions of the drum.
2. The gap width of the recorder or reproducer whichever is the larger.
3. The material of the drum.

If the recorder drum has a radius r and is revolving with frequency ν_0, it can easily be seen that a signal frequency ν will be recorded with a wavelength $\lambda = 2\pi r \nu_0/\nu$. When the gap width of the recording of reproducing head is larger than $\lambda/2$ the output due to that frequency is small. Hence $\pi r \nu_0/g$ is a measure of the high-frequency cut-off of the recorder, where g is the gap width of the recorder or reproducer head. The influence of the graininess of the material comes only when the wavelength is very small. Such cases are not of practical importance in the synchronous magnetic recorder and need not be dealt with here.

Low Frequencies.—Considered as a transmission device the synchronous magnetic recorder does not transmit any frequencies below the fundamental ν_0. Frequencies lower than ν_0 are recorded but are reproduced only as frequencies greater than ν_0. Only odd subharmonics of the fundamental are reproduced with frequency ν_0. The contribution due to subharmonics of ν_0 falls off because they are recorded less number of times during the recording time. This is shown in Fig. 1.

The Effect of the Integration Time.—As mentioned in the general discussion in Section 2, it is essential to have an adequate integration time for the extraction of a weak signal. The integration time reduces the width of each small pass band around the fundamental and its harmonics, thus reducing the over-all bandwidth. Qualitatively the effect of the integration time can be understood thus. Frequencies which are slightly different from the fundamental ν_0 or its harmonics lag or lead in the recording and are partly averaged over by the pick-up head. If the averaging is over a complete period their contribution to the output is zero. Formulæ used in the theory of the ordinary magnetic recording of sound can be adapted to get a quantitative estimate of the shape and size of the pass band about the fundamental ν_0 and its harmonics. It can be shown that if the reproducer is tilted with respect to the sound track then the loss in output is given by

$$A = 20 \log_{10} \left| \frac{\sin (\pi l \tan \alpha/\lambda)}{\pi l \tan \alpha/\lambda} \right| db,$$

where l is the length of the drum; α is the inclination of the reproducer to the length of the drum, and λ is the recorder wavelength. In the case of the synchronous magnetic recorder the tilting takes place, not because of an actual mechanical change of the reproducer head but because of the lagging or leading characteristics of frequencies near the fundamental ν_0 or its harmonics. If $\pm \Delta\nu$ is the frequency deviation from ν_0 or its harmonics, and T is the recording time $\pm \Delta\nu T$ is the number of revolutions by which $\nu \pm \Delta\nu$ lags or leads ν_0. So $2\pi r T \Delta\nu$ is the length by which the frequency $\nu_0 \pm \Delta\nu$ is behind or ahead ν_0. Thus the tilt α of the track of $\nu_0 \pm \Delta\nu$ peaks with respect to ν_0 peaks is given by

$$\tan \alpha = \frac{2\pi r \, T \, \Delta\nu}{l},$$

where l is the length of drum over which recording has been made. With $\lambda = 2\pi r \, \nu_0/\nu$ we get

$$A = 20 \log_{10} \left| \frac{\sin \pi T \Delta\nu}{\pi T \Delta\nu} \right| db$$

For $\Delta\nu = n/T$ where n is an integer the attenuation is complete.

As already inferred the time of integration T narrows down the pass band around ν_0 or its harmonics and the output falls off like a $\sin x/x$ curve. It must be noted that there is a finite output between $\Delta\nu = n/T$ and $(n + 1)/T$ but their contribution falls off rapidly as can be seen from Fig. 2 where $f = T\Delta\nu$.

High Frequency Cut-Off due to Finite Gap Width.—The general expression for the attenuation due to the gap width of the recording or reproducing head is

$$A = 20 \log_{10} \left| \frac{\sin \pi g/\lambda}{\pi g/\lambda} \right| db,$$

where g is the gap width, λ the wavelength. This can be written in terms of frequencies as

$$A = 20 \log_{10} \left| \frac{\sin g\nu/2r\nu_0}{gr/2r\nu_0} \right| db$$

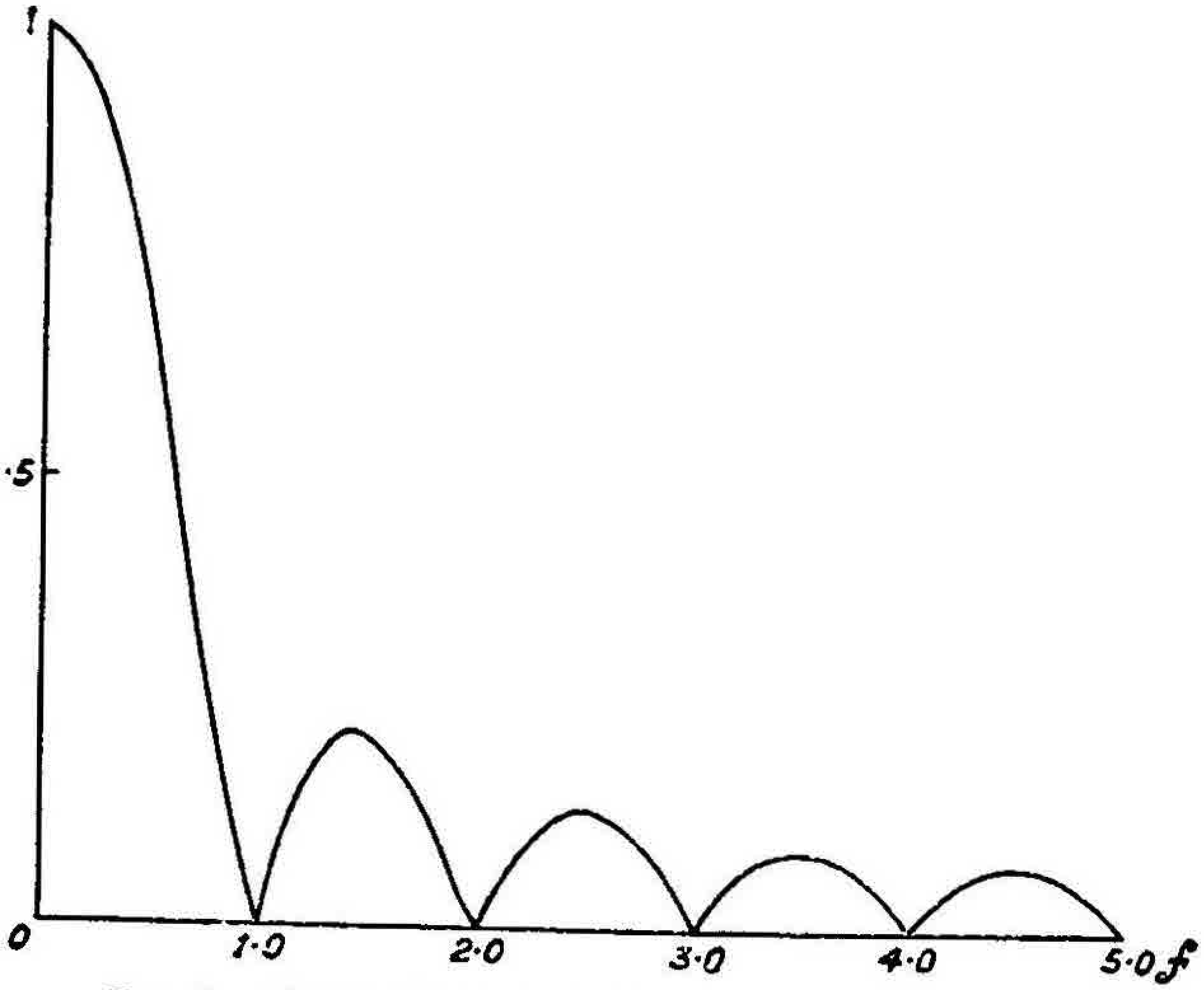

FIG. 2. Shape of the individual elements of the comb

It can easily be seen that for a 20 *db* cut-off $g/2r = \nu'/\nu_0 = 2\cdot85$ for $2r = 9''$ and $g = \frac{1}{8}''$, $\nu' = 200\ \nu_0$; that is upto 200th harmonic of the fundamental can be passed even with recording and reproducing heads with large gap width. This fact is of the highest importance in the usefulness of the recorder which is able to preserve the signal shape and yet achieve a large integration time. This will be of use with signals with a large harmonic content. By making the gap width large it will be possible to admit just only enough harmonics to preserve the main characteristics of a periodic signal.

6. THE SYNCHRONOUS MAGNETIC RECORDER AS A CIRCUIT ELEMENT

The general discussion given above will enable us to design a synchronous magnetic recorder for any specific purpose. The same considerations also throw light on its properties as a circuit element. As a circuit element, it has many peculiar properties and is hardly classifiable into any of the definite categories into which ordinary circuit elements fall. It cannot be described as a passive element because it takes energy from outside and delivers it in the form of a signal. It cannot be described as an active circuit element because it has none of the amplifying properties usually associated with active circuit elements like electron tubes, etc. It can be considered as a three or four terminal network with a suitable frequency and impedence transfer characteristic. It does not exhibit any of the transient characteristics of such networks, however, and behaves like a critically damped galvanometer. It may be said to be periodic in that it has a quite definite frequency of rotation and is highly selective. Its time constant can be increased at will. It stores a certain amount of energy and does not dissipate it and can so be thought of as a device of very high Q and hence high selectivity. It has a comb-like filter characteristic; it admits a wide band yet narrowly. It is practically linear in its response for low frequency signals but high frequencies are not reproduced and hence it has detecting properties and can be used to detect a modulated carrier. This is a characteristic which we have not so far discussed and can be dealt with now.

Adaptability of the Synchronous Magnetic Recorder for Pre-Detector Integration for the Extraction of Weak Signals from Noise—Its Detecting Properties.—In th general theory on the extraction of weak signals from noise a distinction is made between pre- and post-detector integration. The process of detection causes some loss of information regarding the signal. This loss of information can be overcome by pre-detector integration. There are some means of doing this differing widely in the physical principles utilized and their usefulness. However, everywhere the essence of the matter consists in reducing the band-width and increasing the selectivity. As the same obtains in the case of the synchronous magnetic recorder also, there is a possibility of using this for pre-detector integration by using it after the i.f. stages of a receiving system and using a fairly low intermediate frequency.

If the signal is periodic, and the magnetic recorder is synchronized with the signal and not the i.f., it may be made to function as a detector of the signal. In this case it will work like a conventional magnetic recorder of sound where a supersonic current is mixed with the signal current to produce biassing. The supersonic signal is not reproduced because of the high frequency cut-off and only its envelope is reproduced. By using a fairly large level of input, the background fluctuations due to the magnetic medium can be avoided. Because of the property of detecting and the simultaneous smoothing out of noise fluctuations the synchronous magnetic recorder may be useful for pre-detector use.

Summary of Applications of the Synchronous Magnetic Recorder.—The following is a partial list of the possibilities of the Synchronous Magnetic Recorder. Of course with increasing understanding of its properties new developments will emerge.

1. Integrator for erasing noise.
2. Filters.
3. Auto and cross-correlation meters.
4. Fourier analyzer.

5. Use in the reception of periodic pulsed signals in radar.
6. Phase changers with broad band pass characteristics at low frequencies.
7. In plotting of data.

The first has been dealt with in this paper and the experimental work will be given a subsequent paper. Some of the other topics mentioned above will be considered in a third paper.

The interesting properties of the Synchronous Magnetic Recorder offer scope for further theoretical and practical work and it is to be hoped that the instrument comes into wide use.

My thanks are due to Professor R. S. Krishnan for his constant encouragement.

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