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TELECOMMUNICATIONS
A 014

PISTON ATTENUATORS - GENERAL PRINCIPLES

Note: This Issue 2, Page 1, supersedes Issue 1, Pages 1 to 4, dated 2 Nov 43.

1. Information on piston attenuators is to be found in The Services Textbook of Radio, Vol 5, Chap 7 and there is no requirement for a re-issue of a revised copy of this regulation.

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PISTON ATTENUATORS

GENERAL PRINCIPLES

INTRODUCTION

1. In order that a signal generator may be used for the measurement of receiver sensitivity, it is essential that the amplitude of its output be variable and that some means be provided for measuring this amplitude. This has led to the development of various forms of calibrated attenuator, the most familiar of which is the combination of decade box (a resistance network for coarse adjustment in powers of ten) and a slide-wire (for continuous fine adjustment). This type of attenuator suffers from the disadvantage that its characteristic exhibits no simple fundamental law; the calibration of such an attenuator is, therefore, dependent over its whole range upon an external reference standard. Furthermore, the design of such an attenuator for use at frequencies above about 200 Mc. is a matter of considerable difficulty and at wave-lengths of the order of 10 cm. it becomes completely impracticable.

2. More recently, a new type, the piston attenuator, has come into use. This, as will be shown below, can be calibrated directly in decibels and the calibration is, in certain circumstances (see para. 11 below), dependent solely on the physical dimensions of the attenuator. Such attenuators are used in certain Service signal generators.

3. Since the piston attenuator is calibrated in decibels, no *absolute* measurement of power output is available without reference to an external standard. Apart from an initial curved portion of the characteristic, the calibration, as an essential property of all piston attenuators, is strictly linear and the calibration need in theory be carried out at one point only. Special test gear, which itself depends for its use on this fundamental property of strict linearity, has to be used for this purpose.

Basic theory

4. The mode of propagation of electro-magnetic waves in a perfectly conducting, infinitely extended tube, filled with a loss-free dielectric, can be shown to be such that the amplitude of oscillation is expressible in the form :—

$$A = A_0 e^{-jmx} \quad .. \quad .. \quad .. \quad .. \quad (1)$$

where the direction of x is parallel to the axis of the tube. The value of m is given by :—

$$m^2 = \frac{\omega^2}{c^2} - k^2 \quad .. \quad .. \quad .. \quad .. \quad (2)$$

where c is the velocity of the wave in the unbounded medium and ω has its usual meaning of $2\pi f$. For a tube of circular section of radius r, the value of k can be shown to be subject to one of the conditions :—

$$J_n(kr) = 0 \quad .. \quad .. \quad .. \quad .. \quad (3.a)$$

$$J_n'(kr) = 0 \quad .. \quad .. \quad .. \quad .. \quad (3.b)$$

according to whether the electric vector ((3.a)—E waves) or the magnetic vector ((3.b)—H waves) has a component in the direction of the axis of the tube. These boundary equations (which belong to the class of mathematical expressions known as Bessel functions) can be satisfied by an indefinite number of different discrete values of kr, corresponding to different modes of propagation.

5. For relatively low frequencies, $\omega^2/c^2 < k^2$ and m is imaginary. Reference to equation (1) will show that the wave is then attenuated exponentially. With increase of frequency, the rate of attenuation decreases until, at the critical frequency when $\omega^2/c^2 = k^2$, it becomes zero, the wave is propagated without loss and further increase of frequency serves only to reduce the wave-length of the radiation in the tube. Tubes carrying waves above the critical frequency are usually known as wave guides, and an elementary account of their special properties has already been published in Tels. A 011.

6. In the case of piston attenuators, we are concerned only with the case of attenuated waves (*i.e.*, waves at frequencies below the critical frequency) in air-filled tubes. Substituting in equation (1) the value of m (which will be imaginary) found from equation (2) and taking logarithms, we have :—

$$\log A = \log A_0 - x\sqrt{k^2 - \omega^2/c^2}$$

If ω^2/c^2 is small compared with k^2, we may write :—

$$\log A = \log A_0 - kx \quad .. \quad .. \quad .. \quad (4)$$

and we see that, for this condition, the attenuation per unit length is independent of frequency and dependent only on the value of k, *i.e.*, upon the mode of propagation utilised and on the physical dimensions of the tube. (This latter dependent is introduced by equations (3), which will give k in terms of r, the radius of the tube).

7. If we take amplitudes A_2 and A_1 at two points along the tube, x_2 and x_1 distant from the origin, we shall have (by substituting in equation (4) and subtracting) :—

$$\log A_2/A_1 = -k(x_2 - x_1)$$

The expression on the left of this equation (being a natural logarithm) represents amplitude attenuation in nepers; to convert it to decibels, both sides must be multiplied by $20 \log_{10} e$, *i.e.*, by 8.686. We have, therefore :—

$$\text{attenuation in db} = -8.686\, k(x_2 - x_1) \quad (5)$$

It will now be clear that the attenuation bears a linear relation to the length of tube along which it occurs and that if the value of k were known, the tube could be marked out with a linear scale calibrated in decibels.

8. The smallest possible value of k for a tube of radius r is given by the mode of propagation (H_1 wave) corresponding to the solution $kr = 1.84$ of equation (3.b). Making this substitution in equation (5), the rate of attenuation is found to be 16/r db per unit of x; this is found in practice to be correct to within 1% for free-space wave-lengths down to about 25r. Instead of stating the rate of attenuation as 16/r db per unit of x, it is usually more convenient to express it as 16 db per radius, *i.e.*, a distance measured along the tube equal to its radius will give an attenuation of 16 db.

9. The next smallest value of k is given by the mode of propagation (E_0 wave) corresponding to the solution $kr = 2.40$ of equation (3.a); the corresponding rate of attenuation is 21 db per radius, this value being correct to within 1% for wave-lengths down to about 20r. Successive larger values of k, corresponding to other modes of propagation and giving larger rates of attenuation, are not of practical importance, except as possible sources of error.

10. The theory is, of course, applicable to tubes of rectangular or square section, but the different boundary conditions result in rates of attenuation different from those calculated for tubes of circular section. Since square tubes have been used in the signal generator No. 5, the values are of some practical importance; in this case, equations (3.a) and (3.b) are replaced by the condition :—

$$ka = \pi\sqrt{m^2+n^2}$$

where a is the length of a side of the section and m and n are integers. Successive values of k may readily be calculated by taking increasing values of m and n, with the proviso that wave-types H_{00}, E_{00}, E_{01}, E_{10} do not exist; the smallest value of k (corresponding to H_{10}) is therefore 3.14 nepers (27.3 db) per length of side, comparing favourably with the value of 32 db per diameter for the corresponding mode of propagation in circular tubes.

Application of the theory

11. The theoretical treatment suggests the possibility of making an attenuator with a linear decibel scale, by projecting waves into a tube and providing a suitable collector, fitted to a piston, which can be moved longitudinally within the tube. It is first necessary to consider what conditions must be fulfilled, if such a system is to attain its theoretical expectations; these conditions can be most readily grasped by an examination of the assumptions that have been made in the theoretical argument. These are as follows :—

(*a*) *The material of the tube is perfectly conducting.* In practice, the conductivity of copper or brass is sufficiently high to introduce no appreciable error.

(*b*) *The dielectric is loss-free.* This is so nearly true of air that no appreciable error is introduced.

(c) *The tube is a perfect cylinder (or rectangular tube).* The tube can be manufactured to tolerances completely adequate for the accuracy required. However, tubes of square section are more difficult to prepare and the general trend of design is, in consequence, towards cylinders.

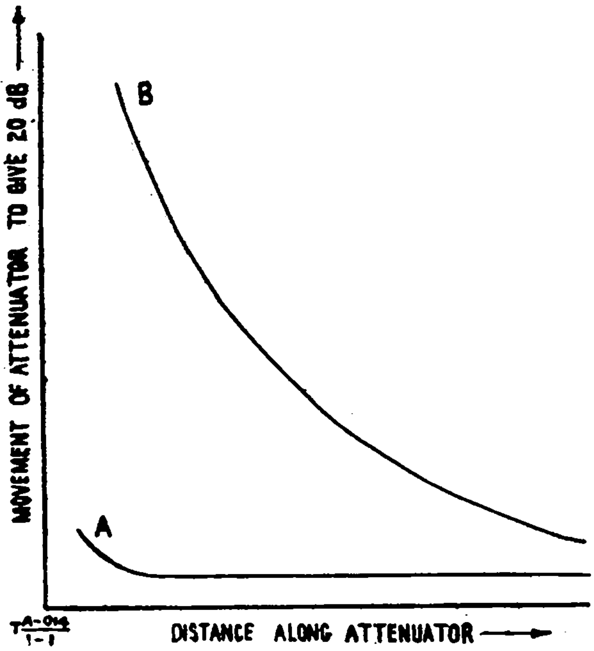

Fig. 1.

(*d*) *Rate of attenuation is independent of frequency.* This, as can be seen from para. 6, is substantially true only if ω^2/c^2 is negligible compared with k^2, which is true (paras. 8 and 9) for tubes of which the diameter is no greater than about 1/10 of the wave-length of the radiation concerned.

(*e*) *The wave is pure.* We have considered only that case in which the wave is propagated in a single mode. It is, however, possible for radiation to be propagated in what is effectively two or more modes simultaneously; this might be more correctly expressed by stating that it is possible for two or more waves of differing field configurations to be propagated simultaneously along a single tube. In such cases, the attenuation does not follow a simple exponential law and a linear calibration is impossible.

It will be clear that (*d*) and (*e*) are the assumptions of practical importance; these will be considered separately at greater length.

12. Assumption (*d*) involves a consideration of the optimum radius of the tube; several factors must be taken into account and the decision is inevitably a compromise. For wave-lengths in the region of 5 cm., the rule that the diameter must be not greater than 1/10 of the wave-length would give a tube of 0.25 cm. radius as an upper limit. Not only is the excitation of a very narrow tube a matter of some difficulty, but the rate of attenuation—which is inversely proportional to radius—is very rapid. A Service signal generator is required to have a discrimination of the order of ½ db, and ½ db, for a tube of 0.25 cm. radius using E_0 waves, occupies only 0.006 cm. along the tube. The mechanical construction of a piston to permit of this accuracy is far from easy. On the other hand, if the diameter is materially increased, the rate of attenuation—and hence the calibration—becomes frequency-sensitive, which is undesirable. In practice, a radius of about 0.3 cm. is used for 5-cm. work and a certain degree of frequency-sensitivity must be tolerated. At the other end of the scale—say, 50 Mc.—the opposite difficulty arises. If the tube is very narrow compared with the wave-length, it is difficult to excite correctly; but, the greater the diameter of the tube, the greater the length needed for a satisfactory range of attenuation and the more cumbersome the attenuator becomes. In practice, a radius of 2 to 2.5 cm. will probably be used at such frequencies.

Importance of correct excitation

13. Assumption (*e*) is the more important. It shows that the purity of the wave is a fundamental necessity and the means of excitation of the tube, therefore, of the greatest importance. It is not possible to excite a tube in such a way as to produce a completely pure wave; it is, however, possible to reduce the unwanted components to a minimum by suitable excitation and (in certain cases) by the use of a screen. A proportion of higher-order modes will always be present, but will be attenuated more rapidly than the desired mode and, after a certain length of the tube, will be negligible in comparison. There will, therefore, be an initial length of tube over which the attenuator scale is not linear; assuming it is proposed to work only on the linear portion of the characteristic, there will be an initial attenuation which cannot be reduced. For a well-made piston attenuator, this should be not greater than 20 db; in other words, the maximum power that can be drawn

from the attenuator with this restriction is 20 db down on the oscillator output. In practice, a further 5 or 6 db can be obtained if an error of about $\frac{1}{4}$ db can be tolerated; this additional, but less accurate, range is sometimes provided on a signal generator, but is distinctively marked on the attenuator dial. The effect of different means of excitation can be seen from the curves given in Fig. 1.

14. Curve A was obtained from a well-made piston attenuator operating at 50 cm. correctly excited; the characteristic is curved until about 21 db and is then linear for a further 90 db (the end of the useful range is, of course, determined by the noise level of the receiver used for detection, which level, in turn, is partly dependent on the frequency and conditions under which the receiver is being operated). Curve B was obtained from a similar attenuator which had deliberately been wrongly excited and the characteristic is curved over the entire range. This characteristic is far worse than could be obtained from a Service signal generator, but will serve to emphasize the importance of correct excitation.

15. Brief consideration may be given to the mode of propagation selected. H_1 or E_0 waves are used, but a comprehensive comparison of the advantages and disadvantages of the two types is not yet available. It is, perhaps, justifiable to suggest that the tendency is to use H_1 for the longer, and E_0 for the shorter wave-lengths, though there have been many exceptions to this rule. However, the mode of propagation selected governs the means of excitation used; the problem of correct excitation is closely associated with the problem of *monitoring* the output. This latter problem must, therefore, now be considered.

MONITORING SYSTEMS

General

16. To measure receiver sensitivity, relative attenuations, such as are given on the db scale, are of little value unless they can be referred to some arbitrary standard. It is, therefore, necessary to ensure that the oscillator of the signal generator is injecting into the piston attenuator a power which either is known or can always be set to the same unknown, but convenient, level.

H_1 waves

17. Historically, the first method used for centimetric wave-lengths appears to have been the pea-lamp monitor. A pea-lamp (similar to a normal flashlamp bulb) is mounted in the attenuator as shown in Fig. 2.

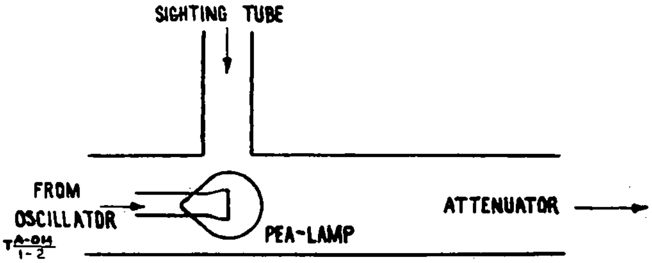

Fig. 2.

The power of the oscillator is adjusted until the pea-lamp just glows, experiment having shown that different observers under different conditions will agree on this point to within 1%; the coupling between oscillator and pea-lamp is locked in this position and a fine adjustment of oscillator power is provided to cover a small range either side of the glowing point. The lamp filament is the exciting electrode (producing H_1 waves) and the power is, therefore, measured, as ideally it should be, at the point of injection. This system has the following disadvantages:—

(*a*) The exciting electrode is far from ideal and unwanted modes of propagation are produced in inconveniently high proportions. This results in a high initial attenuation, which is especially serious at wave-lengths of the order of 10 cm., at which wave-lengths only relatively low-powered oscillators are at present available.

(*b*) The lamp and its connecting wires constitute a circuit which will be resonant at a certain frequency. The monitor is, therefore, frequency-sensitive.

Eliminating disadvantages

18. The first means of overcoming disadvantage (*a*) is to improve the design of pea-lamp. Much of the unwanted radiation is derived from the connecting wires and, by designing lamps in which the connecting wires are not able to radiate into the tube, considerable improvement has been obtained. Further improvement can be obtained by interposing a suitable screen of the type shown in Fig. 3 between the lamp and the main attenuator tube.

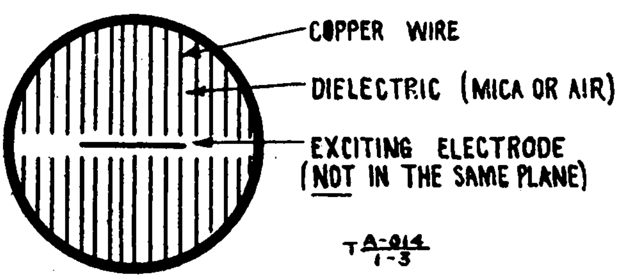

Fig. 3.

Such a screen permits H_1 waves to pass freely, but discriminates against E_0 waves, which are a troublesome constituent of the radiation produced. The horizontal gap is desirable, since it prevents the dissipation of power in the numerous small closed circuits that would otherwise be available.

19. So long as the signal generator has to cover only a limited range of frequencies, disadvantage (*b*) can be overcome by suitable design of the pea-lamp connections. If, however, a wide range is essential—e.g., 8 to 12 cm.—some form of monitor tuning control may have to be introduced. Such a system has been used in experimental signal generators, but no Service signal generators of this type are envisaged at present.

20. An alternative means of estimating the power dissipated in the pea-lamp filament is to incorporate the lamp in a bridge circuit. There will clearly be a definite relationship between the resistance of, the temperature of, and the power dissipated in, the filament; a simple bridge circuit can be designed that will enable the resistance of the filament (varied by adjusting the power injected into it) to be balanced against an arbitrary setting of a variable resistance. No service signal generator of this type is envisaged at present.

21. A simpler monitoring arrangement available at lower frequencies is the following (Fig. 4) :--

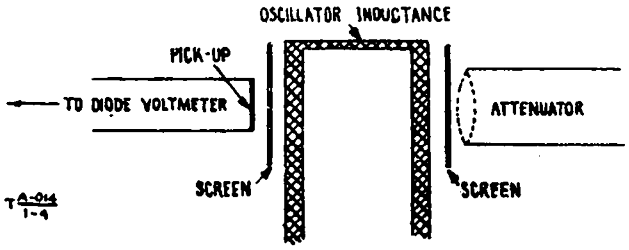

Fig. 4.

E_0 waves

22. The monitoring of signal generators with E_0 propagation is less simple. Fig. 5 indicates two methods which are available.

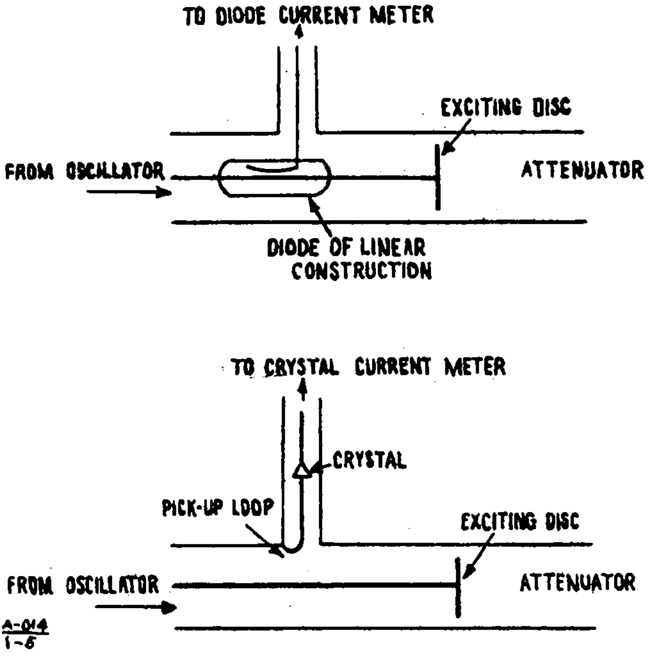

Fig. 5.

It should be noted that the design of a screen for E_0 waves such as was used for H_1 presents considerable difficulty and does not appear to have been attempted for piston attenuators. Fortunately, however, the method of excitation for E_0 waves does not appear to introduce any appreciable H_1 component—which, being more slowly attenuated, would be very troublesome—provided that the dimensions of the exciting disc are carefully chosen.

23. In conclusion, it must be made clear that the above brief account constitutes by no means an exhaustive list of the various types of monitoring system available. The function of this E.M.E.R. is only to draw attention to the general problems involved ; details of the monitoring systems employed in Service signal generators will be provided in the E.M.E.Rs. dealing with the individual equipments.

COLLECTOR MECHANISMS

24. The design of collector must clearly be conditioned by the frequency concerned and the mode of propagation employed. A type commonly used for H_1 waves at wavelengths down to about 10 cm. is shown in Fig. 6.

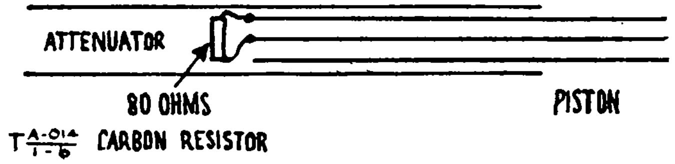

Fig. 6.

An important consideration is the impedance as seen by the receiver looking back into the collector. This should, ideally, be the impedance as seen by the receiver under normal operating conditions and is commonly 80 Ω. To avoid interaction between the receiver input circuits and the attenuator, the receiver is usually buffered from the attenuator by the insertion of a sufficent length of suitable cable. Full details of collector mechanisms employed in Service signal generators will be given in the E.M.E.Rs. dealing with the individual equipments.

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