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SOME APPLICATIONS OF PERMANENTLY MAGNETIZED FERRITE MAGNETOSTRICTIVE RESONATORS

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Approved

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Introduction

There are many cases in which the reaction of a sharply resonant mechanical body upon an electrical circuit can be advantageously employed. Probably the most familiar of these involve quartz crystals as frequency control of oscillators, elements of lattice filters, and the like. The use of magnetostrictively coupled resonators is less well established, probably because in the past such resonators have seriously reduced the Q of their actuating coils and have usually required a magnet for "bias". The advent of the so called "ferrite" material has eliminated these drawbacks and makes the magnetostrictive resonator a practical device of negligible cost compared to a crystal, at least for frequencies of the order of a megacycle or less. The discussion in this bulletin is limited largely to ferrite resonators of toroidal form permanently magnetized with closed lines of biasing flux.

General Discussion

A familiar magnetostrictive resonator is shown in Fig. 1. A nickel rod R is maintained in a partly magnetized condition by the horse shoe magnet, and alternating current in the winding alternately increases and decreases the magnetization of the rod. This results in a corresponding decrease and increase in the length of the rod because a nickel rod shrinks in proportion to its magnetization. If the frequency of the alternating current is made the same as the natural frequency of longitudinal vibration of the rod, the amount of motion produced by a given amplitude of current is greatly increased. The "mechanical Q" of the rod may be defined as the ratio of the natural frequency of the rod to the difference between the two frequencies (one a little above and the other a little below the rod frequency) at which the rod motion is equal to its maximum value divided by the square root of two.

The resonator described has the merit that if the rod is thin compared to its length it retains enough magnetization to continue to operate even after the magnet is removed. However, it has the drawback that eddy currents in the nickel, even if the rod is laminated, cause losses which make the apparent Q of the coil low. Furthermore, the mechanical Q of a nickel rod is not very high, being only of the order of two or three hundred.

Ferrites as Magnetostrictive Resonators

If in Fig. 1 a rod of a suitable ferrite is substituted for the nickel, the Q of the coil is not only not lowered but may be greatly increased, because the resistivity of the ferrite is so great as to preclude eddy currents. Furthermore the mechanical Q of the ferrite is quite high, of the order of several thousand, the exact value depending on the composition used and to some extent on the amplitude of vibration, the intensity of magnetization and various other factors. Unfortunately, however, the coercive force of the ferrites best suited for resonator use is so small that even in the case of very thin rods, the free poles developed at the rod ends by magnetization are sufficient to demagnetize the rod if the magnet is removed.

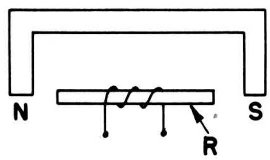


Fig. 1 - Magnetostriction rod resonator.

Permanent Magnetization of Ferrites

If instead of a rod, a torus of ferrite is magnetized (by direct current flowing in a toroidal winding) no free poles are created and a considerable residual magnetization remains in the torus after the magnetizing current ceases. In some ferrites the intensity of this residual magnetization is very near optimum for magnetostriction purposes. The number of ampere turns required to produce this magnetization is small, so that the torus can be magnetized by passing a single wire through it and connecting the wire momentarily to an ordinary storage battery. The circuit can be completed by the very short duration contact of a hammer against a block of metal.

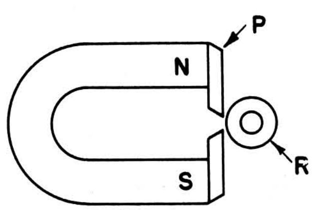


Fig. 2 - Magnet arrangement for circularly magnetizing a ferrite rod.

It is also possible to produce the same kind of magnetization of the torus, although of lesser intensity, by means of a magnet, as shown in Fig. 2. Here pole pieces P of iron are placed on the poles of the magnet to provide a narrow gap in the magnetic circuit. The ferrite torus R is placed against this gap as shown, and then pulled straight away. Due to the easy saturation of ferrite more magnetic energy is stored in the form of clockwise lines of flux going around the larger portion of the torus which is remote from the pole pieces, than in the short portion adjacent to the pole pieces in which the flux lines run counterclockwise. When the torus is pulled away, there remains a circular magnetization of intensity determined by the difference in path lengths through the ferrites between pole pieces. If the gap is small compared to the torus diameter the residual magnetization is of the order of half as much as is produced by the direct-current method of magnetizing. This method is therefore of value only when it is necessary to magnetize a solid cylinder or disc or other body which has no hole in it to pass a wire through.

The Bias and Driving Fluxes Not in the Same Direction

The basic method for producing mechanical forces in a magnetostrictive material is to superpose a "driving" magnetic field upon a constant or "bias" flux in the material. If

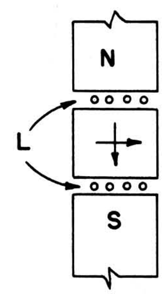


Fig. 3 - Magnet and driving fields for producing shear.

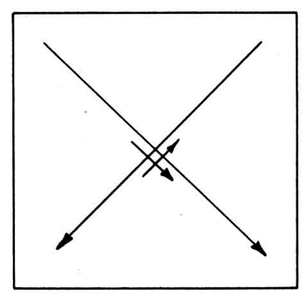


Fig. 4 - Diagram of flux components producing shear.

the driving field is colinear with the bias flux, the result is a simple contraction or extension of the material along the common direction of the bias and driving fields, as in Fig. 1. If, however, the driving field is at right angles to the bias flux, a shearing force is produced. Fig. 3 shows a small square sample of magnetostrictive material in which magnet poles N,S produce a bias flux indicated by the vertical vector, while current in a driving coil L wrapped around the sample produces a driving flux indicated by the small horizontal vector. Each of these vectors can be thought of as composed of two components at right angles, as shown in Fig. 4. It will be seen that along one diagonal of the sample the driving flux component adds to the bias component, while along the other diagonal they oppose. The result is to shorten the one diagonal and elongate the other, so that the sample becomes slightly diamond shaped. But such a deformation of a square constitutes a shearing strain of the material and the axis of the shear may be defined as being perpendicular to the plane of the sample. If the driving field had not been taken as at right angles to the bias, only its component at right angles would create shearing stress, so that finally the shearing stress may be defined as proportional to the vector product of the bias and driving fluxes. That is, its magnitude is proportional to the scalar product of the two fluxes multiplied by the sine of the angle between them, and its direction is perpendicular to the plane containing the bias and driving fluxes.

Some Combinations of Bias and Driving Fluxes in Toroids

In a toroid (or disc or cylinder) the three coordinates may be called radial, circumferential, and axial. The nine combinations of bias and driving fluxes along these three coordinates are shown in Table I.

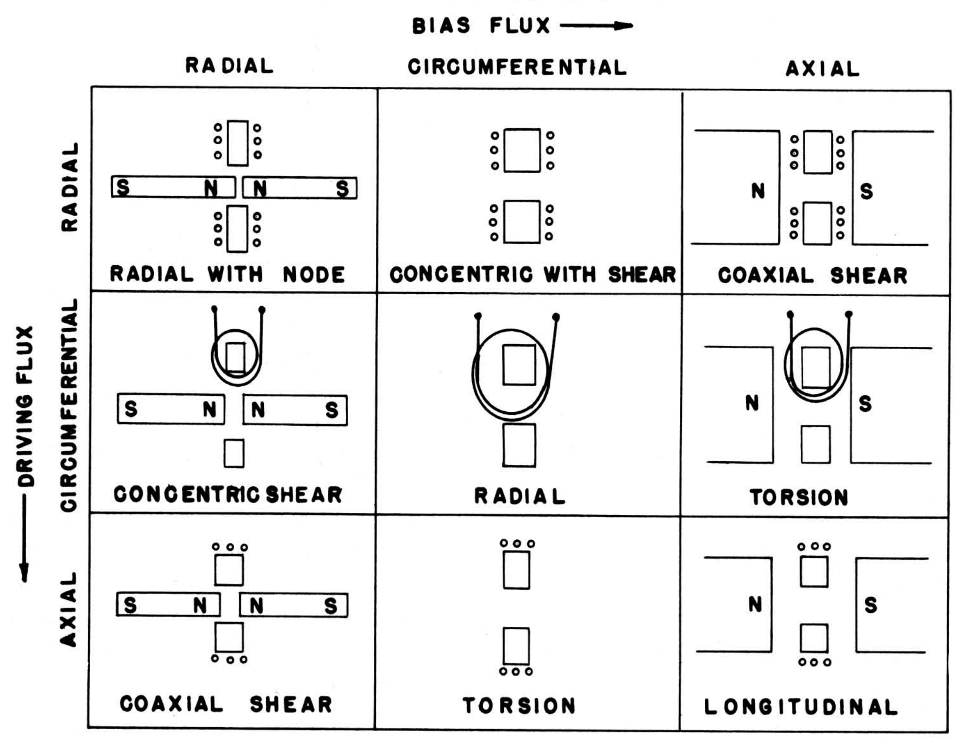
In Table I the first column shows a pair of bar magnets with like poles together to produce radial bias flux, the third column shows the torus between unlike poles to have axial bias flux while the middle column shows no magnet because the torus can be permanently magnetized in the circumferential direction. The same types of vibration are found in squares symmetrically located with respect to the main diagonal of the table, as interchanging the bias and driving fluxes makes no difference except to the practicabilitv of the arrangement. The various types of vibration are:

"Radial Vibration with Node" means that the inner part of the ring moves radially while the outer part moves in the opposite direction, although also radially.

"Radial Vibration" means that all parts of the torus move radially and in the same sense. It is the "fundamental" of which the preceding mode is the first overtone.

Table I

Various combinations of driving coil arrangements and bias fluxes for toroidal-ferrite resonators.



"Longitudinal Vibration" implies simple longitudinal motion as in Fig. 1 although due to Poisson's ratio there is of course some concomitant radial motion just as in the radial vibrations there will be some axial motion.

"Concentric Shear" means that the outer part of the torus moves circumferentially in one sense while the inner part rotates in the opposite sense.

"Torsion" is a simple twisting of the torus on its axis, the ends turning in opposite senses.

"Coaxial Shear" is axial motion of concentric shells, the outer ones moving in opposite sense to the inner ones.

Of the various arrangements of Table I the middle column is of special interest as no magnets are required. The arrangements in the other columns, however, are not necessarily less desirable for some applications. For example, a stronger coupling can be obtained by using the torsion drive shown in column 3 than that in column 2. The frequencies of vibration in these three modes are given in the Appendix. It may be noted, however, that the torsion frequency depends only on axial length, the concentric shear only on radial dimensions, while radial frequency depends on all the dimensions, although very little on axial lengths. The radial and torsional modes are generally the most useful as the "winding" for the radial mode may consist of a single conductor passing through the torus, while the torsional mode may be used for driving a torsion mechanical filter.

Coefficient of Coupling

In any magnetostrictive resonator the efficiency of operation depends upon the magnetostrictive activity of the resonator material. From the point of view of circuit analysis and design, however, the most useful measure of efficiency is what may be termed the coefficient of coupling between a given coil and the resonator with which it is associated. If the coil is tuned by a condenser to the same frequency as the resonator, the system will be found to have two natural frequencies, one above and one below the resonator frequency. The difference between these two, divided by the resonator frequency, is the coefficient of coupling. (The same definition gives the coefficient of coupling between the coils of any pair of like-tuned-electrical circuits.) This coefficient can be readily measured with a "Q-meter". The coil, with resonator in place, is connected to the Q meter and the condenser thereof is adjusted until the coil is tuned to the same frequency as the resonator as evidenced by equality of the two responses observed when the frequency alone is varied. The difference between the frequencies at which the response peaks occur, divided by the mean frequency, is very closely equal to the coefficient

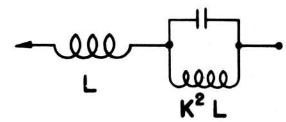


Fig. 5 - Equivalent circuit for magnetostriction resonator.

of coupling. The coefficient depends on how closely the winding can be associated with the resonator. With a toroidal winding and the radial mode of vibration, coefficients up to about 10 per cent are obtainable. The combination of coil and resonator can be replaced, for purposes of circuit analysis, by the equivalent circuit of Fig. 5, where L is the inductance of the coil with resonator in place, and K is the coefficient of coupling (expressed as a fraction of unity, not as per cent). The antiresonant frequency of the divided circuit is the same as the natural frequency of the resonator, and its Q the same as the mechanical Q of the resonator.

Applications

(1) Perhaps the simplest application of a permanently magnetized ferrite torus is for frequency control of an oscillator. Fig. 6 shows a simple circuit for the purpose, which requires only one winding on the resonator, and this may consist of only a single wire passing through the torus. In the absence of mechanical vibrations of the ring the circuit between junctions a and b is inductive, so that oscillation cannot occur. But this circuit can become nearly purely capacitive at a frequency slightly above the natural frequency of the

resonator if the Q of the resonator is high and the coefficient of coupling sufficiently large. Then oscillations will occur when the circuit LC is tuned to approximately the resonator frequency if the transductance of the tube exceeds a value determined by the circuit impedances. A 6J6 tube with 90 volts or more on the plate has been found sufficient with a reasonably high Q coil at L. The non-oscillating plate current is limited to 4 milliamperes by the cathode bias resistor. By varying the tuning of LC, higher frequency oscillations at other resonator modes than the simple radial mode can often be produced. To give an idea of resonator size it may be noted that a torus of 0.82 cm outer diameter and a hole of about 0.15 cm diameter gives radial frequency oscillations at 380 kc.

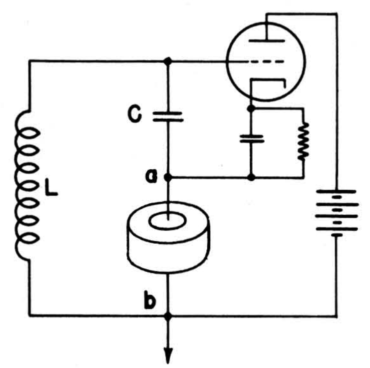


Fig. 6 - Oscillator circuit employing magnetostriction resonator.

Oscillations are more easily obtained if a toroidal winding of several turns is put on the ring. Or, equivalently, if the primary of a transformer with very small leakage inductance is connected between points a and b, the secondary of the transformer being a single turn linked with the torus.

The oscillator circuit is of course not limited to radial vibrations of the torus, as it may also be operated in any mode where sufficient coefficient of coupling is obtainable; in particular the torus may be arranged for torsional operation as shown in the lower middle square of Table I. In this case the coupling is improved, if the torus is short, by putting inert magnetic core material on each side of the torus. The oscillator described is intermediate in frequency stability between a tuned circuit oscillator and a quartz crystal oscillator, while the cost of the ferrite element is negligible.

(2) A simple three-circuit filter may be made by employing a long torus (i.e., a pipe or cylinder) as an intermediate "circuit" between a pair of tuned circuits. See Fig. 7.

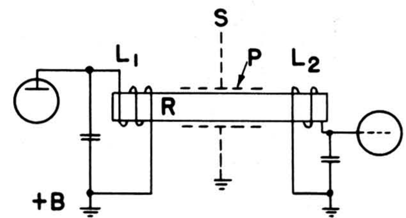


Fig. 7 - A three-circuit filter with a ferrite rod as middle circuit.

In this case the resonator R operates in torsion and is preferably three or more half waves long. It passes through a metal pipe P and shielding S which prevents direct coupling between coils L_1 and L_2. Current in L_1 drives the resonator in torsion, and by the inverse process, torsional vibrations in the output half wavelength induce voltage in L_2. The bandwidth obtainable in this filter is limited by the coefficient of coupling, and this in turn varies inversely with the square root of the number of half waves in the resonator. Fig. 8 shows the trans-

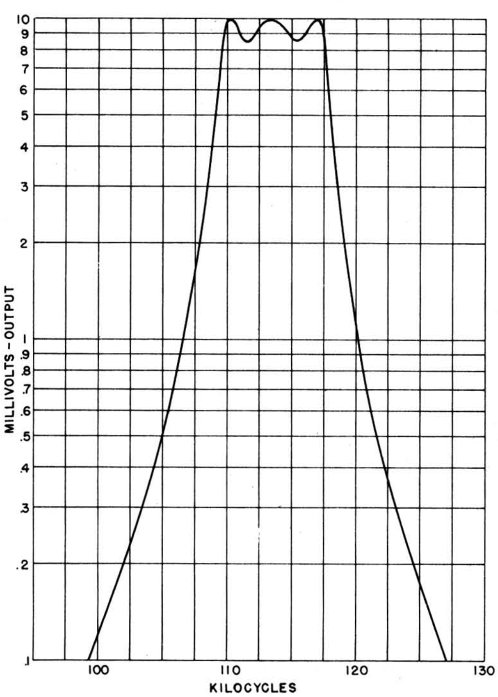


Fig. 8 - Performance curve of the filter of Fig. 7.

mission characteristic of a filter of this sort, operating at the third harmonic of the rod and adjusted to give a Tchebyscheff characteristic with 1.3 db peak-to-valley ratio.

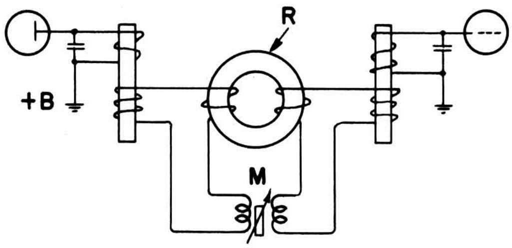


Fig. 9 - Another three-circuit filter.

(3) Another way to eliminate direct coupling between input and output coils is to provide auxiliary mutual inductance to buck out the undesired coupling. Fig. 9 shows such an arrangement, using a toroidal resonator in the radial mode. To avoid winding many turns on the torus, a step-down transformer arrangement is used. The bucking mutual is adjusted by a movable magnetic core M. Fig. 10 shows the performance of such a filter. The dotted curve shows effect of incomplete bucking, which causes the output to fall to 0.06 millivolt at 298 kc, then rise again to a maximum of 0.067 at 303 kc. (Values below 0.1 are not shown in Fig. 10.)

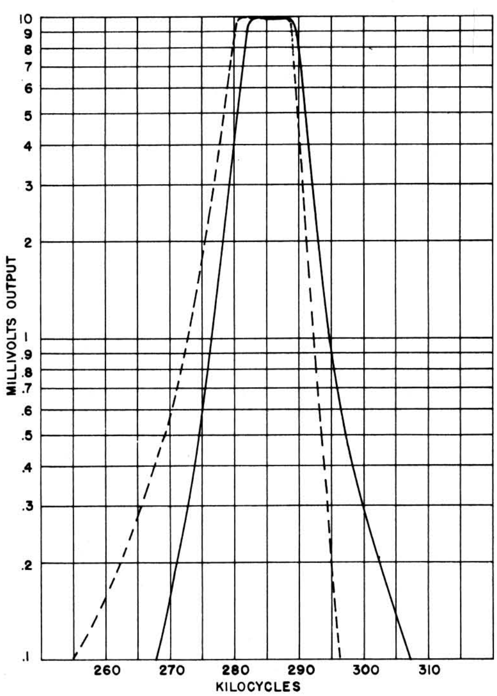


Fig. 10 - Performance curves of the filter of Fig. 9 with different adjustments.

(4) If for the bucking transformer i the above circuit another resonator torus i used, and the two have suitable different frequencies, a differential type of filter results. Fig. 11 shows a curve of such a filter.

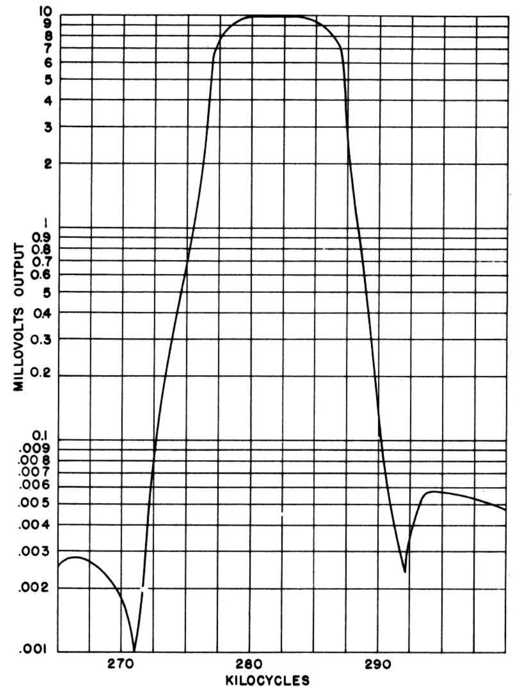


Fig. 11 - Performance curves of a lattice filter employing two ferrite resonators.

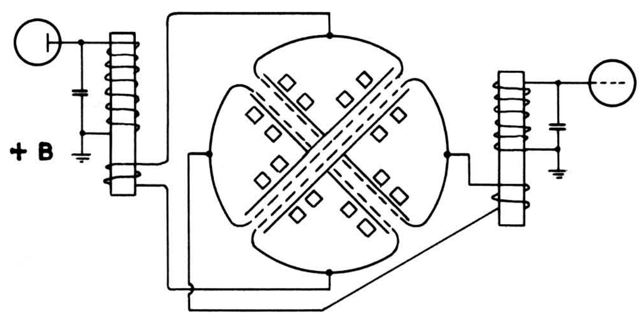


Fig. 12 - A lattice filter employing eight ferrite ring-shaped resonators.

Lattice filters with more than two ferrite rings can be readily designed and easil constructed by putting the rings on thin wall tubes through which only two wires need to be run. Fig. 12 shows, for example, how eight rings each of a different frequency from the others, are arranged to form a lattice equivalent to a cascade of eight tuned circuits. Th chief difficulty encountered in this type of filter is to obtain a selection of rings each having the required coefficient of coupling as well as the proper frequency.

(5) A somewhat different way to add a ferrite resonator to an ordinary pair of tuned circuits is shown in Fig. 13, and its performance curve in Fig. 14. Here all coils are tuned by their correspondingly numbered condensers to the (torsion) frequency of the ferrite ring in L_3 which is flanked by cylinders of unmagnetized ferrite to increase the coefficient of coupling. This is particularly necessary if the rejection points are to be pushed far apart, as the separation of these points, divided by the mid-band frequency, is equal to the coefficient of coupling between L_3 and the ring. From the equivalent circuit (Fig. 5) it will be seen that this is a "mid series terminated m-derived constant K" filter section.

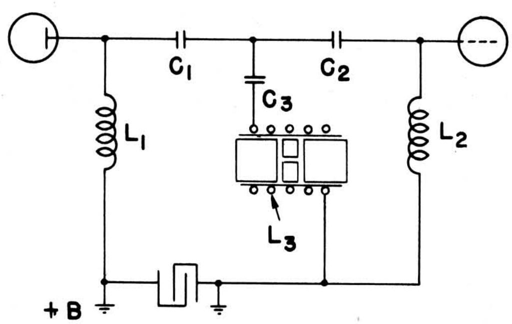


Fig. 13 – An "m-derived" filter employing a ferrite torsion resonator.

By comparison with the dotted and dashed curves of Fig. 14 showing the performance of the same end circuits, (L_1C_1 and L_2C_2) coupled loosely (the narrow curve) and with critical coupling (the broad curve) by simple mutual inductance, as in an ordinary i-f transformer, it is seen that a great deal of improvement is obtained by the addition of the ferrite and its circuit.

The inherent frequency constancy of the ferrite resonator makes it possible to tune this filter in a radio receiver without requiring a signal generator to provide the proper intermediate frequency. The input and output circuits are first detuned, and any strong signal is tuned in. This will peak up sharply at the ferrite frequency, so that the desired intermediate frequency is known to be impressed on the filter. Next, the junction of C_1 and C_2 may be shorted to ground so that input and output circuits are only very loosely coupled by the inductance of the shorting lead. They may therefore be peaked independently. On removing the short, the filter is in tune except for C_3 which must be adjusted so that the rejection points fall outside the transmission band, preferably at approximately equal distances on each side. The spacing between rejection points is not adjustable except in the original construction at which time the coefficient of coupling is fixed.

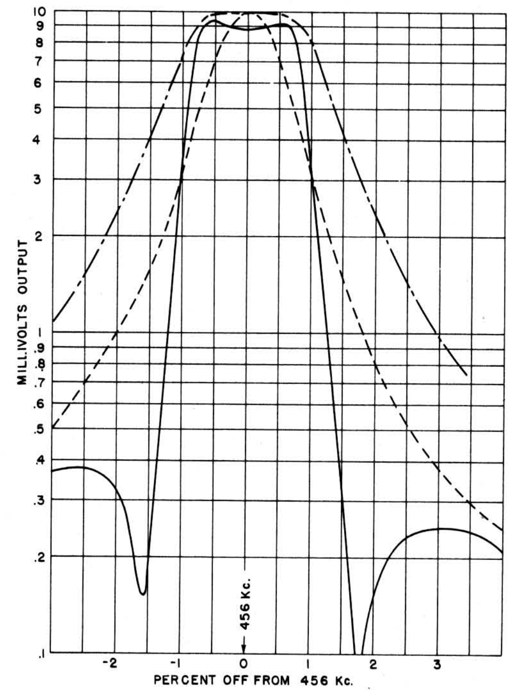


Fig. 14 – Performance curve of the filter of Fig. 13; dashed curves are for ordinary coupled circuits for comparison.

(6) Multi-section torsion filters of high efficiency (low insertion loss) and great selectivity can be made if the end mechanical resonators are ferrite tori. Provided the bandwidth is not too great (not over some 5 per cent) the tuned circuits associated with the ferrite can thus act as the end circuits of the filter, the required terminating resistances being in the form of the electrical resistances in the tuned circuits. Inherent resistance in the electrical circuits sets the lower limit to the bandwidth. The ferrite can be cemented to the metal part of the filter very satisfactorily with polyvinyl acetate.

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Appendix

Velocities in Ferrites

In a homogeneous infinite medium, compression waves travel with a velocity which will be called V_2, shear (or torsion) waves with a velocity V_1 which is roughly half of V_2. In a thin rod the compression or longitudinal waves travel with a velocity V_r which is a little less than V_2, while in a thin infinite sheet the compression wave velocity V_s is between V_r and V_2. Wave lengths corresponding to these velocities will be indicated by λ with corresponding subscripts. In every case the relation $V = \lambda f$ holds where f is the frequency.

The velocities in ferrite depend considerably upon its composition and heat treatment, and to some extent upon intensity of magnetization and temperature. As to temperature, the frequency of a longitudinally vibrating rod falls about 30 parts in a million for each degree centigrade rise in temperature. The frequency increases somewhere in the order of 1 per cent in going from weak to strong bias magnetization. Typical values for the velocities in a strongly magnetostrictive ferrite are:

$V_1 = 3.33 \quad 10^5$ cms/sec
$V_2 = 5.7 \quad 10^5$ cms/sec
$V_r = 5.25 \quad 10^5$ cms/sec
$V_s = 5.4 \quad 10^5$ cms/sec

Frequency Formulas for Toroids

The fundamental frequency of a longitudinally vibrating thin rod is $V_r/2L$ where L is its length in cms.

A torsion rod (or pipe or torus) has frequency $V_1/2L$.

A thin disc with no hole has lowest radial frequency $\frac{2.166}{2\pi a} V_s$ if Poisson's ratio for the material is 1/3, which is approximately the case for aluminum. (a is the radius.)

The radial frequency of a long solid cylinder is the same except that V_2 is used in the formula in place of V_s.

The presence of a hole in a disc lower the radial frequency by an amount not readily given by any simple formula. However, if the hole in a thin disc is so large that a thin ring results, the perimeter of the ring is one wave length at V_r, i.e., $f = V_r 2\pi a$.

A long thin walled pipe has the slightly higher radial frequency $V_s/2\pi a$.

A solid disc of any thickness vibrates in concentric shear according to the relation $\frac{\lambda_1}{a} = \frac{2\pi}{5.135}$ at its lowest frequency, i.e.,

$$f = \frac{5.135}{2\pi} \frac{V_1}{a}.$$

If there is a large hole, the frequency approaches $V_1/2W$ where W is the radial thickness of the wall.

Ferrites for Magnetostriction

Almost any ferrite exhibits some magnetostriction, but best results have been obtained. with a simple nickel ferrite (74.69 grams of NiO plus 159.68 grams of Fe_2O_3) heated to 1300° — 1400° C an hour and a half or so, and cooled slowly.