

MECHANICAL FILTERS FOR RADIO FREQUENCIES*

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Summary—The high Q and small size of metal resonators make them desirable for use in multisection filters for low radio frequencies. This paper describes a simple type of band-pass filter composed of loosely coupled metal resonators with magnetostrictive drive and take-off. Filter characteristics with very sharp frequency discrimination may be obtained by employing a sufficiently large number of sections. Filters of this type are readily constructed for frequencies up to about half a megacycle and with bandwidths from about three per cent down to a small fraction of one per cent. The voltage gain of an amplifier stage utilizing such a filter is generally considerably lower than that of a stage employing electrical circuit coupling, especially at the higher frequencies and wide bands.

THEORY AND MATHEMATICAL DEVELOPMENT OF MECHANICAL FILTERS

A VIBRATING metal rod has a rather low decrement compared to an electrical circuit. For example, the Q of a mechanical resonator or "tank" is of the order of a few hundreds for nickel, several thousands for various steels, and as high as ten thousands for aluminum and its alloys. Furthermore, at radio frequencies the metal tank is small and cheap compared to the corresponding electrical tank so that many of them can be used in a filter.

An electrical circuit is simple compared to a high-frequency mechanically vibratory system. In the electrical case there is only one independently variable quantity, for example, the current. In the mechanical system, however, there may be vibrations in any of the three dimensions. Thus, while a long metal rod may carry longitudinal vibrations governed by the same equations as for an electrical transmission line, it may in addition carry waves of torsion, flexure, and other varieties. One has only to glance over the approximate treatment of the vibrations of a simple cylinder given in Section 199 of A. E. H. Love's *A TREATISE ON THE MATHEMATICAL THEORY OF ELASTICITY*, Fourth Edition, Cambridge University Press, 1927, in order to realize how complicated must be the vibration pattern in more elaborate structures such as are needed for filter operation. For these reasons it appears that the variety of structures providing filter

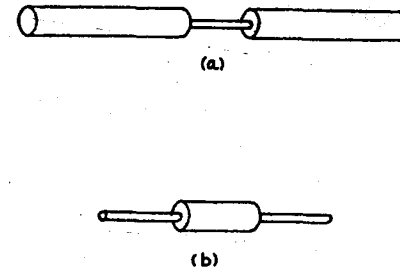


Fig. 1 (a)—Neck type single section filter; (b)—Slug type filter section.

characteristics is almost endless. In what follows, only such constructions will be considered as will, by virtue of symmetry and dimensions, operate in a substantially single mode of vibration analogous to the electrical transmission line. For this purpose the longitudinal mode will be chosen, although other modes, especially torsion, could be used.

The basic unit of the filters to be described is a single section filter composed of a pair of similar longitudinal resonators loosely coupled together so as to possess a pair of resonant frequencies marking the limits of its transmission band. Figure 1-a shows, as one way of making such a section, a pair of half-wavelength resonators connected together by a neck so thin as to act like a weak spring. Both ends of each resonator are motional loops at each of the resonant frequencies. On the other hand Figure 1-b shows a pair of quarter-wave resonators coupled by a "slug" which is relatively thick so that it acts somewhat as a heavy mass. In this case only the free ends of the resonators are motional loops. The band limits in either case can be determined by calculating the frequencies at which the tanks are resonant when vibrating in the same phase and in opposite phases. However, to obtain a more complete picture it is desirable to make use of the fact that these filter sections are mathematically equivalent to electrical filters composed of equal lengths of transmission line connected by a piece of line of different characteristic impedance.

Figure 2 shows the electrical filter section corresponding to Figure 1. Its tank portions have electrical length θ_1 and characteristic impedance Z_1 while the connecting portion has length θ_2 and impedance Z_2 . The pass bands for a filter composed of any number of such sections connected end to end are the frequency ranges within which the iterative impedance of the section has a real component so that it can accept power from the driven end. The expression for the iterative impedance may be obtained by applying the definition of iterative

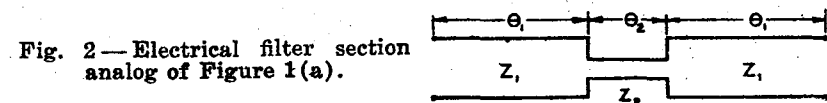


Fig. 2—Electrical filter section analog of Figure 1(a).

* Decimal Classification: R 886.1.

impedance, that is, by equating the unknown iterative impedance to the input impedance of the section when its output is connected to the same unknown impedance. It is perhaps simpler, however, to make use of the fact that the square of the iterative impedance is the product of the input impedances when the section is open circuited and short circuited at its center. By either method the square of the iterative impedance is found to be:

$$Z_1^2 \frac{(\tan \theta_1 + \phi \tan \frac{1}{2}\theta_2)(\phi \cot \frac{1}{2}\theta_2 - \tan \theta_1)}{(\cot \frac{1}{2}\theta_2 - \phi \tan \theta_1)(\tan \frac{1}{2}\theta_2 + \phi \tan \theta_1)} \quad (1)$$

Which may also be written

$$\frac{Z_1^2 \tan^2 \theta_1 - 2\phi \tan \theta_1 \cot \theta_2 - \phi^2}{\phi^2 \tan^2 \theta_1 - 2/\phi \tan \theta_1 \cot \theta_2 - 1/\phi^2} \quad (2)$$

in which expressions ϕ stands for the ratio Z_2/Z_1 .

Since a pass band occurs in any range of θ_1 in which the above expressions are positive, it is evident that band limits are given by the roots of both the numerator and denominator of these expressions. If ϕ is either very small or very large the roots occur in closely spaced pairs, i.e., the pass bands are narrow. Within a pass band defined by a pair of roots of the numerator it is evident that the iterative impedance falls to zero at the band edges and has a maximum near midband. Denominator roots on the other hand define bands in which the iterative impedance rises to infinity at the band edges and is minimum at midband.

In a given structure the ratio θ_2/θ_1 is fixed so that Expressions (1) and (2) can be simplified for a number of particular values of this ratio. For example, if $\theta_2 = \theta_1$, a series of pairs of band edges is

given by $\tan^2 \theta_1 = 2\phi + \phi^2$ and another series by $\tan^2 \theta_1 = \frac{2}{\phi} + \frac{1}{\phi^2}$.

These expressions hold good for either neck-type or slug-type filters, the former type being defined as one having a value of ϕ small compared to unity, while the latter has ϕ large compared to unity. One of the important cases in practice to which the above equations apply is the slug-type filter with quarter-wave tanks. The first of the two equations is used since a large value of $\tan \theta_1$ is required. In this case the angular difference between the values of θ_1 satisfying the equa-

tion is readily determined to be approximately $\frac{2}{\phi} \left(1 - \frac{1}{\phi}\right)$ for large values of ϕ . Since the angular length of the tanks is $\pi/2$ the fractional bandwidth, that is the ratio of bandwidth in cycles per second to the midband frequency in cycles per second, is $\frac{4}{\pi} \frac{1}{\phi} \left(1 - \frac{1}{\phi}\right)$.

It may be noted in passing that the equations indicate the existence of pass bands when the elements are a multiple of a half wave in length, but that the fractional bandwidth in this case is determined by the square root of ϕ (or its reciprocal, according to the type of filter) so that an impractically great disparity between tank and coupler impedances is required to obtain a narrow band. This is the case treated for transmission line filters by Warren P. Mason in his book, *ELECTRO-MECHANICAL TRANSDUCERS AND WAVE FILTERS*, pages 75-77, D. Van Nostrand Co., 1942.

Another important case in practice is $\theta_2 = \frac{1}{2}\theta_1$ for which a straightforward solution gives an approximate fractional bandwidth $\frac{2}{\pi} \left(1 - \frac{\phi}{2}\right)$ for tanks a half-wave long and small ϕ . Again, there are other pass bands of lesser interest for the same structure.

One more particular case of importance is $\theta_2 = \frac{1}{3}\theta_1$. This covers a section composed of resonators three-quarter waves long coupled by a slug one quarter wave long. This is a desirable section for a magnetostriction driven slug-type filter because the drive and take-off resonators have motional nodes available for the coupling coils. The

fractional band in this case is approximately $\frac{4}{3\pi} \frac{1}{\phi} \left(1 - \frac{1}{3\phi}\right)$ for large values of ϕ . Comparing this band with the band previously found for a section with quarter-wave resonators coupled by quarter-wave slugs, it will be seen that the bandwidth is nearly, although perhaps not exactly, inversely proportional to the number of quarter waves composing the resonator.

While the bandwidth can be expressed explicitly for various simple relations between θ_1 and θ_2 as illustrated above, it can also be determined approximately in the general case, at least for the case of narrow bands. For referring back to Expressions (1) and (2), the

roots of the numerator occur when $\tan \theta_1 = \phi \frac{\cos \theta_2 + 1}{\sin \theta_2}$, while root-

of the denominator occur when $\tan \theta_1 = \frac{1 \cos \theta_2 + 1}{\phi \sin \theta_2}$. If now the band is sufficiently narrow so that $\sin \theta_2$ can be considered as constant throughout the band, then the angular bands between roots are approximately $\frac{2\phi}{\sin \theta_2}$ for ϕ very small, and $\frac{2}{\phi \sin \theta_2}$ for ϕ very large. From these expressions it is evident that in every case the band is minimum when $\sin \theta_2 = 1$, i.e., when the coupling element is an odd multiple of a quarter-wave long. It will also be noted that considerable departure from the optimum length of coupler element is possible without much increase in bandwidth.

A reasonably convenient graphical solution for Expression (1) which applies to any ratio θ_2/θ_1 can be carried out as follows: Two circles are drawn with their centers at the origin, one with radius unity and the other with radius ϕ . Straight lines are drawn tangent to each circle at its top, bottom, and two sides. A line from the origin

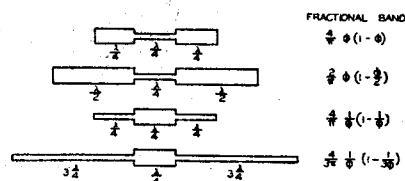


Fig. 3—Fractional bands produced by various practical single section filters.

at angle θ_1 intersects lines tangent to the unit circle at points proportional to $\tan \theta_1$ and $\cot \theta_1$. Another line at angle $\frac{1}{2}\theta_2$ intersects the ϕ circle tangent lines at points giving $\phi \tan \frac{1}{2}\theta_2$ and $\phi \cot \frac{1}{2}\theta_2$. By revolving the two lines from the origin while keeping the ratio of their angles constant the value of θ_1 may be determined which makes the numerator of Expression (1) vanish. The same construction will give all the roots. However, as this method of analysis is not likely to be required in view of the solutions already obtained for the more important practical cases it will not be elaborated in further detail. For convenient reference these practical cases are assembled in Figure 3. From this table approximate bandwidth for tanks of greater length can be inferred by assuming the bandwidth to vary inversely as the tank length, while the band is substantially unaffected by the length of the coupling element so long as it is an odd multiple of a quarter wave.

PRACTICAL LIMITATIONS ON BANDWIDTH

In a mechanical filter, the characteristic impedance of each portion is the product of its cross-sectional area and the intrinsic impedance

of the material of which it is made, the latter quantity being in turn the product of its density and the velocity of propagation of longitudinal waves along that portion. If all the filter is made of the same material, the quantity ϕ is simply the ratio of cross sections, assuming that the sections are small enough so that the velocity is the same in all portions. As has been demonstrated, ϕ or $1/\phi$ must be of the order of the desired fractional bandwidth. If a one per cent band is required, this means that a neck-type filter turned out of round stock must have a neck diameter only about one-tenth that of the tanks. It is easy to see that narrowness of band is limited by flimsiness of the structure. Matters are even worse if the filter is cut out of flat strip material (which would otherwise be a desirable construction because of the ease of punching such filters out in quantity) because in this case the neck width must be ϕ times the tank width. At this point it might be thought that while there is a limit to the smallness of ϕ practically obtainable in neck-type filters, ϕ could be made as large as desired in slug-type filters by simply making the slug large enough. Unfortunately, however, if the slug diameter is made too large it begins to vibrate in various undesired modes. Such undesired responses could perhaps be avoided by careful design or even employed to provide rejection points outside the pass band,¹ but for present purposes it appears preferable to keep the design as noncritical as possible by keeping all extraneous responses well away from the desired pass band.

A simple expedient for narrowing the band of the type of section heretofore discussed without changing the practically obtainable value of ϕ is to use longer tanks. This, however, cannot be carried too far as it results in an inconveniently long filter if many sections are employed, and also brings other pass bands too close to the desired band. A second expedient which applies to slug-type filters is to use thin walled tubing for the tanks so as to reduce their cross sectional area without a corresponding loss of sturdiness. In addition a material of higher intrinsic impedance may be used for the slugs than that used for the tanks. For example, steel slugs may be drilled and soldered to nickel plated aluminum rod or tube tanks. By the use of one or more of these expedients, bands sufficiently narrow for many purposes have been obtained without resulting in too flimsy a structure. One combination that has proved satisfactory employs steel ball bearings (annealed for easy drilling) soldered on thin wall nickel tubing. While this filter is not readily analyzed mathematically it has

¹ Mason, U. S. Patent 2,345,491, for example.

been found that a ball diameter of about a quarter wave is suitable, the bandwidth being controlled by the choice of tube diameter and wall thickness. It is thought that balls are less likely to develop extraneous resonances than the corresponding cylindrical slugs because the lowest natural frequency of a ball a quarter wave in diameter is nearly twice the operating frequency. The lowest frequency of a steel ball one inch in diameter is about 100 kilocycles, while for other sizes the frequency is inversely proportional to diameter.

FILTERS FOR VERY NARROW BANDS

From the foregoing it is evident that to obtain bands as narrow as the high Q of aluminum makes possible, or to obtain moderately narrow bands in the case of filters punched out of strip stock, some radically different method for obtaining sufficiently loose coupling is necessary. Many such methods have been tried with more or less success. For example, the coupling element may be connected between

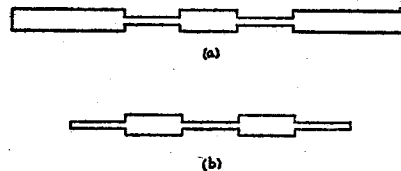


Fig. 4(a) — Twin quarter-wave neck-type of single-section filter;
(b) — Twin quarter-wave slug-type of single-section filter.

points on the tanks near motional nodes where the same coupling element is less effective. Again, linear tanks may be coupled by inertia effects, for example, by one or more small steel ball bearings pressed between the sides of parallel tanks; the different kinetic energies imparted to the balls when the tanks vibrate in and out of phase produce two natural frequencies in the system and the bandwidth is less the nearer the balls are located to motional nodes of the tanks. But the simplest and most satisfactory method so far discovered for obtaining a very narrow band is to use what will be called multiple-neck or multiple-slug coupling elements. Figure 4 shows neck and slug-type sections coupled by twin elements. In Figure 4(a) two half-wave tanks are coupled by twin quarter-wave necks separated by a quarter-wave slug, while in Figure 4(b) two quarter-wave slugs are separated by a quarter-wave neck. A physical picture of the operation of these coupling systems may be had by considering one element adjacent to a tank as the actual coupling element while the other two act as two quarter-wave transformers in tandem which transform the impedance of the other tank to a value still further out of line with that

of the coupling element. The central element of these sections need not be of the same impedance as the tanks, but it facilitates analysis and is a convenient construction.

The pass bands and terminating impedance may be determined exactly as in the case of the simple coupling elements by obtaining an expression for the iterative impedance of the section. The derivation is, of course, more lengthy and leads to a more complicated expression for the square of the iterative impedance, namely,

$$\frac{Z_1^2 \tan^4 \theta - (\phi^4 + 2\phi^3 + 3\phi^2 + 4\phi) \tan^2 \theta + (2\phi^3 + 3\phi^2)}{\phi^4 \tan^4 \theta - (1/\phi^4 + 2/\phi^3 + 3/\phi^2 + 4/\phi) \tan^2 \theta + (2/\phi^3 + 3/\phi^2)} \quad (3)$$

when all five elements of the section are of equal length. The bands of chief interest are those which occur when the elements are in the vicinity of a quarter-wave long, or odd multiple thereof. The bandwidth may be determined from the above expression, but for practical purposes it is sufficient to figure that the band is narrower by the factor ϕ (or $1/\phi$ for slug-type filters) as compared to the corresponding filter with a single coupling element. Another factor ϕ may be obtained by adding another pair of quarter-wave elements to form a triple-neck or triple-slug coupling. Thus, by using a sufficient number of elements in the coupler it is possible to obtain as narrow a band as desired without requiring ϕ to be impractically large or small. Another way of looking at the multiple coupler is to consider it as a low-pass filter operating above cutoff and hence attenuating, in a non-dissipative manner, vibrations passing through in either direction. From this point of view it seems probable that other forms of filters operating in an attenuating band could be employed as loose coupling means between tanks of the composite filter.

CHOICE OF MATERIALS

For the internal sections of any filter it is generally desirable to use a material of the highest possible Q . For this reason aluminum would be the unquestioned choice except for its large temperature coefficient of frequency, (about 200 parts per million per degree Centigrade). Where temperature stability is of primary importance, some isoelastic material such as the nickel alloy "Ni-Span C" may be used. This alloy has good magnetostrictive activity and better Q than nickel but is not as yet obtainable in thin walled tubing. It is available in standard wire gauges, and filters have been made by soldering steel balls on the wire. Although the Q of nickel is low compared to some

other metals, it is still high enough for filters that are not extremely narrow band and do not require extremely sharp cutoff. These three materials are the ones that have been mostly used. The steels have high Q but have much higher intrinsic impedance than aluminum which, as will be shown later, makes it more difficult to terminate the filter non-reflectively. Thin walled steel tubing however, might be a good choice in some cases. Table I shows some of the properties of interest in connection with filter design for a few common materials.

The data given were obtained from single samples three inches long, nickel plated where necessary to provide magnetostriction. The samples were inserted through a hole in a shield and small coils were placed on each end. In every case the coils were tuned off the resonant frequency of the sample to prevent loading. The signal generator was connected to one coil and a vacuum tube voltmeter to the other. The frequencies at which the output voltage dropped to 70.7 per cent of its maximum value were then determined and their difference divided into the center frequency to determine the Q of the sample.

Table I

Material	Density gms/cm ³	Longitudinal Velocity in Thin Rod $\times 10^{-5}$ cm sec	Intrinsic Impedance $\times 10^{-6}$	Q
1. Aluminum	2.73	5.11	1.39	4000
2. Armco Iron	7.76	5.13	3.98	850
3. Beryllium Copper	8.26	3.73	3.08	4000
4. Brass (Hard)	8.54	3.64	3.11	2500
5. Brass (Soft)	8.5	3.52	2.99	2000
6. Copper	8.95	3.72	3.33	1700
7. Dural	2.81	5.07	1.43	8000
8. Ferrite	4.46	5.58	2.49	1250
9. Invar	8.62	4.01	3.46	5000
10. Kovar	8.19	4.08	3.34	3500
11. Lead	11.3	1.49	1.68	40
12. Molybdenum	10.4	5.63	5.85	1700
13. Monel (K)	10.3	5.67	5.84	3300
14. Nickel	8.88	4.94	4.39	450
15. Ni-Span C	7.99	4.8	3.83	900
16. Phosphor Bronze	8.9	3.52	3.14	2000
17. Silver Solder (BT)	10.1	2.96	2.99	900
18. Solder (50-50)	8.84	2.08	1.84	72
19. Steel (Cold Rolled)	7.71	5.04	3.89	1100
20. Steel (Drill Rod)	7.86	5.13	4.03	900
21. Steel (Stainless)	7.94	4.97	3.95	1500

DRIVE AND TAKE-OFF METHODS

For most purposes the mechanical filter must be driven from an electrical source and deliver power to an electrical load, and there seem to be only two methods of electromechanical conversion available that will operate at radio frequencies with reasonable efficiency. Perhaps the best in the long run, especially at frequencies above about 500 kilocycles, is the piezoelectric method. Permanently polarized barium titanate² appears particularly suitable for filter use. It can be applied in several ways. For the lower frequencies, a thin strip of titanate, silvered on both sides, may be soldered to the side of the end resonator of a filter. The application of radio-frequency voltage between the silver electrodes alternately stretches and contracts the strip in length, thus driving the resonator. Or the resonator may be cut transversely at a motional node and a thin wafer of titanate soldered between the cut portions. In this case the drive is effected by the change of thickness of the wafer when voltage is impressed across it. In both cases, of course, the composite resonator must be tuned after assembly. At very high frequencies the wafer may become a half wave long so as to be a resonator by itself, and replace a half wave of the original filter. Filters using the titanate have been made and tested sufficiently to indicate their possibilities but most of this filter work has employed the other method of drive and take-off, namely, magnetostriction. For this reason the present discussion will be limited to this type of operation, although the reason for using magnetostriction was chiefly that experimentation with the construction of the filter itself can be carried out most readily with the aid of magnetostriction. That is, by using magnetostrictive materials for the resonators or rendering them magnetostrictive by nickel plating them, the resonant frequency of any individual tank can be tested. Also if all the tanks are similar, including the tanks on the ends of the filter which cooperate with the drive and take-off coils, the filter can be made all in one piece and hence conform most accurately to theory.

Probably the main objection to magnetostrictive operation is the poor efficiency, especially at the higher frequencies, due to eddy current losses in the material, which is usually nickel or one of its alloys. This drawback can, however, be largely overcome by employing a material with very little losses. Ferrites, which are magnetic ceramic materials, have negligible eddy current losses and mechanical Q of the order of one or two thousand, and ferrites have been developed

² H. L. Donley, "Barium Titanate and Barium Strontium Titanate Resonators", *RCA Review*, Vol. IX, No. 2, pp. 218-228, June, 1948.

in the laboratory which have as large a magnetostrictive coefficient as nickel. If the end half waves of a filter be replaced by half waves of ferrite of the same characteristic impedance, a very efficient conversion is possible. Drive and take-off ferrite resonators may be cemented to the filter metal, or the ferrite may be copper plated at one end to permit soldering. The use of ferrites seems particularly desirable in broad-band filters when the highest conversion efficiency is required. For narrow-band operation nickel-plated aluminum is very satisfactory.

Figure 5 shows the drive and take-off arrangement typical of all the magnetostrictively-operated filters. A closely fitting coil is placed over the middle of the end half wave of the filter to provide magnetostrictive coupling. A permanent magnet (not shown) is located so as to magnetize the part of the filter under the coil in a longitudinal direction. The field is adjusted to give maximum drive, which requires that the material be something like half saturated. The shorter the piece of magnetostrictive material the stronger the field required. The impedance of the driving coil has a large resistive component due

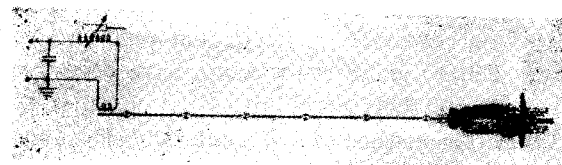


Fig. 5—Typical drive and take-off arrangement for magnetostrictively operated filters.

partly to losses in the material and partly to the motional reaction of the filter. The other coil and the condenser are chosen to constitute an L section matching network to match the driving coil to the source of electrical power, or to the grid of the following tube in the case of the take-off end of the filter. At the right-hand end in the figure is shown a unit comprising the network shown schematically at the left. The filter illustrated is a slug type with three-quarter-wave ends operating at 300 kilocycles with a band of 3 per cent. The tanks are thin wall nickel tubing and the slugs are 3/16-inch steel balls. As a refinement of this arrangement the tuning core shown at the left may consist of a ferrite rod whose length is chosen to give mechanical resonance just outside the transmission band. This steepens the cutoff considerably by destroying the impedance matching action of the network just outside the band. The ferrite must of course also be located in the magnet field but only a weak field is needed to produce the best results. Such rejector ferrites may be put at each end of the filter and in fact a bundle of slightly differently tuned ferrites may be used

to provide multiple rejection points, although this complication is not likely to be justified. The rejector ferrites are used as tuning cores also since their rejecting function is not much affected by their exact location in the coil.

STAGE GAIN

Since filters are normally used as a coupling means between two amplifier tubes, the gain of such a stage is a matter of some importance. However, since the gain is secondary to the prime function of selectivity not many gain measurements have been made. A few examples will give an idea of what can be expected. In the case of a ball on a nickel tube filter operating at 300 kilocycles with a 3 per cent band, a voltage gain of 9 was measured between 6SJ7 tube grids. A 100-kilocycle filter with band width 2.5 per cent and having ferrite drive and take-off elements gave a voltage gain approximately 70 per cent of that obtained from ordinary tuned-circuit coupling. The gains obtained appear to be less the higher the frequency as well as the broader the band.

TERMINATIONS

The least satisfactory thing about mechanical filters seems to be their termination. A filter should be terminated in a resistance equal to the iterative impedance of the section and this is not constant over the band, as has been noted. Without some form of damping in the filter the output consists of a series of peaks with deep valleys between. If the filter is made of relatively low Q material such as nickel, and is sufficiently narrow band, the peak-to-valley ratio may be satisfactory without any additional terminating resistance. The same is of course true of any material if the band be made narrow enough. But perhaps the only way to get a perfect termination without depending on losses within the filter is to extend the filter a few sections beyond the take-off point and introduce sufficient losses into these extra sections so that vibrations entering these sections are substantially damped out by the time they are reflected back to the pick-up point. This arrangement, however, allows most of the power transmitted to flow past the pick-up point and relatively little into the useful load. The best compromise method so far discovered is to provide the tightest possible magnetostrictive coupling between the drive and take-off filter elements and their associated coils, which assures maximum power transfer and also provides a corresponding amount of mechanical damping of the end resonators; and then if the peak-to-valley ratio is still too great, to add mechanical resistance until the best shaped response curve is obtained. One way to add damping is to coat the

end resonators with a viscous material such as vaseline or silicone oil, but it sometimes happens that this not only damps the resonator but also appreciably detunes it. A theoretically better way to add a pure mechanical resistance is to connect the end of the filter to a long rod of lossy material having characteristic impedance chosen (by giving it the correct diameter) to match the filter impedance somewhere inside the band. In practice a rather short rod-shaped piece of viscoloid cemented by its own solvent to the filter tip has been found to reduce very bad peak-to-valley ratios to an acceptable value. Tungsten loaded neoprene is even better. Of course, it is desirable to provide as great as possible a proportion of the required damping by the reaction of

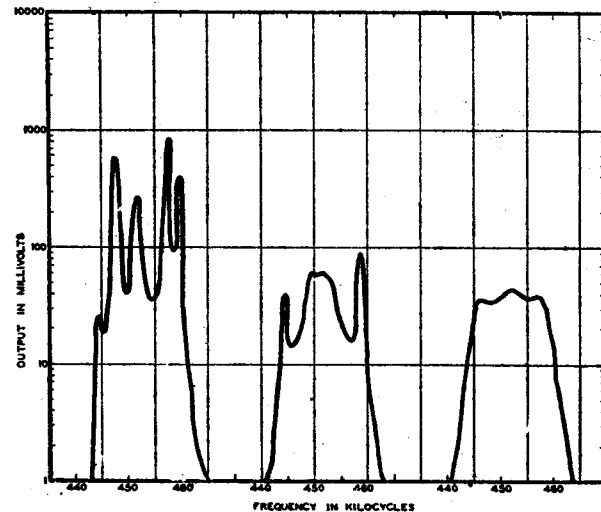


Fig. 6—Effect of viscoloid end pieces on both ends, one end, and totally removed.

the drive and take-off circuits; for this reason the mechanical impedance of the tanks should be made as low as possible in proportion to the magnetostrictive coupling. For example, if the take-off tank is a nickel-plated aluminum tube of given diameter and thickness of plating, then the thinner the wall, the less the filter impedance and hence the less the terminating resistance required. Thus, since the reaction damping is constant, it should be possible to make the wall thin enough so that no extra damping is needed. On the other hand, if the end tank is nickel-plated solid rod, it will be seen that small diameter favors the ratio of magnetostrictive coupling to filter impedance. While the termination problem cannot be said to be solved in an entirely satisfactory manner, yet, by a certain amount of cut and try with a given filter, very useful performance can be obtained for bands as wide as commonly desired. Figure 6 shows three curves for

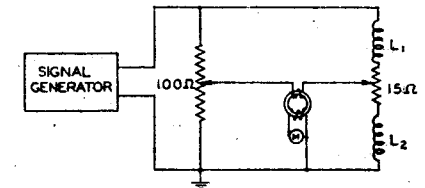
a four-section aluminum filter having a 15-kilocycle band centered on 452 kilocycles. The curve with the high peaks is without viscoloid end pieces, the smoothest curve is with pieces on both ends, while the middle curve has a piece on the output end only.

TUNING-UP METHODS

The individual resonators of a filter should be tuned to the same frequency. It is probable that commercially manufactured filters can be made to such close tolerances that no tune-up will be required, providing the bandwidth is large compared with the tolerance. However, very narrow band filters and experimental filters will usually require tuning up.

The bridge circuit of Figure 7 has been useful for this purpose. L_1 and L_2 are identical small universal wound coils. The output transformer is wound on a high permeability torus. The meter is a Ballantine vacuum tube voltmeter giving full scale deflection on ten millivolts input. The magnetostrictive resonator to be tested is placed in coil L_2

Fig. 7—Bridge circuit for tuning up mechanical filters.



and, preferably, a similar piece of material is placed in L_1 . A polarizing magnet is placed near the specimen. The bridge is then brought near balance by means of the variable resistors. There should, however, be sufficient unbalance to give about half scale reading on the meter, and the unbalance should be with respect to the resistive component of the coil containing the specimen. Thus when the frequency of the source is adjusted to be the same as the resonant frequency of the sample the motional resistance produced in the coil by vibration of the sample shows up as a change in meter reading. With high Q resonators this dip or rise in reading is so sharp that the frequency of the generator must be changed very slowly to avoid passing over the response without noticing it. The bridge is a very sensitive indicator of mechanical resonance when operated near balance and with considerable input voltage. It will in fact indicate vibrations of metal discs and rings produced by the interaction of a magnet field with eddy currents set up in the disc or ring by coupling to the bridge coil. (For example, a new Roosevelt dime responds to 112-kilocycle excitation).

For the purpose of testing the tanks of a complete filter all the tanks not being tested must be so damped or detuned as to leave the frequency of the free tank in the test coil substantially unaffected by resonance of the others. This can usually be accomplished by putting tight fitting clamps on the adjacent tank or tanks. Gripping the adjacent tanks firmly between the fingers will sometimes be sufficient. When each resonator has been tested, if it is found that any one is too far out of line with the others, it is then tuned either up or down by filing. Filing away material at motional loops increases the frequency while filing at nodes decreases it. For decreasing the frequency of a neck-type filter it is more of a reversible operation to put a ring of solder around one or both ends of the resonator and then file solder off until the frequency is correct. This method of testing can be used for any filter, whether intended for magnetostrictive or piezoelectric operation, provided the resonators are made of magnetostrictive material or are nickel plated.

In the case of wide band filters there may be difficulty in sufficiently freeing the tank under test from effects of the adjacent tanks, because of the tight couplings. Of course, in the case of very wide bands the filter should not require tune-up because the tolerances are great enough to permit sufficiently accurate machining in the first place. However, it may be well to mention a type of filter construction that permits individual tune-up of each tank without difficulty. This method applies to single neck-type filters particularly. Each resonator is turned out separately with an eighth-wave tip wherever a neck should be. Then when the tips are butt welded or soldered together and excess solder filed off, the structure is indistinguishable from a one piece filter, by eye at least. It is, of course, not nearly as solid. This method has been used with resonators turned out of nickel-plated aluminum rod stock which leaves the tips unplated and requires aluminum solder. The tips are first tinned and then sweated together in a jig that keeps them lined up. They must be tuned up before tinning. The amount of solder left in the joint after the ends are pushed tight together and the excess removed is so small that it has no apparent effect on the distribution of the resonant frequencies within the band. Filters made this way have been found to have resonances occurring very accurately at the intervals predicted by theory.

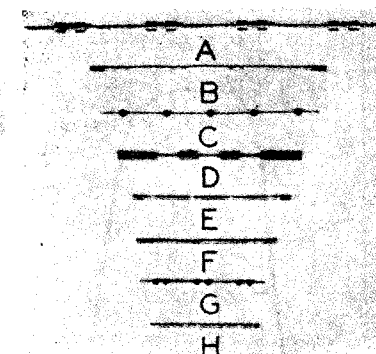
TORSION FILTERS

The propagation of torsional waves along a rod is governed by the same equations as for linear vibrations, except that the velocity is

only about 60 per cent as great. This makes low-frequency filters more compact but is undesirable for frequencies so high that tanks are inconveniently short. There is, however, one important difference in favor of torsional operation which is that the quantity corresponding to characteristic impedance is in the case of torsional operation proportional to the fourth power of the diameter rather than to the square as was the case for linear vibrators. Thus the same filter which gives a wide band when operated linearly will give a narrow band when operated in torsion. Or to put it another way, a narrow band torsion filter can be made without very great disparity in diameter between the tank and coupler portions.

In order to use a filter in the torsional mode some modification of the drive and take-off arrangement is necessary. While there are a number of ways in which torsion may be produced, it has been found

Fig. 8—Examples of mechanical filters showing various constructions and coupling means. See Table II.



that the most simple and satisfactory method is to nickel plate only one half of the circumference of the drive and take-off tanks and to apply a transverse magnet field in the plane including the edges of the plating. The combination of the constant transverse magnetization with the alternating longitudinal magnetization produced by the driving coil gives a resultant magnetization which swings back and forth in direction about a mean position approximately transverse to the axis of the resonator, thus tending to twist the resonator ends first one way and then the other about the central plane. If the resonator being driven includes more than one half-wave, the adjacent half-waves may be plated on opposite sides of the resonator so that if the driving coil extends over both half-waves, the torques produced in the various half-waves will be additive in effect.

A particular application of the torsion filter is for extremely narrow band operation which can be achieved by the use of multiple-

neck coupling and which is made possible by the fact that magnesium has a uniquely high Q when operated in torsion,³ namely about 100,000.

SOME ILLUSTRATIVE EXAMPLES

In conclusion several filters are shown in the photograph Figure 8 to illustrate physical embodiments of the various types described. Table II gives the frequency and bandwidth of each of these.

Figures 9 and 10 show typical characteristic curves to give an idea

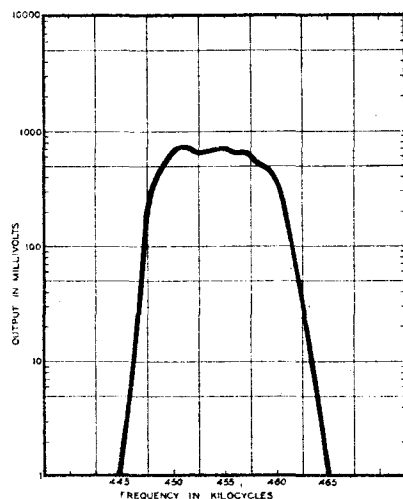


Fig. 9—Characteristic curve of an eight section filter employing steel balls on thin wall nickel tubing.

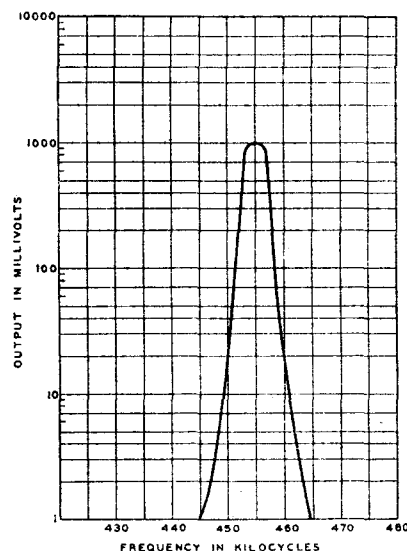


Fig. 10—Characteristic curve of a three section filter employing twin steel ball couplers on nickel tubing. Filter "G" of Figure 8.

of the performance possible. It should be remembered that the greater the precision of construction and tuning up and the more carefully the termination is worked out, the better will be the characteristic curve. The curve of Figure 9 could be improved by better termination.

Figure 11 shows one example of a complete unit. The drive and take-off coils are in the cans as are the coils and condensers of the

³ W. P. Mason and H. J. McSkimin, "Energy Losses of Sound Waves in Metals Due to Scattering and Diffusion", *Jour. Appl. Phys.*, Vol. 19, No. 10, p. 945, October, 1948.

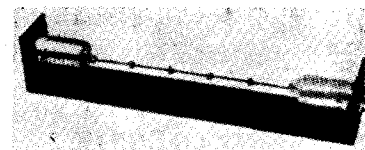


Fig. 11—Example of a complete unit. Drive and take-off coils as well as impedance matching networks are in the cans.

impedance matching networks. The magnets could be in the cans but were actually attached to the end balls that are gripped by the spring fingers.

Table II—Data on Filters Shown in Figure 8

Filter	No. of Sections	Type	Materials	Midband Frequency	Band
A	4	Twin Slug	Ni. plated Al. with steel slugs	200 Kc	300 cps
B	4	Twin Neck	Brass with Ferrite ends	260 Kc	12 Kc
C	5	Slug	Steel Balls on Ni-Span C Wire	300	9
D	1	Triple Neck	Strip Ni.	300	9
E	4	Neck	Al. with Ferrite & Viscoloid Ends	455	7
F	3	Twin Neck	Al. with BaTiO ₃ Drive & Take-off	455	7
G	3	Twin Slug	Steel Balls on Ni. Tubing	455	4
H	8	Neck—Torsion Operation	Ni. Plated Al.	455	8

REFERENCES

Other references to mechanical filters adapted to radio frequency operation include:

R. Adler, "Compact Electromechanical Filter," *Electronics*, Vol. 20, No. 4, p. 100, April, 1947.

Kinsley, U. S. Patent 2,342,869.

Mason, U. S. Patent 2,342,813.