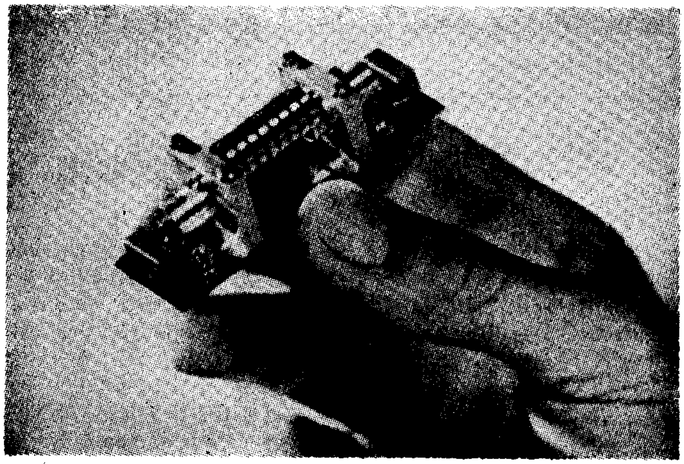
How To Use Mechanical I-F Filters



Mechanical filter takes less room than most 455-kc L-C filters and gives superior shape factor to i-f response characteristic

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THE MECHANICAL FILTER was developed to fill the need for a compact and permanently-tuned bandpass filter at intermediate frequencies. The selectivity characteristic is achieved by means of overcoupled mechanical resonators driven by magnetostriction. Frequency response is characterized by a nearly flat top and steep skirts on both sides of the pass band, as shown by Fig. 1.

Figure 2 shows the functional elements of the mechanical filter. A signal current is fed to the input coil at one end causing the nickel driving wire, in the center of the coil, to expand and contract due to the magnetostrictive effect. The resulting longitudinal vibration drives the first resonant disk. Mechanical vibrations are coupled through the six disks by means of three wires acting as springs. At the output end of the filter, the longitudinal motion of the nickel end wire is transformed into an electrical current by the inverse magnetostrictive effect.

The construction details of a complete filter assembly are shown in the photograph. The six center disks comprise a mechanical bandpass network, while those at each end are untuned and function only as rigid supports. Each supporting disk is soldered to a brass tube, which serves as a mounting and shield for the driving coil. Wire leads from the coils are soldered to hermetically sealed feed-through terminals in the base plate, and small mica capacitors are connected across these coils to provide low-Q resonant circuits at each end of the filter.

The complete assembly is mounted and sealed in a brass case 1 inch high, 11/16 inch wide, and 2 11/16 inches long. In application, the filter is connected directly to the plate and grid circuits of tubes.

Characteristics

Magnetostrictively-driven mechanical filters have several advantages over their electrical equivalents. In the region from 100 to 500 kc, the mechanical elements used are extremely small and it is possible to construct filters having better selectivity characteristics than the best of conventional i-f

Rugged fix-tuned interstage coupling units provide steep-skirt selectivity for intermediate-frequency amplifiers used in communications receivers, and in ssb transmitters for eliminating undesired sideband from low-frequency dsb signal

systems in less than the space required by a single i-f transformer.

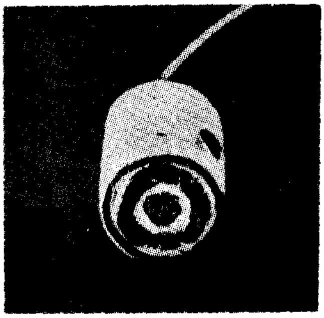
Since mechanical elements with Q's of 2,000 and over are easily obtainable, it is possible to construct filters of extremely narrow bandwidth with characteristics following the theory for lossless elements. This allows filter designs which are unattainable with electrical elements because of their relatively high losses.

A third advantage, that is not immediately apparent, lies in the permanence of the tuning adjustments. Once the various mechanical elements have been constructed, the filter frequency characteristics are permanent and no subsequent trimming is required or is possible. While this makes the initial design difficult in many ways, it removes the usual difficulties with malfunctioning of equipment due to improper trimmer adjustment, coil aging, humidity and other detuning effects. The latter may eventually become the most important characteristic since it has the effect of reducing servicing complexity of already overly complex electronic equipment.

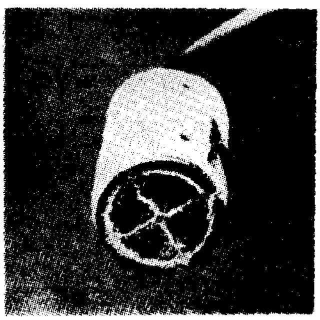
Filter Elements

The mechanical filter bandpass system is composed of metal disks and wires. The disks function as high-Q resonators, while the wires provide coupling between disks and function as magnetostrictive transducers at the terminations of the filter.

Two normal vibration modes of a single disk are illustrated in the photographs. The mode with two rings has been selected for most of the filter work, while the other is a



Lycopodium powder shows desired mode used in mechanical filter



Spurious mode appears close in frequency to desired mode

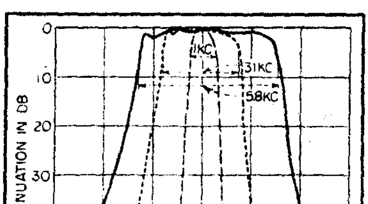


FIG. 1—Frequency response of three different mechanical filter designs described in text

spurious mode appearing relatively close in frequency to the desired mode.

The patterns shown were obtained by burnishing the surface of a disk and sprinkling it with lycopodium powder. The disk is driven with a nickel wire excited by magnetostriction. The resulting vibration caused particles to collect at the nodes; thus the pattern showing two rings indicates that the disk in vibrating with two nodal rings and with both the center and the outside edge moving at high velocity. Similarly, the other pattern shows a mode involving one nodal ring and crossed nodal lines.

An analysis of the vibration of a circular plate shows that an infinite set of different vibration modes exists. These are in general not harmonically related but frequently two will appear rather close together in frequency[1]. The major problems in the design of this type of resonator are first, the selection of a desirable mode of vibration, that is, one well separated from all others, and second, the selection of a thickness-to-diameter ratio such that spurious modes are still further removed. Analysis of thin plates shows that the frequency of the two-ring mode varies inversely as the square of the diameter and directly as the thickness. It has been found experimentally that this relation holds approximately for the relatively thick disk used.

In the mechanical filter assembly, the disk resonator functions as an essentially lossless element. The material selected for disks is a nickel-iron alloy with high Q and zero thermoelastic coefficient. The high Q of a disk is illustrated by the

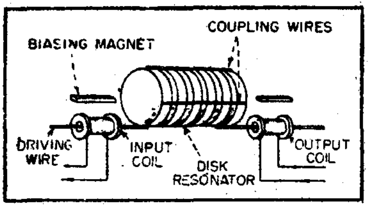


FIG. 2—Components of six-disk mechanical filter

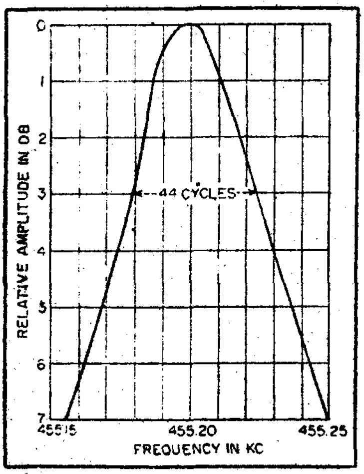


FIG. 3—Single disk resonance curve is down 3 db at 44 cycles

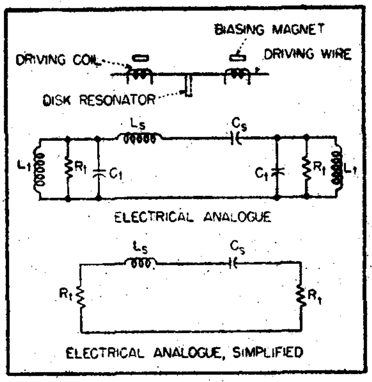


FIG. 4—Single disk filter and electrical analogue

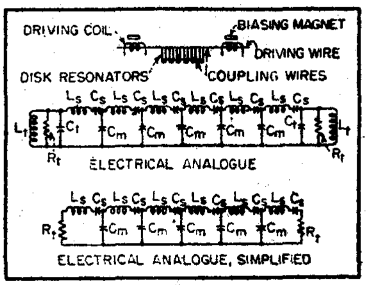


FIG. 5—Six-disk filter and electrical analogue

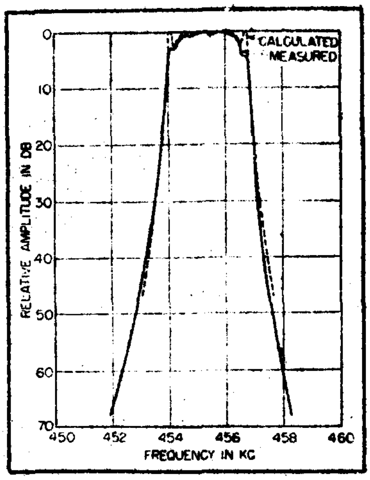


FIG. 6—Calculated frequency response of electrical analogue compared with measured frequency response of a mechanical filter

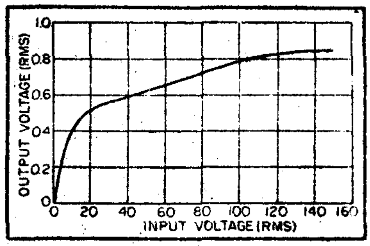


FIG. 7—Mechanical filter overload characteristic at 455 kc

resonance curve of Fig. 3. This curve has a center frequency of 455.2 kc and a half-power bandwidth of 44 cycles. The value of Q calculated from the fractional bandwidth is 10,400.

Mechanical coupling in the filter is provided by three nickel wires welded to the peripheries of disk resonators. These wires function as springs connected between disks. Nickel was selected for use in coupling elements since it gives the desired degree of coupling with a convenient wire size and is easily welded to the disks. The relatively low Q of nickel is not a serious detriment since losses in the coupling elements have a small effect compared with losses in disk resonators.

Commercially pure nickel wire has been found to be an excellent transducer material for use at the filter terminations. It has an inherent Q of the order of 50, controllable by heat treatment and magnetization. Many steel alloys have magnetostrictive properties, but in general they have rather high effective Q's. This makes them undesirable as transducers since added frictional losses are required for proper matching of the filter. Transmission losses using nickel transducers depend on the nature of the driving coils. These coils may be constructed for resonant electrical impedances that vary from a few hundred ohms to 50,000 ohms or higher. The higher impedance coils result in somewhat greater transmission losses because of the lower concentration of flux in the driving wires. Optimum magnetic biasing fields exist for the transducers, but are quite broad. The location of the optimum can be obtained by differentiation of published curves on the relative length versus field strength for nickel.

Analysis and Design

In analyzing the mechanical filter, it has been found convenient to use an electrical analogue for the mechanical vibrating system. The electrical circuit is obtained by using the mechanical-electrical analogy, where velocity is equivalent to current and force is equivalent to voltage. Also, damping is equivalent to resistance, mass to inductance, and stiffness to elastance. In the following paragraphs some considerations involved in filter analysis and design are discussed for a single-disk filter and for a multi-disk filter.

A single-disk mechanical filter and its electrical analogue are shown in Fig. 4. The driving wires at each end of the filter are tuned to antiresonance and correspond to two parallel tuned circuits in the electrical analogue. The disk resonator is equivalent to a series resonant circuit joining the two parallel resonant circuits. Energy loss and transfers in the end elements are represented by resistances in the parallel circuits. The Q of these parallel circuits is sufficiently low so that, in the frequency range of the filter, they may be represented by the resistors R_t. If the output current of the electrical analogue is measured with a constant current source applied to the input, a single resonant peak is obtained.

The fractional bandwidth of the peak is determined by the ratio of the terminating impedance to the series resonant impedance. Similarly in the mechanical filter ($\Delta f/f_r = 2R_t/\omega_o L_r$), bandwidth is determined by the ratio of the impedance of the terminating wires to the disk impedance. Here, mechanical impedance is defined as the ratio of force to velocity.

The bandwidth of single-disk filters can be adjusted by varying the radial position of the transducer wires on the disk. Observation of the vibration pattern indicates that high velocities exist at the center of the disk with a zero velocity region occurring at the first nodal ring. Therefore, the bandwidth of a single-disk filter using specified disks and end wires will be a maximum with the wire attached at the center and will decrease towards zero as the wire is moved out towards the first nodal ring.

A second method of adjusting bandwidth is to vary the cross-sectional area of the end wires. The vibration equations of this wire or rod are analogous to those for an electrical transmission line with velocity taking the place of current and force that of voltage. The equations indicate that the characteristic impedance varies directly as the cross-sectional area of the rod and, therefore, that the antiresonant impedance of a length of line some odd multiple of ¼ wavelength varies directly as the area.

Figure 5 shows a six-disk filter and its electrical analogue. As in the case of the single-disk filter, end wires are equivalent to parallel resonant circuits, and disks to series resonant elements. One new element has been added in the form of bottom capacitance coupling. These capacitors are the electrical analogues for coupling wires less than ¼ wavelength long, welded in place between successive disks. The portion of the wires between disks represents the mechanical equivalent of a short transmission line, or a capacitance. In designing filters with two or more disks, the cross-sectional areas of both driving wires and coupling wires are adjusted to control bandwidth.

The calculated frequency response of the electrical circuit is compared with the measured response of a mechanical filter in Fig. 6. The curves correspond very closely except near the edges of the pass band, where the measured response is less than the calculated value due to losses in resonators and coupling elements.

Performance

The performance characteristics of a six-disk mechanical filter are summarized in Table 1. This filter has been designed to have a 6-db bandwidth of 3.10 kc with a center frequency of 455 kc. The peak-to-valley ratio in the pass band is less than 3 db. The shape factor of the filter response is defined as the ratio of bandwidth measured 60 db below the highest peak to bandwidth at 6-db attenuation. The present filter has a shape factor of less than 2.25 to 1. Improvements approaching a 2 to 1 shape factor should be obtainable by further refinement of the design. The low value of shape factor achieved with mechanical filters permits unusually high rejection of adjacent channel signals in communications receivers.

Transmission loss measured on present filters is less than 26 db. Design improvements on future models will permit tighter coupling between filter driving wires and coils, with a resulting transmission loss of 15 db or less. This loss can be offset easily by one stage of amplification.

The overload input voltage level, listed in the table, is the value of input voltage at which the filter saturates. The effect of saturation is illustrated in Fig. 7. This curve shows the filter output voltage measured as a function of input voltage at 455 kc. The curve is nearly linear from 0 to 10 volts, while the knee occurs at approximately 15 volts. To determine the effect of overload on frequency response, the output voltage was measured as a function of frequency with input voltages ranging from 0.5 to 300 volts rms. No change was observed in the response at these levels. These measurements indicate that the mechanical filter will be suitable for use in receiver i-f strips and similar low-level applications.

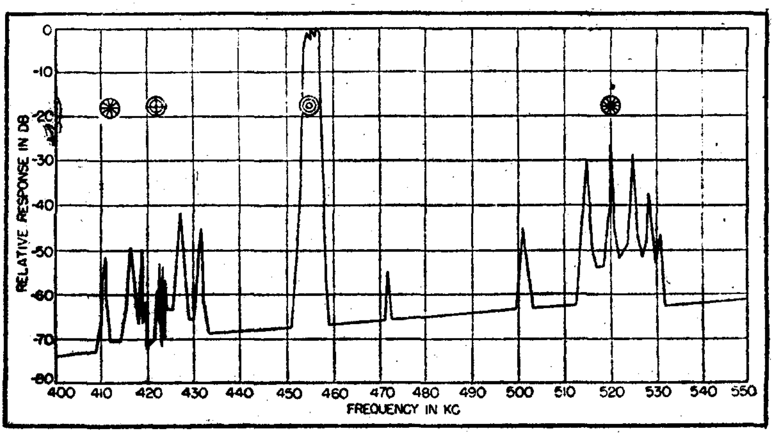


FIG. 8—Spurious response of mechanical filter. Different modes are indicated in circles

Spurious Responses

The spurious responses occurring in the frequency range of a filter are plotted in Fig. 8. The major peaks are a result of disk vibration modes other than the two-ring mode discussed above. Normal vibration patterns are illustrated on the top of the graph at their respective frequencies. The rings and diameters indicate positions of nulls in the vibration pattern. A provision has been made in this filter design to reduce the spurious amplitudes by drilling a hole in the center of each end disk. This has the effect of reducing the frequencies of the three spurious modes shown in Fig. 8, with a consequent decrease of about 20 db in the amplitude of undesired filter responses. Also, the hole drilled in each end disk reduces the mechanical disk impedance to about half the original value, thereby providing half-section terminations for the filter and decreasing the peak-to-valley ratio in the pass band.

The delay characteristic of a mechanical filter is shown in Fig. 9, together with amplitude response. The time delay varies from ½ millisecond to 1 millisecond in the pass band. Two large peaks occur near the edges of the band and a small peak near the center. The dissymetry of the characteristic is caused by a slight mistuning of filter elements.

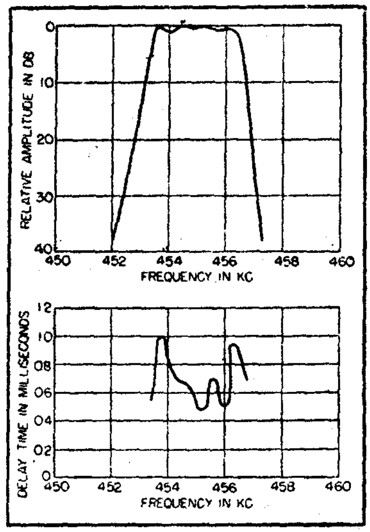


FIG. 9—Amplitude response and delay time of a six-disk mechanical filter

Service Tests

Tests have been made to determine the filter operating characteristics under a variety of service conditions. Since no trimming adjustments are required, the case is hermetically sealed, and no difficulty is expected due to high humidity. The effects of temperature variation are illustrated in Fig. 10. The major change is an increase in peak-to-valley ratio at temperature extremes, as a result of the detuning of filter end wires. The ratio approaches a maximum of 6 db at −30 C and 80 C. The frequency of peaks on the response curve shifted a negligible amount.

To determine the effects of vibration, a filter was subjected to the vibration test in the Army-Navy Specification, AN-E-19. During the test, a 455-kc carrier was fed through the filter to a low frequency receiver. This permitted the detection of any modulation resulting from vibration. No mechanical resonances were observed and no modulation was detected in the range from 10 cps to 55 cps. Response curves measured before and after each test indicated that the filter had suffered no damage.

The service tests described above indicate that mechanical filters will be satisfactory for most commercial applications. It is expected that they will satisfy military requirements when provided with suitable temperature compensation.

Table I—

Performance Characteristics of Six-Disk Mechanical I-F Filter

Operating Frequency	455 kc
Bandwidth at 6 db	3.10 kc±0.25 kc
Peak-to-Valley Ratio	Less than 3 db
Shape Factor (6 db to 60 db)	Less than 2.25
Transmission Loss	Less than 26 db
Overload Input-Voltage Level	15 volts
Operating Temperature Range	−30 C to 80 C
Vibration—Satisfies the Requirements of Army-Navy Specification AN-E-19	
Case Size	1″ × 11/16″ × 2 11/16″
Input and Output Impedance	6,500 ohms

Experimental filters with bandwidths ranging from 800 cycles to 8 kc have been construced at 455 kc and it has been found that, as expected, essentially scaled reproductions of the curves of Fig. 1 are obtained regardless of bandwith when the same number of resonant elements are used. The parameters limiting the bandwidth range for the present design are the practical limits on the size of coupling and driving wires on the narrow end of the scale and the limits on achievable bandwidths of terminating wires in the wide-band direction.

It is believed that a reasonable range of center frequencies lies between 100 kc and 1 mc. The limitation on the lower end lies largely in the size of the elements and on the high end in the precision required for very small elements.

Applications

Filters of various bandwidths have been installed on an experimental basis in the i-f systems of several communication receivers by replacing the first i-f transformer following the mixer by the filter and substituting broad-band circuits for the subsequent i-f transformers.

The 3.10-kc bandwidth filter was found to be useful for ssb reception of a-m signals, allowing a choice of sidebands and consequent reduction of interference. From the curve of Fig. 1, it is observed that, with the carrier placed at 453.5 kc, signals at 453.0 will be rejected by 20 db. At 452.5 they are down 35 db, thus allowing fairly complete rejection of the unwanted sideband.

A second application lies in the field of ssb generation. Assuming a lower limit of 400 cycles in the modulating spectrum, carrier suppression would be 17 db and the lowest frequency component of the other sideband down 29 db, with the higher frequency components suppressed still further. These figures are for a single unit and two cascaded units would provide appreciable improvement.

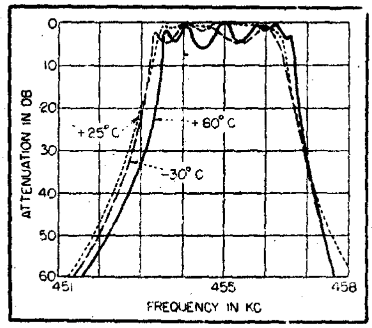


FIG. 10—Curves show temperature dependence of mechanical filters

REFERENCE

(1) Mary D. Waller, Vibration of Free Plates, *Proc. Roy. Soc.*, 211, p 265.