A BAND-PASS MECHANICAL FILTER FOR 100 KILOCYCLES*

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Summary—The detailed design and construction of a mechanical filter which should prove useful in many broadcast applications is presented. This filter has a pass band of 6 kilocycles centered at 100 kilocycles. The results obtained are compared with a similar crystal filter.

Introduction

The use of mechanical filters for radio frequencies has been described by the author and his colleague in a previous article.[1] The detailed theory was developed and some illustrative examples of experimental filters were described.

Considerable development work in this field has been carried on since that time. Recently a program was started on the design of filters suitable for single-side-band radio telephony which would have a pass band in the vicinity of 100 kilocycles. This article describes a mechanical filter design which should prove useful in many broadcast applications.

Theory of Mechanical Filters

As is well known, a chain of cascaded, coupled, resonant circuits will produce a band-pass filtering action. A standard double-tuned intermediate-frequency transformer is an example. Where the number of resonant circuits is larger than two, considerable advantage results if the interior electrical circuits are replaced by acoustic or mechanical resonant circuits thus securing their advantages of small size, stability and inherent high Q.

In a typical case, the electrical resonant input circuit of the filter is coupled by magnetostriction to the first mechanical resonant circuit of the filter which is then in turn coupled mechanically to the next mechanical resonant circuit and so on to the last mechanical resonant circuit which is again coupled to the output electrical circuit by magnetostriction. The mechanical resonant circuits can be half-wave lengths of a suitable metal while the coupling between the mechanical

* Decimal Classification: R386.1.

[1] W. van B. Roberts and L. L. Burns, Jr., "Mechanical Filters for Radio Frequencies," *RCA Review*, Vol. X, pp. 348-365, September, 1949.

resonant circuits can be quarter-wave lengths of the same metal but of a different diameter. This article describes the detailed construction and operation of a filter of this type. Figure 1 shows a comparison between the results obtained from this filter and a commercial single-side-band crystal filter.

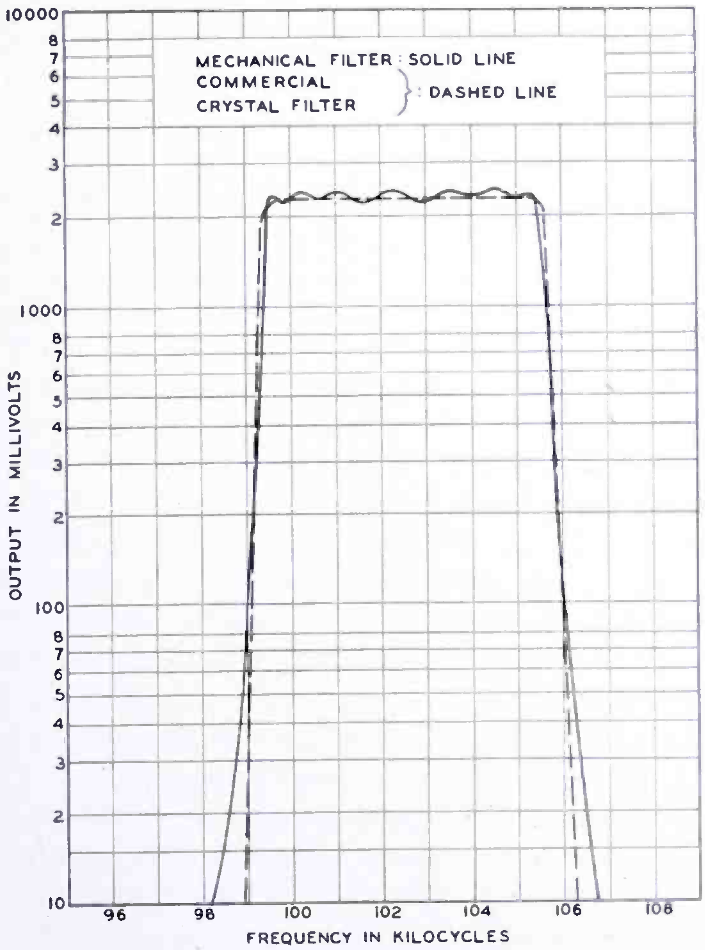

Fig. 1—Response curve of the single-side-band mechanical filter compared with an equivalent quartz-crystal filter.

Construction

Temperature stability was considered of prime importance and this immediately dictated the use of Ni-Span C or some similar constant modulus alloy for the filter construction. Ni-Span C has the added advantage of being magnetostrictive by virtue of its nickel content and thus does not require nickel plating for electrical excitation.

There are many forms which the actual mechanical filter can take but all of these may be divided into two classes: (1) mechanical resonators coupled by a heavy mass, known as slug type of construction, and (2) mechanical resonators coupled by a thin spring, known

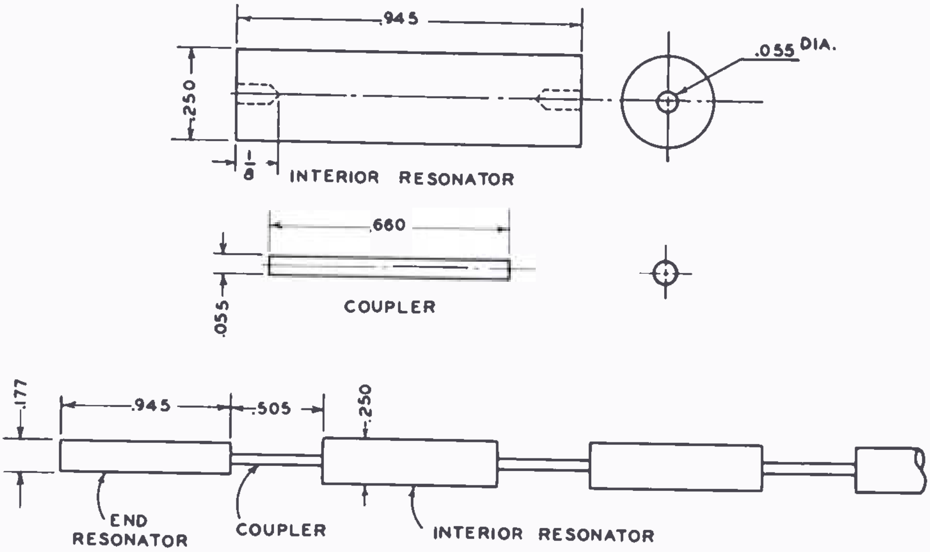

Fig. 2—Details of construction of the mechanical filter.

as neck type of construction.[1] The neck type of construction was chosen for this filter because the mechanical termination is much simplified. In the neck-type filter, an infinite line exactly like the neck provides a resistance termination that matches the iterative impedance of the filter at mid-band, as is evident from Equation (2) of Reference (1). If a slug-type filter is used, a single line acting as termination would have to be inconveniently small or else a more complicated termination would be needed. The filter consists of a series of 8 half-wave resonators coupled by thin necks as shown in Figure 2.

The actual dimensions of the resonators and coupling necks were determined by the design procedure indicated in the Appendix and are given by Figure 2. For convenience, steel couplers were used as the proper size Ni-Span C was not immediately available. The end resonators have half the impedance of the interior resonators in accordance with Campbell filter theory and are thus smaller in diameter as shown.

Before assembly, the resonant frequency of each resonator was checked in the bridge circuit of Figure 3. To use this bridge, the resonator under test is placed in one of the coils and an appropriate magnetic bias established with a permanent magnet. The two potentiometers are then adjusted for a minimum reading on the vacuum tube voltmeter M. Then as the signal generator is slowly tuned through the resonant frequency of the resonator, a sudden increase in

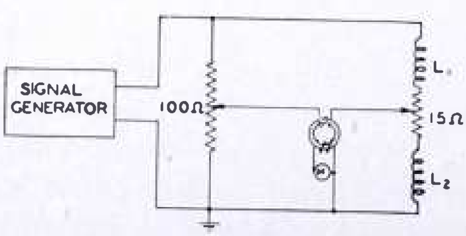

Fig. 3—Bridge circuit for checking the individual resonator responses.

the meter reading will occur. By a process of selection, only resonators that were within 200 cycles per second of each other were used in the filter. Of course resonators that were too low in frequency could be raised by a slight trimming on the lathe but this was not found necessary.

During the actual assembly of the filter, close-fitting rings of 0.015-inch solder (Ag. 72 per cent, Cu. 28 per cent) were placed at each junction between a coupler and a resonator. The fit between the couplers and the resonators was almost a press fit and thus the entire filter was assembled before soldering. An oxygen-hydrogen flame was used to heat each resonator in turn to a cherry red until the solder flowed making a neat fillet at each junction. The oxide formed by the heat of soldering was removed by the gentle application of a buffing wheel. The over-all length of the unterminated filter measured 10⅜ inches.

The terminating resistors are in the form of lossy lines of the proper impedance. Each line consists of five feet of 0.050-inch copper wire which is coiled on a ⅞-inch form and then removed and dipped in self-vulcanizing liquid latex. Each line was given two coats of the rubber and then allowed to dry for 24 hours. The rubber provides the losses for the line as the copper itself is very low loss. Before attaching these lossy lines, a filter response curve was recorded to make sure the soldering process did not upset the tunings of the resonators. The symmetrical response shown by Figure 4 indicates proper tuning of all the elements. The lines were then soft soldered into the end resonators of the filter as is evident in Figures 5 and 7.

The chassis and mounting for the filter and its associated electrical components are shown in Figures 6 and 7. The chassis is approximately the size of a crystal filter that will do the same job. Particular care is necessary to isolate the input circuits from the output circuits as even a small amount of stray coupling will distort the response curve shape at high attenuations. Two entirely separate compartments are provided in the chassis by a dividing shield which has one small hole for the filter to pass through and another for the shielded power leads. A wiring diagram for the chassis is shown in Figure 8.

Results and Discussion

Figures 9 and 10 show the response curves obtained. Figure 1 is a comparison between a three-section crystal filter and the mechanical filter. An interesting comparison between this mechanical filter and a standard high quality communications receiver is given by Figure 11.

The requirements for single-band use are generally given as 80

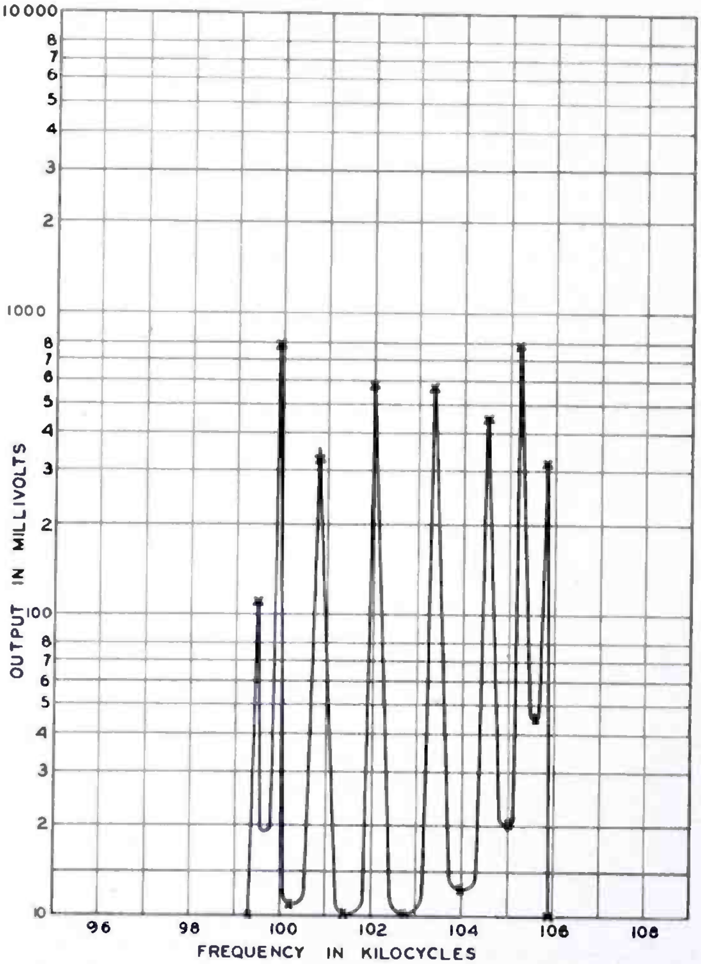

Fig. 4—Response curve of the unterminated mechanical filter.

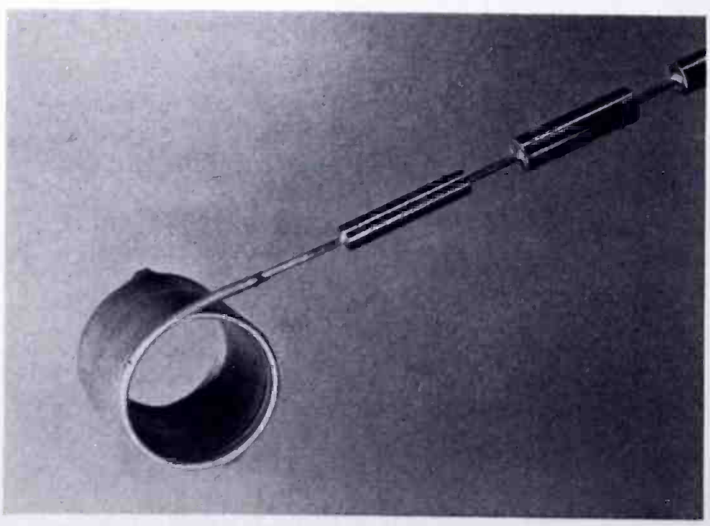

Fig. 5—Lossy line termination attached to one end of the filter.

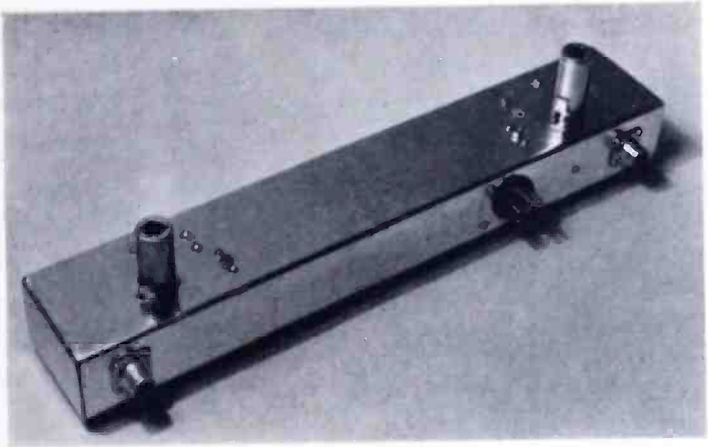

Fig. 6—Top view of mechanical filter chassis.

decibels attenuation, 1 kilocycle from the filter cutoff frequency. As the response curve indicates, this mechanical filter is only about half that good. There are seven sections in this mechanical filter and to double the attenuation would require double the number of sections. With fourteen sections, the mechanical filter would still compare favorably with the crystal filter, which has six double crystals in its three sections.

The ripple in the pass band of the mechanical filter is entirely satisfactory for the use intended. The curve of either Figure 9 or Figure 10 would be satisfactory. Single-sideband crystal filters generally have between 1 and 3 decibels ripple in their pass band although some are

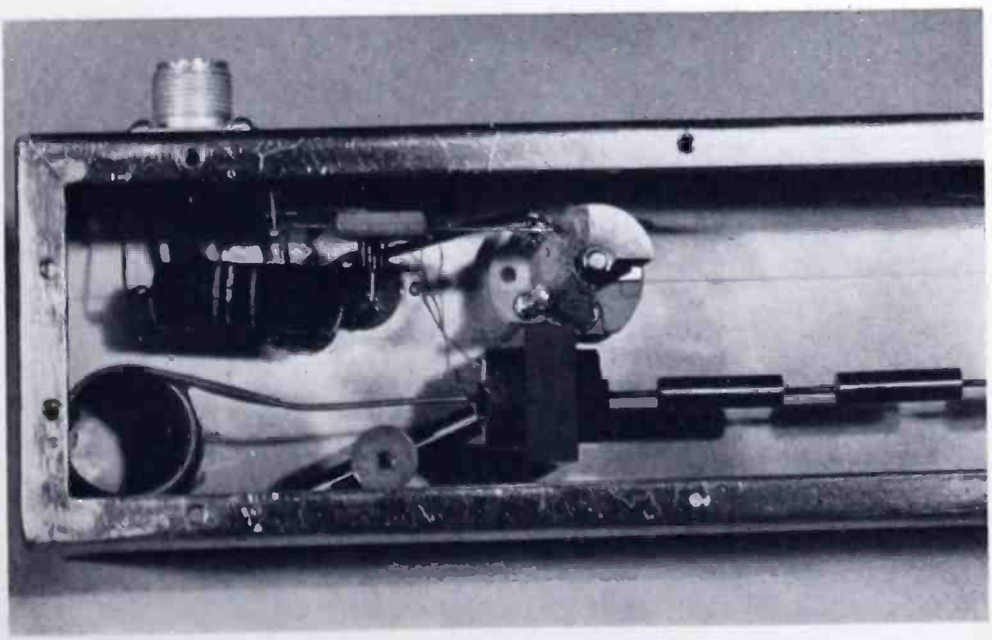

Fig. 7—Bottom view of chassis with cover removed showing wiring and biasing magnet.

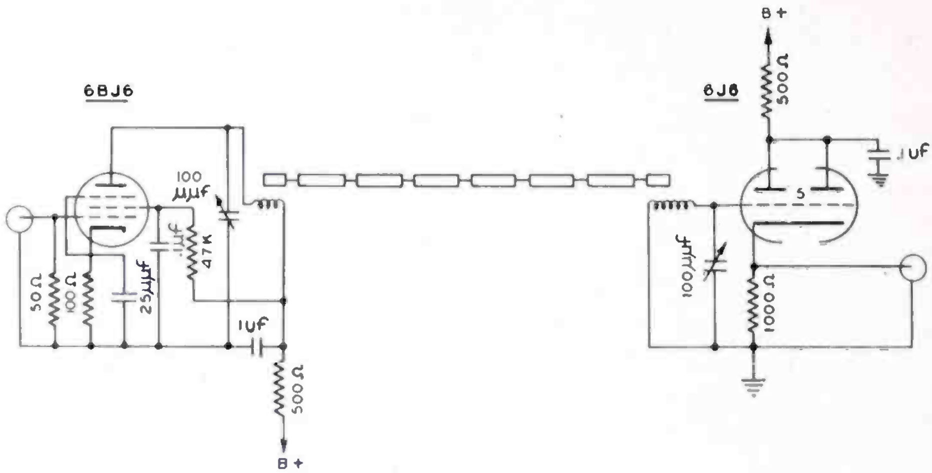

Fig. 8—Circuit diagram of complete filter unit.

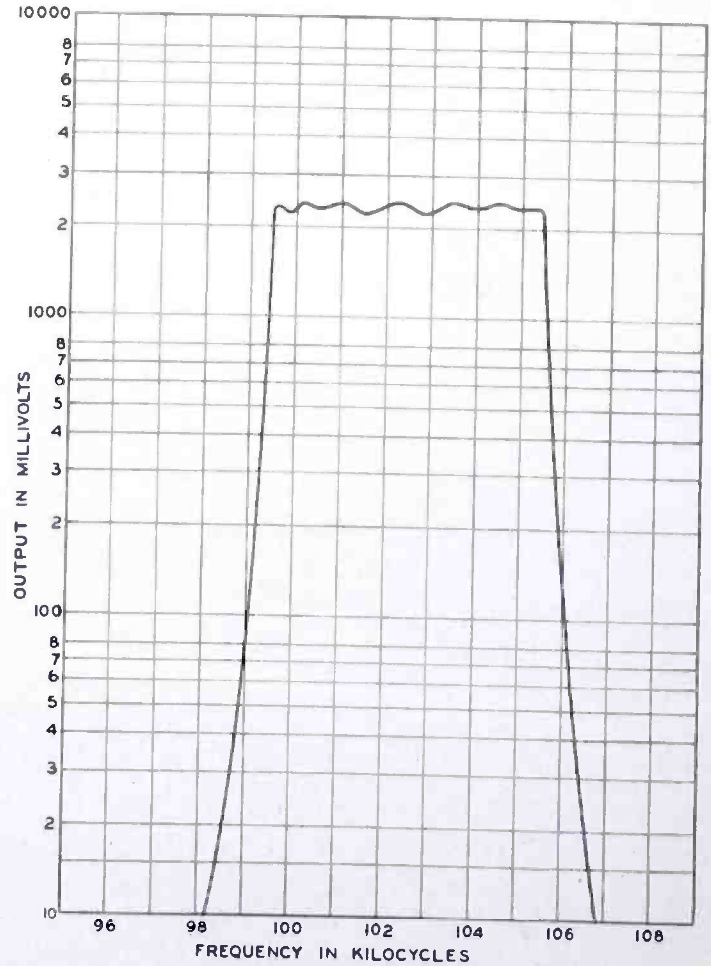

Fig. 9—Response curve of the mechanical filter with compromise terminations.

better. The amount of ripple obtained in a filter such as this is governed to some extent by the choice of the terminating impedance. Figure 10 shows the response curve when the lossy lines at each end have characteristic impedances equal to the characteristic impedance of the coupling elements. As can be seen, reflections are nonexistent over the center portion of the band while relatively bad reflections occur at the edges. By using slightly lower impedance lossy lines at each end as compromise terminations, a lower average mismatch is obtained, resulting in smaller reflections. A compromise recommended by Guillemin[2]

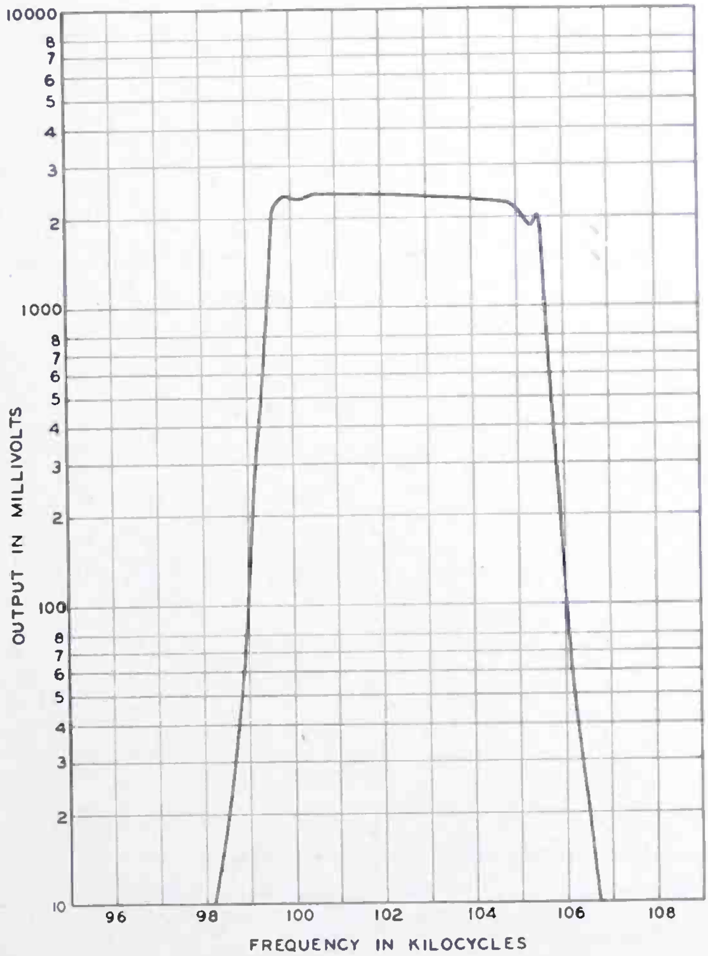

Fig. 10—Response curve of the mechanical filter with the theoretical terminations showing large variations at band edges.

is to make the terminations 60 per cent of the mid-band impedance, however, it has been found that 70 per cent gives slightly better results with this particular filter construction. The resulting response curve is shown in Figure 9.

[2] E. A. Guillemin, *Communication Networks*, Vol. II, p. 297, John Wiley and Sons, Inc., New York, N. Y., 1935.

Perfectly flat response in the pass band could have been obtained by designing the various couplings between the resonators in accordance with established filter theory so as to obtain a "max flat" response.[3] Since the steepness of the cutoff slope would have necessarily been reduced, it was considered more desirable to accept the ripple inherent in the constant-k construction.

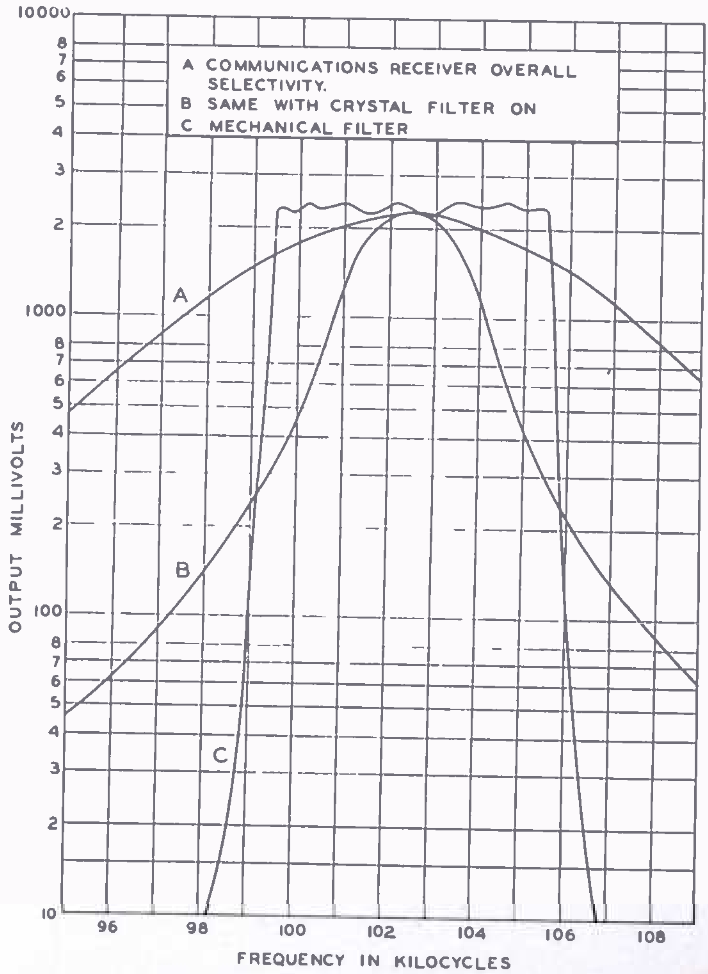

Fig. 11—Response curve of the mechanical filter compared with a standard communication receiver.

The rate of attenuation can be increased by increasing the number of sections as has been previously mentioned. It might be thought that another method of increasing the cutoff rate would be to design the filter couplings so as to obtain a Chebiskev polynomial type of response since it has been shown that this would be optimum for a coupled

[3] Milton Dishal, "Design of Dissipative Band-Pass Filters Producing Desired Exact Amplitude-Frequency Characteristics," *Proc. I.R.E.*, Vol. 37, pp. 1050-1069, September, 1949.

resonator type of filter.[4] However, a calculation according to the procedure of Dishal[3] gives 43.6 decibels attenuation 1 kilocycle from the edge of the pass band of a filter with similar ripple, while an inspection of Figure 9 gives 40 decibels attenuation 1 kilocycle from the upper edge of the pass band. Therefore, designing the filter to give a Chebiskev response would result in very little improvement, and the complexity of the design calculations would be increased many fold.

Apparently the only way of greatly increasing the rate of attenuation at the band edges without increasing the number of resonators is to incorporate some form of rejector arrangement so as to approach an m-derived type of response. This is easily done in the electrical drive and take-off circuits by simply placing high-Q magnetostrictive resonators of the correct frequencies in part of the two coils. Attaching the rejectors directly to the mechanical filter is more difficult and attempts thus far have not been too successful.

The insertion loss of the filter measured from the grid of the first tube to the grid of the second tube is about 8 decibels. By using an untuned line-matching transformer on the input to match the 50-ohm coaxial cable to the first grid, the unit insertion loss was reduced to zero; and by making the output tube a pentode and again using a transformer to match the line to the output tube, a gain of about 6 decibels was realized. Of course the mechanical filter itself still has the same loss. By using magnetostrictive ferrite for the input and output resonators, much higher efficiency can be obtained but some sacrifice in temperature stability would result. Piezoelectric barium titanate can also be used to provide efficient electrical-to-mechanical conversion at the input and output but again the temperature stability would be impaired.

The temperature stability of the filter can be made quite good over the range of —50°C to +80°C by the use of all Ni-Span C construction. As has been noted previously, however, steel couplers were used in the fabrication of this filter and as a result the heat treatment necessary to adjust the thermoelastic coefficient to zero was not carried out.

Two filters of the type described have been built and no trouble was experienced in reproducing the results. Either silver solder or soft solder was found satisfactory for joining the couplers to the resonators. A semipress fit between the parts was found desirable to minimize the detuning effect of the solder. The resonators used were 0.25 inch in diameter but this was an arbitrary choice and a smaller diameter

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[4] P. E. Richards, "Universal Optimum Response Curves for Arbitrarily Coupled Resonators," *Proc. I.R.E.*, Vol. 34, pp. 624-629, September, 1946.

would work as well (of course, the couplers would have to be changed in proportion in order to keep the same band width).

Conclusion

Mechanical filters for 100 kilocycles having various band widths can be designed according to the procedure in the Appendix. The attenuation rate can be controlled by the number of sections in the filter. The ripple in the pass band can be reduced to a satisfactory value by proper termination of the filter using lossy acoustic transmission lines of the correct size. The insertion loss can be reduced by using magnetostrictive piezoelectric ferrite or barium titanate for the electrical to mechanical conversion with some compromise in stability. All Ni-Span C construction insures good temperature stability.

Appendix

Design Procedure for Mechanical Filters

The band width formula for a mechanical filter with half-wave resonators and quarter-wave coupling necks is given by Roberts and Burns[1] as:

$$B = \frac{4}{\pi} \phi \, (1 - \phi),$$

where B is the fractional band width given by $\dfrac{f_2 - f_1}{\sqrt{f_2 f_1}}$,

$$\text{and } \phi = \frac{(\text{area of coupler})\ (\text{intrinsic } Z \text{ of coupler})}{(\text{area of resonator})\ (\text{intrinsic } Z \text{ of resonator})} = \frac{A_c Z_{IC}}{A_R Z_{IR}}.$$

The intrinsic impedance of a material is given by

$$Z_I = (\text{Velocity})\ (\text{Density})$$

The above expression for the fractional band width can be solved for the diameter of the coupler:

$$D_c = \left[\frac{D_R^2 \, Z_{IR}}{2 Z_{IC}} \left(1 - \sqrt{1 - \pi B}\right) \right]^{1/2}.$$

For the filter discussed in this report, $B = 0.06$ (i.e., 6 kilocycles wide, centered on 100 kilocycles),

$D_R =$ diameter of resonator $= 0.25$ inch,

$Z_{IR} =$ intrinsic Z of Ni-Span C resonator $= 3.83 \times 10^6$,

$Z_{IC} =$ intrinsic Z of steel coupler $= 4.03 \times 10^6$.

The diameter of the required coupler then becomes 0.054 inch.

To terminate a Campbell filter properly, a half section must be used at each end. This requires end resonators of ½ the impedance of the interior resonators. Thus

$$\frac{\pi D_I^2}{(4)(2)} = \frac{\pi D_e^2}{4},$$

or
$$D_e = \frac{D_I}{\sqrt{2}} = \frac{0.25}{1.414} = 0.177 \text{ inch},$$

where $D_I =$ diameter of interior resonator,

$D_e =$ diameter of end resonator.

The length of the resonators is found from the relation

$$\lambda = \frac{v}{f},$$

where λ is the length of a full wave,

v is the velocity of sound, and

f is the frequency.

For half-wave resonators,

$$\frac{\lambda}{2} = \frac{v}{2f} = \frac{4.8 \times 10^5}{2 \times 100{,}000 \times 2.54} = 0.945 \text{ inch}.$$

Similarly, for the quarter-wave couplers,

$$\frac{\lambda}{4} = \frac{v}{4f} = \frac{5.13 \times 10^5}{4 \times 100{,}000 \times 2.54} = 0.505 \text{ inch}.$$

The couplers have to be made somewhat longer to allow for insertion into the resonators.

The lossy lines for termination should have 70 per cent of the impedance of the couplers. Note that the lossy lines are copper wire while the couplers are steel.

$$\frac{\pi D_L^2 Z_{IL}}{4} = \frac{\pi D_c^2 Z_{IC}(70\%)}{4},$$

where D_L = diameter of the lossy line,

D_c = diameter of the coupler,

Z_{IL} = intrinsic impedance of line (copper), and

Z_{IC} = intrinsic impedance of coupler (steel).

Thus

$$D_L = \left[\frac{D_c^2 Z_{IC}(.7)}{Z_{IC}}\right]^{1/2}$$

$$D_L = \left[\frac{(.054)^2 (4.03)(10^6)(.7)}{(3.33)(10^6)}\right]^{1/2} = 0.050 \text{ inch.}$$

As stated in the text, the lines were made five feet long.

The location of the center of the pass band turns out to be slightly above 100 kilocycles. For an exact location of the pass band, some cut and try would be necessary.