LB-829

A BANDPASS MECHANICAL FILTER FOR 100 KC

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Approved

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Introduction

Some two years ago at a demonstration held for licensees at RCA Laboratories, Princeton, N.J., (See LB-767, p.13) a project on mechanical filters was among the various exhibits. Shortly thereafter a bulletin, LB-773, *Mechanical Filters for Radio Frequencies* was issued which described in more detail the theory and mathematical development of mechanical filters, along with some illustrative examples of experimental filters which had been made and tested.

Considerable development work in this field has been carried on since that time. More 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 kc. This bulletin 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 bandpass filtering action. A standard double-tuned i-f 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 by magnetostriction to the output electrical circuit. The mechanical resonant circuits can be halfwave lengths of a suitable metal while the couplings between the mechanical resonant circuits can be quarterwave lengths of the same metal but of a different diameter. This bulletin describes the detailed construction and operation of a filter of this type. Fig. 1 shows a comparison between the results obtained from this filter and a commercial single-side-band 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 could 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 as neck type of construction[1]. The neck type of

[1] LB-773, *Mechanical Filters for Radio Frequencies*.

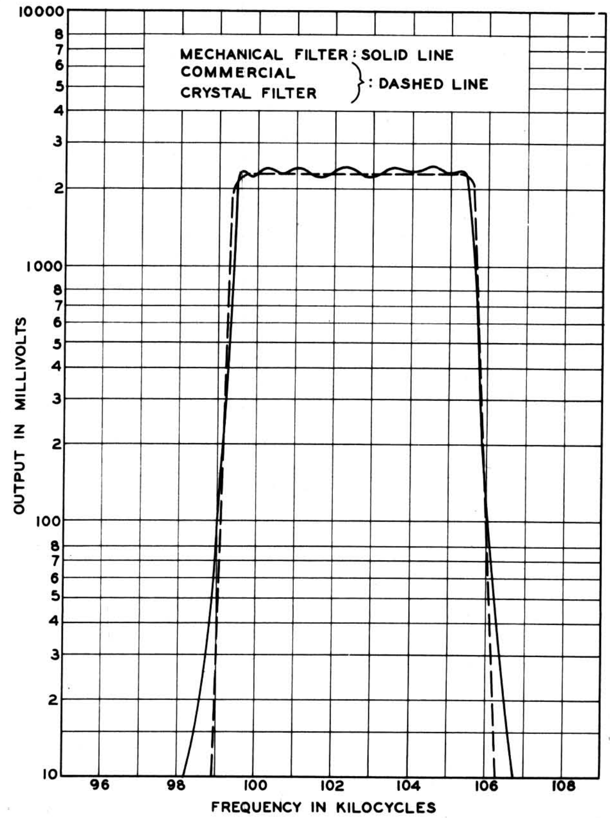

Fig. 1 - Response curve of the single-side-band mechanical filter compared with an equivalent quartz crystal filter.

construction was chosen for this filter because the mechanical termination is much simplified. The filter consists of a series of 8 halfwave resonators coupled by thin necks as shown in Fig. 2. To understand why the termination problem is simplified, note that the end resonator is a halfwave long, the impedance at the junction of the end resonator and its neck is then "transformed" by the halfwave end resonator to exactly the same impedance at the end of the filter, where a resistance equal to the neck impedance can be attached. On the other hand a slug type of filter has a quarterwave end resonator which transforms the high impedance of the coupler down to a very low impedance. In practice this means that a neck type of filter can have a lossy line for a termination resistor that is the same diameter as the neck while a slug type would require a lossy line that is much smaller in diameter than the end resonator and which turns out to be inconveniently small.

The actual dimensions of the resonators and coupling necks were determined by the design procedure indicated in the Appendix and are given by Fig. 2. For convenience, steel couplers were used because 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.

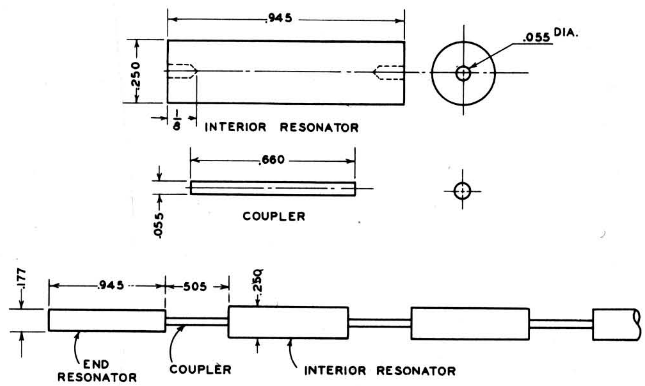

Fig. 2 - Details of construction of the mechanical filter.

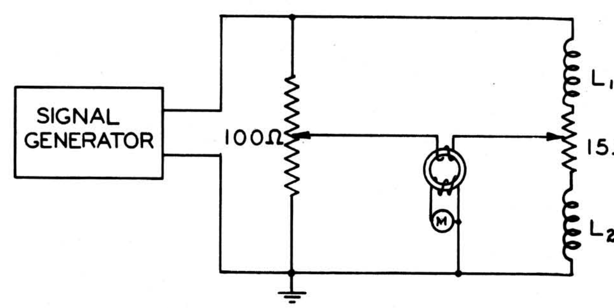

Fig. 3 - Bridge circuit for checking the individual resonator responses.

Before assembly the resonant frequency of each resonator was checked in the bridge circuit of Fig. 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 meter M (Model 300 Ballantine) as the signal generator is slowly tuned through the resonant frequency of the resonator a sudden increase in 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 BT silver solder 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 overall length of the unterminated filter measured 10-3/8 inches.

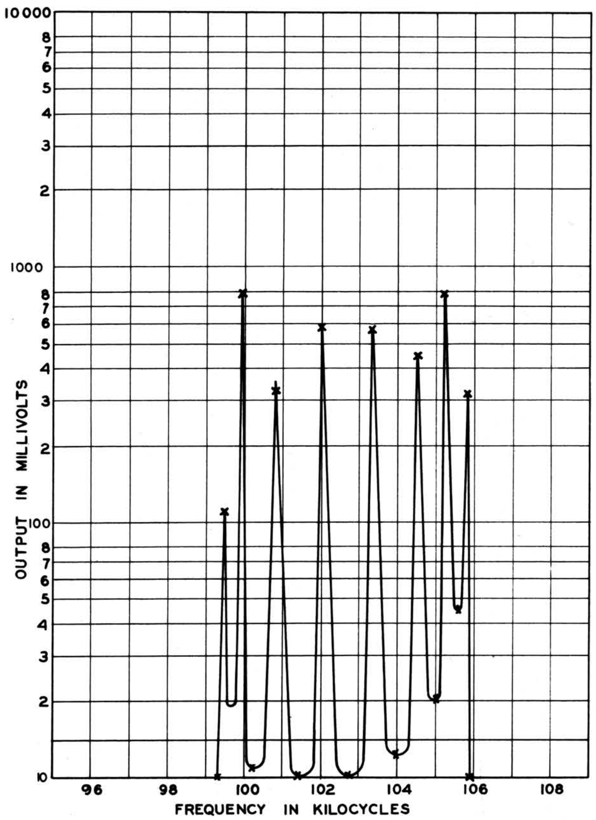

Fig. 4 - Response curve of the unterminated mechanical filter.

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 coiled on a 7/8-inch form, then removed and dipped in self-vulcanizing liquid latex. Two coats of the rubber were given to each line 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 Fig. 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 Figs. 5 and 7.

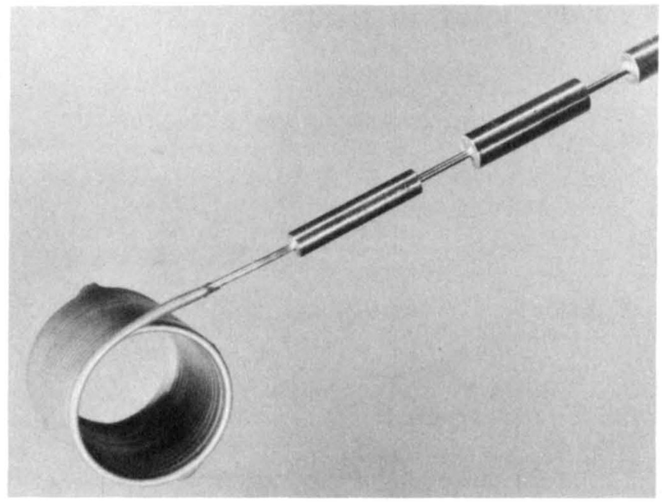

Fig. 5 - Lossy line termination attached to one end of the filter.

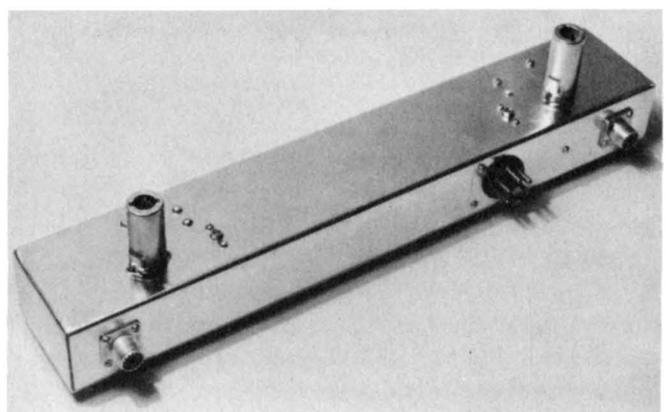

Fig. 6 - Top view of mechanical filter chassis

The chassis and mounting for the filter and its associated electrical components are shown in Figs. 6 and 7. The chassis is an approximate-size copy 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 given by Fig. 8.

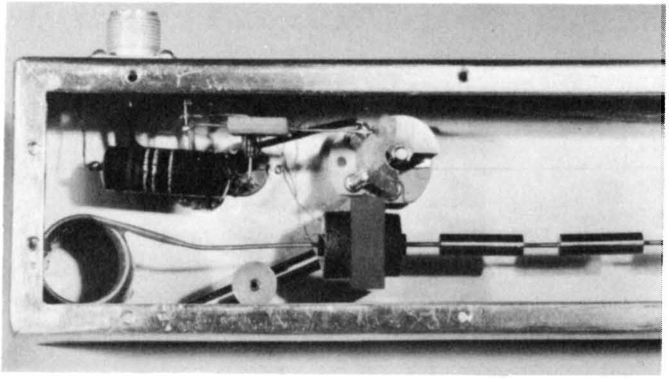

Fig. 7 - Bottom view of chassis with cover removed showing wiring and biasing magnet.

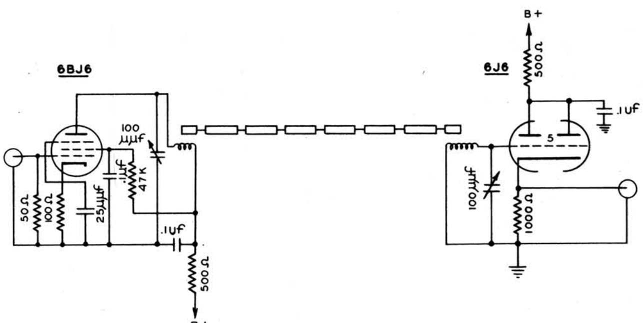

Fig. 8 - Circuit diagram of complete filter unit.

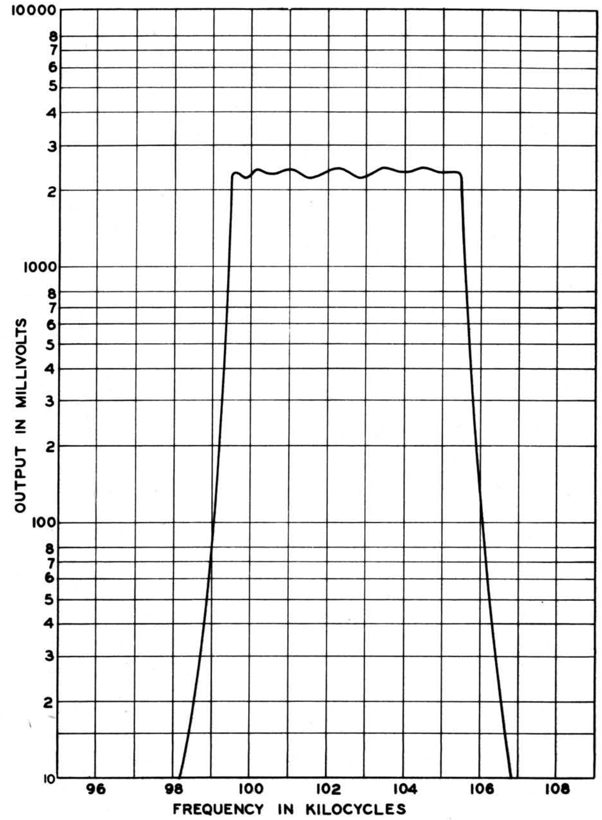

Fig. 9 - Response curve of the mechanical filter with compromise terminations.

Results and Discussion

Figs. 9 and 10 show the response curves obtained. Fig. 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 in Fig. 11.

The requirements for single-sideband use are generally given as 80 db attenuation 1 kc from the filter cutoff frequency. As the response curves indicate, 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 as it 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. Either the curve of Fig. 9 or Fig. 10 would be satisfactory. Single-sideband crystal filters generally have between 1 and 3 db ripple in their passband although some are better. The amount of ripple obtained in a constant k mechanical filter such as this is governed to some extent by the choice of the terminating impedance. Fig. 10 shows the response curve when the lossy lines at each end have an impedance equal to the coupling impedance. As can be seen, reflections are nonexistant 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 recommended compromise is to make the terminations 60 per cent of the midband impedance; however, it has been found that 70 per cent gives slightly better results with this particular filter construction. The resulting response curve is Fig. 9.

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

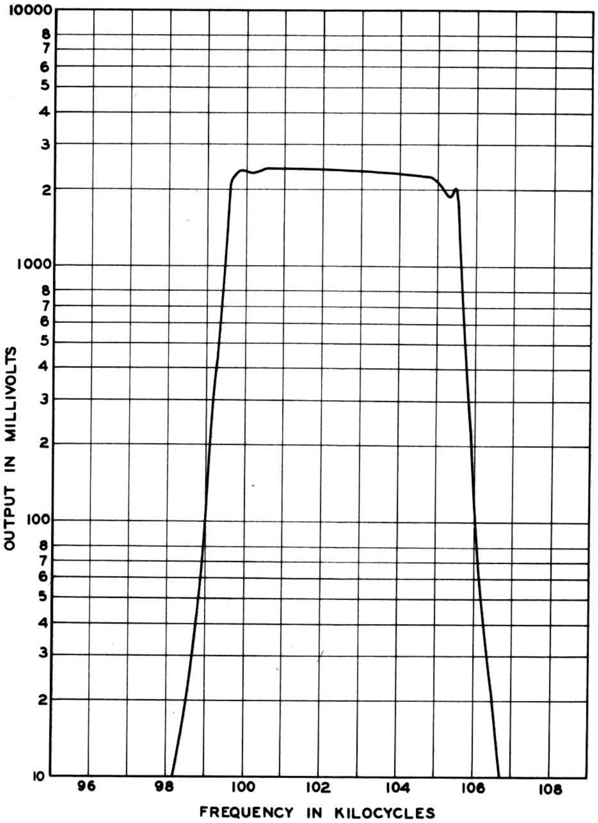

Fig. 10 – Response curve of the mechanical filter with the theoretical terminations showing bad variations at band edges.

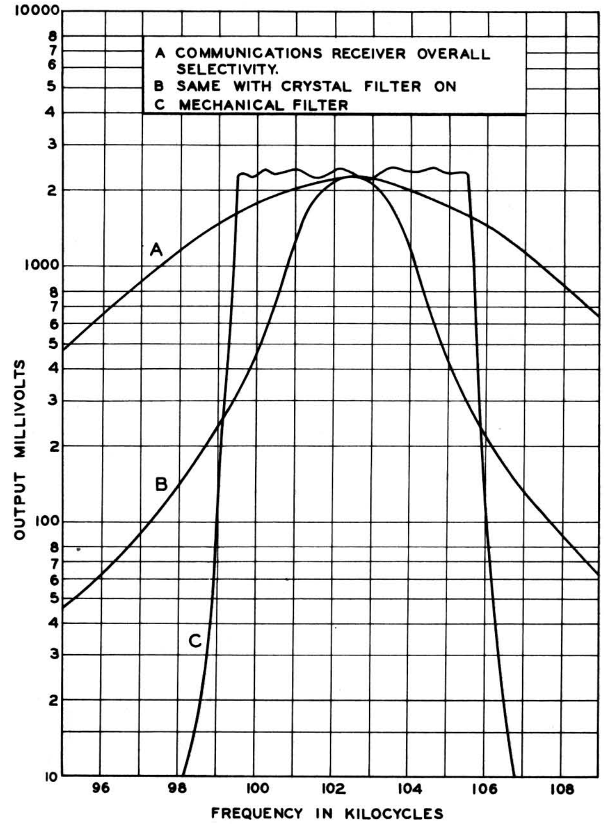

Fig. 11 – Response curve of the mechanical filter compared with a standard communication receiver.

as to obtain a "max flat" response[2]. 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.

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 Chebishev polynomial type of response since it has been shown that this would be optimum for a coupled resonator type of filter.[3] However a calculation according to the procedure of Dishal[4] gives 43.6 db attenuation 1 kc from the edge of the pass band of a filter of the desired shape while an inspection of Fig. 9 gives 40 db attenuation 1 kc from the upper edge of the pass band. Thus, designing the filter to give a Chebishev 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 takeoff 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 db. By using a line-matching transformer on the input to match the 50-ohm coaxial cable to the first grid the unit insertion loss can be reduced to zero and by making the output tube a pentode

[2]Milton Dishal, "Design of Dissipative Band-Pass Filters Producing Desired Exact Amplitude-Frequency Characteristics", *Proc. IRE,* Vol. 37, No. 9, pp 1050-1069, Sept. 1949.

[3]P.E. Richards, "Universal Optimum Response Curves for Arbitrarily Coupled Resonators" *Proc. IRE,* Vol. 34, No. 9, pp. 624-629, Sept. 1946.

[4]loc. cit.

and again using a transformer to match the line to the output tube a gain of about 6 db can be 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.

Using all Ni-Span C construction the temperature stability of the filter can be made quite good over the range of $-50^{o}C$ to $+80^{o}C$. 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 this type have been built and no trouble was experienced in reproducing the result. Either silver solder or soft solder was found satisfactory for joining the couplers to the resonators. A semi-press 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 would work as well (of course the couplers would have to be changed in proportion in order to keep the same bandwidth).

Summary

Mechanical filters for 100 kc having various bandwidths 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 ferrite or piezoelectric barium titanate for the electrical to mechanical conversion with some compromise in stability. All Ni-Span C construction insures good temperature stability.

Leslie L. Burns Jr.

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Appendix

Design Procedure for Mechanical Filters

The bandwidth formula for a mechanical filter with half wave resonators and quarter wave coupling necks is given in LB-773, page 5, Fig. 3, as:

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

where B is the fractional bandwidth given by

$$\frac{f_2 - f_1}{\sqrt{f_2 f_1}}$$

and $$\emptyset = \frac{(\text{area of coupler})(\text{Intrinsic Z of coupler})}{(\text{area of resonator})(\text{Intrinsic Z of resonator})}$$

$$= \frac{A_C Z_{IC}}{A_R Z_{IR}}$$

The intrinsic impedance of a material is given by,

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

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

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

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

D_R = Diameter of Resonator = 0.25 inch
Z_{IR} = Intrinsic Z of Ni-Span C Resonator = 3.83×10^8
Z_{IC} = Intrinsic Z of steel coupler = 4.03 x 10

The diameter of the required coupler turns out to be 0.054 inch.

To properly terminate a Campbell filter a half section must be used on each end. This requires end resonators of one half 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
f is the frequency

Since half wave resonators are desired

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

Similarly for the quarter wave couplers:

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

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 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 the line (copper)
Z_{IC} = intrinsic impedance of coupler (steel)

Thus

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

$$D_L = \left[\frac{(.054)^2 (4.03)(10^8)(.7)}{(3.33)(10^8)} \right]^{\frac{1}{2}} = 0.050 \text{ inch.}$$

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

The exact location of the center of the pass band turns out to be slightly above 100 kc due to the effect of the couplers and the diameter of the resonators. For an exact location of the pass band some cut and try would be necessary in any case.