Compact ELECTROMECHANICAL

Interconnected metal plates that transmit vibrations act as transmission-line type filter. Plates are coupled to electrical circuit by magnetostriction. Filter for 455-kc i-f channel of broadcast receiver has very sharp cutoffs, is small, cheap, easily constructed and efficient

THIS PAPER presents principles of operation and practical design of a novel and rather unconventional wave filter.

In its present form the filter is best suited for the 455-kc intermediate-frequency channel of broadcast and communication receivers; its frequency response is characterized by a flat pass band of well defined width, and by extremely sharp attenuation outside the band limits. Its adjacent-channel selectivity easily surpasses that obtained with much more expensive conventional filters.

Principle of Operation

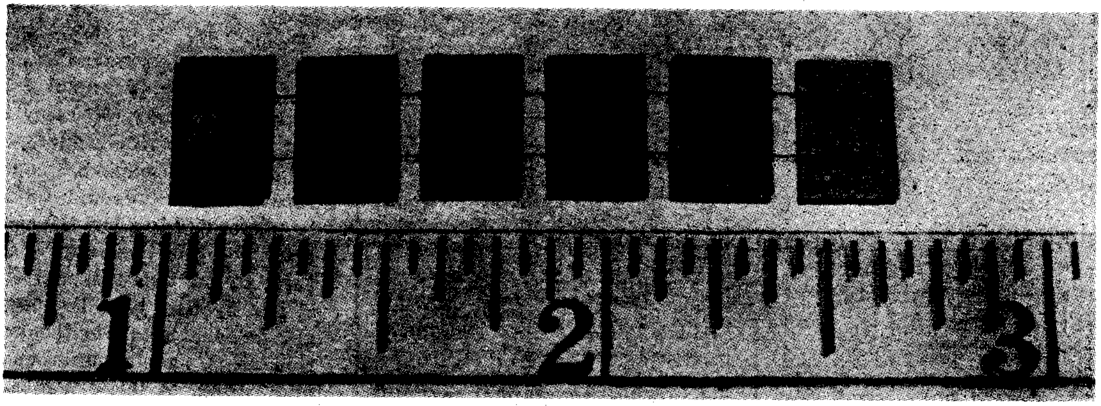
The new filter is of the electromechanical type. Intermediate frequency currents, upon entering the filter, are converted into mechanical vibrations of the same frequency. These vibrations then pass through a structure resembling a ladder, consisting of several mechanically resonant metal plates coupled to each other by wires which act as springs.

This structure forms a bandpass filter for mechanical vibrations. Width of the pass band, as will later be shown, is determined by the design of each individual section; and, because the several sections are all alike, bandwidth does not depend upon the number of sections. Attenuation outside the band limits, however, increases with the number of sections.

To understand the operation of the filter most easily, let us first consider a familiar electrical filter, composed of inductors and capacitors; the type shown in Fig. 1A is rather fundamental and can be found in many books on electrical wave filters.

Such a filter will transmit a band of frequencies starting at the resonant frequency F of the two series elements L_1, C_1 and ending at a somewhat higher frequency $F + W$, where W stands for the bandwidth of the filter. If shunt capacitances C_2 are large compared to the series ones C_1, the fraction C_1/C_2 becomes small compared to unity; the bandwidth ratio W/F is then equal to 2 C_1/C_2. For an i-f filter in which F = 455 kc and W = 9 kc, the bandwidth ratio W/F becomes 0.02 and C_1/C_2 becomes 0.01.

Series elements in the terminating half sections should have only half the reactance of the other series elements. Also, no resistances at all are needed inside the filter, so that, strictly speaking, all inductors



Filter consists of steel plates connected by short wires. Action of components of filter is comparable to that of transmission lines as used in very high-frequency filters, rather than to lumped inductances and capacitances

FILTER

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and capacitors should have infinite Q's; the generator and the load are resistive, however. Their resistance R should be so chosen that the filter will be correctly terminated; for the circuit of Fig. 1A, R becomes numerically equal to the reactance of the shunt capacitances C_2.

The analogy between electrical and mechanical network elements, with masses substituted for inductors and springs for capacitors, is well known; and it appears quite feasible to build a mechanical filter structure, which is fully equivalent to the electrical filter shown in Fig. 1A, by combining masses and springs in analogous fashion. Such filters have been built, especially at the Bell Telephone Laboratories, by Mason, Blackman and Lakatos, and probably by others (See, for instance, Electromechanical Transducers and Wave Filters, by Warren P. Mason, D. Van Nostrand Co., Inc., New York, 1942, page 86).

Distributed Constants

For operation at 455 kc, the masses and springs of such a filter would become inconveniently small, and it is questionable whether a practical design could be developed on this basis.

The way around this obstacle is once more suggested by an electrical analogy. Radio engineers have long been familiar with the transition from lumped circuits to lines with distributed constants. (Line lengths are proportioned to give required input impedances.) This transaction becomes necessary

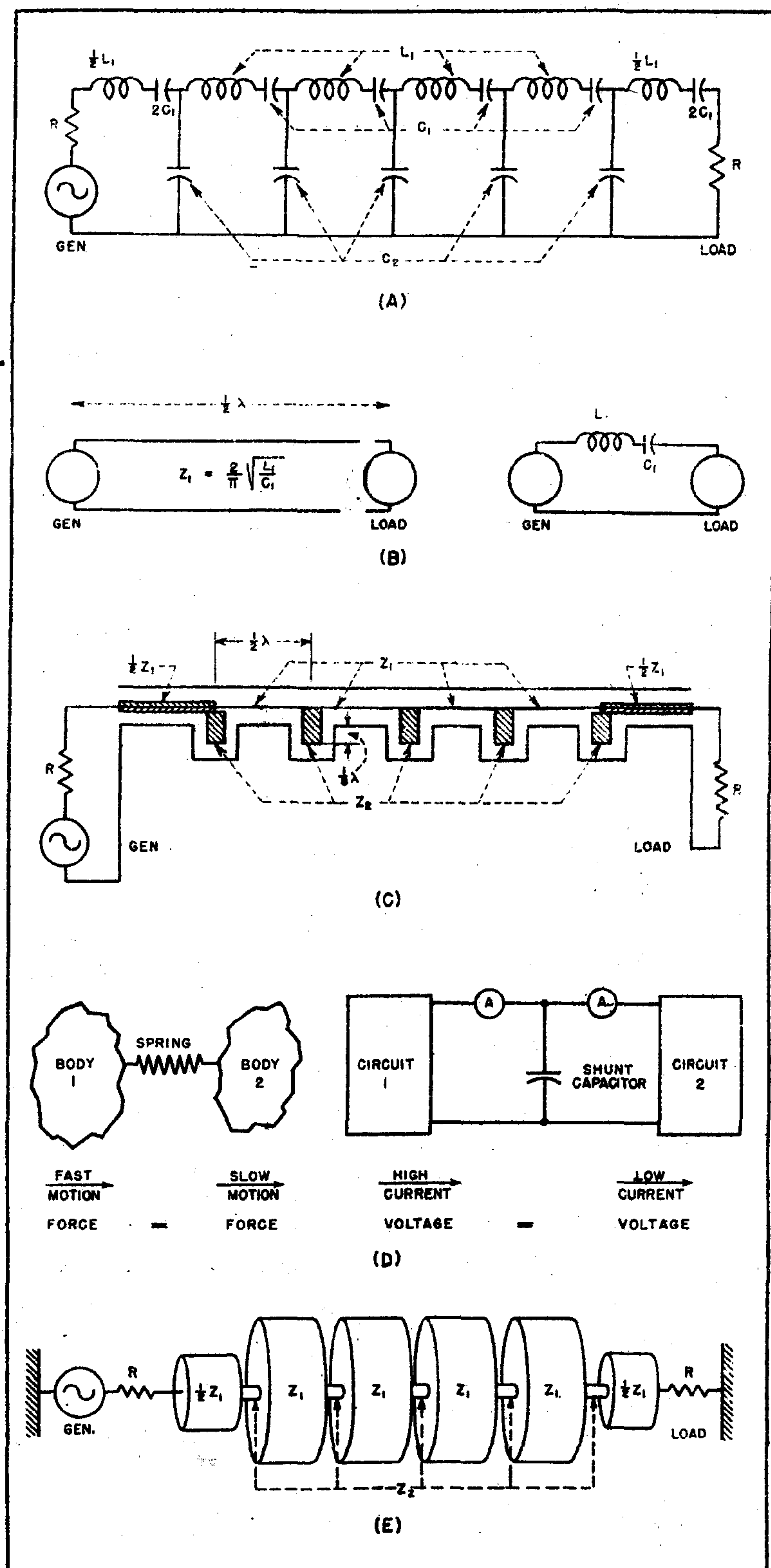

FIG. 1—Electromechanical filter is developed from consideration of electrical filters

when the frequency of electrical circuits is increased to a point where inductors and capacitors become too small to handle. A similar transition exists in the field of mechanical vibrations; only, because sound travels so much more slowly than do electromagnetic fields, the transition must be made at much lower frequencies. Velocity of sound in steel and many other solids is of the order of three miles per second, making the length of a longitudinal wave at 455 kc about one-half inch, and a half-wave resonant line is therefore one-quarter inch long, which is not an inconvenient size.

To learn how to arrange mechanical lines to obtain a filter, let us look first at electrical lines which are more familiar. In the left portion of Fig. 1B, a half-wave line is shown which connects a generator to a load; to the right there appears its lumped-circuit equivalent, an inductance and capacitance in series. The following conditions must be met: Resonant frequency left and right should be the same, and characteristic impedance Z_1 of the line should be equal to $2/\pi$ times (about 64 percent) the reactance of L_1 or C_1 at resonance. Then the two networks become equivalent at all frequencies not too far from the resonant frequency F.

Using the equivalence just stated, series inductors and capacitors of the original filter can be replaced by half-wave lines of the proper impedance. There remain the shunt capacitors. These can best be taken care of by means of open-circuited line stubs less than a quarter wave long. For instance, if the stubs are an eighth wavelength long, their reactance becomes numerically equal to their characteristic impedance, which we may call Z_2.

With these two kinds of line elements, we can now draw the line equivalent of the original filter. Figure 1C shows several half-wave sections of impedance Z_1, shunted at their junctions by open eighth-wave lines of a much lower impedance Z_2. Bandwidth ratio W/F, which was previously equal to $2\ C_1/C_2$, becomes now $(4/\pi)\ (Z_2/Z_1)$. With these relations we design a line.

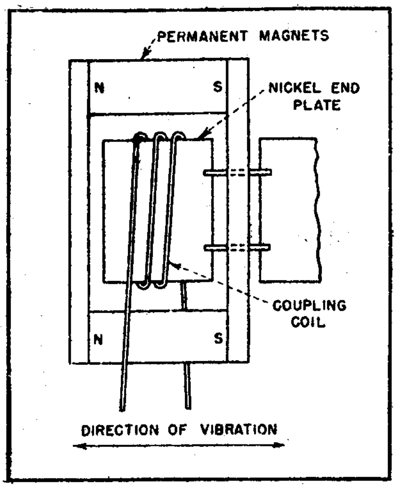

FIG. 2—Magnetostrictive end plates are magnetized and coupled by coils to the electrical circuit

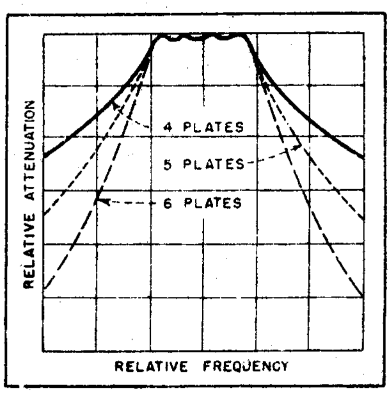

FIG. 3—Cutoff at edges of pass band is sharper for mechanical filters having more plates

To obtain $W = 9$ kc at $F = 455$ kc, Z_2 must be made 1.57 percent of Z_1. It is apparent that the shunting stubs must be cut from lines of very low impedance; also, the impedances of the terminating half-wave lines should be only $0.5Z_1$.

Equivalent Mechanical Filter

We are now almost ready to apply the knowledge gained with the aid of our electrical model to an equivalent device in which mechanical lines are used. Half-wave and eighth-wave mechanical lines can easily be constructed for a given frequency; all we need to know is the velocity of sound propagation in the medium we select. There remains, however, the need for defining the ratio between the impedances of two mechanical lines, for upon such a ratio depends the bandwidth ratio W/F of the filter.

Let us consider a section of mechanical line made of a given solid material in which vibration is propagated longitudinally. For a fibre of line having one unit of cross-sectional area, isolated from the surrounding body, it takes a certain force to produce a desired motion; then, if total cross-section of the line is A units, the total force required to impart the same motion to the entire area will be A times this certain force. In other words: Force for a given motion is proportional to the cross-sectional area. If we think of mechanical force as equivalent to electrical voltage, it follows that mechanical impedance of the line is proportional to its cross-sectional area.

The rules just derived enable us to design mechanical line elements which, when combined, will produce the desired pass band, but we still need to know how these elements should be interconnected. Let us again refer to the electrical analogy, shown in detail in Fig. 1D. A coupling spring between two mechanical objects exerts equal forces upon both, while taking up the difference between their velocities. Similarly, an electrical shunt connected between a generator and a load maintains equal voltages across both, but takes up the difference between generator current and load current. To act in a manner equivalent to electrical shunts, our mechanical eighth-wave stubs should therefore be connected like coupling springs between the half-wave resonating lines.

Figure 1E shows a highly schematized view of the structure which is obtained by joining mechanical lines together in the manner just derived. Any mechanical structure built in accordance with this schematic design will act as a bandpass filter.

Electromechanical Terminations

The figure calls for a mechanical generator on the left and for a mechanical load on the right, both having the proper resistance but no reactance. Because this filter is

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to be used between electrical circuits, generator and load should both be electromechanical converters, somewhat like a speaker and a microphone. For the frequency range near 455 kc, the only suitable converters are piezoelectric or magnetostrictive bars. Such bars always have mass and elasticity, however, and so it seems impossible to construct the desired converters.

To find a way out of this difficulty, let us look once more at the lumped electrical circuit (Fig. 1A) from which our filter was first derived. It is the resistive elements R which cannot be built without introducing reactances. But instead of attempting the impossible, consider the terminating elements R, 0.5 L_1, and 2 C_1 as a unit; together they form a tuned circuit with $Q =$ of $0.5[(L_1/C_1)/R]^{1/2}$. This Q, incidentally, is equal to the reciprocal of the bandwidth ratio W/F, becoming 50 for the 9-kc filter.

If it is permissible to consider the resistive elements as damping tuned circuits which terminate this electrical filter at both sides, then, in analogous fashion, the required resistance can be incorporated into the terminating half-wave lines of the mechanical filter by giving them the proper damping.

Finally, the resistances in the mechanical filter should simultaneously serve as electromechanical converters, which is possible only if the terminating half-wave lines themselves are piezoelectric or magnetostrictive.

Electromechanical Damping

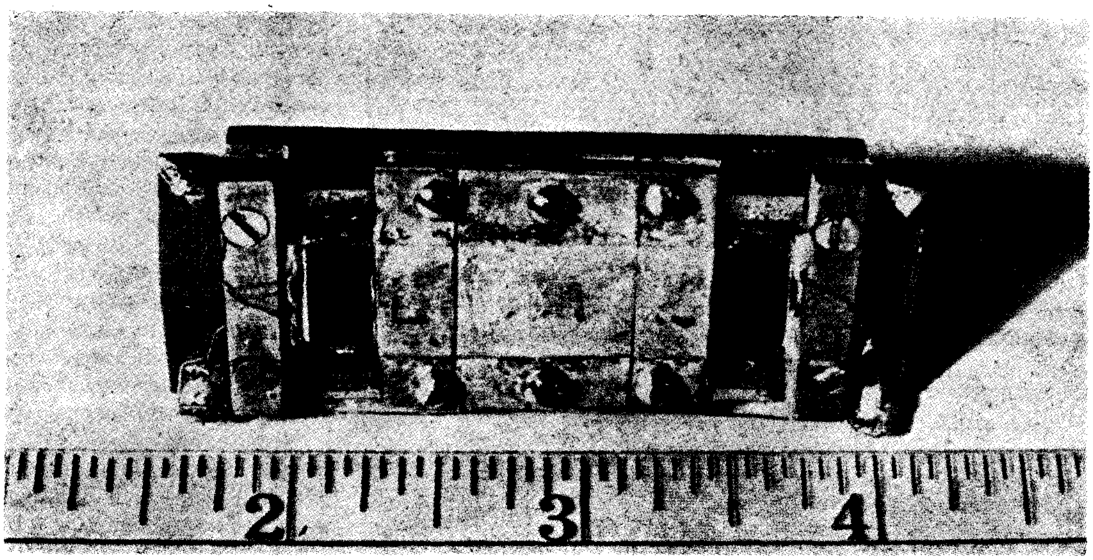
The electromechanical filter must therefore consist of several half-wave resonators with the least possible mechanical damping, coupled to each other and to the terminating elements by eighth-wave lines of much smaller cross section. Electrical properties of all these elements are of no consequence. But the terminating half-wave resonators must be made of piezoelectric or magnetostrictive material. They should have half the impedance of the other resonators, and their damping must be carefully controlled.

A few words about the nature of this damping: If any electromechanical converter—we may, for instance, think of the oldest kind, the rotating d-c generater—is loaded on its electrical side, a reflected mechanical resistance is established which causes expenditure of mechanical energy whenever electrical energy is absorbed from the generator. Mechanical energy consumed by this reflected resistance is not lost but reappears in electrical form.

Evidently, then, reflected mechanical resistance produced by loading the electrical side of converters provides damping. From an efficiency viewpoint it would be best to produce exactly the required amount of damping in this manner and use no frictional damping at all. In piezoelectric converters this is indeed possible, and with them a filter of the type described could be built having nearly ideal transmission. Magnetostrictive converters, at frequencies near one-half megacycle, are not quite as efficient. Only part of the required mechanical resistance can be produced by electrical loading; the remaining portion is inherent in the mechanical damping—internal and external friction—acting upon the two end pieces. Accordingly, a fraction of the incoming electrical energy is lost in the filter input, and an equivalent fraction of the mechanical energy arriving at the filter output is lost there.

The question may therefore be asked why, in spite of these losses, the magnetostrictive type should have been chosen for a practical design. The answer lies in its simplicity, economy and stability.

A typical filter consists of flat



For use in intermediate-frequency amplifier of broadcast receivers, the electromechanical filter is housed in a protective case. Coupling coils are wound around end plates, which are located in the field of permanent magnets

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nickel end plates 0.005 inch thick, stainless steel plates twice as thick (to maintain the required impedance ratio) and pairs of parallel steel wires 0.006 inch in diameter, which connect adjacent plates. It is put together by spotwelding the steel wires to the rectangular plates. To put it into operation, each of the nickel end plates is premagnetized in the direction of vibration, by means of small permanent magnets as shown in Fig. 2, and coils are arranged around each nickel end plate to make it vibrate as a magnetostrictive half-wave bar.

The filter structure is held loosely in place between linings of soft cloth or neoprene inside a flat metal cover. As long as no undue pressure is exerted upon the stainless steel plates, their mechanical Q is quite high, between 2,000 and 4,000, and they come fairly close to pure reactances. Consequently, the losses inside the filter, aside from the conversion loss at the terminations which was discussed before, are very small, and additional stainless steel sections cause no noticeable increase in the attenuation inside the pass band. Every additional section, however, causes sharper cutoff at the band limits. The curves of Fig. 3 show how frequency response varies with the number of sections.

For the six-piece filter shown in the pictures, the combined cross-section of both coupling wires is equal to about 1.5 percent of the cross-section of the stainless steel plates, measured in the direction of vibration. Because they are made of very similar materials, their impedance ratio is also about 1.5 to 100, leading to a theoretical bandwidth of 8.5 kc at 455-kc center frequency. Measured response of this filter is shown in Fig. 4. For purposes of comparison, the i-f response of a conventional receiver of good quality is plotted under the same zero line. It is interesting to note that the mechanical filter transmits the higher audio frequencies, up to about 4 kc, somewhat better than do conventional i-f transformers; but the adjacent carrier (10 kc away) is attenuated 1,000 times by the mechanical filter. The conventional filter needs 20-kc spacing to do the same.

By using coupling wires with other diameters, pass bands up to 14 kc and down to 4 kc have been obtained in experimental filters. For the wider bands, the low Q required in the nickel end plates becomes more difficult to realize.

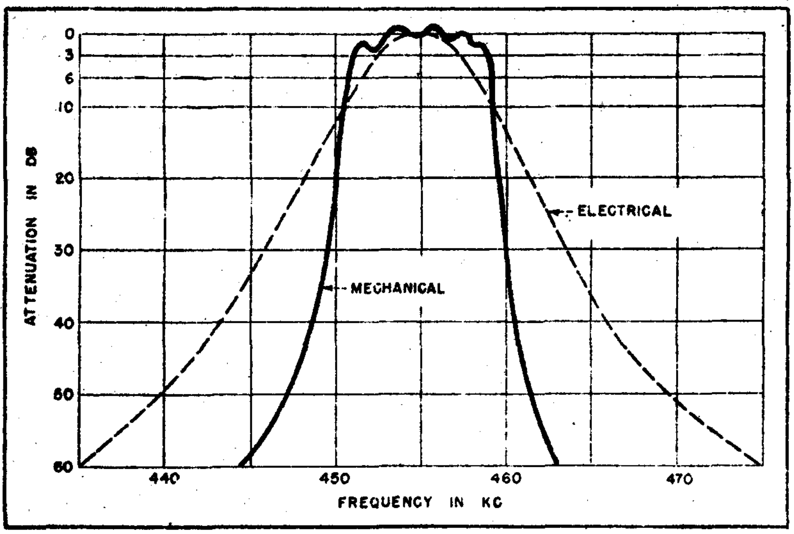


FIG. 4—Comparison of electrical and electromechanical filter bandpass characteristics

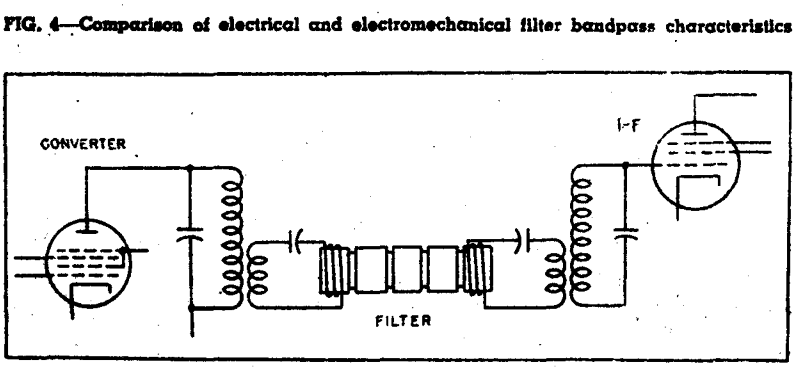


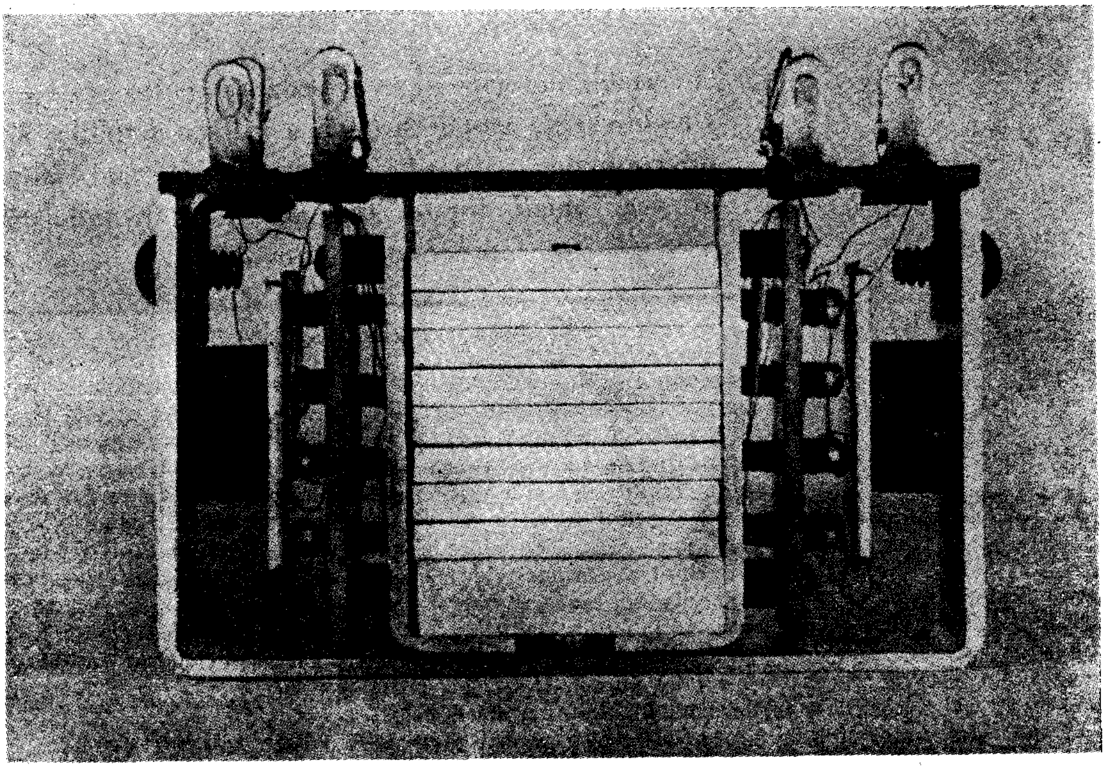
FIG. 5—Electromechanical filter is most effective if used between converter and first i-f amplifier

Use in Receivers

In a radio receiver, the best place for the electromechanical filter is right after the converter, as shown in Fig. 5. The coupling coils which surround the nickel end plates of the filter structure can most easily be wound for impedances of the order of 100 ohms; transformers are used to match this low impedance to the plate circuit of the converter and to the grid circuit of the following i-f tube.

The insertion loss of the filter in its present form is about 14 db. In designing a practical receiver, however, it has been found that some of this loss can be recovered. The matching transformers around the filter can be built with higher impedances than are normally used in i-f transformers, because the mechanical filter greatly relieves the stability requirements for the electrical circuits, permitting the use of a higher L/C ratio. Furthermore, the insertion loss in the filter reduces the overall i-f regeneration. It seems fair to say that, in a balanced i-f design, the net loss caused by introducing the filter in its present form is between 6 and 10 db, corresponding to a reduction in gain by a factor of two or three for a given tube combination.

Temperature variations affect the mechanical resonant frequency of the half-wave plates, causing the pass band as a whole to shift by a small amount. If the plates were made of plain steel, a temperature rise of 50 degrees F would shift the band by somewhat more than one kilocycle. Stainless steels are available which show much smaller frequency shift; plates are prefer-



In experimental receiver, four filters with different bandwidths are assembled in a single structure. Any filter can be selected by four-position switch (switching is simple at the 100-ohm impedance of the filter terminations). Merits of different bandwidths can thus be determined

ably made from such materials.

Receiver Performance

The performance of a broadcast receiver equipped with the six-piece filter described (two times down 4.5 kc off center, 1,000 times down 10 kc off center) is interesting in many respects. It was first suspected that such a set would be hard to tune, but tests with a number of lay listeners did not bear this out. Change in tone quality caused by incorrect tuning sets in at two clearly defined points much more abruptly than in conventional receivers; listeners seem to find it quite easy to tune between these two points.

With correct tuning, tone quality appears to be quite similar to that of conventional sets. One might expect to hear unfamiliar transients around 4,000 cps caused by the unusually sharp cutoff of the pass band, but nothing unusual could be detected. It appears that at 4,000 cps, where the sensitivity and discrimination of the human ear are not as good as in the medium range, an even greater rate of cutoff would be required to produce noticeable transients.

Adjacent-channel selectivity, of course, is the distinctive feature of a receiver using the electromechanical filter. Any desired channel can be tuned in even if there is a strong local signal on an adjacent channel. In Chicago, for instance, it is possible to tune in the New York transmitters WNBC, WOR, WJZ, and WCBS, although there are Chicago stations (three of 50,000 watts and one of 10,000 watts) separated only 10 kc from each of these four New York channels. It would take rather expensive electrical filters to equal this performance.

While economical adjacent-channel selectivity may be a highly desirable feature in broadcast receivers, especially for certain regions, it is of paramount importance for communication receivers. The new filter, together with its coils and magnets, weighs less than an ounce and takes less than one cubic inch of space. Its essential parts are stainless steel, easily manufactured by punching and spotwelding. There are no adjustments which could drift or vary; the frequency response is fixed.

Much further development remains to be done; improvements in the electromechanical conversion efficiency of the nickel end plates would be very useful; and careful study of alloys, dimensions and coupling coil design may well bring such improvements about. Economical production methods must be developed. The present structure seems simple enough, but it has not yet been manufactured in quantity.

It should not be forgotten that this structure represents only one among many possible forms. Other varieties, perhaps based on other modes of vibration, might be found which are simpler, and perhaps can be punched out in a single operation.