THERMAL STABILITY in

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A survey of the most prevalent causes for frequency drift in radio receivers by changes in operating conditions

● In many of the deliberations of the RTPB panels and in the conclusions reached, the matter of frequency stability was the deciding factor in the setting of limits. Methods for the elimination of drift in transmitters have been considered for many years, and little remains to be done in this matter, at least over the prevalent prewar frequency range, but drift in receivers is still a problem that will concern designers for some time.

In a transmitter one can take full advantage of crystal control, having only one, or at most only a few, frequencies to take care of, whereas in the usual receiver, a complete range of frequencies must be handled, making crystal control impractical. In addition, for economic reasons the cost of frequency stabilizing accessories must be kept to a much lower value than can be applied to transmitter design.

In a variable frequency tuning circuit the inductance and capacitance values are affected by temperature changes, humidity changes and by physical distortion of the elements. In precision work there are also a number of other vagaries introduced by the coupling between the variable capacitor shaft and the indicating mechanism.

When a tube is added to a tuned circuit and the other components necessary to make up an oscillator many other factors that affect frequency drift, are introduced. Capacitive changes in the tube due to temperature and to changes in operating voltages become important. The second order effect caused by the losses (which are usually neglected) causes quite important effects on frequency drift, since it is recalled that the true relation of frequency is:

$$f = \frac{\sqrt{L - CR_L^2}}{2\pi L\sqrt{C}}$$

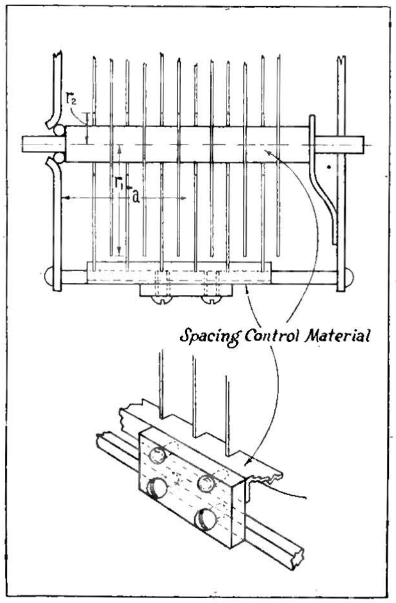
The effective resistance referred to here must include that added by losses in the tube and circuit and that introduced by the useful load. In a receiving set the operating frequency depends largely on the frequency delivered by the oscillator. On the other hand, the load on this oscillator is not large and is more or less constant over the tuning range, so that the effect of loading on drift is less important than in other oscillator applications.

A complete list of all things that affect frequency stability would run to dozens of items, and makes one wonder how any frequency could be continuously received at all. Nature has introduced some compensation, however, since many effects have opposing trends, and it is up to clever designers to help out, by taking advantage of every expedient that will make drift effects cancel. The purpose of this article is to call attention to a few ideas that prove effective.

In the first place, it is practically impossible to set up equations and to prescribe values that will match experimental evidence from actual circuits, because of variations found with production line tuning capacitor characteristics.

If it is difficult to make predictions, why bother at all? It happens that whenever the factors that cause the vagaries in tuning are discovered and improved, it is then possible to make useful studies regarding the more regular effects.

Fig. 1. Outline of typical tuning capacitor frame describing dimensional values referred to in text



Spacing effects

Fig. 1 shows the layout of an ordinary tuning capacitor. If the plates are all perfectly parallel and evenly spaced the capacitance is equal to

$$C = \frac{.353\,(r_1^2 - r_2^2)(N-1)}{S}$$

assuming (N) circular plates. This value of capacitance is the least that this particular unit will ever have, as any misadjustment of spacing (S) will always increase the capacitance over this theoretical minimum. Assume that the normal spacing is set by the designer at .032 in. and that one plate is misadjusted, so that while it is still parallel with others, the spacing is .028 in. on one side and .036 in. on the other. Instead of contributing a capacitance of $\left(\frac{K}{.032} + \frac{K}{.032}\right) = 62.5$ K as it should, it adds an amount $\left(\frac{K}{.028} + \frac{K}{.036}\right) = 63.6$ K, an increase of about 1.8 per cent. However, since this is only one plate out of say 15, the total increment would be only 0.251 per cent, assuming the rest of the plates were perfectly adjusted. This would produce a frequency change of about 1250 cycles per megacycle. As long as this variation remained fixed no harm would result, since a calibration error and not a drift error would be introduced.

Now in any capacitor the spacing depends on maintaining a fixed relationship in an axial direction between the shaft and the stator assembly. The position of the rotor depends on the distance along the shaft from the main bearing* to the center of capacitance, upon the repeatability of the bearing and upon any radial forces that may be applied to it by the driving or indicating mechanism. For a low

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* In a two-bearing capacitor, one bearing is floating to absorb expansion stresses. The opposite bearing here is termed the main bearing.

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coefficient of temperature any variation in these distances and effects must be counterbalanced by the movements of the stator caused by the same temperature change, affecting the expansion of the end plates, insulating plates and metal supports. These latter provide an entirely different physical set-up and the chances are likely that a different amount of movement results.

Many of the unaccountable drifts found in some of the tuning units used in home receivers are due to designs which do not take into account inevitable expansion effects. When two different materials are used in any construction, difference in expansion always results and strains and warpage are bound to occur. A good design will always provide a point where this stress is relieved by a compliance introduced at a proper point, without introducing large capacitance shifts. It is necessary to insure that no slippage occurs under rivet or screw heads caused by forces due to strains set up at extreme temperatures. This is especially important at points where insulating plates are clamped against metal faces, since the expansion of insulating materials is usually much higher than that of any metal.

Effects of spacing

For example, suppose by some strange circumstances a 15-plate capacitor with perfect spacing of .030 in. at 70 deg. F could be obtained. Due to difference in expansion between metals, insulating plates etc., it is assumed that the rotor shaft expands 46×10^{-6} in. per degree F more than the stator assembly. A 25 deg. rise and a distance of 2 in. between the fixed bearing and the point on the shaft at the center of capacitance would produce a total shift of 0.0023 in. This spacing change would cause a capacitance change of .59 per cent or a frequency shift of 3000 cycles per megacycle. This illustrates the extent of the compensation inherent in a multiplate tuning capacitor—a 7.5 per cent change in spacing causing only a .3 per cent change in frequency.

In order to bring this about it is necessary to take care that the effect is not nullified by inadvertent neglect of some other factor. Suppose the capacitor had only 14 plates (13 airgaps). Then the uninterleaved plate would cause a shift of

$$\frac{12 \times 0.59 + 1 \times 13}{13} = 1.5 \text{ per cent, or}$$

a shift 2½ times as great.

It was mentioned above that the frequency was always lowered by any shift in the spacing from that which would be found with perfect spacing. This rule is of general interest only since in practice perfect spacing is never found. Therefore, differences in expansion might just as well improve the spacing equality (increasing the frequency) as to offset it to a greater degree (lowering the frequency). This introduces one rule followed by many designers of precision equipment*—the most precise adjustment of variable capacitors can be obtained by setting the spacing to give minimum capacitance (the highest frequency in a measuring circuit). There is sort of a plateau in the capacitance vs. spacing curve that makes small relative movements ineffective (Fig. 3) and takes care of inevitable slight differences in manufacturing.

Fig. 2. Basic tuning circuit of an oscillator or amplifier. C represents the adjustable portion of circuit capacitance; the elements with triangle prefixes are increments (either positive or negative) produced by temperature, etc.

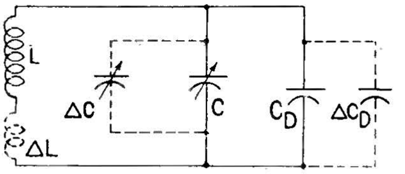


Fig. 3. Capacitance increment produced by an axial shift of rotor so that spacing differs from normal value .032 in.

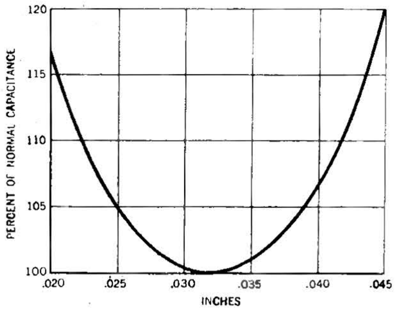
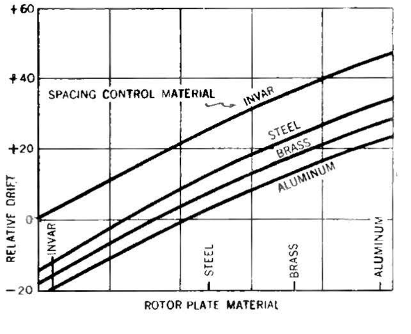


Fig. 4. Wide variety of temperature drift factors can be obtained by altering rotor plates and spacing control materials



In many circuits it is apparent that the designers take what they think will be the easy way out in obtaining a solution to the drift problem — specifying invar plates. This metal, with a low coefficient of linear expansion over a temperature range likely to be encountered in home receiver use, has many uses but is not a cure-all if used without careful consideration, and may even exaggerate the drift problem.

Plate expansion

Suppose we disregard the shaft expansion possibility mentioned above (which, in fact, is the most important effect in many designs) and assume that equal spacing on both sides of all plates is found at all temperatures. The capacitance is proportional to the area of the enmeshed portion of the plates. Area is proportional to the square of some dimension, and the incremental change in area due to expansion is also roughly proportional to the square of the dimensional change. The metal comb, or spacers, or other means of maintaining spacing is also affected by expansion which decreases the capacitance. Technically this is stating in words the idea behind the dimensional formula for capacitance which is considered to be proportional to the first power of a dimension, and is often expressed in "centimeters."

Thus if the same metal is used for plates and spacers the capacitance value changes in accordance with the first power of the expansion factor. If the spacing control material is selected to expand twice as fast as the metal in the plates a very low overall temperature coefficient of capacitance results.

With some experimentation it is possible to duplicate the results that would be obtained from an all-invar construction using this principle. It may be mentioned that the stator plates usually have a larger radius than the rotor plates so the edges of the latter are entirely contained in the space within the stator assembly. For this reason the material used in the stator plates has but little effect on the temperature coefficient, and one needs only study the rotor plate metal. It is thus seen that there are many ways of adding corrective

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*This principle has been followed by the Allen D. Cardwell Mfg. Corp. for many years.

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effects in the design of the oscillator tuning unit itself. These effects, moreover, follow different laws and can be made either positive or negative. No one set of rules can be set up as to a "best" method, as will be shown later. Here a tabulation of possibilities may be of interest.

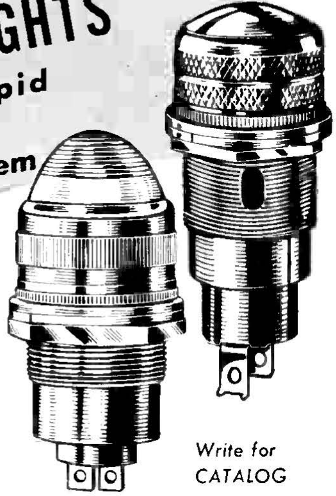
Assume four metals are available for the fabrication of the oscillator tuning unit, one of invar, one with a medium coefficient such as stainless steel, and a third and fourth with higher expansion such as brass and aluminum. Their respective coefficients vary roughly in the following order, 1:12:18:22. To show trends only (but not for design usage, since the absolute values depend on factors not considered) the curves in Fig. 4 give relative values of typical temperature coefficients with typical materials in construction. These curves hold only when the frame and shaft of a capacitor expand equally, keeping airgaps equalized. In the curves here, a positive coefficient indicates that the capacitance increases as temperature is raised. The units are arbitrary but are roughly parts per million per degree Cent.

Non-parallel plates

With some designs of capacitors used in receivers it is easier to equalize the spacing than it is to keep all plates parallel with each other and perpendicular to the axis of revolution. If the latter variation occurs, the temperature coefficient changes in a complex manner as the dial is turned, and there is no way of securing accurate compensation of drift variations, as there is when the condition of unequally spaced but parallel plates exist.

It is quite possible—and, in fact, this method has been used—to provide for compensation of temperature drift by a preliminary misadjustment of the spacing, so that expansion changes move the shaft so as either to improve the spacing or to make it "worse," as the complete circuit characteristics dictate. This is providing for operation at some selected point on the curve Fig. 3, getting either positive or negative compensation at will.

Circuit designers bent on getting lowest drift effects must analyze these tuning capacitor characteristics first and set up acceptance tests that will insure, first that all plates are sufficiently parallel and perpendicular to the axis of rotation. Next in importance, is that the spacing be equalized precisely, according to mechanical gaging tests, or better yet, so as to provide minimum capacitance at the maxi-



mum setting. Only then is it possible to analyze and compensate for other circuit variations brought about by temperature changes.

Fig. 4 shows a typical tuning combination found in receiver oscillator circuits. For first analysis it can be assumed that the loading and resistance factors can be neglected. The frequency at normal temperature is therefore proportional to

$$f_n = k\frac{1}{\sqrt{L(C+C_D)}}$$

At another temperature the frequency f_2 depends on

$$\frac{k}{\sqrt{(L+\Delta L)(C+\Delta C+C_D+\Delta C_D)}}$$

where the values of ΔL and ΔC_D are independent of the setting of the capacitor and may be either positive or negative. The value of ΔC might follow any kind of variation law with setting, however. It might be assumed that the plates are parallel and so ΔC is approximately linearly proportional to C. This is about the only rule that can be assumed with any degree of propriety.

It happens also that it is extremely difficult to measure experimentally the values of ΔC or even of ΔL. If the whole circuit is placed in a temperature oven or icebox, all circuit factors change according to the relation shown in the preceding equation. If only the coil or the capacitor are heated or cooled, it is difficult to ascribe values to the variations in the leads connecting that component to the rest of the circuit. Such leads have both inductance and capacitance effects sufficient to make the complete oscillator no longer representative of the oscillator under test.

It is possible, of course, to measure the total drift more accurately than it is possible to measure almost any other quantity, but it is only when it comes to placing the blame on the various components that difficulties arise. With careful analysis, however, and a few temperature runs, these answers can be arrived at.

One can run a test with the capacitor plates entirely unmeshed. Such a test shows up the combined drift due to ΔL and to ΔC_D since C (and therefore ΔC) is equal to zero. Then it is possible to add another fixed capacitance (one whose temperature coefficient is known) across the circuit, and make another temperature run. From these data (Δf vs. Δt) the relative importance of ΔL and ΔC_D can be determined, assuming, however, that the switching mechanism by which this extra capacitance is added or removed does not influence the results.

In almost any kind of a circuit an actual switch cannot be trusted in this regard. In some set-ups the auxiliary fixed capacitance can be jerked out of the circuit while in operation inside of a temperature chamber, by pulling a string or thread. Two runs, with and without the auxiliary capacitor, are thus possible from which the following relations hold. (Note, the tuning capacitor plates are still in an unmeshed position.)

$$\frac{f_1-\Delta f_1}{f_2-\Delta f_2} = \sqrt{1+\frac{C'_D+\Delta C'_D}{C_D+\Delta C_D}}$$

Here C'_D, $\Delta C'_D$ and C_D are known or measurable, and f_1 and Δf_1 are the frequency and the drift respectively over a temperature range t, with C'_D in place, and f_2 and Δf_2 the equivalent values without C'_D. The Δ values may turn out to be either positive or negative.

The value of ΔC_D computed from eq. (4) can be substituted in eq. (3) and then ΔL obtained. The value of C_D was defined as all the capacitance left in the circuit when the tuning unit plates were entirely unmeshed. This value and the value of ΔC_D will not change at other frequencies as the tuning unit is altered.

It is a debatable matter as to whether ΔL can be assumed to be independent of the value of C since the current distribution may change with frequency and the center of capacitance (and hence the physical length of the circuit) may shift, altering the inductance. Except at UHF, where the lumped inductance does not provide substantially all of the total inductance, the assumption is valid, however.

The value of ΔL can also be checked by providing a switching arrangement that will apply a few volts temporarily across the coil from a battery to heat up the coil, the rest of the components remaining cool. After noting the frequency drift as the temperature is reduced by cooling the whole oscillator, the coil is rapidly heated by this means to a high (but safe) temperature. The actual coil temperature can be determined by noting the resistance change in the battery heater circuit, provided the coil has enough resistance to overshadow the external circuit resistance.

It is one matter to determine the inductance shift with temperature, for a certain coil but a designer will have to go farther and determine coil design factors which will modify this coefficient in some prescribed manner, so that the overall circuit drift is at a minimum. These matters will be taken up in Part II in a succeeding issue.