Reactance Tubes in F-M Applications

The behavior of reactance tubes, particularly with reference to their use in frequency modulation circuits is treated. Emphasis is placed on the physical operation of such tube circuits

By AUGUST HUND

Reactance tube circuits have the property of injecting reactances into associated networks. If the associated network is the frequency determining branch of a tube oscillator whose frequency is not stabilized, then the injected reactance may be used to change the frequency of the generated oscillations. But if the frequency is stabilized (as in a piezoelectric oscillator or in a carrier frequency amplifier which causes no appreciable back actions on the master oscillator) the injected reactance will cause a phase shift of the generated oscillations. Therefore, when the injected reactance varies, frequency modulation will be produced in the former case and phase modulation in the latter case.

The case of FM is of importance since some commercial f-m transmitters are based on reactance tube modulators and considerable frequency deviations can be caused directly with reactance tubes. Such tubes then provide convenient means for translating modulating voltages into proportional frequency variations. Since such tubes can also be employed for injecting fixed reactances into associated networks they are also used in some f-m transmitters for the stabilization of the center frequency of the master oscillator, whose frequency is being modulated.

It is the purpose of this article to bring out basic principles of reactance tubes and their actions on associated networks, especially with regard to their application in modulated oscillators or amplifiers.

Reactance Conditions in Tube Oscillators

Any oscillator which generates sustained oscillations of stable ampli-

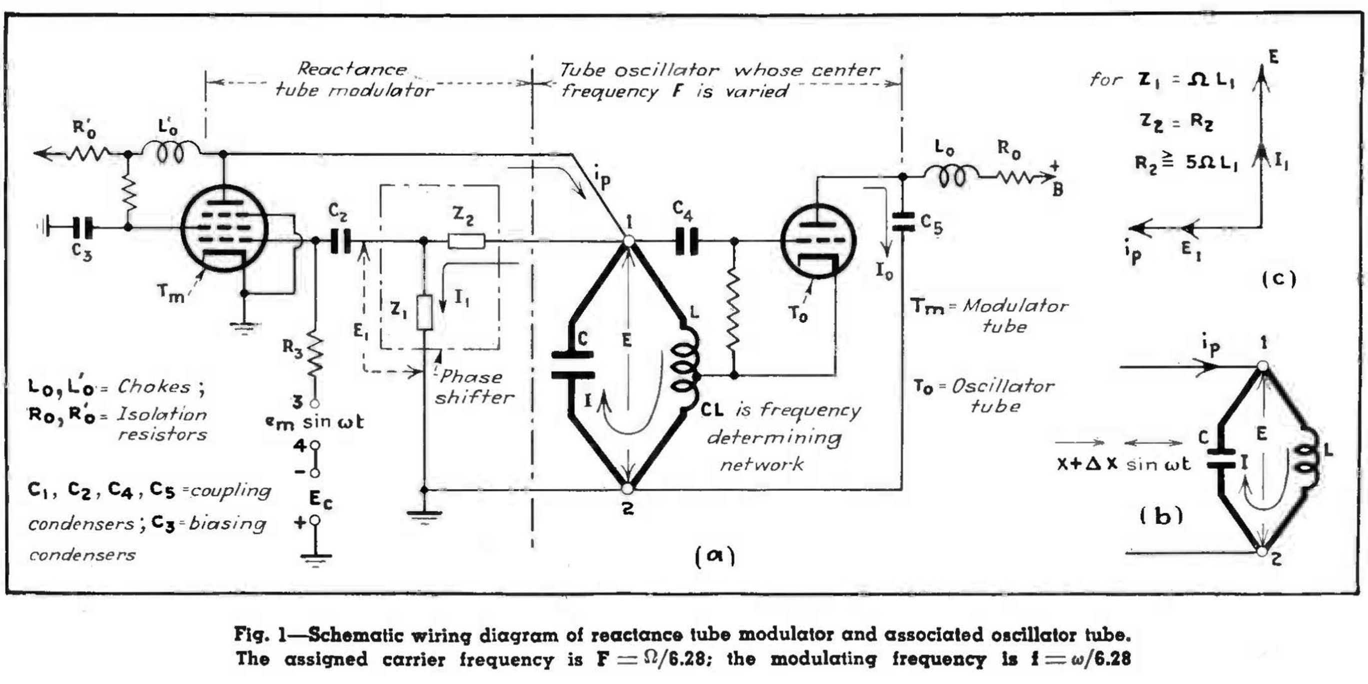

Fig. 1—Schematic wiring diagram of reactance tube modulator and associated oscillator tube. The assigned carrier frequency is $F = \Omega/6.28$; the modulating frequency is $f = \omega/6.28$

tude and fixed frequency, F, requires that the condition of energy balance as well as the condition of phase balance is satisfied. The former causes fixed amplitude of the generated oscillations, while the latter, which concerns us in this discussion, determines the frequency constancy. This can be readily understood from the actions taking place in customary tube oscillators, as is indicated in Fig. 1a for instance.

First let us examine the oscillator network to the right of terminals 1-2, where the tank circuit CL denotes the frequency determining branch associated with oscillator tube T_o. In case of sustained oscillations, both the driving dynamic voltage, E, and the circulating current, I, must have fixed amplitudes. Since the tank circuit CL also represents the plate load of the oscillator tube, oscillations remain sustained and of fixed amplitude only when the energy losses in this circuit are supplied through the coupling condenser C_5. The dynamic grid potential applied to the oscillator tube, T_o from the tank CL, over through the coupling condenser, C_4, must therefore trigger off such a dynamic plate supply current, I_o, that the amplitude of circulating current I remains sustained. This will satisfy the condition of energy balance.

Reactance Condition in Case of Current Resonance

Since the frequency of self oscillations, F, always assumes such a value that the total reactance around the 1-2-1 loop becomes zero, the value of F can remain fixed only when the original in-phase condition is preserved. This is readily understood from the following reasoning. Suppose the tank voltage E produces a grid potential such that the resulting dynamic plate current, I_o, leads the original dynamic supply current slightly. Then, each successive oscillation must also show a corresponding phase advance. The result is that the value of the oscillation frequency will be larger. In the same way when the I_o current lags the original dynamic supply current flowing through condenser C_5, each successive oscillation lags behind the preceding one slightly and the result is a lowering of the frequency F. Therefore, absolute frequency constancy requires that the grid voltage be 180 deg. out of phase with the dynamic plate voltage which causes the current I_o to flow since for such conditions the frequency F of the circulating current I is fixed.

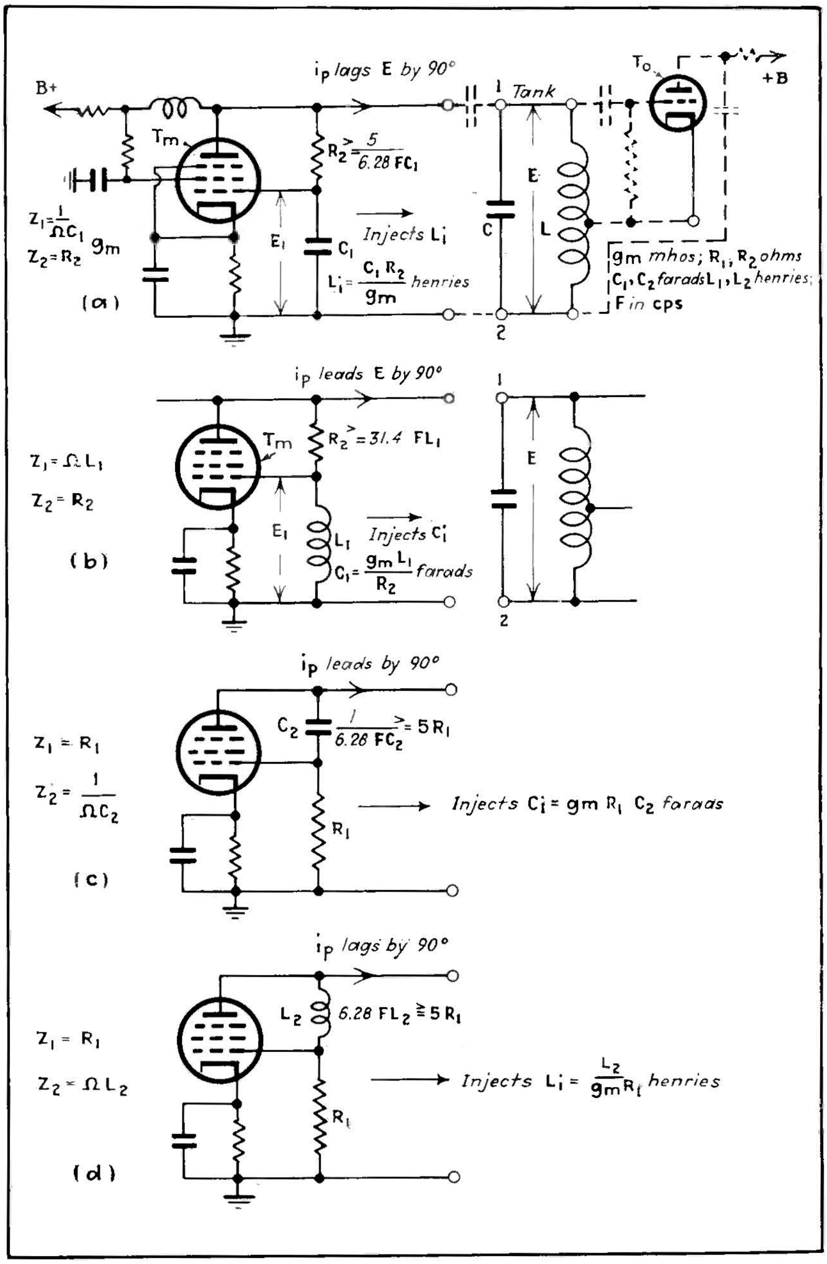

Fig. 2—Schematic wiring diagram of four types of reactance tube networks, with their design equations

Let us now consider the case indicated in Fig. 1b. The tank circuit CL is the same as in Fig. 1a except that the branch to the right of terminals 1-2 is of no concern in this discussion and, therefore, not shown. Looking into terminals 1-2 of Fig. 1b we have a network as in case of current resonance. For pure inductive and capacitive branches the total reactance across terminals 1-2 would be infinite in case of oscillations of natural frequency. Since any physical coil of effective inductance L_e has an effective resistance R_e, its impedance is of the form $Z = R_e + j\,\Omega\,L_e$ where $\Omega = 6.28F$. The reactance is proportional to the operating frequency F and L_e and may have a positive or a negative value depending on the magnitude of F. The resistive and reactive components of Z at any frequency are given by the expressions:

$$\left.\begin{aligned} R_e &= \frac{R}{[1-\Omega^2 CL]^2 + \Omega^2 C^2 R^2} = \frac{R}{m} \\ X_e &= \Omega L_e = \Omega\left[\frac{L\,(1-\Omega^2 C L) - C R^2}{m}\right] \\ &= \Omega\left[\frac{L - C\,(R^2 + \Omega^2 L^2)}{m}\right] = \Omega\, p/m \end{aligned}\right\} \quad (1)$$

The expression $Z = R_e + jX_e$ refers

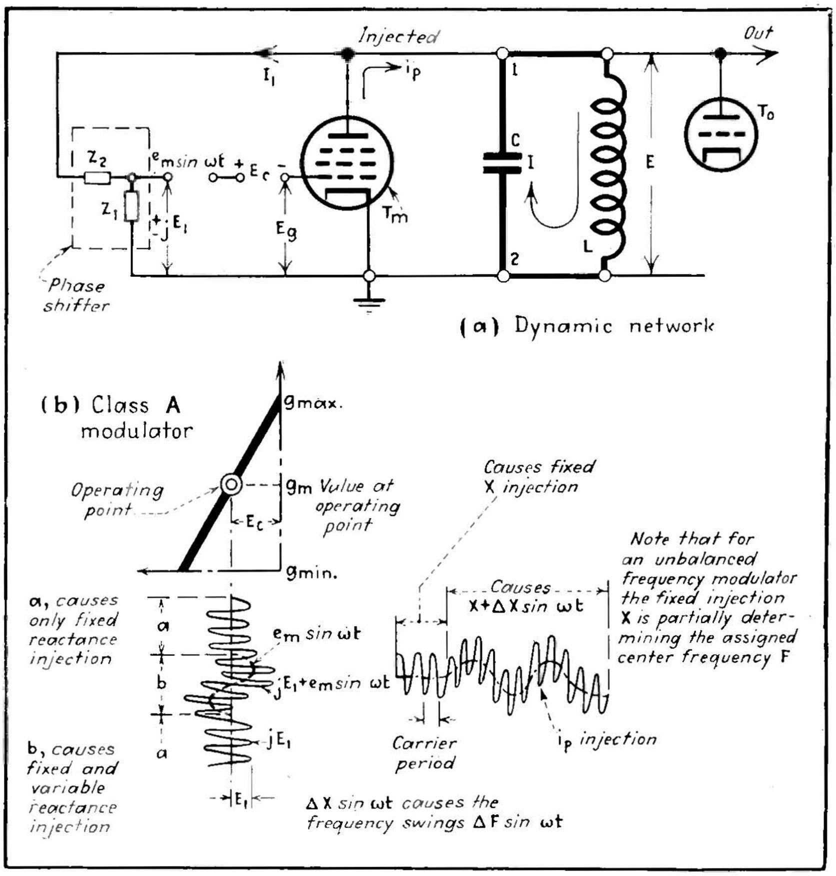

Fig. 3—Dynamic network of oscillator tube and reactance tube injector circuit (a), with wave forms of modulated and unmodulated signals illustrating variation of transconductance of modulator tube

to the equivalent resistance R_e and series reactance X_e when looking into the 1-2 terminals of the oscillator tank CL. We are only interested in the expression $X_e = p\Omega/m$ of Eq. (1) since for tube oscillations of natural frequency this reactance must vanish. This happens when p becomes zero, leading to

$$L = C\,(R^2 + \Omega^2 L^2) \qquad (2)$$

This is the exact expression required for tank resonance and shows that the impedance looking into terminals 1-2 of Fig. 1b is not infinite but has a finite value since

$$Z = \sqrt{\frac{R^2 + \Omega^2 L^2}{(\Omega\, RC)^2 + (\Omega^2\, CL - 1)^2}} \qquad (3)$$

is the expression for the absolute value of the effective impedance of the parallel branches across terminals 1-2 holding for any frequency F.

Reactance Modulation

Of engineering interest in this discussion is, how the frequency, F may be varied by means of a modulating current or its corresponding voltage. Eq. (2) which is the criterion for zero reactance, that is, the natural frequency of oscillations, shows that we have three means of accomplishing this. One is by a change or variation of the value of C, the second by a variation of L, and the third by a variation in R. From a practical point of view, the latter variation is not as easy to accomplish as that in which either capacitance or inductance variations (in synchronism with a modulating current) may be injected across the terminals 1-2 of Fig. 1b.

From the discussion given above we learned that a leading current fed back through condenser C_5, in order to sustain oscillations (Fig. 1a causes an increase of the oscillation frequency F while a lagging current causes a somewhat smaller oscillation frequency. We have in the arrangement of Fig. 1b a means for changing the natural period of the CL-tank if we can inject a suitable current i_p into the tank circuit CL. It is to be realized that the current i_p now comes from a separate source rather than from the plate circuit of the oscillator tube T_o. When the current i_p of Fig. 1b is of same frequency as the tank voltage E but leading E by 90 time deg., then this injected current may be assumed as flowing through the capacitive branch since the original circulating current I is likewise leading E by 90 deg. in this branch. This means that the condenser branch carries more current than the inductance branch of the tank. This has the same effect as though the capacitance C had been increased to a value $C + \Delta C$ causing an oscillation constant $(C + \Delta C)L$ instead of CL. The result is that the tank in the oscillator branch of Fig. 1a will produce a current of frequency of $F - \Delta F$ rather than of F, where ΔF is the corresponding decrease in frequency produced by the injected current. On the other hand it is also possible to imagine that the 90 deg. leading i_p current flows entirely in the L branch of Fig. 1b which means that it is in antiphase with the original I-current in the L branch and, therefore, causes a smaller current in this branch than in the condenser branch. This is equivalent to saying that the effective inductance of this branch must have increased to a value $L + \Delta L$ causing an oscillation constant $C(L + \Delta L)$ which must be identical with the value of $(C + \Delta C)L$ in order to account for the same frequency change ΔF as above. Inasmuch as the first way is the more direct, the circuit may be considered to be changed by an amount ΔC and we may assume that a capacitance reactance X_c is injected across the capacitive branch of the tank.

In exactly the same way it is evident when we inject a current i_p which lags the tank voltage E by 90 deg. the result is equivalent to an inductive reactance injected across the inductive branch. If ΔL denotes the corresponding inductance variation which acts in parallel with a constant inductance L, the resultant inductance is $L_e = L\Delta L/(L + \Delta L)$ and the oscillation constant CL_e indicates that the oscillation frequency is increased to some value $F+\Delta F$. Hence, injection of a positive inductance ΔL across the 1-2 terminals causes an increase of oscillation frequency while injection of a negative inductance—ΔL causes a decrease in F. Hence, if ΔL sin (6.28 ft) is injected by means of a corresponding i_p current we have to deal with a corresponding reactance injection ΔX sin ωt which modulates the oscillation frequency sinusoidally. In a similar way, if ΔC sin ωt is injected across the terminals 1-2 of Fig. 1b we have likewise a reactance modulation.

Hence, in either case, whether

sinusoidal capacitive or inductive injections occur, we obtain sinusoidal frequency variations. When both sinusoidal capacitive and sinusoidal inductive injections of same respective maximum amplitudes are impressed across the 1-2 terminals simultaneously, the respective frequency excursions from the center frequency will be twice as large as that for either one alone. We have then the case of push-pull reactance injections.

From this discussion we note that for sinusoidal currents i_p of carrier frequency F which lead or lag behind the tank voltage E, by 90 deg. we have fixed frequency shifts of $\pm \Delta F$, respectively, from the natural frequency, F, of the oscillator tank. Since the i_p current which is injected can have a phase difference other than $\pm$ 90 time degrees with respect to the tank voltage E, such currents will inject equivalent impedances across the terminals 1-2.

Reactance Tube Modulators

Since it is good engineering practice to inject the i_p variations by means of a separate tube, such as the modulator tube T_m of Fig. 1a, the circuit performance is explained for a network as used in practice. In Fig. 1a it will be noted that the frequency determining network is part of the oscillator. Across the terminals 1-2 is connected a network which takes a comparatively small current I_1 from the tank circuit. The purpose of this current is to build up a suitable voltage $E_1 = Z_1 I_1$ across the shunt element Z_1 of a phase shifter Z_1, Z_2. This voltage is essentially applied across the control grid and cathode of the modulator or reactance tube T_m. The dynamic plate current i_p of the reactance tube is then equal to $g_m E_1$ and in phase with E_1 if g_m is the grid to plate transconductance of the reactance tube.

Suppose we desire to inject a fixed capacitance C_i across the condenser C. For such a requirement terminals 3-4 are shorted and only the varying voltage E_1 acts in the grid circuit of tube T_m. Since for a C_i injection, i_p has to lead E by 90 deg. the series element Z_2 of the phase shifter is an ohmic resistance R_2 which is at least five times the value of the reactance ΩL_1 formed by an inductance L_1 for the shunt arm Z_1 of the phase shifter. The voltage E_1 across this inductance is then 90 times degrees ahead with respect to the tank voltage E since for such relative dimensions of R_1 and ΩL_1 the small phase shifter current I_1 is essentially in phase with the driving voltage E. Since $i_p = g_m E_1$, the injected current i_p leads E also by 90 deg.

It is an easy matter to derive the formula for computing the injected fixed capacitance C_i in terms of known factors. Since E is the driving voltage for any currents flowing in the capacitance branch it must be also the voltage which drives the current i_p through the injected capacitance C_i. Hence, $E/i_p = 1/(\Omega C_i)$ and

$$\frac{E}{i_p} = \frac{E}{g_m E_1} = \frac{E}{g_m \Omega L_1 I_1} = \frac{R_2}{g_m \Omega L_1} \qquad (9)$$

because E/I_1 is essentially equal to R_2 for $R_2 \geqq 5\Omega L_1$. We have then for the injected capacitance reactance

$$\frac{1}{\Omega C_i} = \frac{R_2}{g_m \Omega L_1}$$

and the design formula

$$C_i = \frac{g_m L_1}{R_2} \text{ farads} \qquad (4)$$

if the grid-plate transconductance g_m of the reactance tube is in mhos, R_2 in ohms and L_1 in henries. In a similar way the other formulas given in Fig. 2 in connection with the reactance modulators are derived.

Any other types of phase shifters can be used in order to inject out-of-phase currents into the frequency determining network. It is not necessary at all that an electrical connection exist between the tube oscillator and the reactance tube modulator since out-of-phase currents can just as well be injected through magnetic coupling. In each case it is essential that the amplitude of the injected current be fixed so that no additional amplitude modulation occurs also.*

Fixed reactance injections have many applications. They are employed, for instance, for the stabilization of the assigned frequency in

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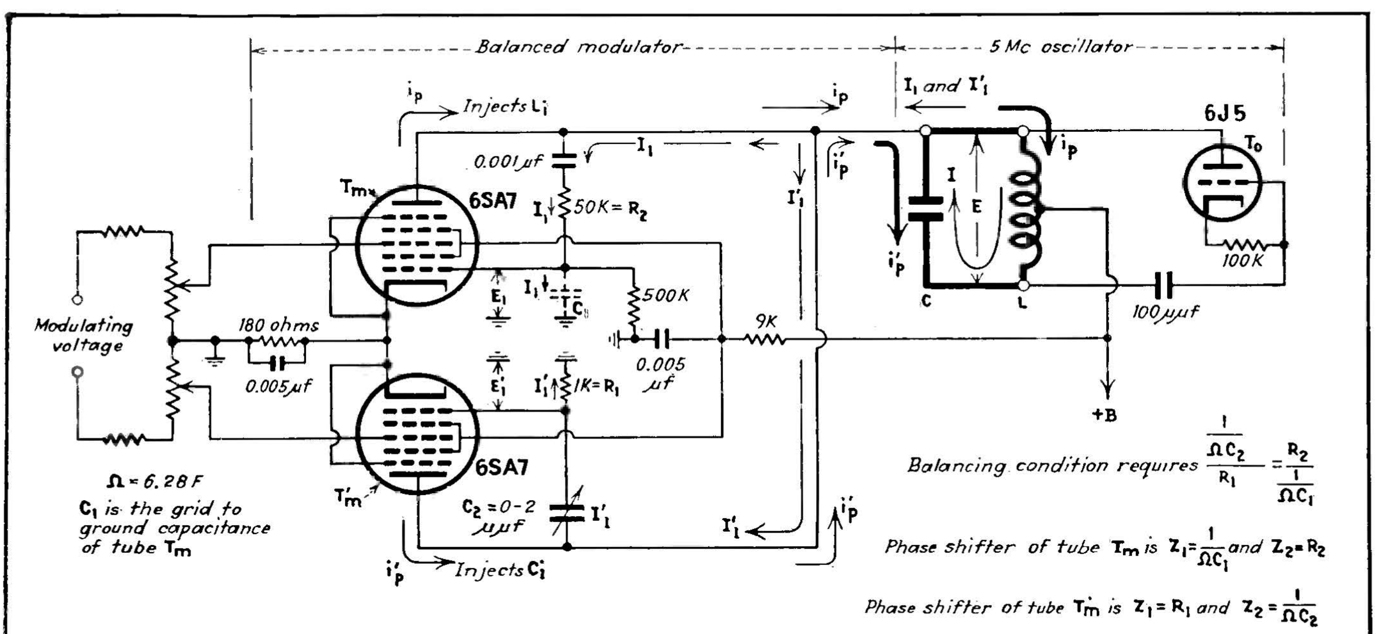

Fig. 4—Diagram of balanced modulator and oscillator tube to illustrate the current and voltage conditions which occur for a balanced modulator

time constant is not small enough the calibration will change for rapid impulses since C_1 will be only partially discharged between impulses. The time constant cannot be varied at will by changing R_1, because if values much lower than 200,000 ohms are used, the grid of T_1, may fail to regain control after an impulse.

Lower counting ratios may be obtained by decreasing the capacity of C_2, or by increasing the value of C_1. If C_2 or R_2 are varied, the time constant C_2R_2 should be kept small, because impulses received during the charging time of C_2 are not counted. However, the discharge must not be too fast, or the mechanical counter will not be able to register. It is also necessary not to use too low a value for R_2, or the safe plate current of T_2 will be exceeded. C_2 must be large enough so that at the slowest impulse rate which is to be registered, it will not lose too much charge through leakage. The leakage in the condenser itself is also a factor, so a well insulated condenser is needed, and electrolytic condensers would not be suitable.

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Errata

OUR ATTENTION has been called to certain errors which, unfortunately occurred in the article, "Amplitude, Frequency and Phase Modulation" by August Hund, in the September issue of *Electronics*.

Page 50. The term above the brackets in Eq. (4) should have read:

$$f \Delta \theta \cos 2 \pi ft.$$

Page 51. For conditions of PM and FM Eq. (7) should have read:

$$I_t = I_m \sin (\Omega t + \beta \sin \omega t)$$

Text immediately under Eq. (7) should read: "where $\beta = \Delta\theta$ for PM, $\beta = \Delta F/f$ for FM, and $K = i_m/I_m$ for AM".

Line 12, third column, should read: "much different for PM and FM as".

In Fig. 4, the term above the words "Modulating agency" should read $1/f$.

Page 54. Line 35, second column, B_1 should have read -0.3276.

In this issue Mr. Hund called our attention to certain changes in illustrations which were received too late to alter cuts. In the lower left-hand corner of Fig. 1, page 68, C_1 should be deleted. In Fig. 2(c), *gm* should, of course, be g_m.

Reactance Tubes in F-M

(Continued from page 71)

f-m transmitters. The center frequency stabilization is then based on the property that the transconductance of a reactance tube can be changed by varying the grid bias. Any slow drifts in the center frequency F can be made to cause direct voltages at the output of a frequency discriminator, whose polarity depends on the direction and whose magnitude depends on the magnitude of the drift. The output voltages vary the grid bias of the modulator tube and causes such reactance drifts as to bring the center frequency of the associated master oscillator to the assigned value.

With respect to variable reactance injections, reference is made to Fig. 3a showing the dynamic network of the tube oscillator which is being modulated by means of a reactance tube T_m. In Fig. 3b is shown the action for a class A modulator for which g_m varies linearly over the entire operating range. For balanced push-pull modulators the fixed injections cancel while the respective dynamic reactance injections are additive so that twice the frequency excursion is obtained. In Fig. 4 is shown a balanced reactance tube modulator with tubes and dimensions as often employed in practice. Tubes T_m and T'_m are like tubes and are excited by the tank voltage E causing the respective exciting currents I_1 and I'_1 which in turn cause the respective carrier frequency voltages E_1 and E'_1 on respective modulator tubes T_m and T'_m. These voltages cause the dynamic plate currents i_p and i'_p which are in phase with E_1 and E'_1, respectively. Hence, i_p lags E by 90 time degrees and causes, therefore, inductive reaction injections. The dynamic plate current i'_p leads the tank voltage E by 90 deg. and produces capacitive reactance injections. The combined effect is a push-pull reactance injection which for balance cancels the fixed injections and leaves only dynamic injections which cause twice the frequency swing.

SEE ALSO PAGE 142

* Many useful modulators with numerical values are described in a forthcoming publication on Frequency Modulation.