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FREQUENCY OF THE THREE-PHASE R-C COUPLED OSCILLATOR

PART I. Non-reactive anode load resistance.

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(*Received for publication, September* 14, 1955)

ABSTRACT. When the three stages of the conventional three-phase R–C oscillator are identical, the oscillations normally produced are of radio frequency $\omega=\sqrt{3}/RC$ where R and C are the tuning resistance and capacitance. This simple formula holds when the anode load resistance is non-reactive and the cathode impedance is zero. When these conditions are not satisfied the expression for frequency becomes much more complicated.

The case of finite cathode impedance of varied nature when anode load resistance is non-reactive is discussed in the present paper. Results of experimental observations are also given. It has been found that a capacitative cathode impedance causes an increase while an inductive cathode circuit causes a decrease in frequency over the $\sqrt{3}/RC$ value. A purely resistive cathode impedance does not affect the frequency in any way.

INTRODUCTION

It was shown in a previous communication (Rakshit and Bhattacharyya, 1946) that the conventional circuit of the three-phase R-C oscillator, with components selected for producing audio frequency oscillations, invariably generates radio frequencies by virtue of the stray and inter-electrode capacities. Such a three-phase oscillator can be made to generate audio frequency oscillations only with certain modifications introduced in the simple circuit. When the three stages are identical such as shown in figure 1, it has been shown that the oscillations produced are of radio frequency given approximately by

$$\omega=\sqrt{3}/RC \qquad \dots \quad (1)$$

where R is the effective anode load resistance taking the effect of grid leak of the next stage into account, and C is the sum of C_1 the external tuning condenser and C_s the total stray and interelectrode capacity across C_1. In practice, the three condensers C_1 of the three stages are replaced by a three-gang condenser between the common ground line and the three anodes.

In deriving equation (1) the anode load resistance R was assumed to be purely resistive and the a.c. impedance of the cathode-to-ground circuit was assumed to be negligibly small. The present paper gives an account of the influence of cathode impedance on the frequency of the generated oscillations. The assumption of non reactive load resistance is justified when it is of the carbon or metallised type. When small resistances are used for generating very high frequencies it has

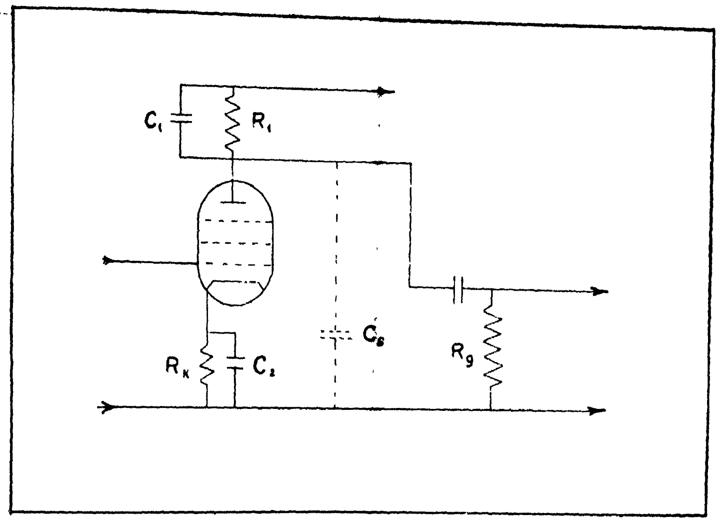
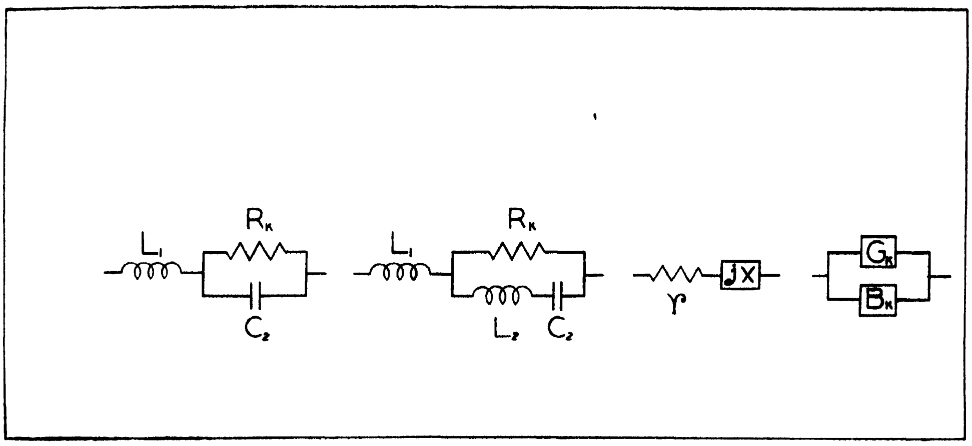


Fig. 1

been found (Rakshit and Mallik, 1953) that the inductances associated with the load resistances are responsible for increasing the effective load and gain and hence for maintaining the oscillation. In fact the highest frequencies have been obtained with small wire-wound resistances as load.

CATHODE IMPEDANCE AND ITS EFFECT

The impedance of the cathode circuit of an oscillator valve is composed of the cathode lead inductance L_1 in series with the parallel combination of cathode biasing resistance R_k and the by-pass condenser C'_2. For operation at sufficiently high frequencies, if a suitable mica condenser is used for by-pass, the cathode impedance may approximately be represented by figure 2(a). For operation at comparatively low frequencies when a paper condenser is used for by-pass the cathode impedance would be roughly as in figure 2(b), because a paper condenser is usually associated in series with its capacitance some inductance L_2 which may not be negligible. In general, therefore, the cathode circuit impedance may be represented by a very small resistance r in series with a reactance X, as shown in figure 2(c), or the parallel equivalent as in figure 2(d) where the admittance Y is the sum of conductance G_k and susceptance B_k. It may be noted in this connection that this impedance will have appreciable magnitude at frequencies well above or well below the self resonance frequency of the cathode circuit. Again, for the same working frequency the influence of the cathode impedance will increase with decrease of anode load resistance.



(a) (b) (c) (d)

Fig. 2

It can be shown (Sturley, 1949) that the effect of a cathode load Z_k between cathode and ground of a screen-grid or pentode amplifier is to cause a reduction in the effective anode load Z_{eff} in the form

$$Z_{eff} = \frac{Z_0}{1+g_m Z_k} \qquad \dots \quad (2)$$

where Z_0 is the actual anode load, Z_k is the cathode-ground impedance and g_m is the mutual conductance of the amplifier valve. This expression for Z_{eff} holds good when the screen is decoupled to cathode. When, however, the screen is decoupled to ground, a voltage is developed across Z_k due to variations in screen current and the effective anode load then becomes

$$Z_{eff} = \frac{Z_0}{1+g_k Z_k} \qquad \dots \quad (3)$$

where $g_k = g_m + g_s$, g_s being the screen current-grid voltage slope conductance. In the case of non-aligned-grid valves, g_k is approximately $1.25 g_m$. Since Z_{eff} is dependent upon Z_k it is obvious that the frequency of oscillations of the three-phase oscillator will also be affected by the presence of Z_k.

In addition, the presence of Z_k also affects the grid input admittance. It has been shown [Sturley, 1949] that whereas normally the grid input admittance is ωC_{gk}, the effect of Z_k is to introduce across the input a parallel combination of R_g and C_g given by

$$R_g = \frac{(G_k+g_k)^2+(B_{gk}+B_k)^2}{B_{gk}(G_kB_{gk}-g_kB_k)}$$

and

$$C_g = \frac{C_{gk}[G_k(G_k+g_k)+B_k(B_{gk}+B_k)]}{(G_k+g_k)^2+(B_{gk}+B_k)^2} \quad \ldots \quad (4)$$

where C_{gk} is grid-cathode capacitance
and $B_{gk} = \omega C_{gk}$.

It will be seen that the effect of Z_k on input resistance is appreciable only when the working frequency is high and the effect on input capacitance is appreciable when the tuning capacity is small. On the whole, the anode load resistances for which the results have been reported (Table IV) are such that the high frequencies are generated, and hence the effect of Z_k is appreciable, only when the tuning capacity is small.

The effect of cathode impedance on the frequency of oscillations, in so far as change of anode load is concerned, is discussed below for a few typical cases. The effect due to change in input impedance will be considered in connection with the results given in Table IV.

EFFECT OF CATHODE IMPEDANCE ON OSCILLATOR FREQUENCY

When the anode load resistance is non-reactive,

$$Z_0 = R/(1+jwCR)$$

and

$$Z_{eff} = \frac{R}{(1+j\omega CR)(1+g_kZ_k)} = \frac{R}{(1+j\omega CR)[1+g_k(r+jX)]} \quad \ldots \quad (5)$$

In any practical case, the resistive component (r) of the cathode impedance is negligibly small compared with the reactive component (X) except near series resonance frequency of the cathode load. In general, we may re-write expression (5) in the form

$$Z_{eff} = \frac{R}{(1+g_kr-\omega CRg_kX)+j[\omega CR(1+g_kr)+g_kX]} \quad \ldots \quad (6)$$

The phase angle (θ) of the load is obviously given by

$$\tan\theta = \frac{-[\omega CR(1+g_kr)+g_kX]}{1+g_kr-\omega CRg_kX} \quad \ldots \quad (7)$$

and the stage gain (A) by

$$A = \frac{g_mR}{[(1+g_kr-\omega CRg_kX)^2+\{\omega CR(1+g_kr)+g_kX\}^2]^{\frac{1}{2}}} \quad \ldots \quad (8)$$

Oscillations are maintained when $A > 1$ and the frequency of the oscillations is given by $\tan\theta = -\sqrt{3}$ [Rakshit and Bhattacharyya, 1946]. The frequency in the present case is thus given by

$$\frac{\omega CR(1+g_k r)+g_k X}{1+g_k r-\omega CRg_k X} = \sqrt{3} \quad \ldots \quad (9)$$

When the reactive component (X) of the cathode impedance is negligibly small, i.e. very near series resonance frequency of the cathode circuit, the frequency is given by

$\omega CR = \sqrt{3}$ or $\omega = \sqrt{3}/RC$, as in equation (1).

It will be noted in this connection that when the anode load resistance is non-reactive, the oscillation frequency is the same whether the cathode impedance is zero or is a pure resistance.

When the working frequency is higher than the resonance frequency of the cathode circuit, the cathode impedance is inductive and we may put $X = \omega L'$, L' being of course a function of the frequency . Equation (9) then becomes

$$\frac{\omega CR(1+g_k r)+g_k\omega L'}{1+g_k r-\omega^2 CRg_k L'} = \sqrt{3}$$

giving $$\omega = \frac{-[CR(1+g_k r)+g_k L']+[\{CR(1+g_k r)+g_k L'\}^2+12CRg_k L'(1+g_k r)]^{\frac{1}{2}}}{2\sqrt{3}RCg_k L'} \quad (10)$$

$$\approx \frac{-[CR(1+g_k r)+g_k L']+[CR(1+g_k r)+g_k L'][1+\frac{6CRg_k L'(1+g_k r)}{\{CR(1+g_k r)+g_k L'\}^2}]}{2\sqrt{3}RCg_k L'}$$

when $12CRg_k L'(1+g_k r) \ll \{CR(1+g_k r)+g_k L'\}^2$. Hence, as a first approximation,

$$\omega = \frac{\sqrt{3}}{RC+\frac{g_k L'}{1+g_k r}}$$

In the limit, if $g_k r \ll 1$, $\omega = \dfrac{\sqrt{3}}{RC+g_k L'}$ ... (11)

It will be noted from equation (11) that the presence of inductance L' in the cathode circuit causes a reduction in the oscillator frequency, the deviation from the $\sqrt{3}RC$ value being greater with increase in L', i.e. with increase in workingfre-quency above the cathode resonance frequency.

When the working frequency is less than the cathode resonance frequency, the cathode impedance becomes capacitative and we may put $X = -1/\omega C'$. Substituting this value of X in (9) , we get

$$\omega = \frac{\sqrt{3}[C'(1+g_k r)+g_k RC]+[3\{C'(1+g_k r)+g_k RC\}^2+4g_k RCC'(1+g_k r)]^{\frac{1}{2}}}{2CC'R(1+g_k r)} \quad \ldots \quad (12)$$

$$\approx \frac{\sqrt{3}[C'(1+g_k r)+g_k RC]}{CC'R(1+g_k r)}+\frac{g_k}{\sqrt{3}[C'(1+g_k r)+g_k RC]}$$

since in any practical case $g_k RC \ll C'$. As a first approximation therefore

$$\omega=\frac{\sqrt{3}}{RC}+\frac{\sqrt{3}g_k}{C'(1+g_k r)}+\frac{g_k}{\sqrt{3}[C'(1+g_k r)+g_k RC]}$$

In the limit, if $g_k r \ll 1$, we have

$$\omega=\frac{\sqrt{3}}{RC}+\frac{\sqrt{3}g_k}{C'}+\frac{g_k}{\sqrt{3}(C'+g_k RC)} \quad \ldots (13)$$

Equations (12) and (13) show that when the cathode circuit becomes capacitative, the oscillator frequency is higher than that given by the simple formula $\omega=\sqrt{3}/RC$ The deviation from the $\sqrt{3}/RC$ value increases with decrease in effective cathode circuit capacity C' i.e., with decrease in operating frequency below the cathode resonance frequency.

Condition for maintenance of oscillation: Equation (8) for A shows that for all practical purposes since the terms involving g_k are negligibly small compared with the other terms, the maintenance condition becomes approximately

$$A=\frac{g_m R}{[1+\omega^2 C^2 R^2]^{\frac{1}{2}}}> \quad \ldots (14)$$

When cathode impedance is zero, $\omega=\sqrt{3}/RC$ and the condition becomes

$$g_m R > 2 \quad \ldots (15)$$

When cathode impedance is inductive, $\omega<\sqrt{3}/RC$ according to equation (11). This shows that for a fixed anode load resistance, when the cathode circuit is inductive, oscillations can be maintained for a value of g_m less than that required when the cathode impedance is zero. In other words, since cathode circuit is inductive for higher operating frequencies obtained with smaller values of R, the inductive cathode enables oscillations to be maintained with values of R lower than that given by $g_m R=2$. For a given R, therefore, the lower the tuning capacity the higher is the generated frequency and hence higher is the gain, i.e., the lower the tuning capacity the greater is the amplitude of the oscillation maintained.

When, however, the cathode impedance is capacitative $\omega CR>\sqrt{3}$ according to equation (13) and hence a value of $g_m R$ greater than 2 is required for maintenance of oscillations.

EXPERIMENTAL OBSERVATIONS

Determination of stray capacity across the external tuning condenser.

The total tuning capacity consists of (i) the external tuning condenser and (ii) tqe stray including interelectrode capacity across it. This has been estimated by plotting $1/f$ against external tuning condenser as was done originally by Rakshit and Bhattacharyya (1946). For this the anode load resistances are to be such that the formula $\omega = \sqrt{3}/RC$ holds without any appreciable error. This corresponds to $CR \gg g_k L'$ in case of inductive cathode circuit and to $CR \ll C'/g_k$ in case of capacitative cathode circuit. From measured values of L' and C' as described below and with the usual values of tuning condensers it is found that the required conditions are satisfied when the anode load resistances are not less than about 1000 ohms or so.

A number of carbon type resistances with nominal value of 1000 ohms were therefore measured and three of equal magnitude were selected for use as anode load resistances in the oscillator. The oscillator valves were also selected by actual measurements with voltages same as those to be applied in the oscillator. The cathode by-pass condensers were also selected by measurements as described in section 2 below.

With valves and components thus selected, the generated frequencies for different values of the external tuning capacity were measured as given in Table I.

TABLE I

Load Resistance R_1 = 1,071 ohms; R_g = 33,000 ohms.

Dial reading of the variable capacitor	Capacity of each section of the three-gang condenser in $\mu\mu F$	Observed frequency in Mc/s.	$\frac{1}{f_{mc/s}}$
2465	494	0.520	1.923
2300	440	0.5728	1.746
2100	372	0.6605	1.514
1900	306	0.7742	1.292
1700	250	0.9206	1.086
1500	200	1.1063	0.9009
10	107	1.7688	0.567
800	80	2.199	0.455
500	45	3.028	0.329
200	18	4.529	0.221
000	9.5	5.500	0.182

The plot of $1/f$ against external tuning capacity is a straight line as shown in figure 3. The intercept on the negative side of the capacity axis gives the total stray and interelectrode capacity (C_s) which in this particular case is found to be 40 $\mu\mu f$.

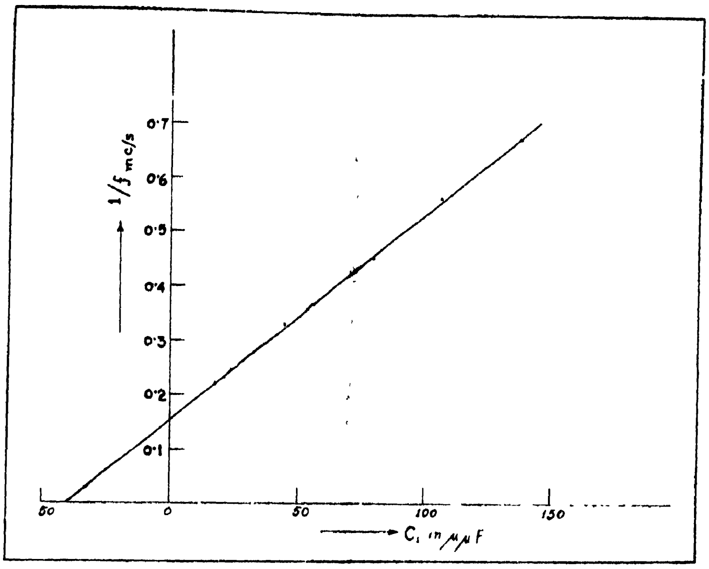


Fig. 3

2. *Measurements on the cathode circuit.*

In order to ascertain the validity of the working formula in any particular case it is necessary to estimate the constants C_2, L_2 and L_1 of the cathode circuit as given in figure 2(*b*).

The capacity C_2 of the cathode by-pass condenser was estimated from measurement with 1 kc/s bridge at which the self inductance L_2 would not produce any appreciable effect on the measured value of C_2.

The value of L_2 was determined by resonance method working at a frequency much higher than the self resonance frequency of the cathode by-pass condenser. The equivalent inductance of L_2 and C_2 in series at a frequency ω is obviously given by

$$L_{eq} = L_2 - \frac{1}{\omega^2 C_2} \quad .$$

When $L_2 \gg 1/\omega^2 C_2$, L_{eq} is approximately equal to L_2. From measurements of L_{eq} at 13, 20 and 23 Mc/s the average value of L_2 came out in a typical case to be approximately $0.1\mu H$. From such measurements on a number of by-pass condensers, three were selected having almost identical values of L_2 and C_2.

For measurement of L_1 the self resonant frequency of the cathode circuit was first estimated in the following way. As explained earlier, when the working frequency is higher than the cathode resonance frequency, the observed frequency should be less than the $\sqrt{3}/RC$ value as given in equation (10). On the other hand, when the working frequency is less than the cathode resonance frequency, the observed frequency would be higher than the $\sqrt{3}/RC$ value as given in equation (12).

If therefore the difference between the observed frequency and that calculated from the $\sqrt{3}/RC$ formula is plotted against observed frequency, we should get a curve crossing the observed frequency axis at a point which gives the self resonance frequency of the cathode circuit. To get the desired result it is obvious that the anode load resistance of the oscillator should be so chosen as to be able to generate frequencies both above and below the cathode resonance frequency.

In calculating the frequency from the $\sqrt{3}/RC$ formula, the value of R was naturally taken to be the parallel combination of actual anode load resistance and grid leak of the next stage. Furthermore, the working conditions were so adjusted, especially by controlling g_m with the cathode bias resistance that the grids of the oscillator valves were not driven positive.

The results for three different load resistances are given in Table II.

TABLE II

Actual Load Resistance in Ohms R_1	Effective Load Resistance in Ohms R	Tuning Capacitance including strays in $\mu\mu F$ C	Observed Frequency in Mc/s. f_o	Calculated Frequency given by $f_c = \frac{\sqrt{3}}{2\pi CR}$	$f_o - f_c$ in Kc/s.
606	595.07	534	0.900	0.8675	32.5
		480	0.993	0.965	28
		412	1.144	1.124	20
		346	1.353	1.338	15
		290	1.603	1.598	5
		240	1.924	1.930	− 7
		120	3.785	3.860	75
462	455.62	534	1.168	1.133	35
		480	1.284	1.260	24
		412	1.481	1.469	12
		346	1.752	1.748	− 4
		290	2.066	2.086	20
		240	2.482	2.521	39
393	388.37	534	1.364	1.329	35
		480	1.502	1.478	24
		412	1.729	1.723	6
		346	2.028	2.051	−23
		290	2.387	2.447	60
		240	2.863	2.957	94

The plots of the difference between the observed and calculated frequencies against the observed frequency for these three cases are given in figure 4. It will be noted that each of them cuts the observed frequency axis at approximately the same point. The self resonance frequency of the cathode circuit may therefore be taken as 1.75 Mc/s without appreciable error.

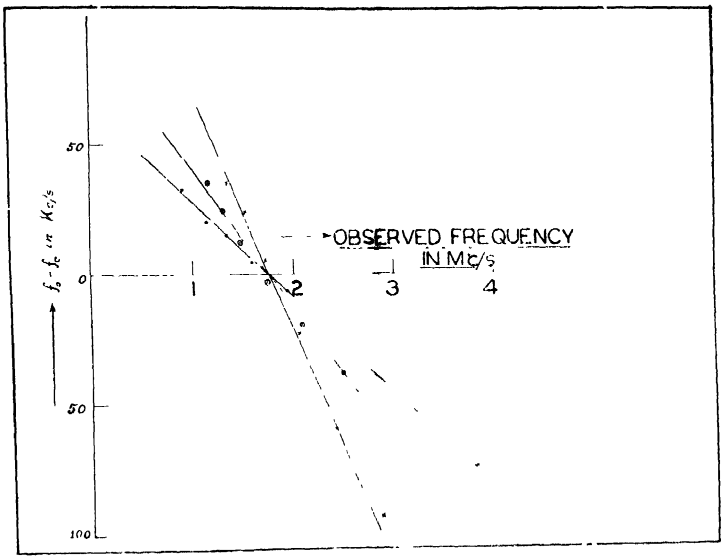


Fig. 4

In order to estimate L_1 it may be noted that the cathode circuit is approximately as depicted in figure 2(b), the cathode by-pass resistance R_k being above 200 ohms. From the reactance values of the series combination of L_2 and C_2 as given in Table III it will be obvious that within the frequency range 1-16Mc/s,

$$\omega L_2 - 1/\omega C_2 \leqslant 200.$$

TABLE III

Frequency in Mc/s.	$\omega L_2 - \frac{1}{\omega C_2}$
1	2.492
2	0.304
3	0.844
4	1.733
6	3.249
8	4.636
10	5 971
12	7.279
14	8.573
16	9.858

As a first approximation, therefore, we can neglect the effect of R_k in finding the reactance X of figure 2(c). The error involved in such approximation will comparatively be large in the case of the lowest and the highest frequencies. The following data will give an idea of the error in any particular case. At $\omega = 2\pi \times 10^6$, the series equivalent of L_2 and C_2 is a capacity of reactance 2.49 ohms, while the reactance of the exact equivalent is 2.49 ohms—this corresponds to anode load resistance 606 ohms with R_k increased to 1000 ohms to avoid positive grid drive. Again, at the higher frequency limit of $\omega = 2\pi \times 16 \times 10^6$, the series equivalent is an inductance of reactance 9.85 ohms, while the reactance of the exact equivalent is 9.82 ohms—this corresponds to anode load resistance 276 ohms with $R_k = 210$ ohms. On an average, therefore, the error in neglecting the shunting effect of R_k is extremely small. Hence for all practical purposes the cathode circuit may be taken as composed of L_1, L_2 and C_2 all in series. From the value of C_2 and the cathode resonance frequency of 1.75 Mc/s, $L_1 + L_2$ comes out to be $0.162\mu H$, giving the value of L_1 to be $0.062\ \mu H$. This agrees closely with the value of L_1 as calculated from the dimensions of the cathode lead of a broken valve of the same type and make as the oscillator valves.

3. COMPARISON OF OBSERVED AND CALCULATED FREQUENCIES

The observed frequencies under different operating conditions, the calculated frequencies and the various factors involved in the calculation are given in Table IV. It will be noted that in order to ensure proper working conditions the cathode bias had to be comparatively larger for higher load resistances and accordingly g_k also changed. Furthermore, for the same load resistance, the cathode bias had to be slightly increased for the lowest tuning capacities since the gain and hence amplitude of oscillations tend to increase with decrease in tuning capacity.

As pointed out earlier, the effect on frequency due to Z_k causing change in input impedance is expected to be appreciable only when the tuning capacity is small. For each load resistance the frequencies for tuning capacities 49.5 and $120\mu\mu f$ have therefore been calculated by taking this effect into account. The change of input capacity due to Z_k is maximum when load resistance and tuning capacity are both small. The reduction in input capacity when the load resistance is 273.48 ohms, and tuning capacity $49.5\mu\mu f$ is only $0.2\mu\mu f$. The change in C'_g for all other cases is therefore negligible and hence the change in input conductance alone has been taken into account.

It will be seen from Table IV that the calculated frequencies are almost equal to the observed values. In all the cases $g_k r$ has been found to be $\leqslant 1$ and hence when the cathode circuit is capacitative the frequency has been calculated from equation (13). For the inductive cathode, equation (11) has been used whenever $(CR + g_k L')^2 \gg 12CRg_k L'$, otherwise equation (10) has been used. In some cases the values according to both the equations have been shown to give an idea of the error in using the simple formula (11). The frequencies obtained from equation (11) are greater than those from the complete formula (10) which

TABLE IV

C_s=Stray and interelectrode capacitances = $40\mu\mu F$: R_g = 33,000 ohms: $L_2 = 0.1\mu h.$: $C_2 = 0.051\mu F.$: cathode resonant frequency = 1.75Mc/s.

Load resistance, taking effect of R_g in Ohms	Total tuning Capacitance including stray in $\mu\mu F$	Observed Frequency $w/2\pi$ in Mc/s	Nature of Z_L	C' in $\mu\mu F$ or L' in μh	Cathode bias in Volts	$g_k \cdot 10^3$ $(=1.25g_m)$	$CRg_k \cdot 10^6$	$(CR - g_kL')^2 \cdot 10^{18}$	$12CRg_kL' \cdot 10^{18}$	Calculated Frequency in Mc/s.	Equation No. used for calculation	Calculated Frequency $F = \frac{\sqrt{3}}{2\pi CR}$ in Mc/s.
595.07	534	0.900	Capacitative	0.06935	-3	4.5	0.00143			0.8917	13	0.8675
										0.8912	12	
	480	0.993	..	0.07525	..	..	0.00128			0.9869	13	0.965
	412	1.144	..	0.0890	..	..	0.00110			1.1425	13	1.124
	346	1.353	..	0.1268	..	..	0.00092			1.3509	13	1.338
	290	1.603	..	0.3169	..	..	0.00077			1.6032	13	1.598
	240	1.924	Inductive	0.0281	..	..		20432.4	216.79	1.9285	11	1.930
										1.9226	10	
	120	3.785	..	0.1275	..	..		55150.5	490.16	3.8411	11	3.860
										3.7530	10	
	49.5	8.892	..	0.156	-3.15	4.1		879.5	222.99	8.7730	10	9.356
455.62	534	1.168	Capacitative	0.0920	-2.7	5.63	0.00136			1.1550	13	1.133
	480	1.284	..	0.1165	..	..	0.00123			1.2790	13	1.260
	412	1.481	..	0.1798	..	..	0.00105			1.4799	13	1.469
	346	1.744	Inductive	0.00036	..	..		24852.2	3.87	1.7486	11	1.7486
	290	2.066	..	0.04577	..	..		17518.3	408.46	2.0827	11	2.086
										2.0705	10	
	240	2.482	..	0.08151	..	..		12057.5	602.15	2.5105	11	2.521
										2.4800	10	
	120	4.816	..	0.1408	..	..		3056.9	518.40	4.9858	11	5.042
										4.7908	10	
	49.5	11.104	..	0.1582	-2.8	5.1		530.4	215.17	10.9530	10	12.223

TABLE IV (*contd.*)

Load resistance, taking effect of R_g in Ohms	Total tuning Capacitance including stray in $\mu\mu F$	Observed Frequency $w/2\pi$ in Mc/s.	Nature of Z_k	C' in $\mu\mu F$ or L' in μh	Cathode bias in Volts	$g_k \times 10^3$ $(=1.25 g_m)$	$CRg_k \times 10^6$	$(CR - g_kL')^2 \times 10^{18}$	$12CRg_kL' \times 10^{18}$	Calculated Frequency in Mc/s.	Equation No. used for calculation	Calculated Frequency $F=\frac{\sqrt{3}}{2\pi CR}$ in Mc/s.
388.37	534	1.364	Capacitative	0.1299	−2.5	6.6	0.00136			1.3470	13	1.329
	480	1.502	..	0.1896	..	..	0.00123			1.4910	13	1.478
	412	1.729	..	2.093	..	..	0.00105			1.7408	13	1.723
	346	2.028	Inductive	0.0414	.	..		18130.3	440.60	2.0473	11	2.651
										2.0345	10	
	290	2.387	..	0.0750	..	..		12796.5	669.09	2.4368	11	2.447
										2.4058	10	
	240	2.863	..	0.1033	..	..		8815.4	762.57	2.9360	11	2.957
										2.8760	10	
	120	5.540	..	0.1491	..	..		2259.9	548.63	5.8103	11	5.915
										5.4940	10	
	49.5	12.428	..	0.1589	−2.65	5.9		396.1	213.34	12.3660	10	14.339
273.48	534	1.874	Inductive	0.0207	−2.2	9.35		21384.3	339.54	1.8850	11	1.887
										1.8768	10	
	480	2.059	..	0.0449	..	..		17343.0	662.60	2.0932	11	2.099
										2.0736	10	
	412	2.366	..	0.0734	..	.		12850.9	928.65	2.4260	11	2.446
										2.3890	10	
	246	2.754	..	0.0967	..	..		9125.8	1026.48	2.8857	11	2.913
										2.8088	10	
	290	3.248	..	0.1150	..	..		6461.9	1023.87	3.4290	11	3.476
										3.3030	10	
	240	3.872	..	0.1290	..	..		4467.9	950.22	3.9254	10	4.199
	120	7.280	..	0.1528	..	..		1165.1	560.69	7.2855	10	8.399
	49.5	15.948	..	0.1602	−2.3	8.25		210.1	214.63	15.8090	10	20.362

are nearer to the observed frequencies. In general, the difference between the values from (10) and (11) increases with increasing frequency and hence for the high frequencies it is essential to use the complete formula.

CONCLUSION

The effect of cathode impedance on the frequency of the three-phase *R-C* oscillator when the anode load resistances are purely resistive has been discussed in the present paper. From a comparison of the observed frequencies and the values given by the simple equation $\omega = \sqrt{3}/RC$ (Table IV) it will be noticed that the cathode impedance considerably influences the frequency of the generated oscillations when the working frequency is high. The question of reactive anode load resistances will form the subject matter of a subsequent communication.

ACKNOWLEDGMENT

The authors are thankful to the Council of Scientific & Industrial Research for a grant to carry out the investigations and for permission to publish the results.

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