Integrated Circuits and Applications
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Oscillators and Waveform Generators
Lecture - 23
Wien Bridge, Colpitt's and Hartley Oscillators

So, in the last lecture I have discussed about the RC phase shift oscillator and we have derived the expression for the frequency of oscillations and the condition for the gain to sustain the oscillations. So, today we will discuss another audio frequency oscillator called as a Wein Bridge oscillator. This is also another type of RC oscillator where the feedback circuit consists of R and C elements. So, the circuit diagram of this Wein Bridge oscillator is. So, this is basically a inverting amplifier unlike the RC phase shift oscillator where the amplifier is non-inverting amplifier. So, this is non-inverting amplifier unlike the RC phase shift oscillator where the amplifier is inverting amplifier.

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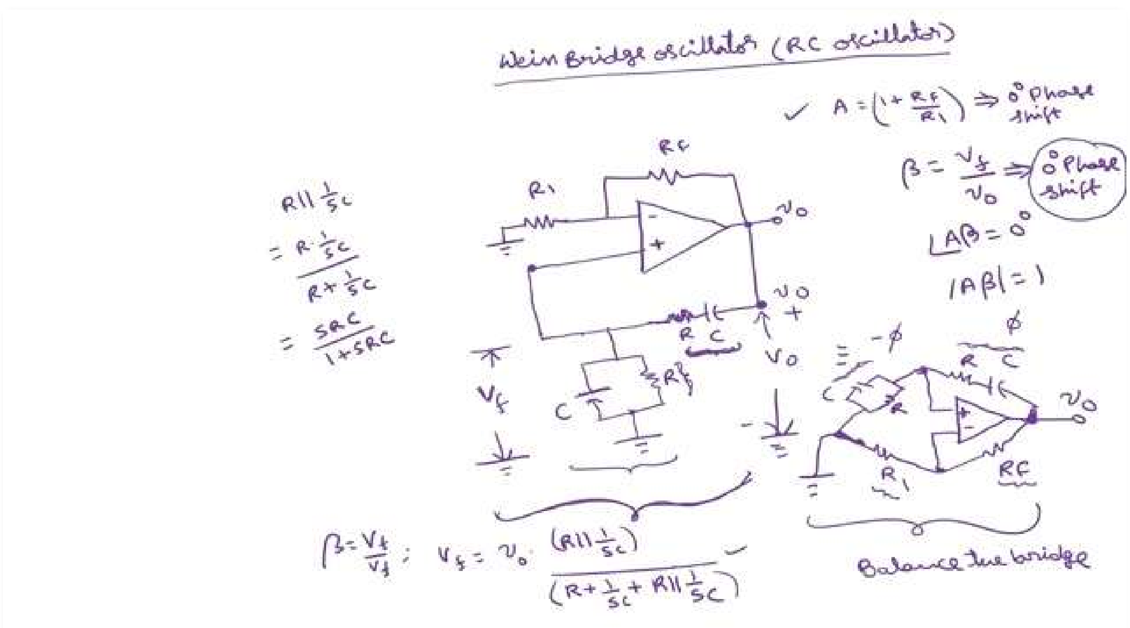

This is output, this is R_F, this is R_1. Basically, the signal here will be amplified with the gain of $1+\frac{R_F}{R_1}$. The gain A will be $1+\frac{R_F}{R_1}$. So, this will provide 0 degree phase shift because there is no minus sign.

So, the feedback network if I assume that this output voltage here is v_f. So, this feedback factor \beta is given by the input here is v_o with respect to ground, β is $\frac{v_f}{v_o}$. So, I am going to derive the expression for this one. So, this also should provide 0 degrees phase shift. So, that overall phase angle will be 0 degrees and magnitude you have to make as unity. This is the condition for the sustained oscillations. Now, here there is one RC section in series, another RC section in parallel here. So, we have to nullify the phase angle provided by this RC section by this parallel RC section so that the overall resultant phase angle will be 0. So, why the name Wein Bridge? So, if you want to write the equivalent circuit of this, this is equivalent to a bridge type of circuit. Here the output is taken, here we will take four arms of the bridge, this is R_1, this is R_F, this is series RC circuit, this is parallel RC circuit and this point will be grounded. Here the output v_o is taken. So, these two circuits are same this and this. We can see that at the positive terminal. So, one edge will goes to series RC, another edge will goes to parallel RC, this is parallel RC and from this output of the op-amp we will take the output v_o and the other end of this output will goes to R_F, this is R_F whereas the negative terminal will goes to R_1. So, these two are same.

So, in order to get 0 phase shift in the feedback path, you have to balance the bridge. In the sense this R_1 will provide 0 phase shift, R_F also provide 0 phase shift. If this provides phase shift of 5, then this parallel RC section has to provide the phase shift of minus 5 so that these two will be get cancelled, then the bridge is said to be balanced that is why the name Wein Bridge Oscillator. So, you can take either of the circuit to derive the expression for the frequency of oscillations. So, what is the gain of this amplifier A is equal to $1 + \frac{R_F}{R_1}$ and what is β? $\frac{v_f}{v_o}$. So, from this circuitry what is v_f in terms of v_o? v_f is equal to v_o into R in parallel with $\frac{1}{sC}$ is this impedance divided by. So, this impedance will be total impedance, this will be $R + \frac{1}{sC} + R || \frac{1}{sC}$. This is series combination, this is parallel combination. We are taking the output voltage across the parallel combination so that vo into parallel combination impedance divided by the total impedance, series combination impedance plus parallel combination impedance. So, what is R in parallel with $\frac{1}{sC}$ is equal to $\frac{R\frac{1}{sC}}{R+\frac{1}{sC}}$. So, this is equal to sC, sC will get cancelled and then sRC in the numerator $1 + sRC$.

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$$v_f = v_o \cdot \frac{\left(\frac{sRC}{1+sRC}\right)}{\frac{(1+sCR)}{sC} + \frac{sRC}{1+sRC}} = v_o \cdot \left(\frac{sRC}{\cancel{1+sRC}}\right) \frac{sC(\cancel{1+sRC})}{(1+sRC)^2 + s^2RC^2}$$

$$s^2 = -\omega^2$$

$$\Rightarrow v_f = v_o \cdot \frac{s^2RC^2}{s^2R^2C^2 + 2sRC + 1 + s^2RC^2}$$

$$\therefore \beta = \frac{v_f}{v_o} = \frac{s^2RC^2}{s^2R^2C^2 + 2sRC + 1 + s^2RC^2}$$

$$s = j\omega$$

$$\beta = \frac{-\omega^2RC^2}{-\omega^2R^2C^2 + 2j\omega RC + 1 - \omega^2RC^2}$$

So, if I substitute this here what will be v_f? v_f is equal to v_o into the parallel combination of R with $\frac{1}{sC}$ is $\frac{sRC}{1+sRC}$. This is $\frac{sRC}{1+sRC}$ divided by $R+\frac{1}{sC}$ series combination plus parallel combination is $\frac{sRC}{1+sRC}$. Again, here this will becomes sRC whole divided by sC, this can be simplified as $\frac{1+s}{sC}$. Now, again here the LCM is $sC(1+sRC)$.

So, this will be equal to $v_o(\frac{sRC}{1+sRC})$ is the numerator, the numerator will be. So, this will be reverse s, $sC(1+sRC)$ will be in the numerator, denominator will be $(1+sRC)^2+s^2RC^2$. So, if you further simplify. So, this $(1+sRC)$, $(1+sRC)$ will get cancelled and the numerator will be v_f is equal to $v_o s^2RC^2$ divided by $s^2R^2C^2+2sRC+1$ which is $(sRC+1)^2+s^2RC^2$, okay is it correct. So, $v_o(\frac{sRC}{1+sRC})$ is the numerator, denominator will be $\frac{sC(1+sRC)}{(1+sRC)^2+s^2RC^2}$.

So, therefore, $\beta=\frac{v_f}{v_o}$, this is equal to $\frac{s^2RC^2}{s^2RC^2+2sRC+1+s^2RC^2}$. So, in order to find out the frequency of oscillations s should be $j\omega$. So, if I substitute $s=j\omega$ here, β becomes s^2 becomes $(j\omega)^2$ which is equal to $-\omega^2$, $\frac{-\omega^2RC^2}{-\omega^2RC^2+2j\omega RC+1-\omega^2RC^2}$. Now, this R parallel with $\frac{1}{sC}$ will be R in parallel with $\frac{1}{sC}$ will be $\frac{R\frac{1}{sC}}{R+\frac{1}{sC}}$. So, which is equal to sC will get cancel. So, we will get $\frac{R}{1+sCR}$. So, if I substitute this value here and here and if you simplify this expression for v_f.

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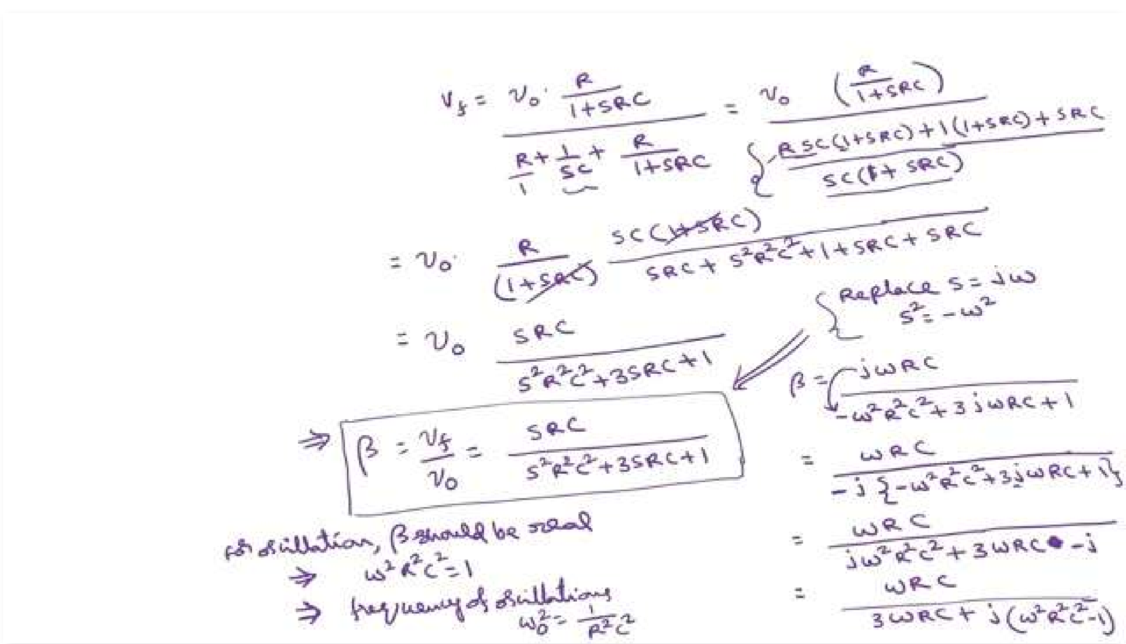

So, what will be this v_f now? v_f is equal to $\frac{R}{1+sRC}$, $\frac{\frac{R}{1+sRC}}{R+\frac{1}{sC}+\frac{R}{1+sRC}}$. So, if I take again LCM as $(1+sRC)sC$ what will be this? This is equal to $v_o(\frac{R}{1+sRC})$ divided by here the denominator is $sC(1+sRC)$ is LCM. So, this will be R into R by 1.

So, we will get both the terms $sC(1+sRC)$ plus 1 here sC is there. So, it will get $1+sRC$ $1(1+sRC)$ plus R, $(1+sRC)$ is there. So, we will get sC. So, this will be $v_o(\frac{R}{1+sRC})$ and if we take this into numerator this will goes to numerator this will become the denominator. So, $sC(1+sRC)$ divided by.

So, what is the denominator? this is sRC into 1 is sRC plus sRC into sRC is $s^2R^2C^2+1+sRC+sRC$.So, this $(1+sRC)$ $(1+sRC)$ will get cancelled this is equal to v_o sRC divided by total $3sRC$ $s^2R^2C^2+3sRC+1$. So, implies what is β? $\frac{v_f}{v_o}$ this is equal to $\frac{sRC}{s^2R^2C^2+3sRC}$. This is expression for the β. Now, in order to derive the expression for the frequency of oscillations. So, we have to make the imaginary part of β equal to 0 similar to the analysis that we have done in RC phase shift oscillator.

So, in order to obtain this real and imaginary part we will replace s with $j\omega$. So, what happens to s^2? $j^2\omega^2$ which is just simply $-\omega^2$. So, if I substitute this here. So, what will be β? $\frac{j\omega RC}{-\omega^2R^2C^2+3j\omega RC+1}$. So, this j if I take to the denominator becomes $-j$.

So, this is equal to ωRC divided by $-j\{-\omega^2R^2C^2+3j\omega RC+1\}$. Or this is equal to ωRC divided by this $-j$ into minus becomes $+j$ $j\omega^2R^2C^2$ and this $-j$ into $+j$ becomes $-j^2$ which is equal to $+1$ $+3\omega RC$ plus this becomes $-j$. So, what is the imaginary part? and what is the real part? ωRC divided by real part is $3\omega RC$ plus imaginary part is j if I take as common $(\omega^2R^2C^2-1)$. For sustained oscillations what is the condition? A is real. So, β also should be real implies imaginary part is 0 means $\omega^2R^2C^2=1$ implies what is the frequency of oscillations? $\omega_o^2=\frac{1}{R^2C^2}$.

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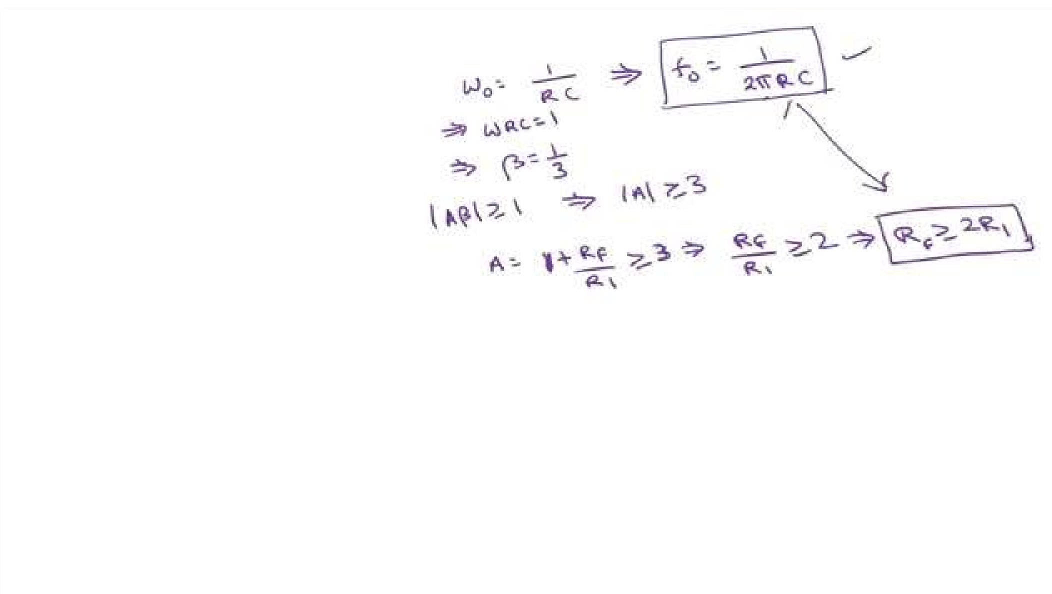

Or $\omega_o=\frac{1}{RC}$ or $f_o=\frac{1}{2\pi RC}$. This is the expression for the frequency of oscillations of Wein Bridge oscillator. So, at this frequency of oscillations what will be the value of β? β is this. So, this becomes 0 and this ωRC becomes 1 from this ωRC is 1. So, if I substitute that so, this ωRC is 1. So, what happens to β this is 1 this is 1 and this is 0.

So, $\frac{1}{3}\times 1$ is $\frac{1}{3}$. So, implies $\beta = \frac{1}{3}$, but we know that for sustained oscillation $|A\beta| \geq 1$ implies $|A|$ should be ≥ 3. So, what is A? is equal to $1 + \frac{R_F}{R_1}$ should be ≥ 3 implies $\frac{R_F}{R_1}$ should be ≥ 2 $3 - 1$ is 3 minus this 1 implies $R_F \geq 2R_1$. So, these are the two design expressions to design the Wein Bridge oscillator. This is second type of RC oscillator. So, these RC oscillators are suitable for audio frequency applications. So, for radio frequency applications we have to go for the LC oscillators.

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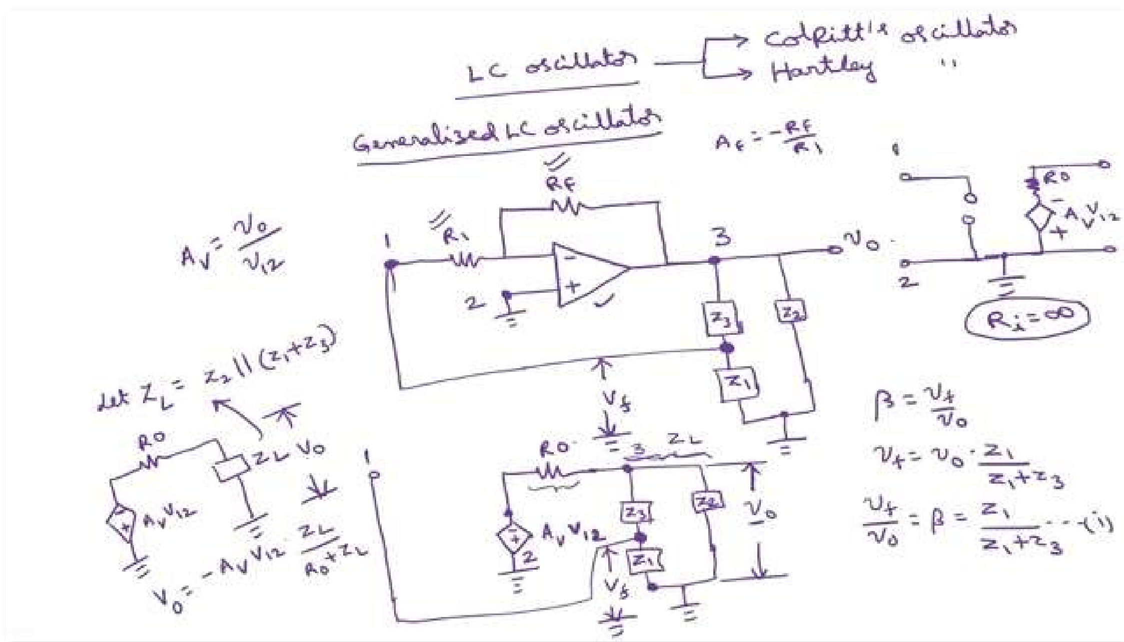

There are two types of LC oscillators similar to the RC oscillator one is called Colpitts oscillator and the second one is called Hartley oscillator. So, before going for this Colpitts and Hartley oscillator first I will derive the expression for the generalized LC oscillator. Then I will substitute the values of this impedances in case of a Colpitts oscillator in case of Hartley oscillator okay. First, I will take the generalized LC oscillator. So, the circuit diagram of a generalized LC oscillator is this is also type of inverting amplifier. So, the feedback path here will be consisting of three impedances. Later I will replace these impedances with L and C elements so that we can derive the Colpitts oscillator. So, here the output vo is taken and this is v_f a part of this output will be fed back to the input and this we will call as Z_1, Z_2, Z_3 this is R_1, R_F.

So, the gain of this amplifier is R_F is equal to $-\frac{R_F}{R_1}$ into of course, this voltage okay. This is nothing, but v_f. So, in order to derive the expression for the frequency of oscillations first I will draw the equivalent circuit. So, in the earlier lectures we have discussed the internal circuitry of the operational amplifier okay. So, that is nothing, but here we will be having input resistance, then there will be a output resistance, there will be a voltage source this will be grounded which is minus plus.

If I call this as terminal 1, terminal 2 this is R_i, this is R_o, A_v is the say voltage gain into v_{12} this is the output voltage. Now, here if I assume that the operational amplifier is ideal R_i will be infinite. And in the equivalent circuit for the sake of simplicity I will just not show this R_1 and R_F. So, what will be the equivalent circuit of this operational amplifier we are going to replace with this equivalent circuit with R_i is equal to infinite means this will acts as a open circuit this will acts as a open circuit here. So, the equivalent circuit will be now if I call this as a terminal 1 and this as terminal 2, this as terminal 3.

So, terminal 1 this is connected to the ground, this is connected to this point, then there will be no connection between this terminal 1 and this point except for that here this ground. So, there will be a voltage source with ground, this will be your terminal 2, this terminal 2, this is minus plus, this is A_v times v_{12} and this is output resistance, this output resistance R_o and this will be connected to this point, this is terminal point 3. So, where this is connected to Z_3, Z_1 and then Z_2. So, this overall this one will be grounded and here of course, we will take the output.

This is Z_2, Z_1, Z_3 this is R_o, this is terminal 1 and this point will be connected to here, see here this one will be connected to here, so a central point between Z_1 and Z_3. So, this is the equivalent circuit okay. Now, this will be your v_f with respect to the ground, this will be v_o. So, β is nothing but $\frac{v_f}{v_o}$. So, what is v_f in terms of v_o? v_o into this is v_o between this point and this point, there is a voltage divider.

So, we are taking v_f across Z_1. So, $\frac{Z_1}{\mathrm{Z_1+Z_3}}$ implies $\frac{v_f}{v_o}$ is equal to β, this is equal to $\frac{Z_1}{\mathrm{Z_1+Z_3}}$, this is one expression. Then what about this output voltage v_o? So, the overall gain will be here, this is v_o and this is v_{12}. So, overall gain A_v is given by $\frac{v_o}{v_{12}}$. So, in terms of v_{12} what is v_o first of all? So, this v_o in terms of this v_{12}. So, you can see that this voltage Av into v_{12} is the total voltage between this point to ground, this ground also of course.

And there is a resistance here and there will be parallel combination of this and we are taking this output across this parallel combination. So, let this parallel combination as Z_L, Z_L is equal to $Z_2 \mid\mid (Z_1 + Z_3)$, this entire circuitry this you are calling as Z_L. Then what will be equivalent circuit?

So, here this is voltage source minus plus this is grounded, this is A_v into v_{12}, A_v into v_{12} and this is R_o. Now, this will be total Z_L, this is also grounded, this Z_L is this, this is R_o and here we are taking output v_o. So, what is v_o is equal to this is minus sign because plus is grounded. So, this is of opposite polarity minus A_v into v_{12} and we are taking the output across Z_L means $\frac{Z_L}{\mathrm{R_o+Z_L}}$.

So, this is if I substitute this Z_L also here, A becomes this A if I call this overall gain as A, this is v_o is the output voltage v_{12} is the input voltage. So, $\frac{v_o}{v_{12}}$ from here $\frac{v_o}{v_{12}}$ will be your A that is equal to $-A_v$ times this $\frac{v_o}{v_{12}}$ is equal to $-A_v \frac{Z_L}{\mathrm{R_o+Z_L}}$. Here Z_L is $Z_2 \mid\mid (Z_1 + Z_3)$, this is equal to $\frac{Z_2(Z_1+Z_3)}{Z_1+Z_2+Z_3}$. If I substitute this here implies what is A? $-A_v$ times this is Z_2, Z_L is $Z_2, Z_2(Z_1 + Z_3)$

divided by $Z_1 + Z_2 + Z_3$ is the numerator is Z_L whole divided by R_o plus again Z_L is same thing $Z_2(Z_1 + Z_3)$ divided by $Z_1 + Z_2 + Z_3$.

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$$A = \frac{v_o}{v_{12}} = \frac{-A_v Z_L}{R_o + Z_L}; \quad \text{here } Z_L = Z_2 \parallel (Z_1 + Z_3) = \frac{Z_2(Z_1+Z_3)}{Z_1+Z_2+Z_3}$$

$$\Rightarrow A = \frac{-A_v \left[\frac{Z_2(Z_1+Z_3)}{(Z_1+Z_2+Z_3)}\right]}{R_o + \left[\frac{Z_2(Z_1+Z_3)}{Z_1+Z_2+Z_3}\right]} = \frac{-A_v Z_2(Z_1+Z_3)}{R_o(Z_1+Z_2+Z_3)+Z_2(Z_1+Z_3)}$$

$$\beta = \frac{Z_1}{Z_1+Z_3}$$

$$\text{For oscillations, } A\beta = 1 \Rightarrow \frac{-A_v Z_2 \cancel{(Z_1+Z_3)}}{R_o(Z_1+Z_2+Z_3)+Z_2(Z_1+Z_3)} \cdot \frac{Z_1}{\cancel{(Z_1+Z_3)}} = 1$$

$$\therefore A\beta = \frac{-A_v Z_1 Z_2}{R_o(Z_1+Z_2+Z_3)+Z_2(Z_1+Z_3)}$$

$$Z = j\omega L \text{ (or)} \quad Z = \frac{1}{j\omega C} = -\frac{j}{\omega C}$$

$$\left\{\begin{array}{l} Z_1 = jX_1 \\ Z_2 = jX_2 \\ Z_3 = jX_3 \end{array}\right\} \text{ where } \boxed{X = \omega L \text{ (or) } -\frac{1}{\omega C}}$$

So, if I take $Z_1 + Z_2 + Z_3$ as LCM in the denominator, so that will cancel with this one. So, you will get this as $\frac{-A_v Z_2(Z_1+Z_3)}{R_o(Z_1+Z_2+Z_3)+Z_2(Z_1+Z_3)}$. This is your A expression and β we have derived as $\frac{Z_1}{Z_1+Z_3}$. So, $A\beta$ is equal to 1 for oscillation the condition is. So, implies A is $\frac{-A_v Z_2(Z_1+Z_3)}{R_o(Z_1+Z_2+Z_3)+Z_2(Z_1+Z_3)}$ into β is $\frac{Z_1}{Z_1+Z_3}$ this should be equal to 1.

So, this get cancelled. So, you will get $A\beta$ is equal to now $\frac{-A_v Z_1 Z_2}{R_o(Z_1+Z_2+Z_3)+Z_2(Z_1+Z_3)}$. Here Z_1, Z_2, Z_3 are the impedances okay. So, this is of the form of $Z = j\omega_L$ or $\frac{1}{j\omega C}$. So, what I will do is I will call this Z_1 as jX_1, Z_2 as jX_2, Z_3 as jX_3 where X can be ωL or $\frac{-1}{\omega C}$ because j we have taken the numerator this will equal $\frac{-j}{\omega C}$. So, j if I take as common it will be 1 by -1 by ωC. So, the X we are going to substitute later either ωL or $\frac{-1}{\omega C}$ depends upon the type of impedance that we are going to obtain.

Now, by substituting these values here what is $A\beta$? Therefore, $A\beta$ is equal to $-A_v$ times $Z_1 Z_2$ means (jX_1) (jX_2) divided by R_o into $X_1 + X_2 + X_3$ means j if I take as common and this will be $X_1 + X_2 + X_3$ plus we have $Z_2(Z_1 + Z_3)$. Z_2 is jX_2, $(Z_1 + Z_3)$ is j also common here. So, this becomes j^2 $X_1 + X_3$. So, this j^2 is -1 and this j into j is also -1.

So, this minus minus becomes plus. So, this will be now $A_v X_1 X_2$ divided by what is the real part and what is imaginary part $-X_2(X_1 + X_3)$ is real part $+jR_o(X_1 + X_2 + X_3)$ is imaginary part. But for the oscillations $A\beta$ should be real implies imaginary part is 0. This is 0 means $(X_1 + X_2 + X_3) = 0$. This is the condition for the oscillations.

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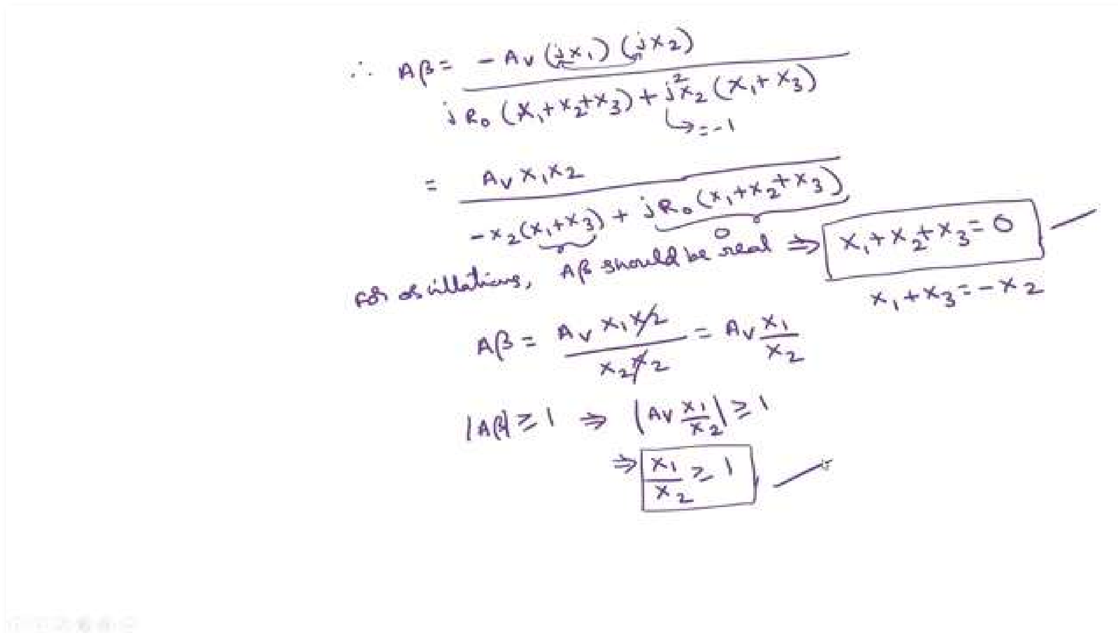

If $X_1 + X_2 + X_3$ is 0 what happens to $A\beta$? This term becomes 0 and what is $X_1 + X_3$ from this $X_1 + X_3$ will be $-X_2$.

So, if I substitute this $-X_2$ minus minus becomes plus. So, $A\beta$ is equal to $A_v X_1 X_2$ divided by X_2, $-X_2$ into $-X_2$ becomes $+X_2$. This X_2 X_2 will get cancelled will get this is equal to $A_v \frac{X_1}{X_2}$. Then $|A\beta| \geq 1$ implies A_v into $|A_v \frac{X_1}{X_2}|$ should be greater than or equal to 1 implies $\frac{X_1}{X_2}$ should be greater than or equal to 1.

These are the conditions for the oscillations. Now, we will substitute here this Z_1, Z_2, Z_3 with either impedances or capacitances. Thereby, we will get this Colpitts and Hartley oscillator okay.

So, Colpitts oscillator first. Colpitts oscillator can be obtained by a replacing X_1, X_2 with capacitor and X_3 is inductor. So, the corresponding circuitry will be this. Here the output is taken, this is grounded. Here in the feedback path, you have two capacitances and this point is grounded and there will be a inductance. This is the feedback network $L\ C\ C\ R_1, R_F$. So, X_1 will be $\frac{-1}{\omega C}$. If I call this as C_1 and C_2 for example, this X_1 is $\frac{-1}{\omega C_1}$, X_2 is $\frac{-1}{\omega C_2}$ and X_3 is ωL.

If I substitute this, what is the condition for the oscillations? $X_1 + X_2 + X_3$ should be 0 implies $\frac{-1}{\omega C_1} + \frac{-1}{\omega C_2} + \omega L = 0$. So, what is ωL? $\frac{1}{\omega C_1} + \frac{1}{\omega C_2}$. This ω you can take as common if you take to the other side implies $\omega^2 L = \frac{1}{C_1} + \frac{1}{C_2}$.

This is equal to $\frac{C_1+C_2}{C_1C_2}$ or ω^2 is equal to $\frac{1}{L}$ times $\frac{C_1+C_2}{LC_1C_2}$ or what is ω? $\sqrt{\frac{C_1+C_2}{LC_1C_2}}$. This we call as frequency of oscillations implies f_o is equal to $\frac{1}{2\pi}$ square root of $\frac{1}{2\pi}\sqrt{\frac{C_1+C_2}{LC_1C_2}}$.

If I define the equivalent capacitance as let C_T total capacitance is $\frac{C_1C_2}{C_1+C_2}$. So, then this f_o becomes $\frac{1}{2\pi\sqrt{LC_T}}$. So, this becomes this becomes $\frac{1}{C_T}$. So, here C_T is this.

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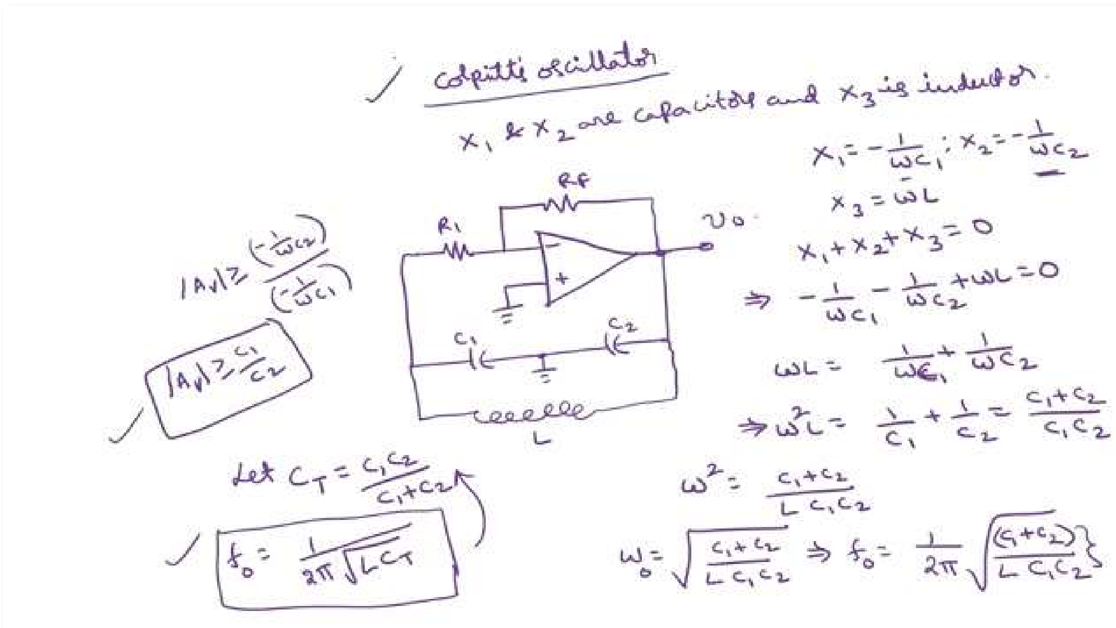

This is the expression for the frequency of oscillations. Now, what will be the condition on the gain? So, here $|A_v|$ should be greater than or equal to $\frac{X_2}{X_1}$. So, here this expression should be $|A_v|$ should be greater than or equal to $\frac{X_2}{X_1}$. What is X_2? What is X_1? X_2 is this X_1 is this. So, should be greater than or equal to $\frac{(\frac{-1}{\omega C_2})}{(\frac{-1}{\omega C_1})}$.

So, minus minus get cancelled omega get cancelled. So, $|A_v|$ should be greater than or equal to $\frac{C_1}{C_2}$ this is another condition. So, subjected to this condition the frequency of oscillations is $\frac{1}{2\pi\sqrt{LC_T}}$. So, this is the frequency of oscillations of Colpitts oscillator.

And the other type of LC oscillator is called Hartley oscillator. Here this is reverse X_1, X_2 is inductors and X_3 is capacitance. This is the circuit diagram of Hartley oscillator. This we call as L_1, L_2, C. So, what is X_1 is ωL_1, X_2 is ωL_2, X_3 is $\frac{-1}{\omega C}$. And the condition for the oscillations which we have derived is $X_1 + X_2 + X_3$ should be 0 implies $\omega L_1 + \omega L_2 - \frac{1}{\omega C}$ should be 0 or $\omega(L_1 + L_2) = \frac{1}{\omega C}$ or $\omega^2 = \frac{1}{C(L_1+L_2)}$.

So, therefore, frequency of oscillations ω_o is given by $\sqrt{\frac{1}{C(L_1+L_2)}}$ or $f_o = \frac{1}{2\pi\sqrt{(L_1+L_2)C}}$.

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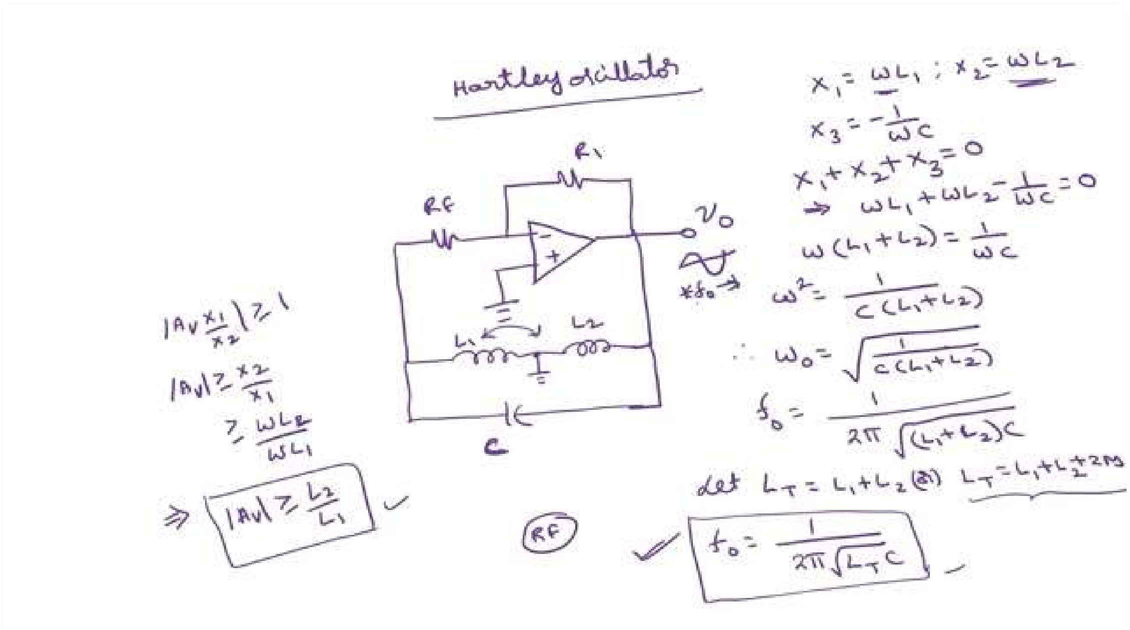

Let $L_T = L_1 + L_2$. If I assume that there is no mutual inductance between L_1 and L_2 or if I assume that mutual inductance also there $L_T = L_1 + L_2 + 2M$, M is mutual inductance. Then what will be frequency of oscillations? is $\frac{1}{2\pi\sqrt{L_T C}}$. Here L_T depends upon the mutual inductance $L_1 + L_2$ or $L_1 + L_2 + 2M$. This is the total inductance of two inductors connected in series with mutual inductance of F. And what is the another condition $\left|A_v \frac{X_1}{X_2}\right|$ should be ≥ 1 or $|A_v|$ should be $\geq \frac{X_2}{X_1}$.

This is greater than or equal to X_2 is ωL_1, X_1 is ωL_1, X_2 is ωL_2, $\frac{\omega L_2}{\omega L_1}$, ω ω get cancelled. So, $|A_v|$ should be greater than or equal to $\frac{L_2}{L_1}$. So, with this condition we will get the frequency of oscillations as $\frac{1}{2\pi}$ the resultant inductance times the capacitance. So, here the two types of LC oscillators. So, normally this will be used to design RF frequencies of the order of mega Hertz.

So, this is all about these sinusoidal oscillators which can generate the sinusoidal signal whose frequency is this. We can generate the rectangular waveform triangular waveform also that we will discuss in the next lecture. Thank you.