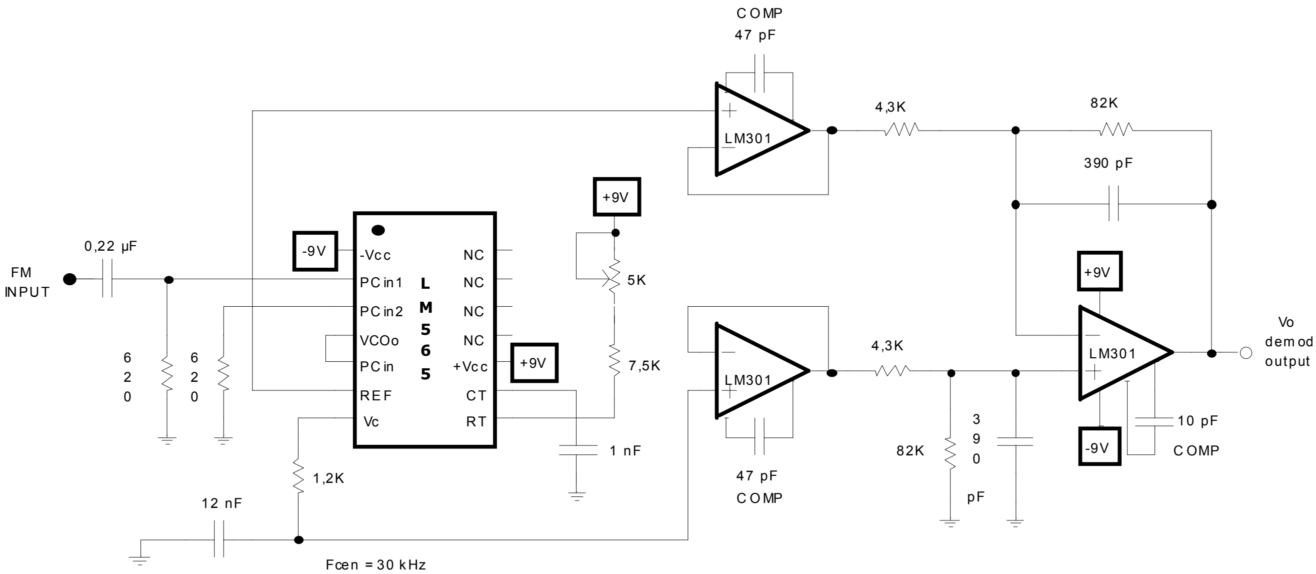
P L L E X E R C I S E

No.1 FM demodulator Analysis



A) Draw a block diagram of the overall FM demodulator and derive its TF $\Delta V_o(S)/\Delta\omega_{in}(S)$

B) Determine K_d, K_v, F_{n1}, ζ_1 and F_{n2} of the PLL demodulator and then sketch its gain response - label with relevant parameters. Explain why the demodulator has a Butterworth response.

C) If F_{car} = 30 kHz, ΔF = 2 kHz and F_{mod} = 500 Hz, sinewave modulation, what is the minimum, maximum and average phase error and the demodulated voltage? Use pages 10 or 11 of theory notes to read peak phase error.

D) Repeat for F_{mod} = 5 kHz.

E) Derive the general TF for $\Delta\Phi_e(S)/\Delta\omega_{in}(S)$ and then calculate the exact values of the phase error for steps C and D.

F) For what modulation frequency is the phase error maximum?

G) Explain the function of the last stage.

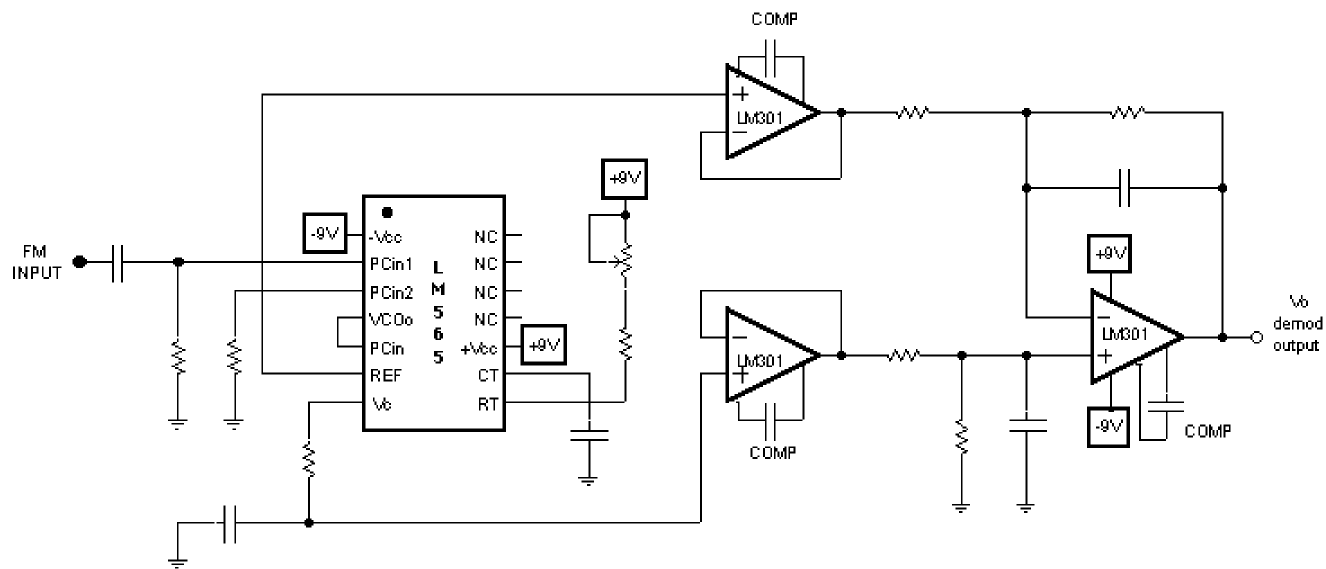
H) What is amplitude of the demodulated O/P signal, the HF ripple at the final output and the % ripple if the FM input has F_{mod} = 500 Hz, ΔF = 2 kHz at F_{car} = 30 kHz.

I) Simulate the demodulator gain response and the phase error response to an FM input with sinewave modulation.

J) Simulate for determination of lock range and capture range.

K) Simulate for determination of output HF ripple.

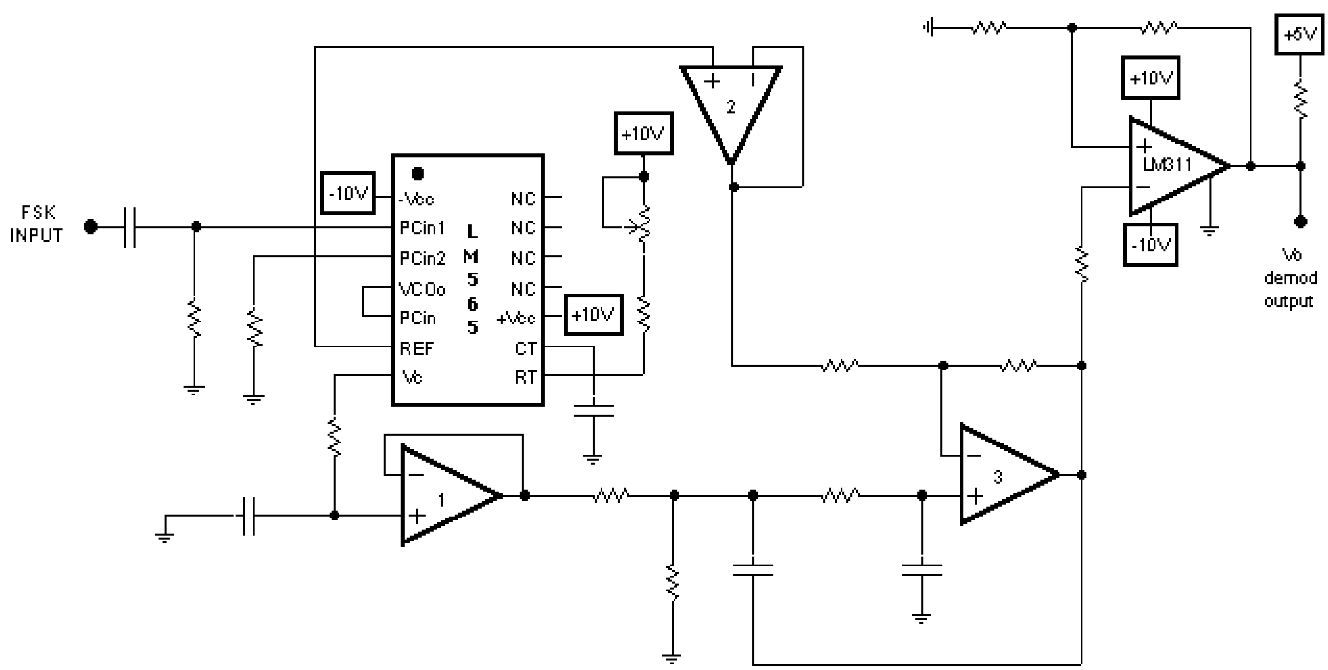
No.2 FM demodulator Design



Design a 3rd order FM demodulator that has a low-pass Bessel response, given the following input signal.
FM input: F_{car} = 100 kHz ΔF = 0 to 10 kHz Modulation: sinewave, F_{mod} = 0 to 3 kHz
Final output: 0 to 5V_p

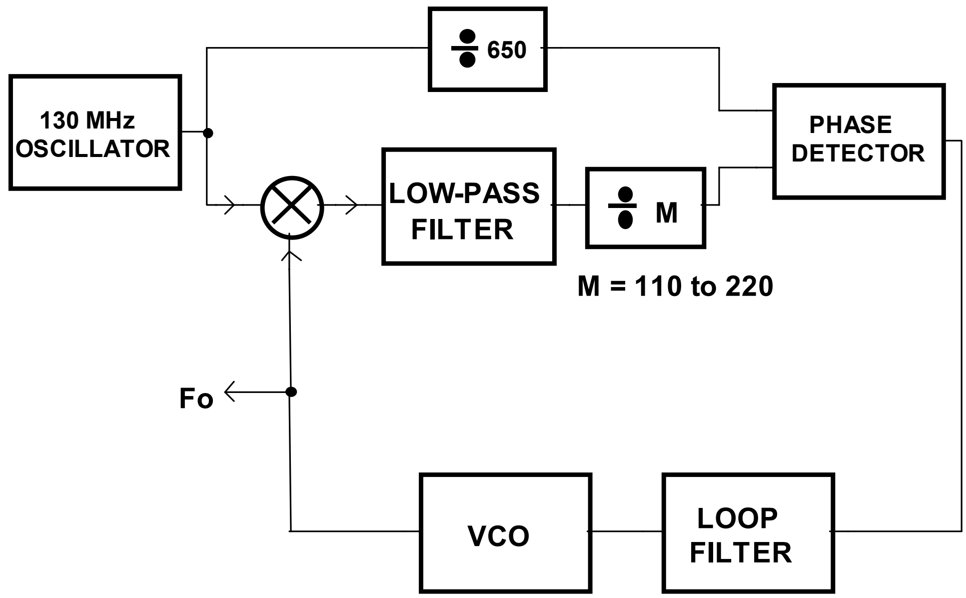
Select F_n of PLL for a reasonable phase error and large enough to pass the demod signal.

N0.3 FSK demodulator Design



Design a 4th order FSK demodulator that has a Bessel low-pass response with a bandwidth of 15 kHz.
The two input frequencies are 100 kHz and 110 kHz.
What is the maximum bit rate that can be demodulated?

No.4 PLL Frequency Synthesiser Analysis



A) Determine the two possible sets of output frequencies.

B) How do we ensure operation of the synthesiser on one set of frequencies only?

C) Why is there spurious FM sidetones in the spectrum of the output signal? Is this good or bad? How can they be minimized?

D) Are ζ and ω_n constant in this system? Explain.

No.5 RF PLL Synthesizer Design and Analysis

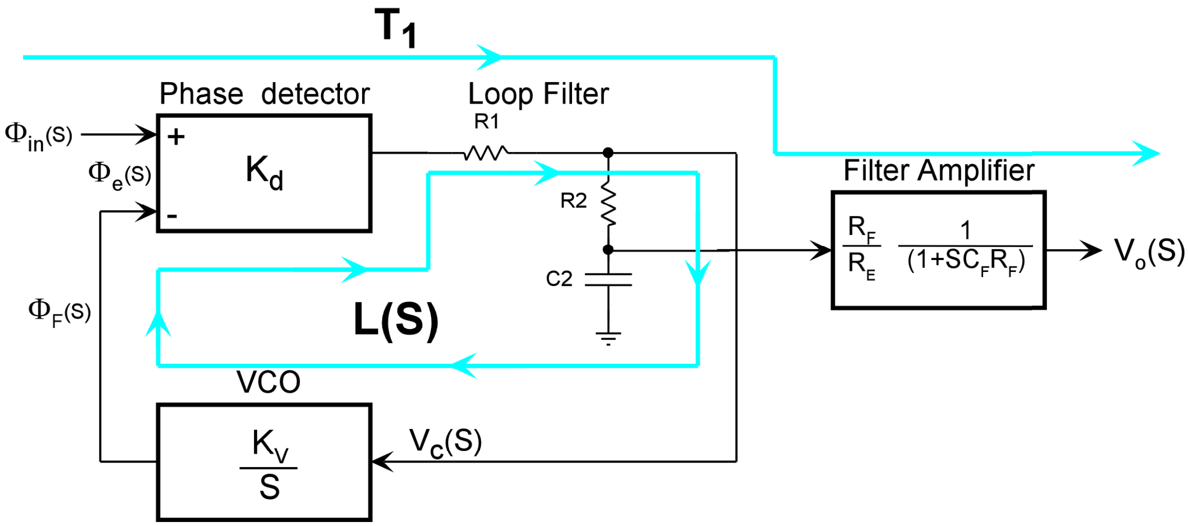
Re-do the example on pages 33 to 40 with the following data:

Using the same frequencies, re-design for a phase margin of 55^o, an ω_p value of 2π*10 kHz and additional spurious sideband attenuation of 20 dB from the R_3C_3 section added to the loop filter.

Modify the SystemView file given for the theory example to simulate your new design.

SOLUTIONS

No.1A)



$$\frac{V_o(s)}{\Phi_{in}(s)} = \frac{T_1 N_1}{1-L(s)} = \frac{K_d \times \dfrac{\frac{1}{SC_2}}{R_1+R_2+\frac{1}{SC_2}} \times \left(\dfrac{R_F}{R_E} \times \dfrac{1}{1+SC_FR_F}\right)}{1-\left[-K_d \times \dfrac{R_2+\frac{1}{SC_2}}{R_1+R_2+\frac{1}{SC_2}} \times \dfrac{K_V}{S}\right]}$$

$$\frac{V_o(s)}{\Phi_{in}(s)} = \frac{T_1 N_1}{1-L(s)} = \frac{K_d \times \dfrac{1}{1+SC_2(R_1+R_2)} \times \left(\dfrac{R_F}{R_E} \times \dfrac{1}{1+SC_FR_F}\right)}{1+\left[K_d \times K_V \times \dfrac{1+SC_2R_2}{1+SC_2(R_1+R_2)} \times \dfrac{1}{S}\right]}$$

$$\frac{V_o(s)}{\frac{\omega_{in}(s)}{S}} = \frac{\dfrac{S\,K_d}{C_2(R_1+R_2)}}{\left(S^2+S\left(\dfrac{1+K_dK_VR_2C_2}{C_2(R_1+R_2)}\right)+\dfrac{K_dK_V}{C_2(R_1+R_2)}\right)} \times \left(\frac{R_F}{R_E} \times \frac{1}{1+SC_FR_F}\right)$$

$$\frac{\Delta V_o(s)}{\Delta\omega_{in}(S)} = \frac{\dfrac{K_d}{C_2(R_1+R_2)}}{\left(S^2+S\left(\dfrac{1+K_dK_VR_2C_2}{C_2(R_1+R_2)}\right)+\dfrac{K_dK_V}{C_2(R_1+R_2)}\right)} \times \left(\frac{R_F}{R_E} \times \frac{1}{1+SC_FR_F}\right)$$

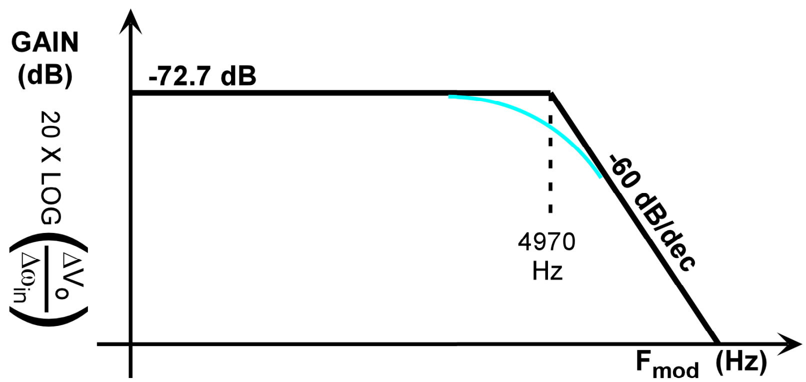
B) $K_d = 0.68$ V/r if $V_{in} > 100\ mV_{pp}$, that is if LM565 phase detector O/P is saturated - see data sheets.

$K_v = 49.4\ F_{cen}/\Delta V_{cc} = 49.4*30K/18 = 82333$ r/s or 13.1 kHz/V.

$$F_{n1} = \frac{1}{2\pi}\sqrt{\frac{K_v K_d}{C_2(R_1+R_2)}} = \frac{1}{2\pi}\sqrt{\frac{82333*0.68}{12n*(3.6k+1.2k)}} = 4962 Hz \qquad \zeta_1 = \frac{1+K_d K C_2 R_2}{2\omega_{n1} C_2 (R_1+R_2)} = 0.5029$$

$$F_{n2} = (2\pi R\ C_F)^{-1} = 4977\ \ Hz$$

F_{n1} and F_{n2} are almost equal and $\zeta_1 \approx 0.5$ which corresponds to a third order Butterworth response whose normalised poles are $\overline{S}_1 = 1\,\underline{/180^o}$ and $\overline{S}_{2,3} = 1\,\underline{/\pm 120^o}$. $\dfrac{\Delta V_o(S)}{\Delta\omega_{in}(S)} = \dfrac{1}{K_V} \times \dfrac{R_F}{R_E} = 231.6\mu$

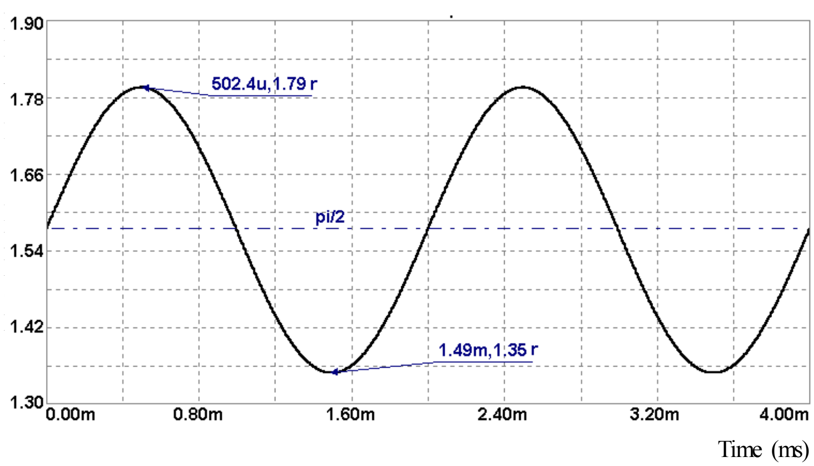


C) $\Delta F = 2$ kHz, $F_{mod} = 500$ Hz, $F_{car} = 30$ kHz

$$\omega_{n1}(\tau_1+\tau_2) = 2\pi \times 4962\ (12n \times (3.6k+1.2k)) = 1.8 \quad and \quad \frac{F_{mod}}{F_{n1}} = \frac{500}{4962} = 0.10076$$

For all phase error graphs, the LF frequency value of $\dfrac{\Delta\Phi_e}{(\Delta F_{in}/F_{n1})} \approx \dfrac{1}{\omega_{n1}(\tau_1+\tau_2)} = \dfrac{1}{1.8}$, therefore we have

$\Delta\Phi_e(peak) \approx \dfrac{(\Delta F_{in}/F_{n1})}{1.8} = \dfrac{2000/4962}{1.8} = 0.224\ r_p$ Average phase error is $\pi/2$ if $F_{cen} = F_{car}$ for LM565



D) ΔF = 2 kHz, F_{mod} = 5 kHz, F_{car} = 30 kHz

$$\omega_{n1}(\tau_1+\tau_2) = 2\pi \times 4962\,\big(12n \times (3.6k + 1.2k)\big) = 1.8 \quad and \quad \frac{F_{mod}}{F_{n1}} = \frac{5000}{4962} = 1.0077$$

At $\frac{F_{mod}}{F_{n1}} = 1$, we read on the phase error graphs (pp 10-11)

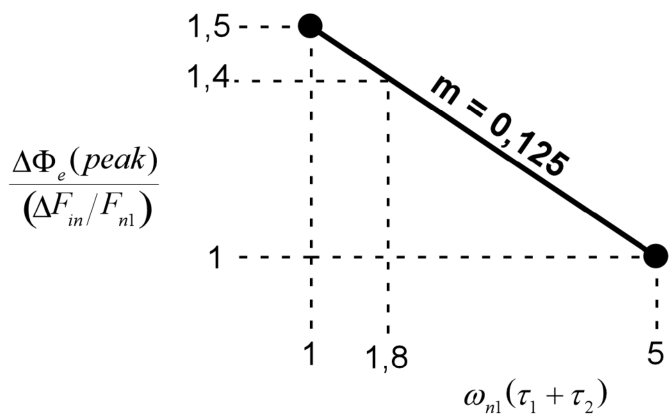
$$\frac{\Delta\Phi_e(peak)}{(\Delta F_{in}/F_{n1})} \approx 1.5 \quad for \quad \omega_{n1}(\tau_1+\tau_2) = 1$$

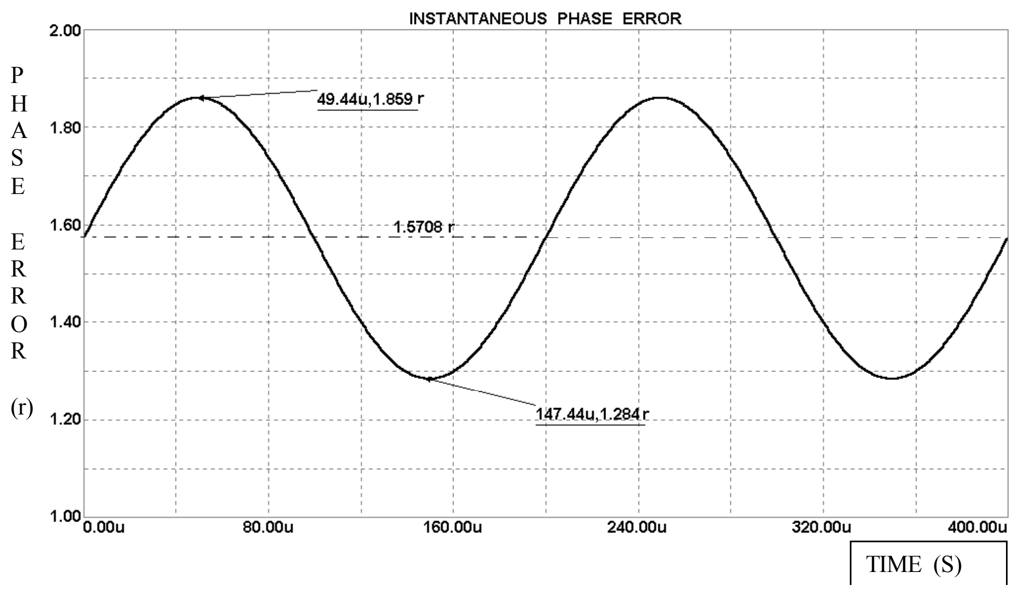
$$\frac{\Delta\Phi_e(peak)}{(\Delta F_{in}/F_{n1})} \approx 1.0 \quad for \quad \omega_{n1}(\tau_1+\tau_2) = 5$$

Using linear interpolation, we have

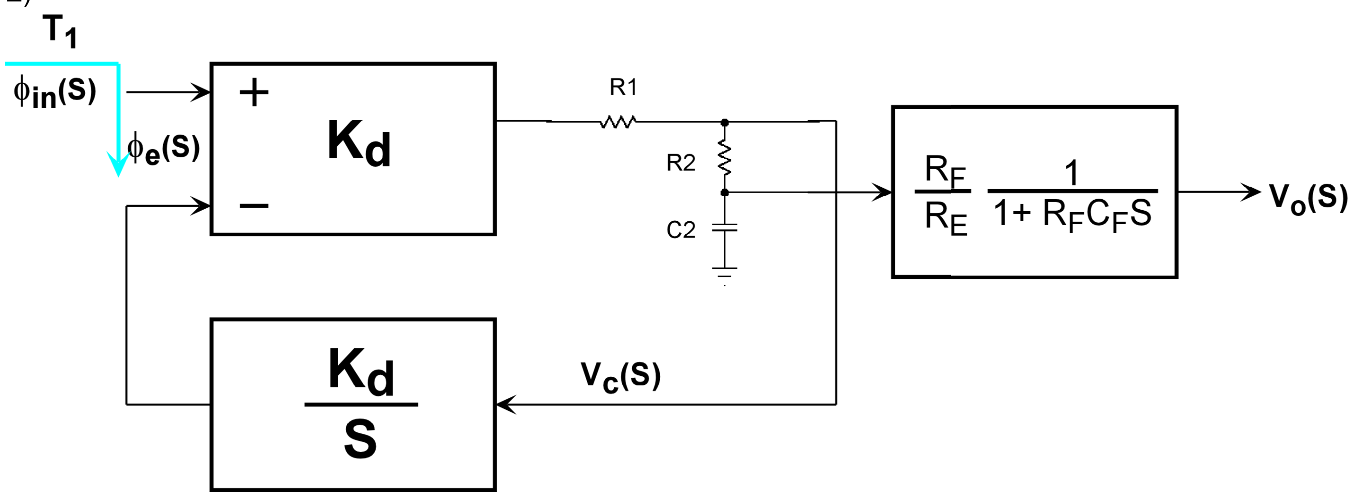
$$\Delta\Phi_e(peak) \approx \frac{(\Delta F_{in}/F_{n1})}{1.4} = \frac{2000/4962}{1.4} = 0.288\ r_p$$

Average phase error is $\pi/2$ if $F_{cen} = F_{car}$ for LM565





E)



$$\frac{\Phi_{e(S)}}{\Phi_{in(S)}}=\frac{T_1N_1}{1-L(S)}=\frac{1\times 1}{1-\left[-K_d\times\dfrac{R_2+\dfrac{1}{SC_2}}{R_1+R_2+\dfrac{1}{SC_2}}\times\dfrac{K_V}{S}\right]}=\frac{1}{1+\left[K_d\times K_V\times\dfrac{1+SC_2R_2}{1+SC_2(R_1+R_2)}\times\dfrac{1}{S}\right]}$$

$$\frac{\Phi_{e(S)}}{\dfrac{\omega_{in(S)}}{S}}=\frac{\dfrac{S\,(1+SC_2(R_1+R_2))}{C_2(R_1+R_2)}}{\left(S^2+S\left(\dfrac{1+K_dK_VR_2C_2}{C_2(R_1+R_2)}\right)+\dfrac{K_dK_V}{C_2(R_1+R_2)}\right)}\qquad\frac{\Delta\Phi_{e(S)}}{\Delta\omega_{in}(S)}=\frac{\left(S+\dfrac{1}{C_2(R_1+R_2)}\right)}{\left(S^2+S\left(\dfrac{1+K_dK_VR_2C_2}{C_2(R_1+R_2)}\right)+\dfrac{K_dK_V}{C_2(R_1+R_2)}\right)}$$

$$\Delta\Phi_{e(S)}=\Delta\omega_{in}(S)\times\frac{\left(S+\dfrac{1}{C_2(R_1+R_2)}\right)}{\left(S^2+S\left(\dfrac{1+K_dK_VR_2C_2}{C_2(R_1+R_2)}\right)+\dfrac{K_dK_V}{C_2(R_1+R_2)}\right)}$$

$$\Delta\Phi_{e}(j\omega_m)=\Delta\omega_{in}(j\omega_m)\times\frac{\left(j\omega_m+\dfrac{1}{C_2(R_1+R_2)}\right)}{\left((j\omega_m)^2+\dfrac{K_dK_V}{C_2(R_1+R_2)}+j\omega_m\left(\dfrac{1+K_dK_VR_2C_2}{C_2(R_1+R_2)}\right)\right)}$$

$$\Delta\Phi_{e}(j\omega_m)=\Delta\omega_{in}(j\omega_m)\times\frac{(j\omega_m+17361)}{\left((j\omega_m)^2+972\times10^6+j\omega_m(31357.8)\right)}$$

$$\Delta\Phi_e(peak)=\Delta\omega_{in}(peak)\times\frac{(j\omega_m+17361)}{\left((972\times10^6-\omega_m^2)+j\omega_m31357.8\right)}$$

For F_m = 500 Hz we have

$$\Delta\Phi_e(peak) = 2\pi \times 2000 \times \frac{(j1000\pi + 17361)}{\left(\left(972\times10^6 - (1000\pi)^2\right) + j1000\pi \times 31357.8\right)} = 0{,}2258\ r\ \underline{/0.179r}$$

Compared to 0.224 r_p found in step C. The phase angle of the phase error signal is the phase shift between the modulation signal and the phase error signal.

For F_m = 5 kHz we have

$$\Delta\Phi_e(peak) = 2\pi \times 2000 \times \frac{(j10000\pi + 17361)}{\left(\left(972\times10^6 - (10000\pi)^2\right) + j10000\pi \times 31357.8\right)} = 0{,}2302\ r\ \underline{/1.066r}$$

Compared to 0.288 r_p found in step D – I guess the graph was not that accurate.

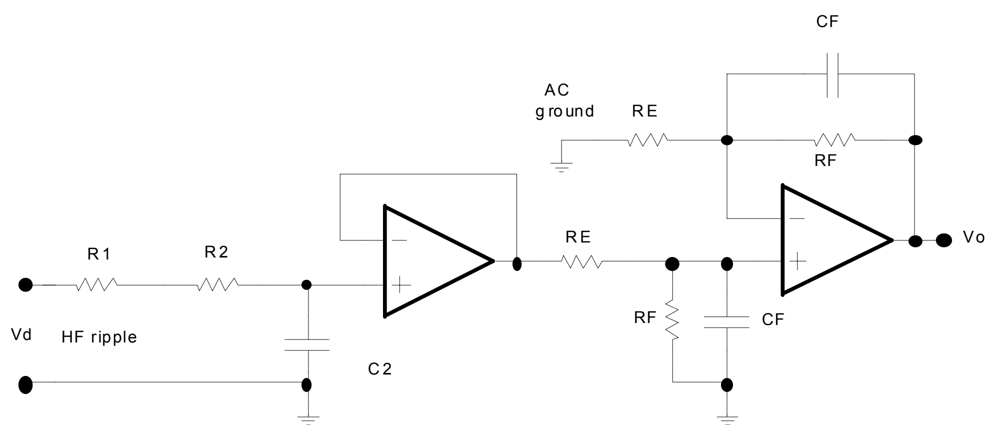
F) For $\omega_{n1}(\tau_1 + \tau_2)$ values of 5 and over the maximum phase error occurs at $F_m = F_{n1}$ = 4962 Hz.

But for $\omega_{n1}(\tau_1 + \tau_2)$ = 1 the peak has shifted to about 0,8 F_{n1}, so my estimate is that for $\omega_{n1}(\tau_1 + \tau_2)$ = 1.8 the maximum phase error will occur at approximately 0.9 F_{n1} = 4466 Hz

G) All yours to answer.

H) Ripple calculation (see chart page 19 of theory section)

From phase detector O/P to final O/P, we have



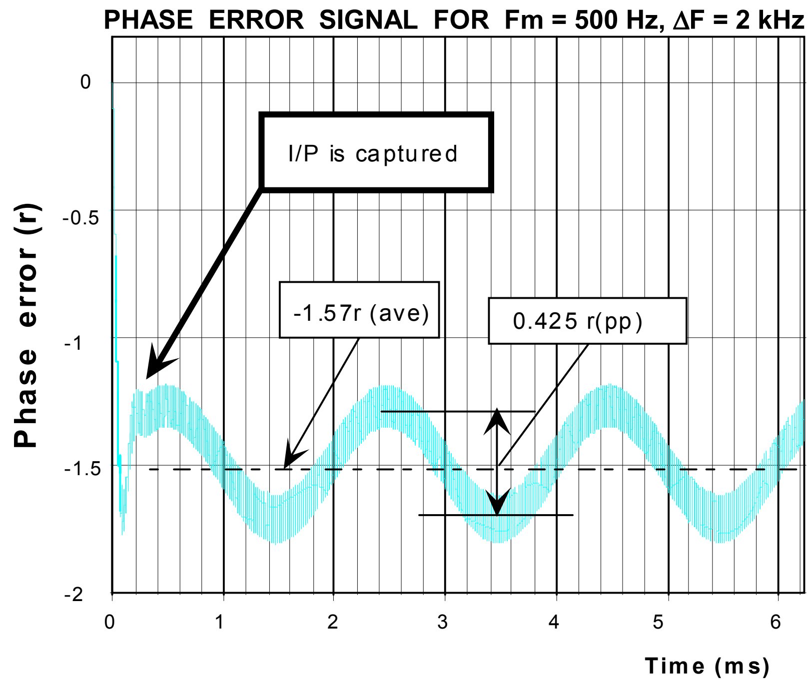
$$\frac{V_o(S)}{V_d(S)} = \frac{\frac{1}{SC_2}}{R_1 + R_2 + \frac{1}{SC_2}} \times \frac{R_F \left\| \frac{1}{SC_F} \right.}{R_E} \approx \frac{1}{SC_2(R_1+R_2)} \times \frac{1}{SC_F R_E} = \frac{A_1}{S} \times \frac{A_2}{S}$$

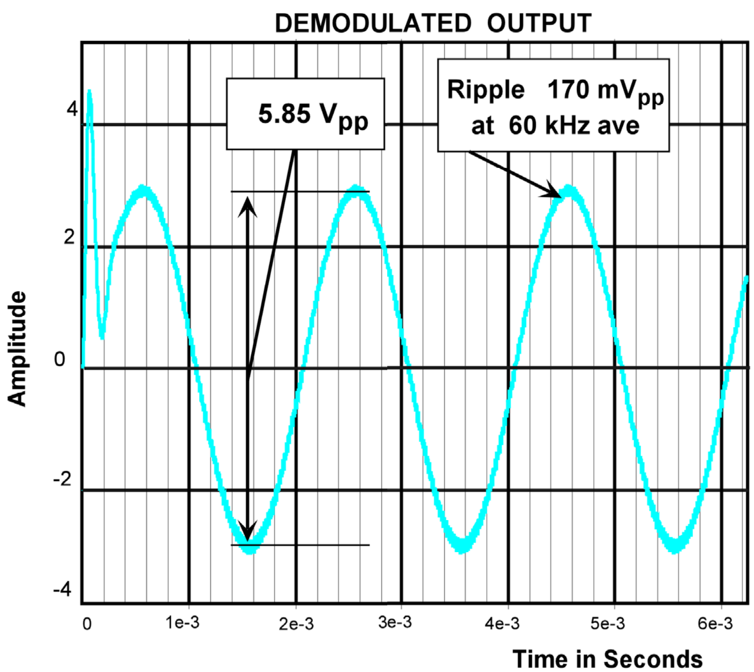
$$\Delta V_o(pp) = \Delta V_o(pp) \times \frac{A_1 A_2}{4\times8\times F_{rip}^2} = 2.16 \times \frac{1}{\left(4300\times390\times10^{-12}\right)\times\left(12\times10^{-9}\times4800\right)\times4\times8\times60K^2} = 194.1\ mV_{PP}$$

O/P signal level $V_o(peak) = \frac{\Delta\omega_{in}}{K_V} \times \frac{R_F}{R_E} = \frac{2\pi\times2000}{82333} \times \frac{82k}{4.3k} = 2.91\ V_p$

% ripple = 194.1m / (2.91*2) *100 = 3.33%

I)



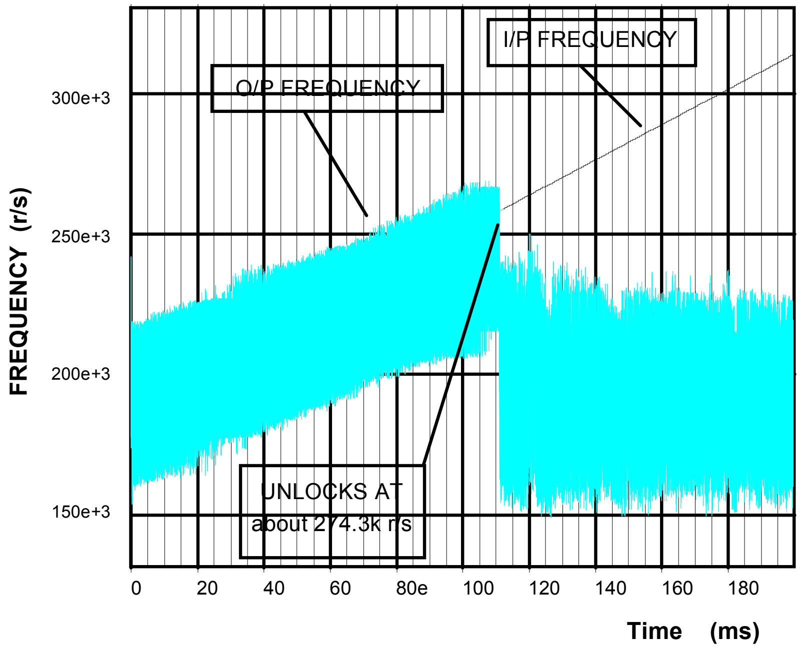


From the previous page, we obtained the following theoretical values:

V_o = 5.82 V_{pp} and ripple of 191.4 mV_{pp}

The ripple component is off because the duty cycle was assumed to be 50% at an average frequency of $F_{rip} = 2F_{car}$ at the phase detector O/P. At F_{min} and F_{max} of the FM signal, the duty cycle is above and below 50% and $F_{rip} = 2F_{min}$ and $2F_{max}$ respectively.

Read ripple at top and bottom of demod O/P and average the two values which should come close to the predicted value for 50% duty cycle.



From the S/V simulation, the lock range is:

$$F_{\max} = \frac{274.3k}{2\pi} = 43.656\,kHz$$

$$F_{cen} = 30\,kHz$$

$$\Delta F_L = F_{\max} - F_{cen} = F_{cen} - F_{\min}$$

$$\Delta F_L = 43.656k - 30k = 13.66\,kHz$$

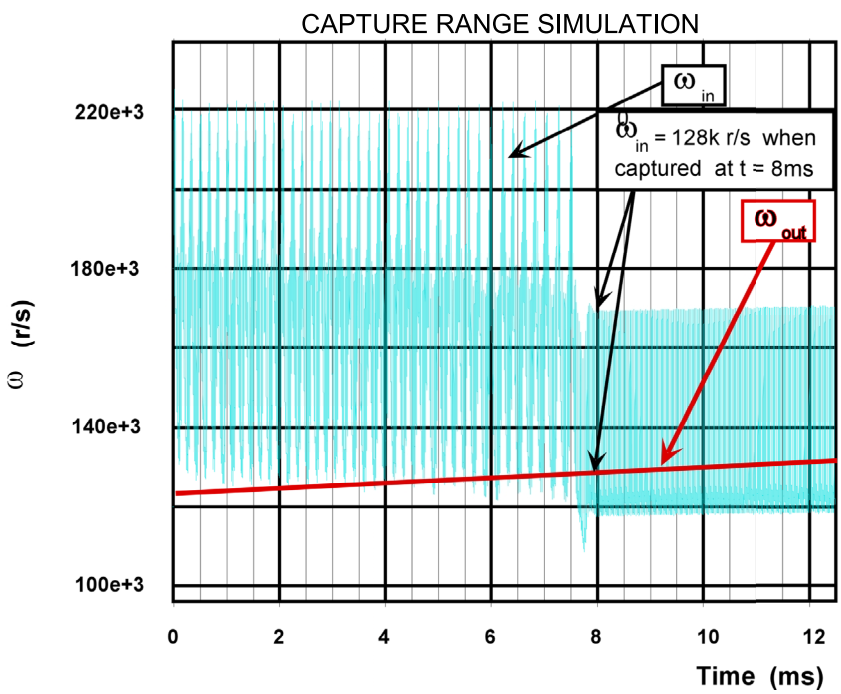
Theoretically we have:

$$\Delta F_{LOCK} \approx \pm\frac{8\times F_{cen}}{\Delta V_{CC}}$$

$$\Delta F_{LOCK} = \pm\frac{8\times 30k}{18} = 13.33kHz$$

NOTE: The simulation shown beside is not to scale – run sim file for a better look at results.

The above simulation was done starting at F_{in} = 30 kHz and then ramping up F_{in} at a rate of 100 kHz/sec. If the ramp rate is too fast then the lock rage will be less – lock range is defined for a slow variation of F_{in}. You can find F_{min} by starting at 30 kHz again but now ramping down F_{in} at –100 kHz/sec (Try it!)



From the S/V simulation, the capture range is:

$$F_{\min} = \frac{128k}{2\pi} = 20.37\,kHz$$

$$F_{cen} = 30\,kHz$$

$$\Delta F_L = F_{cen} - F_{\min} = F_{\max} - F_{cen}$$

$$\Delta F_L = 30k - 20.37k = 9.63\,kHz$$

Theoretically we have:

$$\Delta F_{CAP} \approx \pm\frac{\sqrt{2}}{2\pi}\times\sqrt{2\zeta\omega_n K_o K_d - \omega_n^2} = \pm\frac{\sqrt{2}}{2\pi}\times\sqrt{2\times 0{,}5\times(2\pi\times 4962)\times 82333\times 0{,}68 - (2\pi\times 4962)^2}$$

$$\Delta F_{CAP} = \pm 11.73\,kHz$$

Nos.2, 3 and 5 you are on your own – see theory examples for help.

N0.4 A) F_o = 86 MHz to 108 MHz or F_o = 152 MHz to 174 MHz with steps of ΔF_o = 200 kHz
B, C and D are yours.