Name: Roll Number:

Laboratory 4

A:	/2	B:	/5	C:	/8	Tot:	/15

Filters: Passive, Active and Magical

Goal

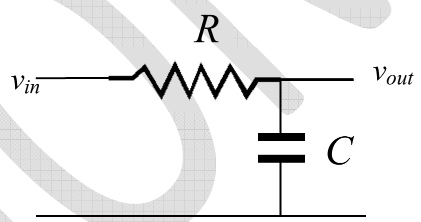
Today's lab consists of three parts with increasing difficulty level. Please complete each part sequentially and get it examined before continuing to the next. Make neat circuit connections on your breadboard – you can reuse them for each part of the exercise.

Recall from the lecture that the decibel scale for voltages is defined as: Gain (in dB) = 20 $\log_{10}(v_{out}/v_{in})$

Part A: Passive low-pass filter

Fig 1 shows a *passive* low pass filter made with a resistor *R* and capacitor *C*.

Fig 1

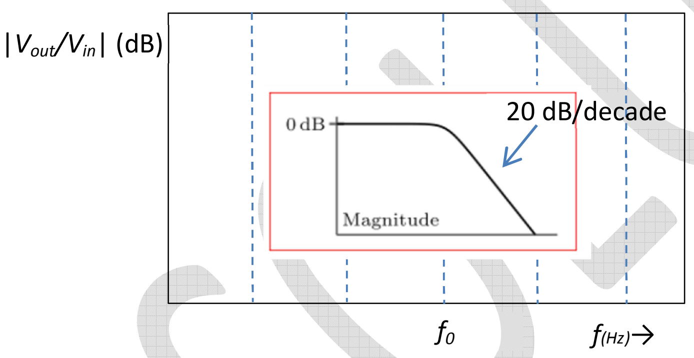


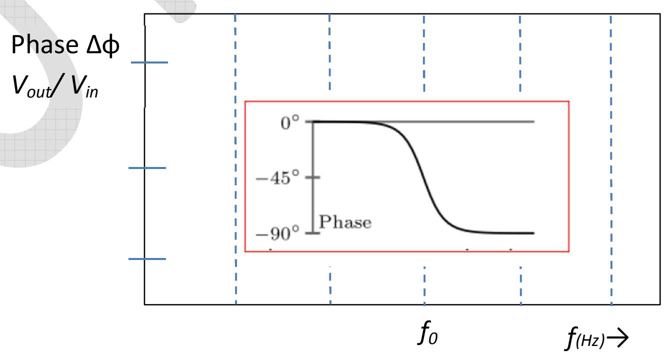
Take the capacitor's frequency-dependent impedance to be $J_C = 1/j\omega C$ (where *j* is complex):

Calculate the Bode plot of the *magnitude* and *phase* of the response v_{out}/v_{in}

Make the plots below as a function of *frequency* in dB scale.

In your response plots, label the axes carefully. On the x-axis (*f*) indicate the frequency f_o where the magnitude of the response falls to -3 dB. (it obviously starts out at 0 dB i.e. $v_{out}/v_{in}=1$ at $\omega=0$)





Gain is down by -3dB [20 log (1/sqrt(2))] at f_0

Phase loss is -45° at f_0 and goes on to -90° by $10f_0$

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Calculate and build a circuit on your breadboard for a low-pass filter with cut-off frequency $\omega_o = 2\pi*1$ *kHz*

Note carefully the *type* of capacitor indicated in Fig 1 and choose accordingly

(is the polarity of voltage across C fixed or changing?)

Make a few observations and demonstrate that your filter behaves as expected from the Bode plot calculated above (measurements at five frequencies of v_{in} differing by an order of magnitude each are sufficient)

R = 1.6 kΩ, C=0.1μF (non-polar) should give $f_0 = 1$ *kHz*

(Note - I have been somewhat sloppy with usage of ω and f : the specifications take care of 2π)

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Name: *Roll Number:*

Part B: Active Low pass filter

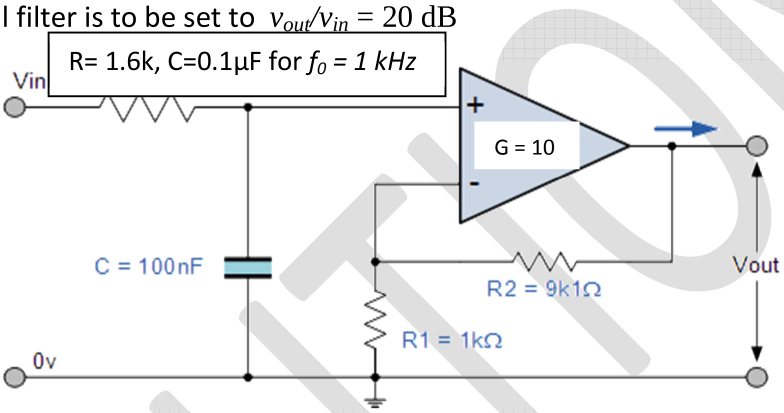
As it is clear from Part A, a passive low-pass filter suffers from the problem that in the pass band the transfer function $v_{out}/v_{in} = 1/sqrt(1+\omega^2R^2C^2)$ is 1 (0 dB) only for DC signals at ω=0 and starts falling for $\omega>0$

We would like to setup a filter which has DC gain > 1 so that signal attenuation is minimal in the pass band.

We have learnt in earlier exercises how to add controlled gain to a signal using an opamp in negative feedback. Design a *first order* low pass filter by adding opamp operating with negative feedback loop to the passive filter of Part A for signal amplification. It must have an overall gain that you can set by choosing appropriate values of the components. Draw your filter design below:

Pick component values to set the filter cutoff frequency $\omega_o = 2\pi*1\ kHz$ as before.

DC gain of the overall filter is to be set to $v_{out}/v_{in} = 20$ dB



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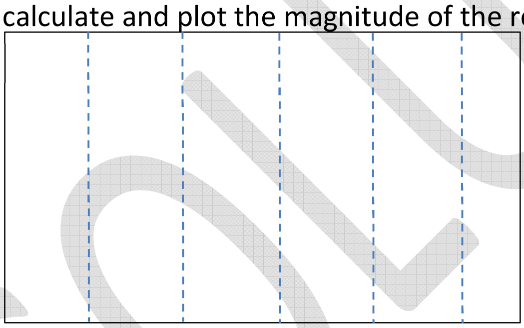
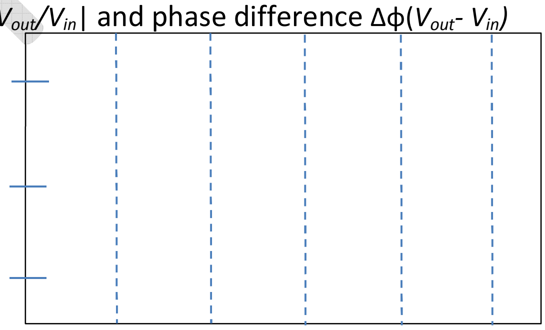
As before, calculate and plot the magnitude of the response $|V_{out}/V_{in}|$ and phase difference $\Delta\phi(V_{out}- V_{in})$

$|V_{out}/V_{in}|$ (dB)



$\omega\rightarrow$

Phase Δϕ V_{out} / V_{in}



$\omega\rightarrow$

/1

Note: G*B = 10^6 Hz is fixed GBWP of LM741. In open loop, G=10^6 so B = 1 Hz

Here with G=10, B = 10^5 Hz, so the opamp pole is far out at 10^5 Hz

The RC filter action is happening way down near *$f_0 = 10^3$ Hz. So the opamp feedback loop phase hardly makes a difference to this bode plot. The amplitude plot is pushed up by 20 dB (voltage gain is 20 dB at f=0, 20-3 = 17 dB at f_0 and 0 dB and $10f_0$)*

Make connections on your breadboard to implement your active filter design. Demonstrate that its operation matches the expectation from your Bode plot at five frequencies of v_{in}

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Part C: Filter without input –an oscillator

Consider carefully the phase shift Δϕ at the pole frequency in the active filter design of part B.
Our objective in Part C is to deliberately setup controlled oscillations in the circuit at a specified frequency.
Expand on the design of Part B to make such an oscillator – this is called a phase shift oscillator.

Hints:
Recall the concepts discussed in class about the danger of loop phase shift getting to -180°: at that point the feedback becomes positive and the circuit starts oscillating.

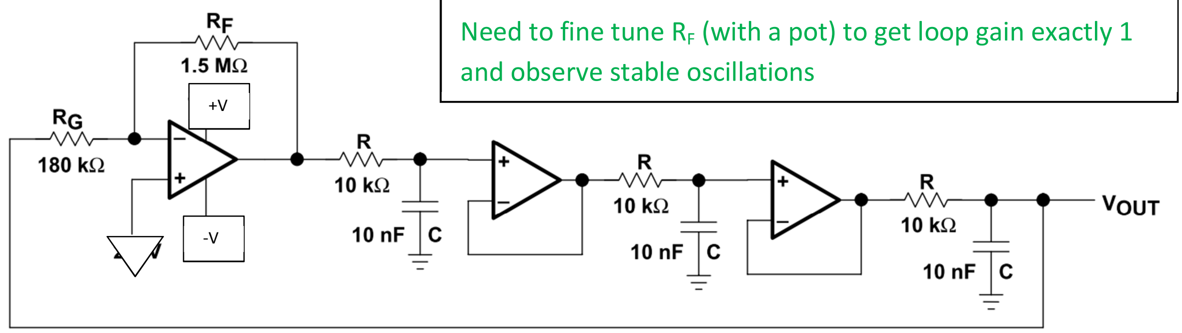
- You can cascade a few copies of the active filter of Part B and feed the output back to the input to explicitly set the loop phase shift to -180°
- You have to set the intermediate stage gains such that overall loop *amplitude* gain is exactly 1 – if it is less than 1 the oscillations will die down, if it is more than 1 the oscillations will quickly increase until the opamp(s) saturates. We suggest that you set the gain in one of the stages, and keep the other stages with unity gain feedback. Then it would be possible to fine-tune the loop gain to setup stable oscillations

Such an oscillator is called a phase shift oscillator because it relies purely on the phase shift of signals passing through the circuit stages to create sine wave oscillations.

Draw your design here:

R= 1.6k, C=0.1μF gives oscillations at 1.732 kHz
R=10k, C= 10nF shown here gives oscillations at 2.76 kHz

Need to fine tune R_F (with a pot) to get loop gain exactly 1 and observe stable oscillations



/3 design
/1 calc.

Each of the 3 stages must give -60° & tan(60) = 1.732 → $\tan^{-1}(\omega/\omega_0) = 60°$
$\omega_{osc} = \omega_0 * 1.732 = 2\pi * 1\ kHz * 1.732 = 2\pi * 1.732\ kHz$
Gain of each stage is ½ at ω_{osc} so total gain is down by $(½)^3 = 1/8$. Must compensate with $1+R_F/R_G = 8$
Perhaps R_F of 1.5 MΩ is excessive – try with smaller values.

Calculate the components required to make the circuit oscillate at $\omega_{osc} = 2\pi * 1.732\ kHz$
Hint:ω_{osc} is set to this peculiar value so that you can reuse the calculations of Part B: you will need to re-calculate the phase loss at this frequency for each stage, and the amplitude attenuation which has to be compensated to bring the total loop gain back to 1.

Build up your circuit on the breadboard and demonstrate its oscillation output.

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(Excerpted from http://www.ti.com/lit/an/sloa060/sloa060.pdf page 16-17)

8.2 Phase-Shift Oscillator, Single Amplifier

Phase-shift oscillators have less distortion than the Wien bridge oscillator, coupled with good frequency stability. A phase-shift oscillator can be built with one op amp as shown in Figure 14. Three RC sections are cascaded to get the steep slope, $d\phi/d\omega$, required for a stable oscillation frequency, as described in section 3. Fewer RC sections results in high oscillation frequency and interference with the op-amp BW limitations.

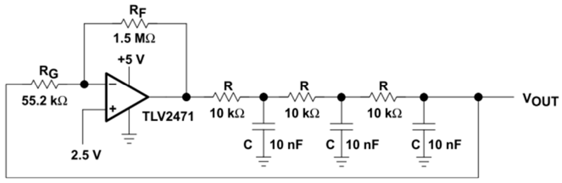

Figure 14. Phase-Shift Oscillator (Single Op Amp)

The usual assumption is that the phase shift sections are independent of each other, allowing equation 14 to be written. The loop phase shift is $-180°$ when the phase shift of each section is $-60°$. This occurs when $\omega = 2\pi f = 1.732/RC$ ($\tan 60° = 1.732\ldots$). The magnitude of β at this point is $(1/2)^3$, so the gain, A, must be 8 for the system gain of unity.

$$A\beta = A\left(\frac{1}{RCs + 1}\right)^3 \tag{14}$$

The oscillation frequency with the component values shown in Figure 14 is 3.76 kHz rather than the calculated oscillation frequency of 2.76 kHz. Also, the gain required to start oscillation is 27 rather than the calculated gain of 8. These discrepancies are partially due to component variations, however, the biggest factor is the incorrect assumption that the RC sections do not load each other. This circuit configuration was very popular when active components were large and expensive. But now op amps are inexpensive, small, and come four-to-a-package, so the single-op-amp phase-shift oscillator is losing popularity. The output distortion is a low 0.46%, considerably less than the Wien bridge circuit without amplitude stabilization.

Phase-Shift Oscillator, Buffered

The buffered phase-shift oscillator is much improved over the unbuffered version, the penalty being a higher component count. Figures 16 and 17 show the buffered phase-shift oscillator and the resulting output waveform, respectively. The buffers prevent the RC sections from loading each other, hence the buffered phase-shift oscillator performs more nearly at the calculated frequency and gain. The gain-setting resistor, R_G, loads the third RC section. If the fourth buffer in a quad op amp buffers this RC section, the performance becomes ideal. Low-distortion sine waves can be obtained from either phase-shift oscillator design, but the purest sine wave is taken from the output of the last RC section. This is a high-impedance node, so a high impedance input is mandated to prevent loading and frequency shifting with load variations.

The circuit oscillated at 2.9 kHz compared to an ideal frequency of 2.76 kHz, and it oscillated with a gain of 8.33 compared to an ideal gain of 8. The distortion was 1.2%, considerably more than the unbuffered phase-shift oscillator. The discrepancies and higher distortion are due to the large feedback resistor, R_F, which created a pole with C_{IN} of approximately 5 kHz. Resistor R_G still loaded down the lost RC section. Adding a buffer between the last RC section and V_{OUT} lowered the gain and the oscillation frequency to the calculated values.

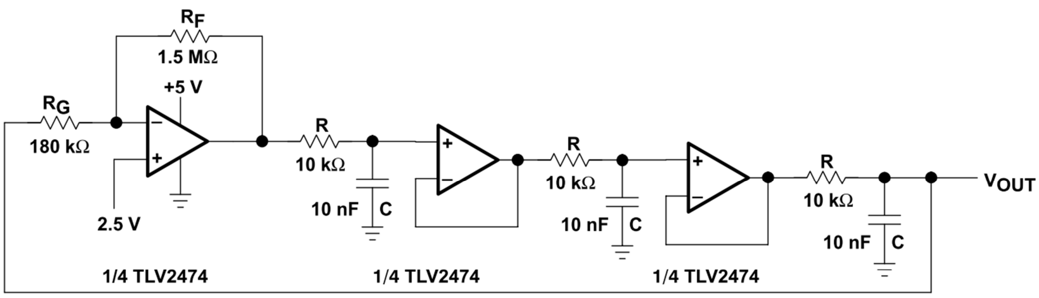

Figure 16. Phase-Shift Oscillator, Buffered