Assignment 05

EE 538 Spring 2020
Analog Circuits for Sensor Systems
University of Washington Electrical & Computer Engineering

Due: May 9, 2020
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In [1]:
```
# Imports
import os
import sys
import cmath
import math
import matplotlib.pyplot as plt
import matplotlib
import numpy as np
import pandas as pd
import ltspice
import sympy as sp
from scipy import signal
%matplotlib inline
from IPython.core.interactiveshell import InteractiveShell
InteractiveShell.ast_node_interactivity = "all"
```

In [2]:
```
def read_ltspice(file_name,ftype='trans',units='db'):
    cols = []
    arrs = []
    with open(file_name, 'r',encoding='utf-8') as data:
        for i,line in enumerate(data):
            if i==0:
                cols = line.split()
                arrs = [[] for _ in cols]
                continue
            parts = line.split()
            for j,part in enumerate(parts):
                arrs[j].append(part)
    df = pd.DataFrame(arrs,dtype='float64')
    df = df.T
    df.columns = cols
    if ftype=='trans':
        return df
    elif ftype=='ac':
        if units=='db':
            for col in cols:
                if df[col].str.contains(',').all():
                    df[f'Mag_{col}'] = df[col].apply(lambda x: x.split(',')[0])
                    df[f'Mag_{col}'] = df[f'Mag_{col}'].apply(lambda x: x[1:-2])
                    df[f'Mag_{col}'] = df[f'Mag_{col}'].astype('float64')
                    df[f'Phase_{col}'] = df[col].apply(lambda x: x.split(',')[1])
                    df[f'Phase_{col}'] = df[f'Phase_{col}'].apply(lambda x: x[0:-2])
                    df[f'Phase_{col}'] = df[f'Phase_{col}'].astype('float64')
        if units=='cartesian':
            for col in cols:
                if df[col].str.contains(',').all():
                    df[f'Re_{col}'] = df[col].apply(lambda x: x.split(',')[0])
                    df[f'Re_{col}'] = df[f'Re_{col}'].astype('float64')
                    df[f'Im_{col}'] = df[col].apply(lambda x: x.split(',')[1])
                    df[f'Im_{col}'] = df[f'Im_{col}'].astype('float64')
        df['Freq.'] = df['Freq.'].astype('float64')
        return df
    else:
        print('invalid ftype')
```

In [3]:
```
def read_ltspice_wc(file_name):
    lines = []
    with open(file_name) as fh:
        for line in fh:
            if line.startswith("Step Information:"): continue
            lines.append(line)
    cols = []
    arrs = []
    for i,line in enumerate(lines):
        if i==0:
            cols = line.split()
            arrs = [[] for _ in cols]
            continue
        parts = line.split()
        for j,part in enumerate(parts):
            arrs[j].append(part)
    df = pd.DataFrame(arrs)
    df = df.T
    df.columns = cols
    return df
```

Problem 1: Difference amplifier analysis

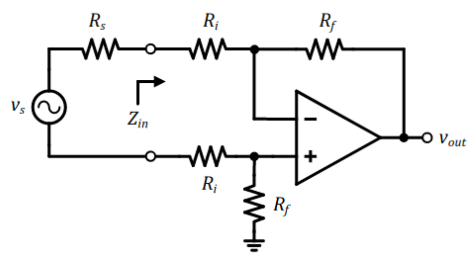


Figure 1. Difference amplifier

A difference amplifier is driven by a sensor with source impedance R_s. Let R_f = 10kΩ and R_i = 100Ω. Assume ideal opamp behavior.

a) (5 points) Derive an expression and determine a value for the DC differential input impedance Z_{in} of the amplifier. Determine the source impedance R_s that results in a maximum of 0.1% attenuation of the input voltage.

b) (5 points) Simulate the amplifier in Ltspice using the UniversalOpamp2 component (default parameters). Plot Z_{in} up to 10MHz using AC analysis to show how it varies as a function of opamp gain.

Reference:[http://leachlegacy.ece.gatech.edu/ece3050/sp04/OpAmps01.pdf (http://leachlegacy.ece.gatech.edu/ece3050/sp04/OpAmps01.pdf)](http://leachlegacy.ece.gatech.edu/ece3050/sp04/OpAmps01.pdf)

Differential Amplifier Stage

$$
\begin{aligned}
Z_{\text{in}} &= \frac{\Delta V_{id}}{\Delta(i^- - i^+)} && = R_i(1+\frac{R_i}{R_f}) \\
\frac{-V_{id}}{2} &= i^-(R_i+R_f) && \rightarrow i^- = \frac{-V_{id}}{2(R_i+R_f)} \\
v^- &= v^+ && = i^- R_f \\
i^+ &= \frac{\frac{V_{id}}{2} - v^-}{R_1} \\
&= \frac{\frac{V_{id}}{2} - \frac{-V_{id}}{2(R_i+R_f)}R_f}{R_1} \\
&= \frac{V_{id}}{2}[\frac{1+\frac{R_f}{(R_i+R_f)}}{R_1}] \\
&= \frac{V_{id}}{2}[\frac{(R_i+R_f)+R_f}{R_1(R_i+R_f)}] \\
i^- - i^+ &= \frac{-V_{id}}{2(R_i+R_f)} + \frac{V_{id}}{2}[\frac{(R_i+R_f)+R_f}{R_1(R_i+R_f)}] \\
&= \frac{V_{id}}{2}[\frac{(R_i+R_f)+R_f}{R_1(R_i+R_f)} - \frac{1}{R_i+R_f}] \\
&= \frac{V_{id}}{2(R_i+R_f)}[\frac{(R_i+R_f)+R_f}{R_1} - 1] \\
&= \frac{V_{id}}{2R_i(R_i+R_f)}[R_i+R_f+R_f-R_i] \\
&= \frac{V_{id}}{2R_i(R_i+R_f)}[2R_f] \\
&= V_{id}\frac{R_f}{R_i(R_i+R_f)} \\
Z_{\text{in}} &= \frac{\Delta V_{id}}{\Delta(i^- - i^+)} \\
&= \frac{V_{id}}{V_{id}\frac{R_f}{R_i(R_i+R_f)}} \\
&= \frac{R_i(R_i+R_f)}{R_f} = R_i(1+\frac{R_i}{R_f}) \\
&= 101\Omega
\end{aligned}
$$

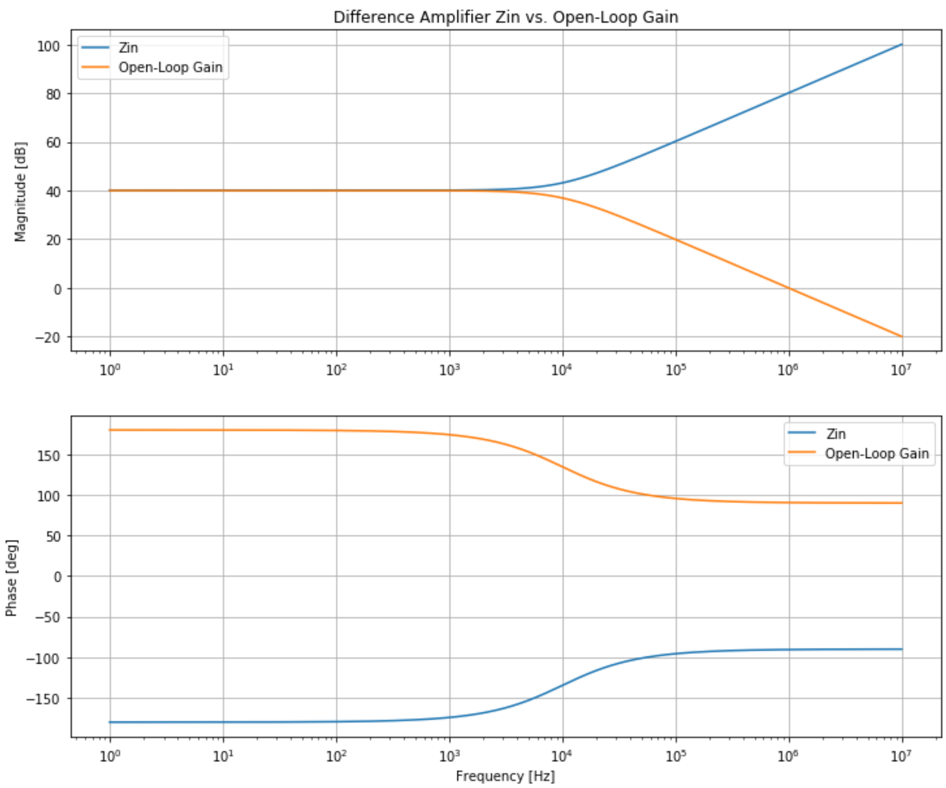
0.1% Attenuation

$$
\begin{aligned}
V_{\text{out}} &= v_S\frac{Z_{\text{in}}}{R_S+Z_{\text{in}}} \\
0.999 &= \frac{101}{R_S+101} \\
R_S &= 0.10\Omega
\end{aligned}
$$

Part B

In [4]:
```
filepath = 'data/diff_amp_relationship.txt'
df = read_ltspice(filepath,'ac')
mag1 = df['Mag_(V(vp)-V(vm))/(I(R1)-I(R4))']
ang1 = df['Phase_(V(vp)-V(vm))/(I(R1)-I(R4))']
mag2 = df['Mag_V(vout)/(V(vp)-V(vm))']
ang2 = df['Phase_V(vout)/(V(vp)-V(vm))']
freq = df['Freq.']
```

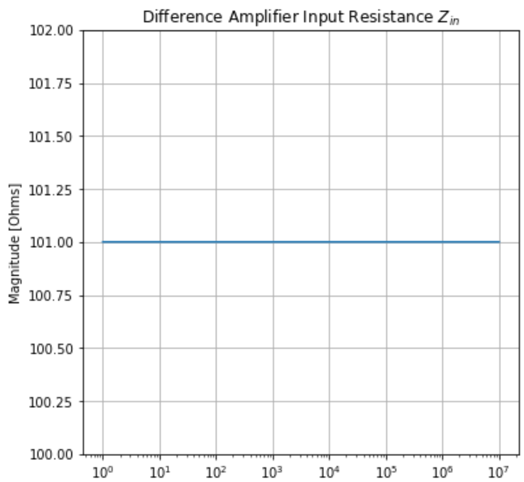
In [5]:
```
#Plot
fig, axs = plt.subplots(2,figsize=(12,10))
axs[0].set_title('Difference Amplifier Zin vs. Open-Loop Gain')
axs[0].semilogx(freq, mag1, label='Zin')
axs[0].semilogx(freq, mag2, label='Open-Loop Gain')
axs[0].set_ylabel('Magnitude [dB]')
axs[0].grid()
axs[0].legend()
axs[1].semilogx(freq, ang1, label='Zin')
axs[1].semilogx(freq, ang2, label='Open-Loop Gain')
axs[1].set_xlabel('Frequency [Hz]')
axs[1].set_ylabel('Phase [deg]')
axs[1].grid()
axs[1].legend()
plt.show();
```



In [6]:
```
filepath = 'data/diff_amp.txt'
df = read_ltspice(filepath,'ac','cartesian')
mag = abs(df['Re_(V(vp)-V(vm))/(I(R1)-I(R4))'])
freq = df['Freq.']
```

In [7]:

```
fig, ax = plt.subplots(1,figsize=(6,6))
ax.set_title(r'Difference Amplifier Input Resistance $Z_{in}$')
ax.semilogx(freq, mag)
ax.set_ylim(100,102)
ax.set_ylabel('Magnitude [Ohms]')
ax.grid()
#ax.legend()
plt.show();
```



Problem 2: Instrumentation amplifier analysis

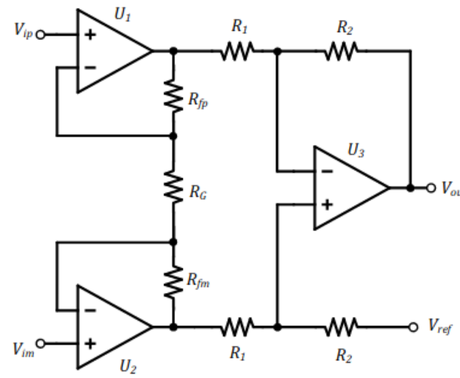


Figure 2. Instrumentation amplifier

Assume the above opamps have a DC gain of 120dB and an f_T of 1MHz. Nominal resistance values are $R_{fp} = R_{fm} = 4.95\text{k}\Omega$, $R_G = 100\Omega$, and $R_1 = R_2 = 10\text{k}\Omega$, all with 0.1% tolerance.

a) (5 points) Determine the differential DC gain of the amplifier and the closed-loop bandwidth. *Ignore resistor mismatch.*

b) (5 points) Based on the value of f_T, what is the closed-loop gain error at 100Hz? *Ignore mismatch.*

c) (5 points) Including the effect of resistor mismatch, what are the CMRR and the worst-case DC gain error? *Assume infinite opamp open-loop gain.*

d) (5 points) Assume U_1 and U_2 have min/max input offset voltages of ±100µV but are otherwise identical. What is the maximum allowable offset of U_3 to achieve a *worst-case input-referred offset* (the offset at V_{out} divided by the differential gain) of 250µV? *Ignore resistor mismatch.*

e) (10 points) Simulate the instrumentation amplifier in Ltspice using the UniversalOpamp2 component with appropriate Avol, GBW, and Vos values. Provide the following in your submission:

1. Image of your schematic showing the DC operating point (DC voltages at all nodes). Use the worst-case mismatch condition for the resistors. How much is the offset affected by resistor mismatch?
2. Plot showing the closed loop gain error at 100Hz using WC analysis. You can do this by selecting 'list' for the sweep type under AC analysis. Note that you need to run 128 iterations (2^7, where 7 is the number of resistors) to cover all mismatch combinations. Compare the contributions to gain error from finite opamp gain and resistor mismatch (i.e. which effect is more significant?).
3. Bode plots demonstrating closed-loop differential gain/phase and closed-loop common-mode gain/phase. For common-mode gain you should use the worst-case mismatch condition for the resistors.

Part A

simple non-inverting

$$
\begin{aligned}
-V_{\text{out}} &= (v^- - v^+)A_{OL} \\
v^- &= \frac{-V_{\text{out}}}{A_{OL}} + v^+ \\
i_1 &= \frac{\frac{-V_{\text{out}}}{A_{OL}} + v_{\text{in}}}{R_G} \\
V_{\text{out}} &= v^- + i_1 R_f \\
V_{\text{out}} &= \frac{-V_{\text{out}}}{A_{OL}} + v_{\text{in}} + \frac{\frac{-V_{\text{out}}}{A_{OL}} + v_{\text{in}}}{R_G} R_f \\
V_{\text{out}} + \frac{V_{\text{out}}}{A_{OL}} + \frac{V_{\text{out}} R_f}{A_{OL} R_G} &= v_{\text{in}} + \frac{v_{\text{in}} R_f}{R_G} \\
V_{\text{out}}(1 + \frac{1}{A_{OL}} + \frac{R_f}{A_{OL} R_G} &= v_{\text{in}}(1 + \frac{R_f}{R_G}) \\
\frac{V_{\text{out}}}{A_{OL}}(A_{OL} + 1 + \frac{R_f}{R_G}) &= v_{\text{in}}(1 + \frac{R_f}{R_G}) \\
V_{\text{out}} &= v_{\text{in}} \frac{A_{OL}(1 + \frac{R_f}{R_G})}{A_{OL} + (1 + \frac{R_f}{R_G})}, \alpha = 1 + \frac{R_f}{R_G} \\
&= v_{\text{in}} \frac{A_{OL}\alpha}{A_{OL} + \alpha} \\
&= v_{\text{in}} \frac{A_{OL}}{\frac{A_{OL}}{\alpha} + 1}, \beta = \frac{1}{\alpha} \\
&= v_{\text{in}} \frac{A_{OL}}{A_{OL}\beta + 1}, \beta = \frac{1}{1 + \frac{R_f}{R_G}} \Bigg|_{R_f = 4.95k, R_G = 100}
\end{aligned}
$$

Instrumentaion amplifier 1st Stage

$$
\begin{aligned}
I_G &= \frac{V_p^- - V_m^-}{R_G} \\
V_{op} &= \frac{-V_{\mathrm{op}}}{A_{OL}} + v_{\mathrm{ip}} + I_G R_{fp} \\
&= \frac{-V_{\mathrm{op}}}{A_{OL}} + v_{\mathrm{ip}} + \frac{\frac{-V_{\mathrm{op}}}{A_{OL}} + v_{\mathrm{ip}} - (\frac{-V_{\mathrm{om}}}{A_{OL}} + v_{\mathrm{im}})}{R_G} R_{fp} \\
&= -\frac{V_{\mathrm{op}}}{A_{OL}}(1 + \frac{R_{fp}}{R_G}) + v_{\mathrm{ip}}(1 + \frac{R_{fp}}{R_G}) + \frac{V_{\mathrm{om}}}{A_{OL}}\frac{R_{fp}}{R_G} - v_{\mathrm{im}}\frac{R_{fp}}{R_G} \\
V_{om} &= \frac{-V_{\mathrm{om}}}{A_{OL}} + v_{\mathrm{im}} + I_G R_{fm} \\
&= \frac{-V_{\mathrm{om}}}{A_{OL}} + v_{\mathrm{im}} + \frac{\frac{-V_{\mathrm{om}}}{A_{OL}} + v_{\mathrm{im}} - (\frac{-V_{\mathrm{op}}}{A_{OL}} + v_{\mathrm{ip}})}{R_G} R_{fm} \\
&= -\frac{V_{\mathrm{om}}}{A_{OL}}(1 + \frac{R_{fm}}{R_G}) + v_{\mathrm{im}}(1 + \frac{R_{fm}}{R_G}) + \frac{V_{\mathrm{op}}}{A_{OL}}\frac{R_{fm}}{R_G} - v_{\mathrm{ip}}\frac{R_{fm}}{R_G} \\
V_{op} - V_{om} &= -\frac{V_{\mathrm{op}}}{A_{OL}}(1 + \frac{R_{fp} + R_{fm}}{R_G}) + v_{\mathrm{ip}}(1 + \frac{R_{fp} + R_{fm}}{R_G}) + \frac{V_{\mathrm{om}}}{A_{OL}}(1 + \frac{R_{fp} + R_{fm}}{R_G}) - v_{\mathrm{im}}(1 + \frac{R_{fp} + R_{fm}}{R_G}) \\
V_{op} - V_{om} &= \frac{-(V_{\mathrm{op}} - V_{\mathrm{om}})}{A_{OL}}(1 + \frac{R_{fp} + R_{fm}}{R_G}) + (v_{\mathrm{ip}} - v_{\mathrm{im}})(1 + \frac{R_{fp} + R_{fm}}{R_G}) \\
V_{\mathrm{out}} &= \frac{V_{op} - V_{om}}{v_{ip} - v_{im}} \\
&= \frac{A_{OL}}{A_{OL}\beta + 1}, \beta = \frac{1}{1 + \frac{R_{fp} + R_{fm}}{R_G}}
\end{aligned}
$$

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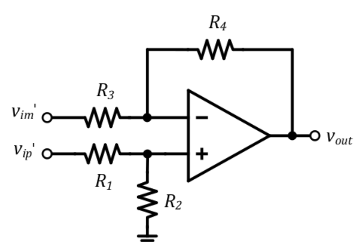
difference amp stage

given: $A_0 \to \infty$



$$R_1 = R_2 = R_3 = R_4 = 10k$$

$$v_{\mathrm{in}} = (v_{ip} + v_{im})\frac{A_{OL}}{A_{OL}\beta + 1}, \beta = \frac{1}{1 + \frac{R_2}{R_1}}$$

$$
\begin{aligned}
\frac{v_{\text{in}} - \frac{V_{\text{out}}}{A_{OL}}}{R_1} &= \frac{\frac{V_{\text{out}}}{A_{OL}} - V_{\text{out}}}{R_2} \\
\frac{V_{\text{out}}}{A_{OL}R_2} - \frac{V_{\text{out}}}{R_2} + \frac{V_{\text{out}}}{A_{OL}R_1} &= \frac{v_{\text{in}}}{R_1} \\
V_{\text{out}}(\frac{1}{A_{OL}R_2} - \frac{1}{R_2} + \frac{1}{A_{OL}R_1}) &= \frac{v_{\text{in}}}{R_1} \\
\frac{V_{\text{out}}}{A_{OL}}(\frac{1}{R_2} - \frac{A_{OL}}{R_2} + \frac{1}{R_1}) &= \frac{v_{\text{in}}}{R_1} \\
\frac{V_{\text{out}}}{A_{OL}}(\frac{1 - A_{OL}}{R_2} + \frac{1}{R_1}) &= \frac{v_{\text{in}}}{R_1} \\
\frac{V_{\text{out}}}{A_{OL}}\frac{(1 - A_{OL})R_1 + R_2}{R_1 R_2} &= \frac{v_{\text{in}}}{R_1} \\
V_{\text{out}}\frac{R_1}{A_{OL}}[\frac{1 - A_{OL} + \frac{R_2}{R_1}}{R_1 R_2}] &= \frac{v_{\text{in}}}{R_1} \\
\frac{V_{\text{out}}}{A_{OL}}\frac{1 - A_{OL} + \frac{R_2}{R_1}}{R_2} &= \frac{v_{\text{in}}}{R_1} \\
\frac{V_{\text{out}}}{-A_{OL}}\frac{A_{OL} - 1 - \frac{R_2}{R_1}}{R_2} &= \frac{v_{\text{in}}}{R_1} \\
V_{\text{out}} &= v_{\text{in}} A_{OL} \frac{\frac{-R_2}{R_1}}{A_{OL} - 1 - \frac{R_2}{R_1}}, \alpha = \frac{-R_2}{R_1} \\
&= v_{\text{in}} A_{OL} \frac{\alpha}{A_{OL} - 1 + \alpha} \\
&= v_{\text{in}} A_{OL} \frac{1}{\frac{A_{OL}-1}{\alpha} + 1} \\
&= v_{\text{in}} A_{OL} \frac{1}{\beta(A_{OL} - 1) + 1}, \beta = \frac{1}{\alpha} = \frac{-R_1}{R_2}\bigg|_{R_1=R_2=10k} \\
&\approx v_{\text{in}} A_{OL} \frac{1}{-A_{OL} + 1}\bigg|_{A_0 \to \infty} \\
&\approx -v_{\text{in}}
\end{aligned}
$$

Differential DC Gain

$$
\begin{aligned}
\frac{V_{\text{out}}}{v_{\text{in}}} &= \frac{A_{OL}}{A_{OL}\beta + 1}, \beta = \frac{1}{1 + \frac{R_{fp} + R_{fm}}{R_G}}, A_{OL} = 10^6 \\
\frac{V_{\text{out}}}{v_{\text{in}}} &= \frac{10^6}{\frac{10^6}{100} + 1} = 99.99\frac{V}{V}
\end{aligned}
$$

Frequency Response

$$
\begin{aligned}
A_{OL}(s) &= \frac{A_0}{1+s\tau} \\
f_{\text{3dB,OL}} &= \frac{1}{\tau} = \frac{f_T}{A_0} \\
A_{CL}(s) &= \frac{A_0}{1+s\tau+\beta A_0} \\
f_{\text{3dB,CL}} &= \frac{\beta A_0}{\tau_{\text{OL}}} = \beta f_T \bigg|_{f_T=1\text{MHz},\beta=0.01} = 10\text{kHz}
\end{aligned}
$$

Part B

Given $f = 100\text{Hz}$

$$
\begin{aligned}
\beta \quad &= \frac{1}{1+\frac{R_{fp}+R_{fm}}{R_G}} = \frac{1}{100} \\
G_{\text{actual}} &= A_{CL} = \frac{A_{OL}}{A_{OL}\beta+1}\bigg|_{A_0=10^6} &&= 99.99 \\
G_{\text{ideal}} &= A_{CL}\bigg|_{A_0\to\infty} = \frac{1}{\beta} &&= 100 \\
\delta_G \quad &= \frac{G_{\text{ideal}}-G_{\text{actual}}}{G_{\text{ideal}}} = 0.01\%
\end{aligned}
$$

Part C

Matched Resistors

$$
\begin{aligned}
\text{CMMR} &= \frac{A_{vd}}{A_{vcm}} \\
A_{vd1} \quad &= 1+\frac{R_{fp}+R_{fm}}{R_G}\bigg|_{R_{fp}=R_{fm}=4.95k,R_G=100} &&= 100 \\
A_{vd2} \quad &= \frac{R_2}{R_1}\bigg|_{R_1=R_2=10k} &&= 1 \\
A_{vcm} \quad &= \frac{V_0}{V_{icm}} &&= 1 \\
\text{CMMR} &= \text{CMMR}_1 \cdot \text{CMMR}_2 \\
&= [1+\frac{R_{fp}+R_{fm}}{R_G}] \cdot \frac{A_{vd2}+1}{4\epsilon} \\
&= 100 \cdot \frac{1+1}{4\cdot 0.001} \\
&= 50000 \approx 93.98\text{dB}
\end{aligned}
$$

Worst Case CMMR

$$\begin{aligned}
A_{vd1} &= 1 + \frac{R_{fp} + R_{fm}}{R_G} \\
&= 1 + \frac{4.95k(1-0.001) + 4.95k(1-0.001)}{100(1+0.001)} &&= 98.8 \\
A_{vd2} &= \frac{R_2}{R_1} \\
&= \frac{10k(1-0.001)}{10k(1+0.001)} &&= 0.998 \\
\text{CMMR} &= \text{CMMR}_1 \cdot \text{CMMR}_2 \\
&= [1 + \frac{R_{fp} + R_{fm}}{R_G}] \cdot \frac{A_{vd2} + 1}{4\epsilon} \\
&= 98.8 \cdot \frac{0.998 + 1}{4 \cdot 0.001} \\
&= 49350 \approx 93.87\text{dB}
\end{aligned}$$

Worst Case Gain Error

$$\delta_G = \frac{G_{\text{ideal}} - G_{\text{actual}}}{G_{\text{ideal}}} = \frac{100 - (98.8 \cdot 0.998)}{100} = 1.4\%$$

Part D

Given: resistors are matached

worst-case input-referred offset $= \frac{V_{\text{out}}}{A_v} = 250uV$

$100uV - (-100uV) = 200uV$ (U1 and U2 total offset voltage)

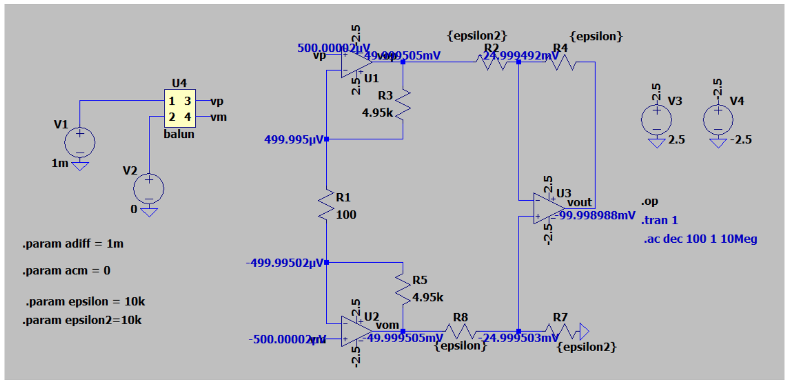
$(250uV - 200uV) \cdot 100\frac{V}{V} = 5mV$ (offset at difference amplifier output)

$$V_{\text{out}} = \frac{-R_4}{R_3} v_{im} + (1 + \frac{R_4}{R_3})(\frac{R_1}{R_1 + R_2})(v_{ip} + v_{os})$$

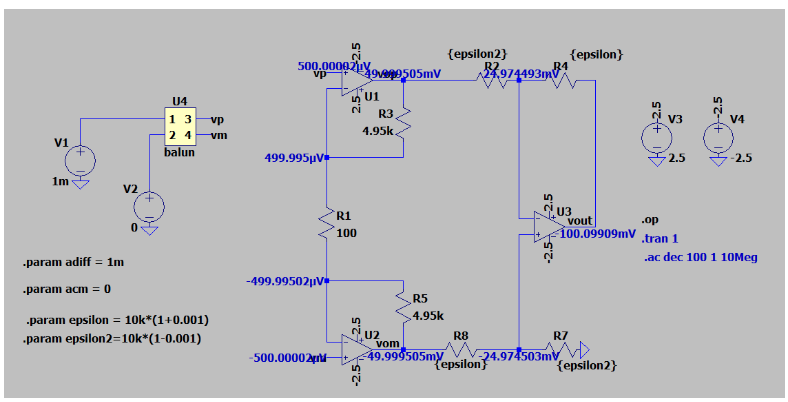
$$5mv = (1 + \frac{R_4}{R_3})(\frac{R_1}{R_1 + R_2}) v_{os}$$

$v_{os3} = 5mV$

Part E.1



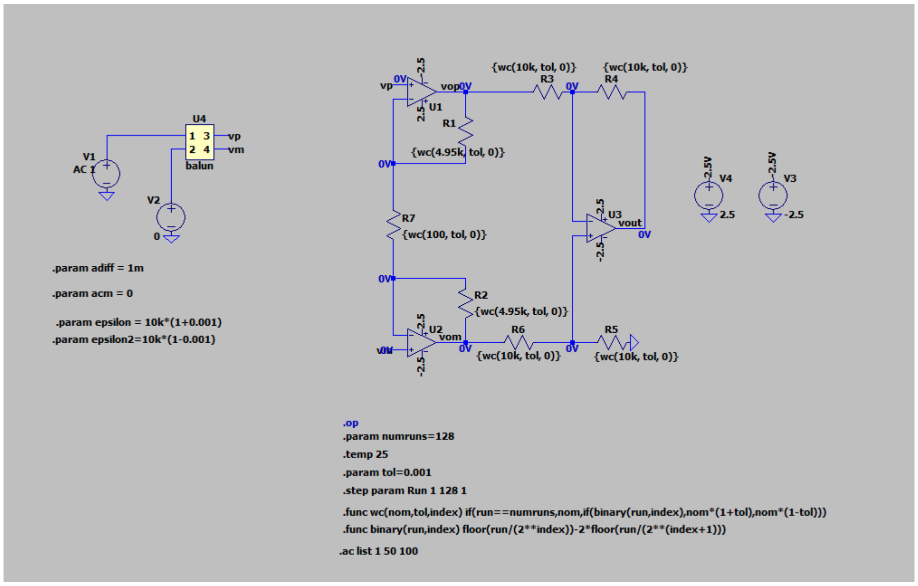
V(vp)	500.000 uV
V(vop)	49.9995 mV
V(vm)	-500.000 uV
V(vom)	-49.9995 mV
V(n001)	499.995 uV
V(n002)	-499.995 uV
V(n003)	-24.9995 mV
V(n004)	-24.9995 mV
V(vout)	-99.999 mV



V(vp)	500.000 uV
V(vop)	49.9995 mV
V(vm)	-500.000 uV
V(vom)	-49.9995 mV
V(n001)	499.995 uV
V(n002)	-499.995 uV
V(n003)	-24.9745 mV
V(n004)	-24.9745 mV
V(vout)	-100.099 mV

The output offset due to mismatched resistors is $\frac{99.999-100.099}{99.999} = 0.1\%$

Part E.2



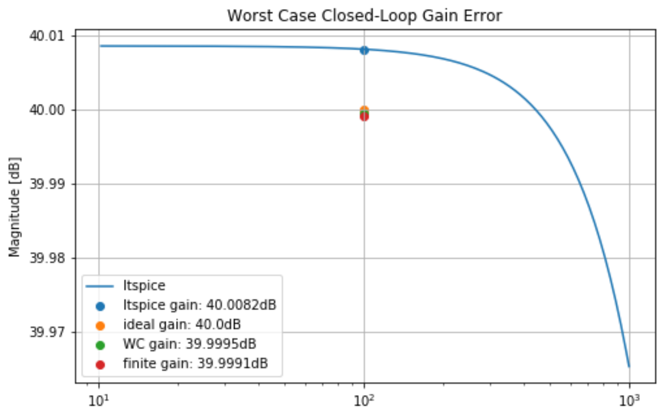
In [8]:
```python
filepath = 'data/instrumentation_amp_CL_vid.txt'
df = read_ltspice(filepath,'ac','db')
df = df[(df['Freq.']>=1e1)&(df['Freq.']<=1e3)]
mag = df['Mag_V(vout)']
freq = df['Freq.']

#Find 100Hz Magnitude
x0 = np.where(freq<=100)[0][-1]
mag100 = mag.iloc[x0]
label = "{:.4f}".format(mag100)
print(f"100Hz magnitude: {label}dB")
```

```
100Hz magnitude: 40.0082dB
```

In [9]:
```python
filepath = 'data/instrumentation_amp_wc_ac.txt'
df = read_ltspice_wc(filepath)
df['mag'] = df['V(vout)'].apply(lambda x: x.split(',')[0])
df['mag'] = df['mag'].apply(lambda x: x[1:-2])
df['mag'] = df['mag'].astype('float64')
df['ang'] = df['V(vout)'].apply(lambda x: x.split(',')[1])
df['ang'] = df['ang'].apply(lambda x: x[0:-2])
df['ang'] = df['ang'].astype('float64')
df['Freq.'] = df['Freq.'].astype('float64')
df = df[df['Freq.']==100]
magwc = min(df.mag)
label2 = "{:.4f}".format(magwc)
print(f"Worst Case 100Hz magnitude: {label2}dB")
```

```
Worst Case 100Hz magnitude: 39.9995dB
```

In [10]:
```
fig, ax = plt.subplots(1,figsize=(8,5))
ax.set_title(r'Worst Case Closed-Loop Gain Error')
ax.semilogx(freq, mag, label='ltspice')
ax.scatter(freq.iloc[x0],[mag100], label=f'ltspice gain: {round(mag100,4)}dB')
ax.scatter([100],[20*np.log10(100)], label=f'ideal gain: {round(20*np.log10(100),4)}dB')
ax.scatter([100],[magwc], label=f'WC gain: {round(magwc,4)}dB')
ax.scatter([100],[20*np.log10(99.99)], label=f'finite gain: {round(20*np.log10(99.99),4)}dB')
ax.set_ylabel('Magnitude [dB]')
ax.grid()
ax.legend()
plt.show();
```

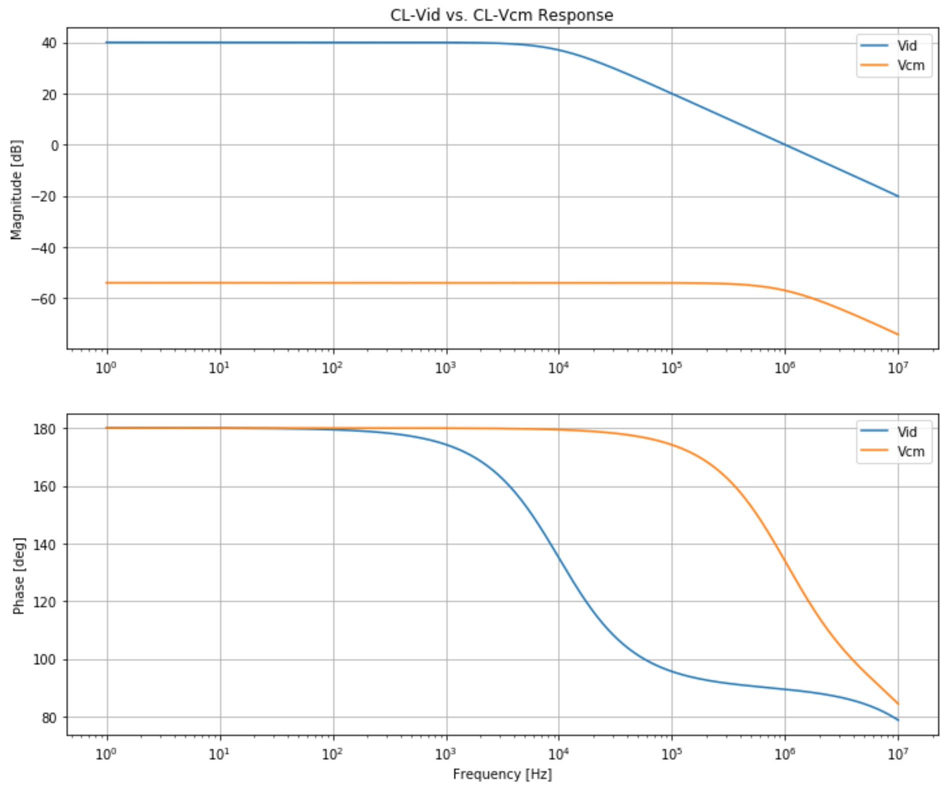


Part E.3

In [11]:
```
filepath = 'data/instrumentation_amp_CL_vid.txt'
filepath2 = 'data/instrumentation_amp_CL_vcm.txt'
df = read_ltspice(filepath,'ac','db')
df2 = read_ltspice(filepath2,'ac','db')
mag1 = df['Mag_V(vout)']
ang1 = df['Phase_V(vout)']
mag2 = df2['Mag_V(vout)']
ang2 = df2['Phase_V(vout)']
freq = df['Freq.']
print(f'Common Mode Rejection Ratio: {round(max(mag1)-max(mag2),4)}dB')
```

```
Common Mode Rejection Ratio: 93.9792dB
```

In [12]:
```python
#Plot
fig, axs = plt.subplots(2,figsize=(12,10))
axs[0].set_title('CL-Vid vs. CL-Vcm Response')
axs[0].semilogx(freq, mag1, label='Vid')
axs[0].semilogx(freq, mag2, label='Vcm')
axs[0].set_ylabel('Magnitude [dB]')
axs[0].grid()
axs[0].legend()
axs[1].semilogx(freq, ang1, label='Vid')
axs[1].semilogx(freq, ang2, label='Vcm')
axs[1].set_xlabel('Frequency [Hz]')
axs[1].set_ylabel('Phase [deg]')
axs[1].grid()
axs[1].legend()
plt.show();
```



In [ ]: