First SPICE Exercise

Fundamentals Of Electronics - a.a. 2018-2019 - University of Padua (Italy)

Pietro Prandini (mat. 1097752)

May 2, 2019

1 Audio amplifier

1.1 Voltage gain and frequency domain - Ideal op. amp.

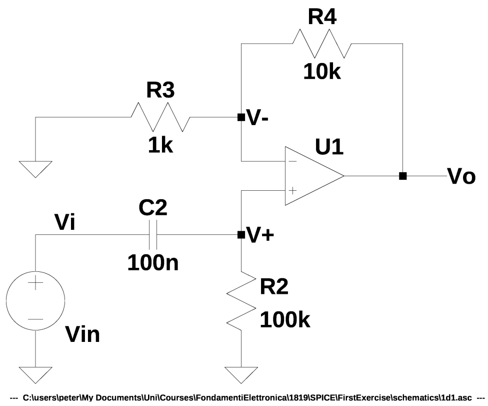

Figure 1: Audio amplifier - Ideal op. amp.

By the analysis of the figure 1's circuit, It's possible to calculate the node V_+ voltage from the ratio of the voltage divider formed by R_2 and C_2, indeed the node V_+ voltage is the same voltage of the resistance R_2 (equation 1).

$$V_+(s) = V_{in}(s)\frac{R_2}{R_2 + \frac{1}{sC_2}} = V_{in}(s)\frac{R_2}{R_2 + \frac{1}{sC_2}}\frac{sC_2}{sC_2} = V_{in}(s)\frac{sC_2R_2}{1 + sC_2R_2} \tag{1}$$

The negative feedback produces the virtual short circuit effect, so the V_- and the V_+ voltages have virtually the same value (equation 2), and, because of the fact that the ideal operational amplifier U_1 isn't absorb current from the V_- and the V_+ nodes, the current of I_{R_4} is the same current of I_{R_3} (equation 3).
The current I_{R_3} is calculated by the Ohm law (equation 4).

$$V_- = V_+ \tag{2}$$

$$I_{R_4} = I_{R_3} \tag{3}$$

$$I_{R_3} = \frac{V_-}{R_3} = \frac{V_+}{R_3} \tag{4}$$

By combining the past considerations it's possible to define the output voltage V_o relating to the voltage input V_{in} (equation 5).

$$V_o(s) = V_+(s) + R_4 I_{R_4} = V_+(s) + R_4 I_{R_3} = V_+(s) + R_4 \cdot \frac{V_+(s)}{R_3} = V_+(s) \cdot \left(1 + \frac{R_4}{R_3}\right) = V_{in}(s) \frac{sC_2R_2}{1 + sC_2R_2} \cdot \left(1 + \frac{R_4}{R_3}\right) \tag{5}$$

Consequently of the equation 5, the transfer function $V_o(s)/V_{in}(s)$ is described by the equation 6.

$$\frac{V_o(s)}{V_{in}(s)} = \frac{sC_2R_2}{1 + sC_2R_2} \left(1 + \frac{R_4}{R_3}\right) \tag{6}$$

Defining K as in the equation 7 and ω_1 as in the equation 8, the transfer function $V_o(s)/V_{in}(s)$ became in the Bode form (equation 9).

$$K = C_2R_2 \cdot \left(1 + \frac{R_4}{R_3}\right) \tag{7}$$

$$\omega_1 = \frac{1}{C_2R_2} \tag{8}$$

$$\frac{V_o(s)}{V_{in}(s)} = K \frac{s}{1 + s\frac{1}{\omega_1}} \tag{9}$$

Finally it's possible to calculate the frequency domain by the analysis of the transfer function's Bode form (equations 10 and 11).

$$K|_{dB} = 20 \log_{10} |K| = \log_{10} \left| C_2R_2 \cdot \left(1 + \frac{R_4}{R_3}\right) \right| = -19.1722dB \tag{10}$$

$$\log_{10} |\omega_1| = \log_{10} \left| \frac{1}{C_2R_2} \right| = 2.0000 \tag{11}$$

1.2 Voltage output waveform - LT1028 op. amp.

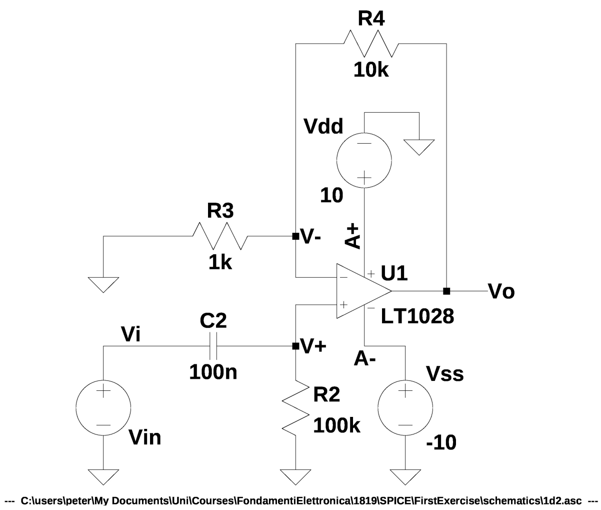

Figure 2: Audio amplifier - LT1028 op. amp.

From now it's considered the circuit of the figure 2.

In order to simulate the waveform output voltage with a sinusoidal voltage input V_{in} with an amplitude of $10mV$ and the frequencies of $1Hz$, $10Hz$ and $10kHz$, it's possible to use a SPICE transient analysis.

1.2.1 Netlist

It's presented the netlist for the SPICE analysis requested.

```
* Audio Amplifier - Waveform
****************************************************************************
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****************************************************************************

* Libraries
.LIB LTC.lib

* Amplifiers
XU1 V+ V- A+ A- Vo LT1028

* Capacitances
C2 Vi V+ 100n

* Generators
Vin Vi 0 DC 0 AC 1 sin(0 10mV {F} 0 0 0)
Vdd A+ 0 DC 10
Vss A- 0 DC -10

* Resistances
R2 V+ 0 100k
R3 V- 0 1k
R4 Vo V- 10k

* Analysis
.step param F list 1Hz 10Hz 100Hz
.tran 0 250m 0 1m uic

.END
```

1.2.2 Graph

This graph is the output of the last netlist presented. There are three curves, one for every frequency analyzed ($1Hz$, $10Hz$ and $10kHz$).

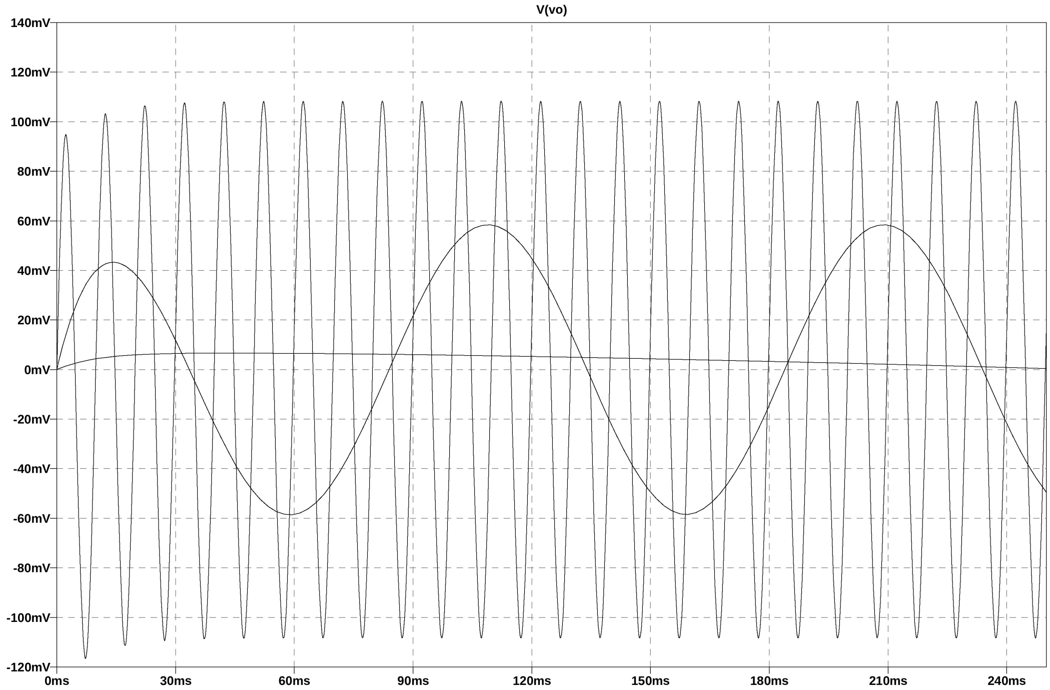

Figure 3: Audio Amplifier - Voltage output waveform

1.3 Bode plot - LT1028 op. amp.

The Bode plot could be generated with a SPICE small signal AC analysis.

1.3.1 Netlist

It's presented the netlist for the SPICE analysis requested.

```
* Audio Amplifier - Bode plot
*****************************************************************************
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*****************************************************************************

* Libraries
.LIB LTC.lib

* Amplifiers
XU1 V+ V- A+ A- Vo LT1028

* Capacitances
C2 Vi V+ 100n

* Generators
Vin Vi 0 DC 0 AC 1 sin(0 10mV {F} 0 0 0)
Vdd A+ 0 DC 10
Vss A- 0 DC -10

* Resistances
R2 V+ 0 100k
```

```
R3 V- 0 1k
R4 Vo V- 10k

* Analysis
.step param F list 1Hz 10Hz 100Hz
.ac DEC 10 1 100k

.END
```

1.3.2 Graph

The Bode plot generated could be visible in the figure 4. The continuous line represents the magnitude and the dashed line represents the phase frequency.

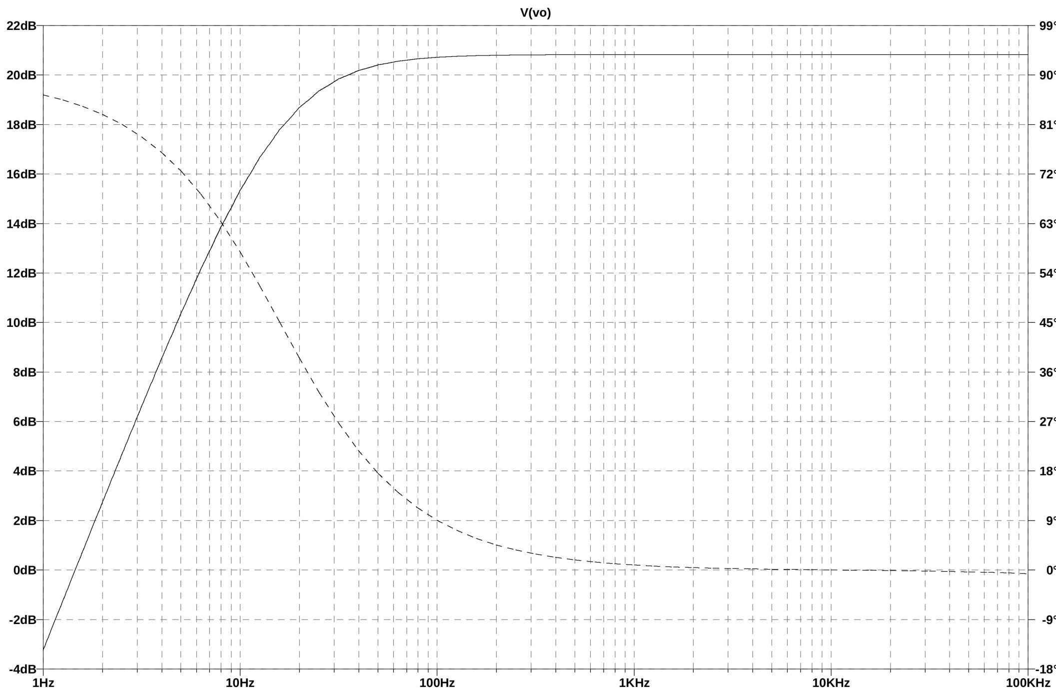

Figure 4: Audio Amplifier - Bode plot

1.4 Saturation - LT1028 op. amp.

The voltage output saturation could be analized by giving an abnormally high voltage input to the input. The next netlist analyzes the voltage output with an input with $100V$ amplitude.

```
* Audio Amplifier - Waveform with abnormal input voltage amplitude
****************************************************************************
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****************************************************************************

* Libraries
.LIB LTC.lib

* Amplifiers
```

```
XU1 V+ V- A+ A- Vo LT1028

* Capacitances
C2 Vi V+ 100n

* Generators
Vin Vi 0 DC 0 AC 1 sin(0 100V 10Hz 0 0 0)
Vdd A+ 0 DC 10
Vss A- 0 DC -10

* Resistances
R2 V+ 0 100k
R3 V- 0 1k
R4 Vo V- 10k

* Analysis
.tran 0 250m 0 1m uic

.END
```

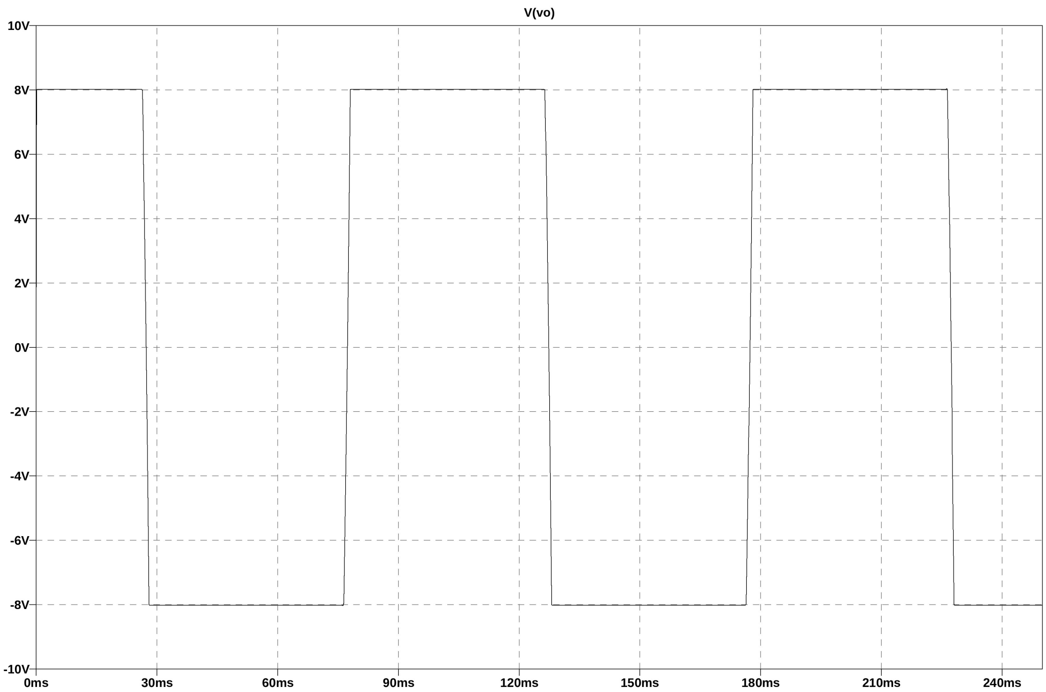

Figure 5: Audio Amplifier - Output voltage saturation

The graph generated (figure 5) makes clear the fact that the voltage output saturation is on $\pm 8V$. So it's possible to calculate wich is the highest input signal that avoids the saturation (equation 12).

$$
\begin{aligned}
|V_o| &\leq 8V \\
\left| V_{in} \cdot \frac{j\omega C_2 R_2}{1 + j\omega C_2 R_2} \cdot \left(1 + \frac{R_4}{R_3}\right) \right| &\leq 8V \\
|V_{in}| \cdot \left| \frac{j\omega C_2 R_2}{1 + j\omega C_2 R_2} \right| \cdot \left| \left(1 + \frac{R_4}{R_3}\right) \right| &\leq 8V \\
|V_{in}| \cdot \frac{\sqrt{(\omega C_2 R_2)^2}}{\sqrt{1 + (\omega C_2 R_2)^2}} \cdot \frac{R_3 + R_4}{R_3} &\leq 8V \\
|V_{in}| \leq 8V \cdot \frac{\sqrt{1 + (\omega C_2 R_2)^2}}{\omega C_2 R_2} \cdot \frac{R_3}{R_3 + R_4} &
\end{aligned}
\tag{12}
$$

In order to have a maximum value of the input voltage V_{in}, the ω could be setted to a static value. For example with $\omega = 10Hz \cdot 2\pi$ the maximum value of the input voltage is $|V_{in}| \leq 1.36701V$ (output voltage graph on figure 6).

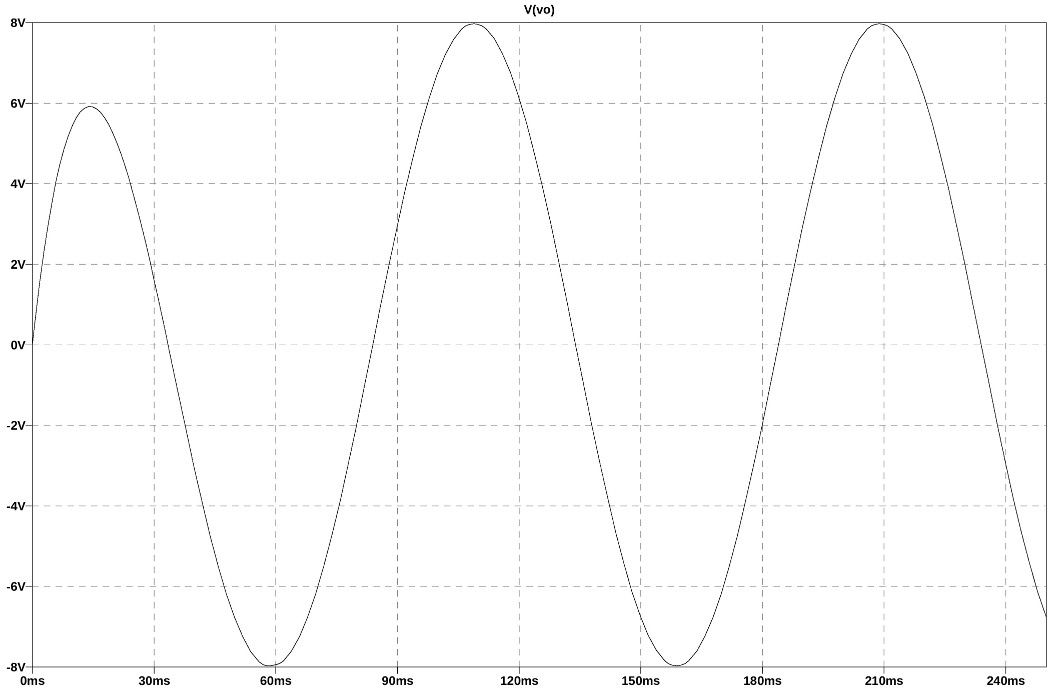

Figure 6: Audio Amplifier - Output voltage with an amplitude of the imput voltage equal to $1.36701V$, frequency equal to $10Hz$

1.4.1 Output voltage waveform - $V_{in} = 2 \cdot |V_{inMAX}|$

The netlist used for plot the output voltage waveform with a double input voltage relatively to the maximum input voltage calculated is:

```
* Audio Amplifier - Waveform Vin = 2*VinMax
******************************************************************************
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******************************************************************************

* Libraries
```

```
.LIB LTC.lib

* Amplifiers
XU1 V+ V- A+ A- Vo LT1028

* Capacitances
C2 Vi V+ 100n

* Generators
Vin Vi 0 DC 0 AC 1 sin(0 {2*1.36701V} 10Hz 0 0 0)
Vdd A+ 0 DC 10
Vss A- 0 DC -10

* Resistances
R2 V+ 0 100k
R3 V- 0 1k
R4 Vo V- 10k

* Analysis
.tran 0 250m 0 1m uic

.END
```

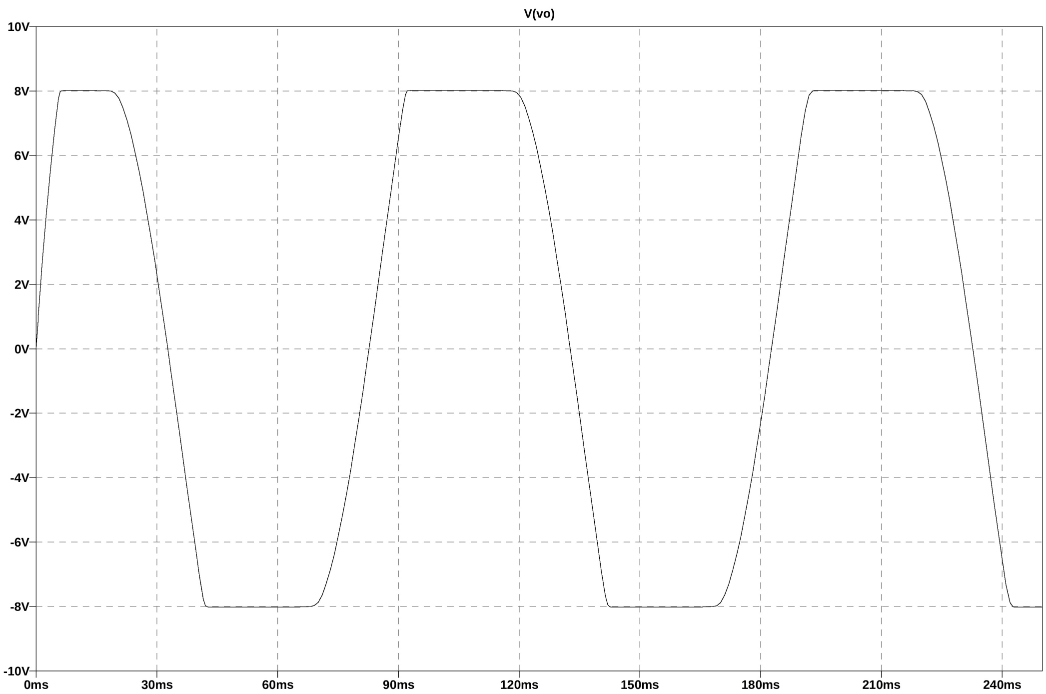

Figure 7: Audio Amplifier - Output voltage with an amplitude of the imput voltage equal to $2 \cdot 1.36701V$, frequency equal to $10Hz$

The graph generated is presented on the figure 7.

1.5 Saturation - LT1028 op. amp. - $R_2 = 109775.2\Omega$

Using the equation 12 and setting $\omega = 10Hz \cdot 2\pi$ the maximum value of the input voltage is $|V_{in}| \leq 1.28091V$ (output voltage graph on figure 8)

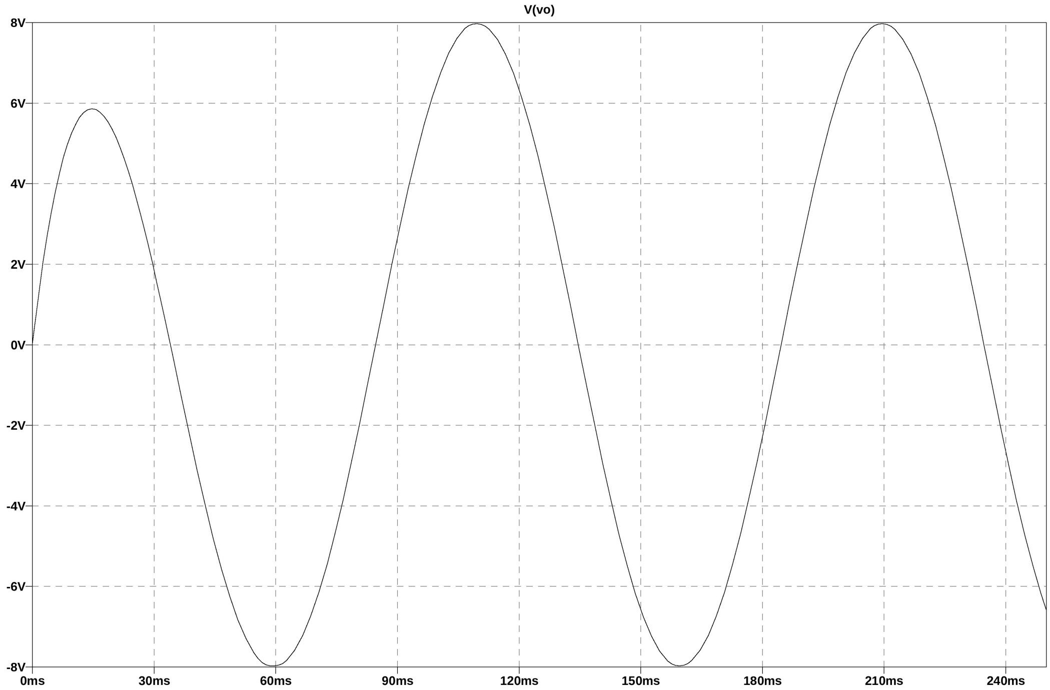

Figure 8: Audio Amplifier - Output voltage with an amplitude of the imput voltage equal to $1.28091V$, frequency equal to $10Hz$, R_2 equal to 109775.2Ω

1.5.1 Output voltage waveform - $R_2 = 109775.2\Omega$ - $V_{in} = 2 \cdot |V_{inMAX}|$

The netlist used for plot the output voltage waveform with a double input voltage relatively to the maximum input voltage calculated is:

```
* Audio Amplifier - Waveform R2 = 109775.2 Vin = 2*VinMax
****************************************************************************
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****************************************************************************

* Libraries
.LIB LTC.lib

* Amplifiers
XU1 V+ V- A+ A- Vo LT1028

* Capacitances
C2 Vi V+ 100n

* Generators
Vin Vi 0 DC 0 AC 1 sin(0 {2*1.28091V} 10Hz 0 0 0)
Vdd A+ 0 DC 10
Vss A- 0 DC -10

* Resistances
R2 V+ 0 109775.2
R3 V- 0 1k
R4 Vo V- 10k
```

```
* Analysis
.tran 0 250m 0 1m uic

.END
```

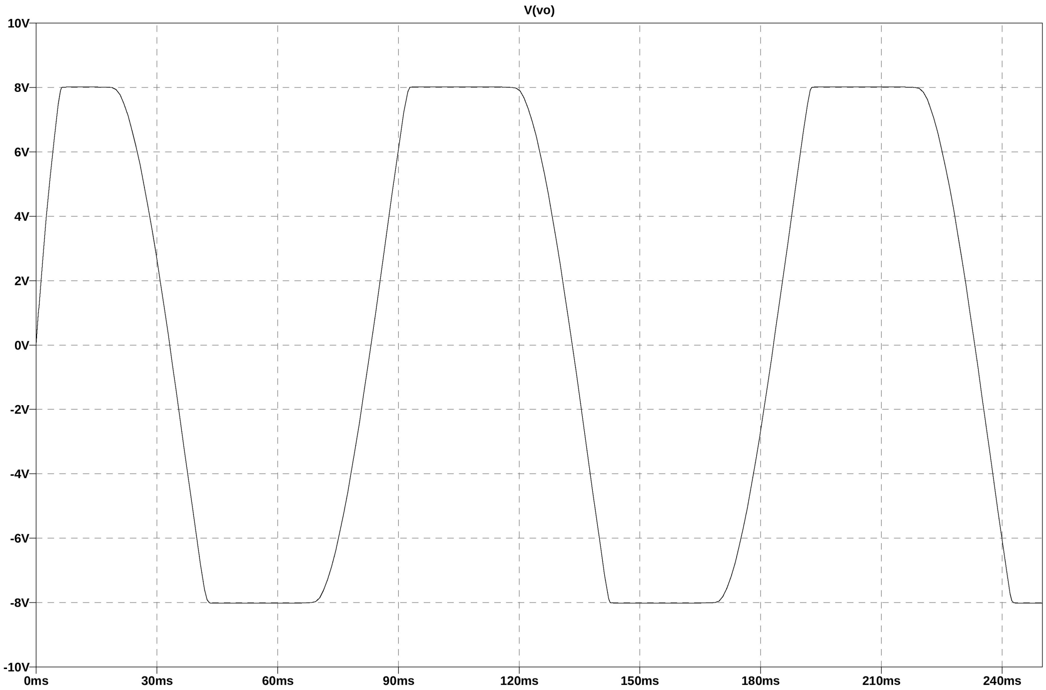

Figure 9: Audio Amplifier - Output voltage with an amplitude of the imput voltage equal to $2 \cdot 1.28091V$, frequency equal to $10Hz$, R_2 equal to 109775.2Ω

The graph generated is presented on the figure 9.

1.6 Power delivered to the amplifier

$$P_{DC} = V_{dd} \cdot I_{dd} + V_{ss} \cdot I_{ss} \tag{13}$$

1.6.1 Case A - $R_2 = 100k\Omega$ $V_{in} = 2 \cdot 1.36701V$

```
* Audio Amplifier - Operating Point R2 = 100k Vin = 2*1.36701V
****************************************************************************
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****************************************************************************

* Libraries
.LIB LTC.lib

* Amplifiers
XU1 V+ V- A+ A- Vo LT1028

* Capacitances
```

```
C2 Vi V+ 100n

* Generators
Vin Vi 0 DC 0 AC 1 sin(0 {2*1.36701V} 10Hz 0 0 0)
Vdd A+ 0 DC 10
Vss A- 0 DC -10

* Resistances
R2 V+ 0 100k
R3 V- 0 1k
R4 Vo V- 10k

* Analysis
.op

.END
```

$$P_{DC} = 10V \cdot (-0.00736621A) + (-10V) \cdot (+0.00736621A) = -0.14732420W$$

1.6.2 Case B - $R_2 = 109775.2\Omega$ $V_{in} = 2 \cdot 1.28091V$

```
* Audio Amplifier - Operating Point R2 = 109775.2 Vin = 2*1.28091V
****************************************************************************
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****************************************************************************

* Libraries
.LIB LTC.lib

* Amplifiers
XU1 V+ V- A+ A- Vo LT1028

* Capacitances
C2 Vi V+ 100n

* Generators
Vin Vi 0 DC 0 AC 1 sin(0 {2*1.28091V} 10Hz 0 0 0)
Vdd A+ 0 DC 10
Vss A- 0 DC -10

* Resistances
R2 V+ 0 109775.2
R3 V- 0 1k
R4 Vo V- 10k

* Analysis
.op

.END
```

$$P_{DC} = 10V \cdot (-0.00736621A) + (-10V) \cdot (+0.00736621A) = -0.14732420W$$

2 Band Pass Amplifier

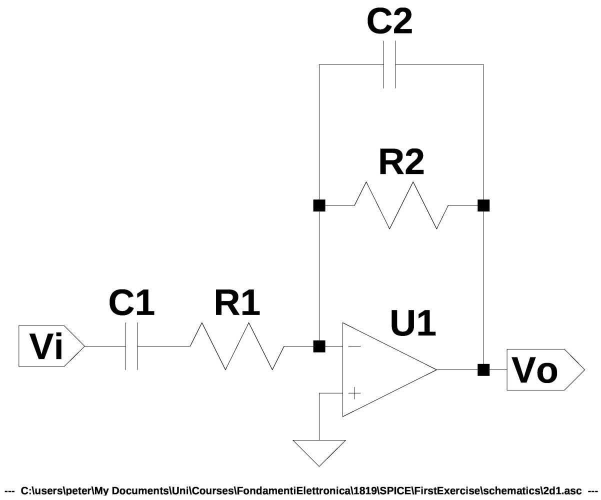

Figure 10: Band pass amplifier - Circuit schematics

2.1 Transfer function

$$\begin{aligned}
V_o(s) &= -(C_2 \parallel R_2) \cdot \frac{V_i(s)}{\frac{1}{sC_1} + R_1} \\
V_o(s) &= -\frac{\frac{1}{sC_2} \cdot R_2}{\frac{1}{sC_2} + R_2} \cdot \frac{sC_2}{sC_2} \cdot \frac{V_i(s)}{\frac{1}{sC_1} + R_1} \cdot \frac{sC_1}{sC_1} \\
V_o(s) &= -\frac{R_2}{1 + sC_2R_2} \cdot \frac{V_i(s) \cdot sC_1}{1 + sC_1R_1} \\
\frac{V_o(s)}{V_i(s)} &= -\frac{sC_1R_2}{(1 + sC_1R_1)(1 + sC_2R_2)} \qquad (14)
\end{aligned}$$

2.2 Determining capacitances and resistances

The conditions to respect are described by the system 15.

$$\begin{cases} R_1 = 1097752\Omega/1000 \\ \omega_1 = \frac{1}{C_1R_2} = 10 \\ \omega_2 = \frac{1}{C_1R_1} = 10^3 \\ \omega_3 = \frac{1}{C_2R_2} = 10^6 \end{cases} \qquad (15)$$

Resolving the system it's possible to find the value of the circuit's capacitances and resistances (system 16).

$$\begin{cases} R_1 = 1097.752\Omega \\ R_2 = 109775.2\Omega \\ C_1 = 910.95256nF \\ C_2 = 9.10953pF \end{cases} \qquad (16)$$

2.3 Bode plot

2.3.1 Netlist

```
* Amplifier bandwidth - Bode plot
*******************************************************************************
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*********************************************************************************

* Ideal Operational Amplifier subcircuit
.LIB opamp.sub

* Amplifiers
XU1 V- 0 Vo opamp Aol=100k GBW=10meg

* Capacitances
C1 Vi N001 910.95256n
C2 Vo V- 9.10953p

* Generators
Vin Vi 0 DC 0 AC 1 sin(0 100mV 100Hz 0 0 0)

* Resistances
R1 N001 V- 1097.752
R2 Vo V- {109775.2*{P}}

* Analysis
.step param P list 0.01 0.1 10 100 1000
.AC DEC 10 1 100MEG

.END
```

2.3.2 Graph

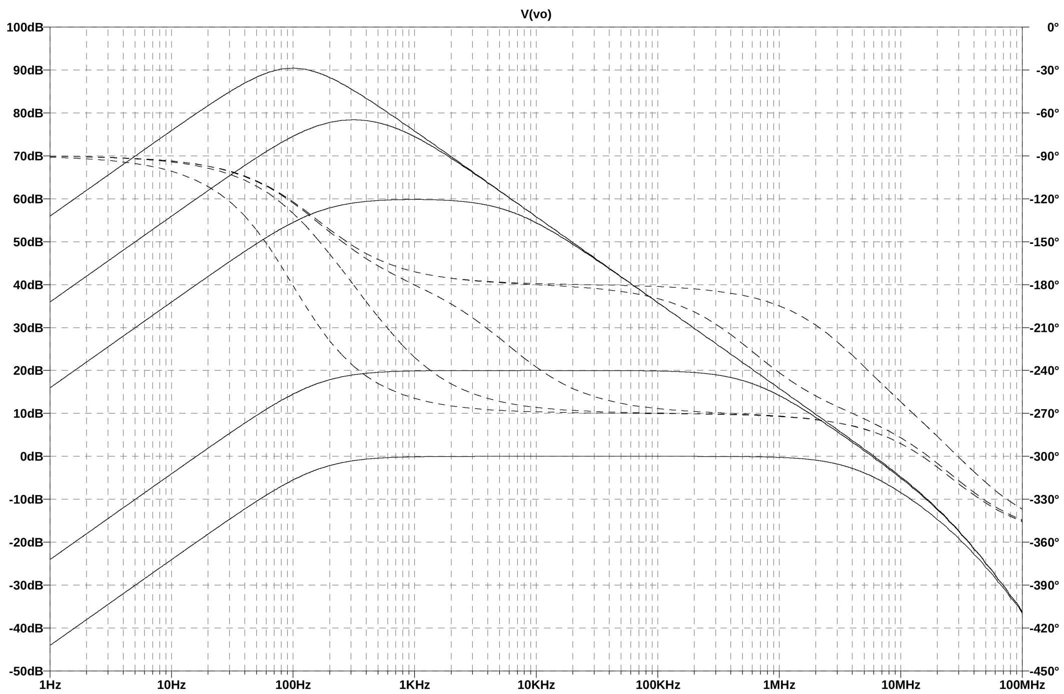

Figure 11: Band pass amplifier - Bode plot

2.4 Output voltage

2.4.1 Vin frequency $10Hz$ $100Hz$

```
* Amplifier pass-band - Output Voltage - Vin frequency 10Hz 100Hz
```

```
*****************************************************************************
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*****************************************************************************

* Ideal Operational Amplifier subcircuit
.LIB opamp.sub

* Amplifiers
XU1 V- 0 Vo opamp Aol=100k GBW=10meg

* Capacitances
C1 Vi N001 910.95256n
C2 Vo V- 9.10953p

* Generators
Vin Vi 0 DC 0 AC 1 sin(0 100mV {F} 0 0 0)

* Resistances
R1 N001 V- 1097.752
R2 Vo V- 109775.2

* Analysis
.step param F list 10Hz 100Hz
.tran 0 250m 0 1m uic

.END
```

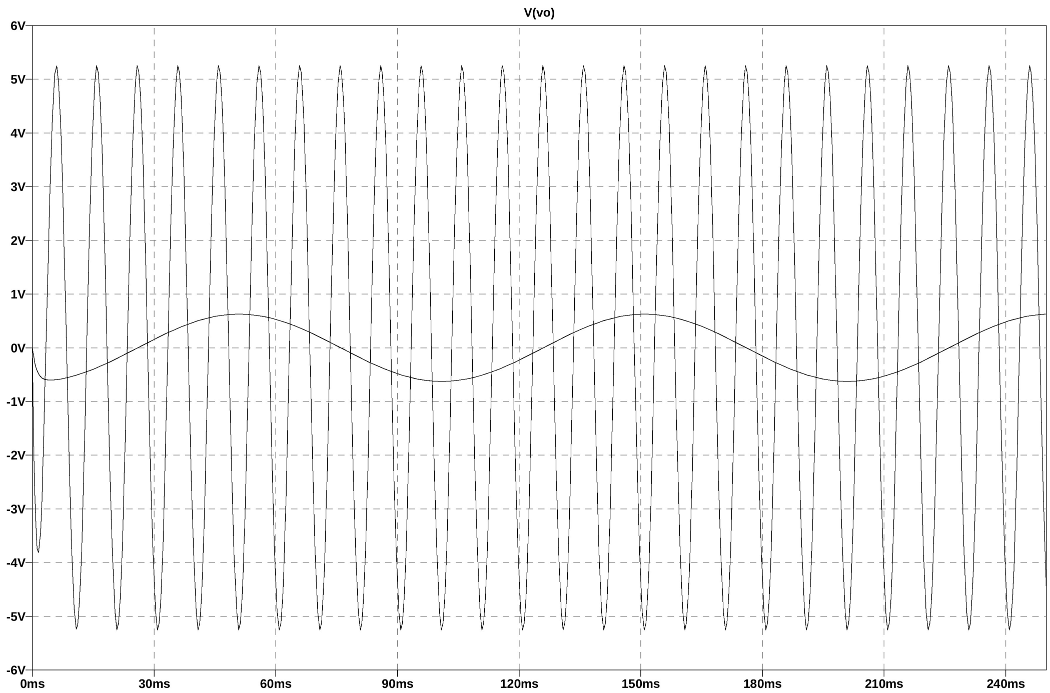

Figure 12: Band pass amplifier - Bode plot - Vin frequency $10Hz$ $100Hz$

2.4.2 Vin frequency $1kHz$ $10kHz$ $100kHz$

```
* Amplifier pass-band - Output Voltage - Vin frequency 1kHz 10kHz 100kHz
***************************************************************************
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***************************************************************************

* Ideal Operational Amplifier subcircuit
.LIB opamp.sub

* Amplifiers
XU1 V- 0 Vo opamp Aol=100k GBW=10meg

* Capacitances
C1 Vi N001 910.95256n
C2 Vo V- 9.10953p

* Generators
Vin Vi 0 DC 0 AC 1 sin(0 100mV {F} 0 0 0)

* Resistances
R1 N001 V- 1097.752
R2 Vo V- 109775.2

* Analysis
.step param F list 1kHz 10kHz 100kHz
.tran 0 2m 0 1m uic

.END
```

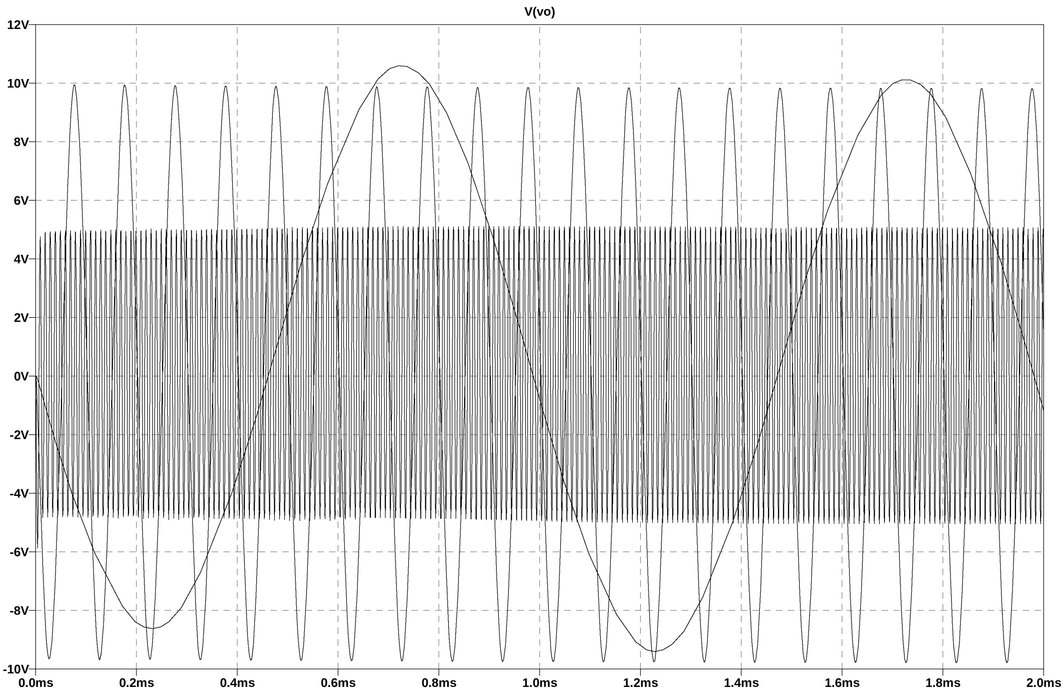

Figure 13: Band pass amplifier - Bode plot - Vin frequency $1kHz$ $10kHz$ $100kHz$

2.4.3 Vin frequency $1MEGHz$ $10MEGHz$ $100MEGHz$

```
* Amplifier pass-band - Output Voltage - Vin frequency 1MEGHz 10MEGHz 100MEGHz
*****************************************************************************
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*****************************************************************************

* Ideal Operational Amplifier subcircuit
.LIB opamp.sub

* Amplifiers
XU1 V- 0 Vo opamp Aol=100k GBW=10meg

* Capacitances
C1 Vi N001 910.95256n
C2 Vo V- 9.10953p

* Generators
Vin Vi 0 DC 0 AC 1 sin(0 100mV {F} 0 0 0)

* Resistances
R1 N001 V- 1097.752
R2 Vo V- 109775.2

* Analysis
.step param F list 1MEGHz 10MEGHz 100MEGHz
.tran 0 20u 0 1m uic

.END
```

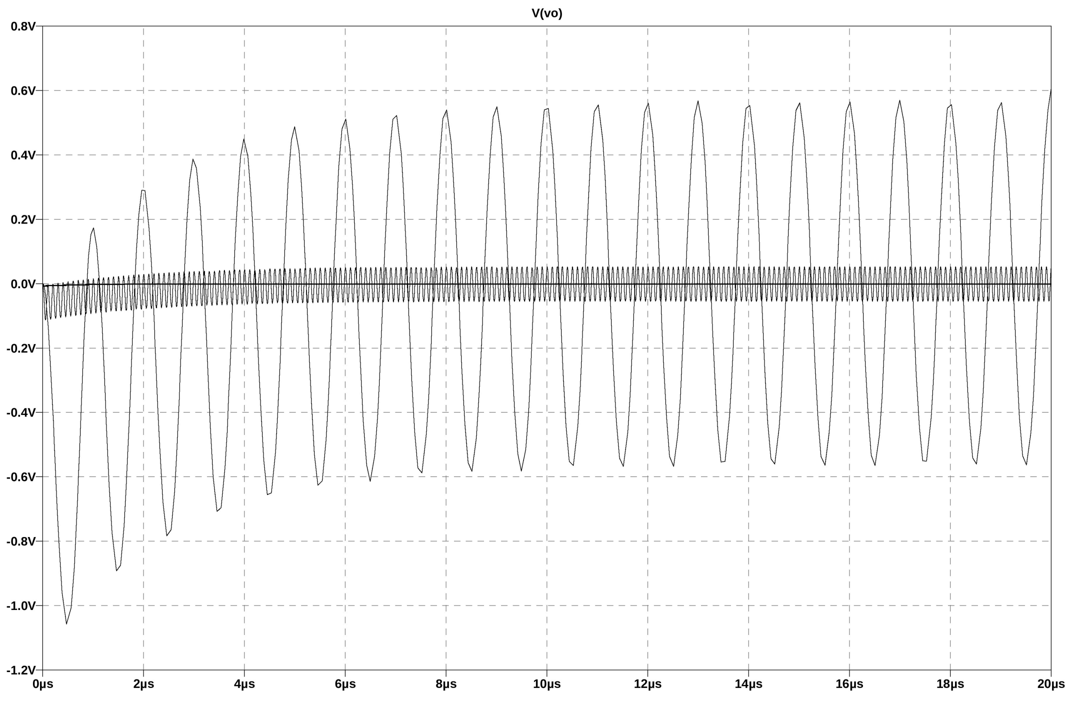

Figure 14: Band pass amplifier - Bode plot - Vin frequency $1MEGHz$ $10MEGHz$ $100MEGHz$

3 Front-end amplifier for resistive bridge with resistometric sensor

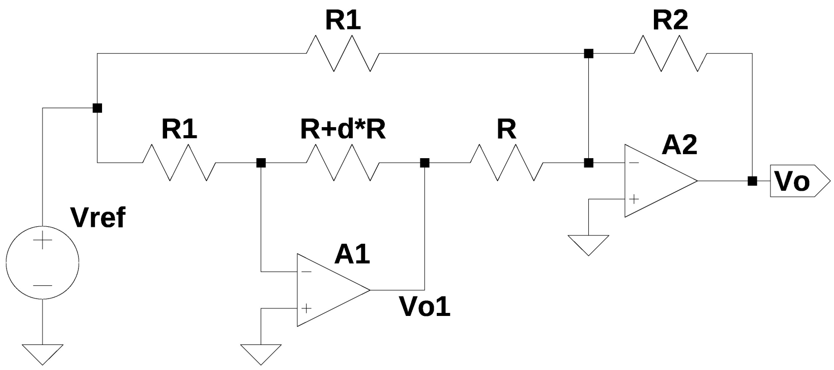

Figure 15: Front-end amplifier for resistive bridge with resistometric sensor

3.1 Output voltage - V_o

$$I_{R_1} = \frac{V_{ref}}{R_1} = -I_{R+\delta R} \tag{17}$$

$$V_{o_1} = (R+\delta R) \cdot I_{R+\delta R} = (R+\delta R) \cdot \frac{V_{ref}}{R_1} = V_{ref} \cdot \frac{R+\delta R}{R_1} \tag{18}$$

$$I_R = \frac{V_{o_1}}{R} = V_{ref} \cdot \frac{R+\delta R}{R_1 R} = V_{ref} \cdot \frac{1+\delta}{R_1} \tag{19}$$

$$I_{R_2} = I_{R_1} + I_R \tag{20}$$

$$\begin{aligned} V_o &= R_2 I_{R_2} = R_2(I_{R_1} + I_R) \\ &= R_2\left(-\frac{V_{ref}}{R_1} + V_{ref} \cdot \frac{1+\delta}{R_1}\right) \\ &= R_2 V_{ref}\left(\frac{-1+1+\delta}{R_1}\right) \\ &= V_{ref}\frac{R_2}{R_1}\delta \end{aligned} \tag{21}$$

3.2 Defining R_2 and R_1

Conditions:

$$\begin{cases} R_2 = \frac{1097752}{20}\Omega \\ \frac{R_2}{R_1} = 20 \end{cases} \tag{22}$$

$$\begin{cases} R_1 = 2.74438k\Omega \\ R_2 = 54.88760k\Omega \end{cases} \tag{23}$$