Design and simulation of piezoelectric transducer test circuit

25769, Sensing and Measuring

Group 18

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Contents

1 | Introduction

1.1 | The system for measuring the force applied to the foot when stepping and its importance

The subject of this project is developing a system to measure and analyze the forces applied to the front and rear of the foot during walking or running. Understanding these ground reaction forces is important for injury prevention, rehabilitation, and athletic performance optimization. Excessive impact forces during foot strike can cause injuries such as stress fractures and plantar fasciitis. On the other hand, optimized foot force patterns can improve efficiency and speed for runners. Currently, force measurements require expensive lab equipment like force plates. This project aims to develop an affordable, wearable sensor system to measure foot forces during real-world activities. Analyzing force data could help identify high-risk movement patterns and guide training improvements. Widespread access to foot force measurement could benefit recreational and competitive athletes as well as clinical populations.

1.2 | The existing systems and specifications

This project involves developing a wearable system to measure forces on the front and back of the foot during walking and running. These ground reaction forces are important biomechanical markers but currently difficult to monitor outside laboratories. This project aims to create an affordable, portable sensor system to quantify foot forces, using pressure sensors attached to the foot. Measuring foot forces could enable injury prevention and optimization for athletes and clinical populations.
Real world apllications of this system include:

- Rehabilitation: foot force measurements could help track recovery progress and identify high-risk movement patterns.
- Athletic performance optimization: Optimized foot force patterns can improve efficiency and speed for runners. Measuring foot forces could help identify high-risk movement patterns and guide training improvements.
- Clinical populations: foot force measurements could help track recovery progress and identify high-risk movement patterns.

Here is some real world examples of the applications of this system:

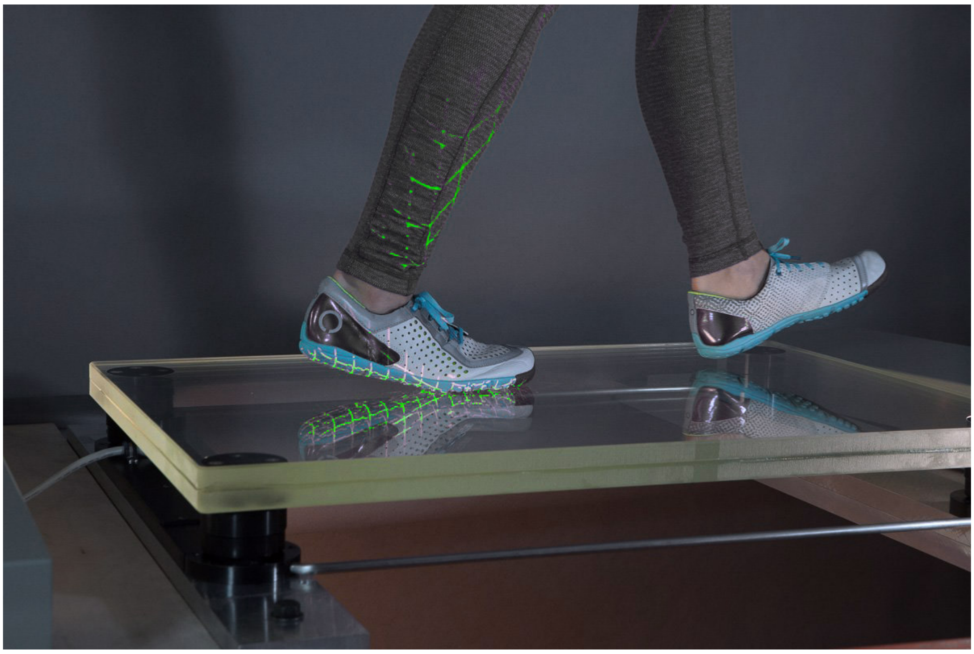

Figure 1.1: A force plate used in a laboratory setting to measure ground reaction forces.

1.3 | What we have done

First we used a matlab code to simulate the input signal of the sensor. Then we designed a circuit to measure the force applied to the sensor. We used LtSpice to simulate the circuit and test it and checked the results.

1.4 | Presentation of information in the rest of the report

In the next section, we will explain the theoretical background of the project. Then we will explain the circuit design and the simulation results. Finally, we will discuss the results and conclude the project.

2 | Theoretical background & assumptions

2.1 | Assumptions

in this project, we have developed a system to measure the forces applied to the front and rear of the foot during walking or running. We assumed that:

1. the frequency of the force applied to the foot is about 1 Hz
2. the maximum force applied to the sensor is about 1000 N
3. the sensor has a white noise with a standard deviation of 0.001 V
4. the urban electric noise frequency is about 50 Hz with a standard deviation of 0.1 V

For a piezoelectric we have the following equation:

$$V = \frac{dFt}{\epsilon_0 \epsilon_r A} \tag{2.1}$$

where :

- V is the voltage generated by the piezoelectric
- d is the piezoelectric coefficient
- F is the force applied to the piezoelectric
- t is the thickness of the piezoelectric
- ϵ_0 is the permittivity of free space
- ϵ_r is the relative permittivity of the piezoelectric
- A is the area of the piezoelectric

We made the following assumptions:

- $d = 2.89 \times 10^{-10} \frac{C}{N}$
- $t = 0.01m$
- $\epsilon_0 = 8.854 \times 10^{-12} \frac{F}{m}$
- $\epsilon_r = 1300$
- $A = 5^2 3.14 \times 10^{-4} m^2$

Thus in the case of the maximum force applied to the sensor, we have:

$$V = \frac{2.89 \times 10^{-10} \times 1000 \times 0.01}{8.854 \times 10^{-12} \times 1300 \times 25 \times 3.14 \times 10^{-4}} = 3.2V \tag{2.2}$$

We assume that this voltage gets 1000 times weaker, so we have:

$$V \simeq 0.0032V \tag{2.3}$$

If we assume that the input signal has a shape of sine wave, we have:

$$V_{Front} = 0.032 sin(2\pi t) \tag{2.4}$$
$$V_{Back} = 0.032 sin(2\pi t + \pi/2) \tag{2.5}$$

Where V_{Front} is the voltage generated by the piezoelectric attached to the front of the foot and V_{Back} is the voltage generated by the piezoelectric attached to the back of the foot.
The signal simulated in Matlab is shown below:

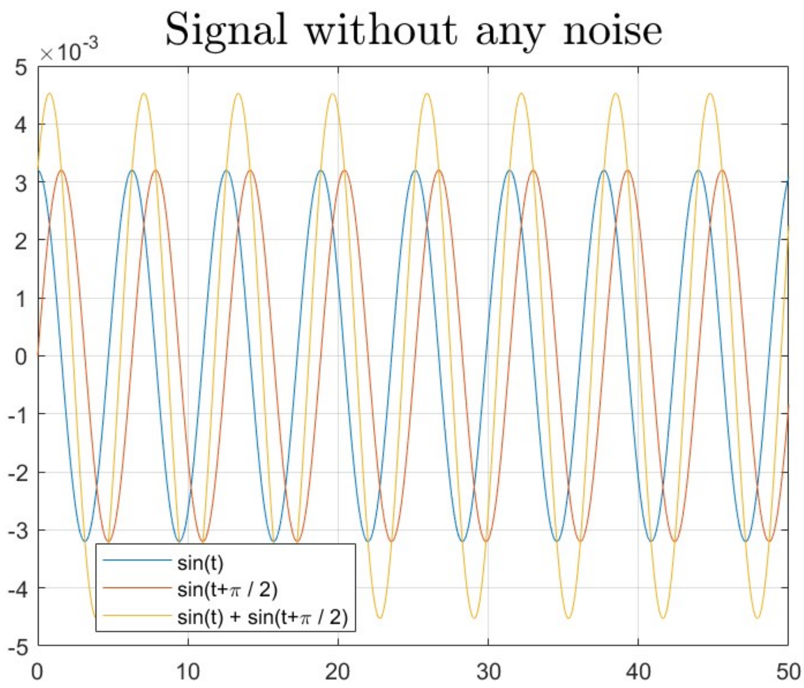

Figure 2.1: The input signal whitout noise simulated in Matlab.

2.2 | Common circuits used to measure the force applied to the foot

2.2.1 | Force plates

The most common way to measure the force applied to the foot is using a force plate. A force plate is a device that measures the forces generated by a body standing on or moving across them. Force plates are used in a variety of settings including clinical, athletic, and industrial settings. Force plates are used to measure the ground reaction forces generated by a body standing on or moving across them, to quantify balance ability and assess gait and posture.

2.2.2 | Pressure sensors

Most common circuits used to measure the force applied have differential amplifiers. A differential amplifier is a type of electronic amplifier that amplifies the difference between two input voltages but suppresses any voltage common to the two inputs. It is an analog circuit with two inputs V_1 and V_2 and one output V_o in which the output is ideally proportional to the difference between the two voltages V_1 and V_2. The gain of the amplifier is given by $A_d = \frac{V_o}{V_1 - V_2}$.

2.2.3 | Filters

Then after ampflying the difference between the two voltages, we need to filter the noise. The most common filters used are low pass filters and high pass filters. A low-pass filter is a filter that passes signals with a frequency lower than a selected cutoff frequency and attenuates signals with frequencies higher than the cutoff frequency. The actual amount of attenuation for each frequency varies from filter to filter. A high-pass filter (HPF) is an electronic filter that passes signals with a frequency higher than a certain cutoff frequency and attenuates signals with frequencies lower than the cutoff frequency. The amount of attenuation for each frequency depends on the filter design.

2.3 | Our circuit

We deisgned a circuit containing two instrumentation amplifiers to measure the force applied to the sensor, then we have a differential amplifier to subtract the two signals and get the difference between the two forces applied to the front and rear of the foot. Then we have a low pass filter to filter the noise and get the original signal. Finally, we have a high pass filter to filter the 50 Hz noise and get the original signal.

2.4 | Theoretical background

2.4.1 | Instrumentation amplifier

An instrumentation amplifier is a type of differential amplifier that has been outfitted with input buffer amplifiers, which eliminate the need for input impedance matching and thus make the amplifier particularly suitable for use in measurement and test equipment. Additional characteristics include very low DC offset, low drift, low noise, very high open-loop gain, very high common-mode rejection ratio, and very high input impedances. Instrumentation amplifiers are used where great accuracy and stability of the circuit both short- and long-term are required.

2.4.2 | Differential amplifier

A differential amplifier is a type of electronic amplifier that amplifies the difference between two input voltages but suppresses any voltage common to the two inputs. It is an analog circuit with two inputs V_1 and V_2 and one output V_o in which the output is ideally proportional to the difference between the two voltages V_1 and V_2. The gain of the amplifier is given by $A_d = \frac{V_o}{V_1 - V_2}$.

2.4.3 | Low pass filter

A low-pass filter is a filter that passes signals with a frequency lower than a selected cutoff frequency and attenuates signals with frequencies higher than the cutoff frequency. The actual amount of attenuation for each frequency varies from filter to filter. A low-pass filter is the complement of a high-pass filter.

2.4.4 | High pass filter

A high-pass filter (HPF) is an electronic filter that passes signals with a frequency higher than a certain cutoff frequency and attenuates signals with frequencies lower than the cutoff frequency. The amount of attenuation for each frequency depends on the filter design. A high-pass filter is the complement of a low-pass filter.

2.4.5 | Noise

Noise is unwanted sound judged to be unpleasant, loud or disruptive to hearing. From a physics standpoint, noise is indistinguishable from sound, as both are vibrations through a medium, such as air or water. The difference arises when the brain receives and perceives a sound.

2.4.6 | White noise

White noise is a random signal having equal intensity at different frequencies, giving it a constant power spectral density. The term is used, with this or similar meanings, in many scientific and technical disciplines, including physics, acoustical engineering, telecommunications, statistical forecasting, and many more. White noise refers to a statistical model for signals and signal sources, rather than to any specific signal.

2.4.7 | Urban electric noise

Electric noise is the random fluctuations in an electrical signal, a characteristic of all electronic circuits. Noise generated by electronic devices varies greatly, as it can be produced by several different effects.

3 | Circuit design

3.1 | Softwares used

We used the following softwares to design and simulate the circuit:

3.1.1 | Matlab

We used Matlab to simulate the input signal of the sensor. Matlab is a programming and numeric computing platform used by millions of engineers and scientists to analyze data, develop algorithms, and create models. Matlab allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages.

3.1.2 | LtSpice

We used LtSpice to simulate the circuit and test it. LtSpice is a high performance SPICE simulator, schematic capture and waveform viewer with enhancements and models for easing the simulation of analog circuits.

3.2 | The input signal

The signal we are trying to measure is the force applied to the foot. We assume that the frequency of the force applied to the foot is about 1 Hz and the maximum force applied to the sensor is about 1000 N. We also assume that the sensor has a white noise with a standard deviation of 0.01 V and the urban electric noise frequency is about 50 Hz with a standard deviation of 0.1 V. We also assume that the input signal has a shape of sine wave. Thus we have:

$$V_{Front} = 0.0032sin(2\pi t) + 0.1sin(100\pi t) + n(t) \tag{3.1}$$
$$V_{Back} = 0.0032sin(2\pi t + \pi/2) + 0.1sin(100\pi t) + n(t) \tag{3.2}$$

Where V_{Front} is the voltage generated by the piezoelectric attached to the front of the foot and V_{Back} is the voltage generated by the piezoelectric attached to the back of the foot and $n(t)$ is the white noise with a standard deviation of 0.001 V. The signal simulated in Matlab is shown below:

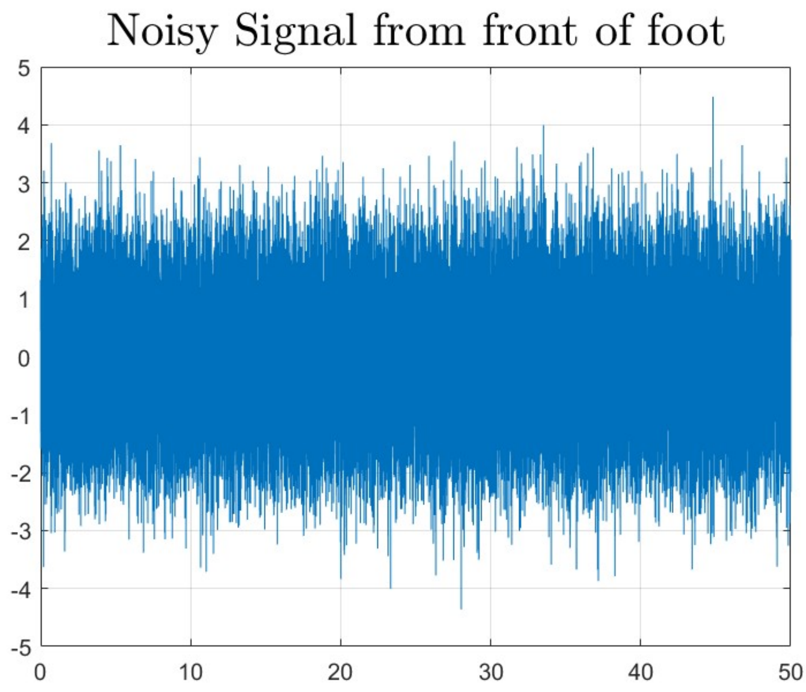

Figure 3.1: Realistic input signal simulated in Matlab.

3.3 | The circuit

The block diagram of the circuit is shown below:

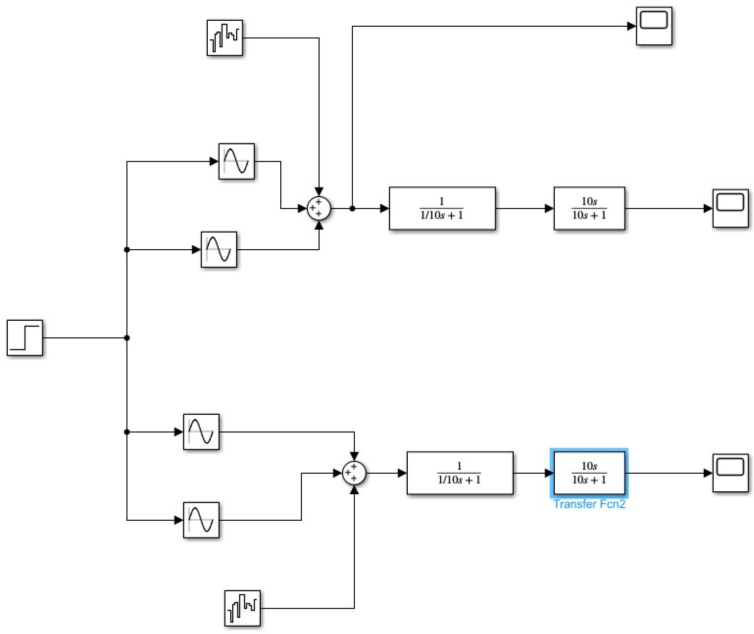

Figure 3.2: The block diagram of the circuit.

Block diagram of the circuit contains 2 important parts:

- The High pass filter: A high-pass filter (HPF) is an electronic filter that passes signals with a frequency higher than a certain cutoff frequency and attenuates signals with frequencies lower than the cutoff frequency. The amount of attenuation for each frequency depends on the filter design. A high-pass filter is usually modeled as a linear time-invariant system. It is sometimes called a low-cut filter or bass-cut filter in the audio domain. High-pass filters have many uses, such as blocking DC from circuitry sensitive to non-zero average voltages or radio frequency devices. They can also be used in conjunction with a low-pass filter to produce a bandpass filter.
- The low pass filter: A low-pass filter is a filter that passes signals with a frequency lower than a selected cutoff frequency and attenuates signals with frequencies higher than the cutoff frequency. The exact frequency response of the filter depends on the filter design. The filter is sometimes called a high-cut filter, or treble cut filter in audio applications. A low-pass filter is the complement of a high-pass filter.

Trnasfer function for a high pass filter is given by:

$$H(s) = \frac{s}{s + \omega_c} \tag{3.3}$$

Where ω_c is the cutoff frequency.
Trnasfer function for a low pass filter is given by:

$$H(s) = \frac{\omega_c}{s + \omega_c} \tag{3.4}$$

Where ω_c is the cutoff frequency.
Fpr the perfrence of the cutoff frequency, we chose $\omega_c = 2\pi Hz$.
Thus desired transfer function for the high pass filter is given by:

$$H(s) = \frac{s}{s + 2\pi} \rightarrow R = 1k\Omega, C = 0.300\mu F \tag{3.5}$$

And desired transfer function for the low pass filter is given by:

$$H(s) = \frac{2\pi}{s + 2\pi} \rightarrow R = 1k\Omega, C = 0.300\mu F \tag{3.6}$$

3.3.1 | The high pass filter

The high pass filter is shown below:

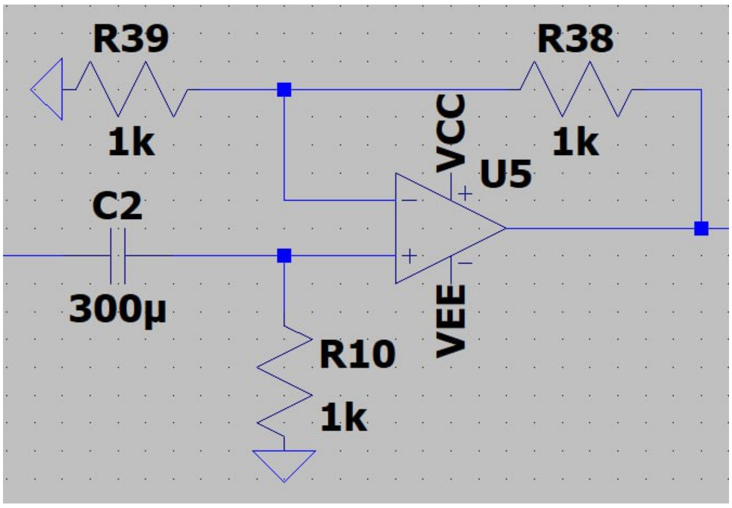

Figure 3.3: The high pass filter.

The high pass filter is designed to filter the urban electric noise. The transfer function of the high pass filter is given by:

$$H(s) = \frac{s}{s + 2\pi} \tag{3.7}$$

3.3.2 | The low pass filter

The low pass filter is shown below:

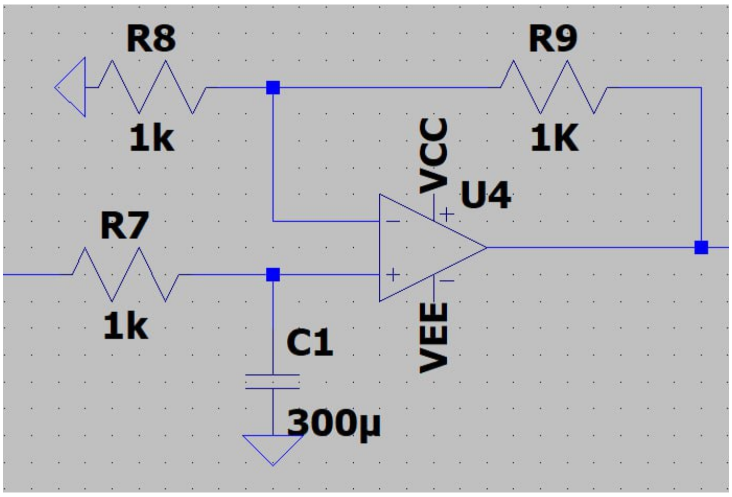

Figure 3.4: The low pass filter.

The low pass filter is designed to filter the white noise. The transfer function of the low pass filter is given by:

$$H(s) = \frac{2\pi}{s + 2\pi} \tag{3.8}$$

3.3.3 | The Instrumentation amplifier

The instrumentation amplifier is shown below:

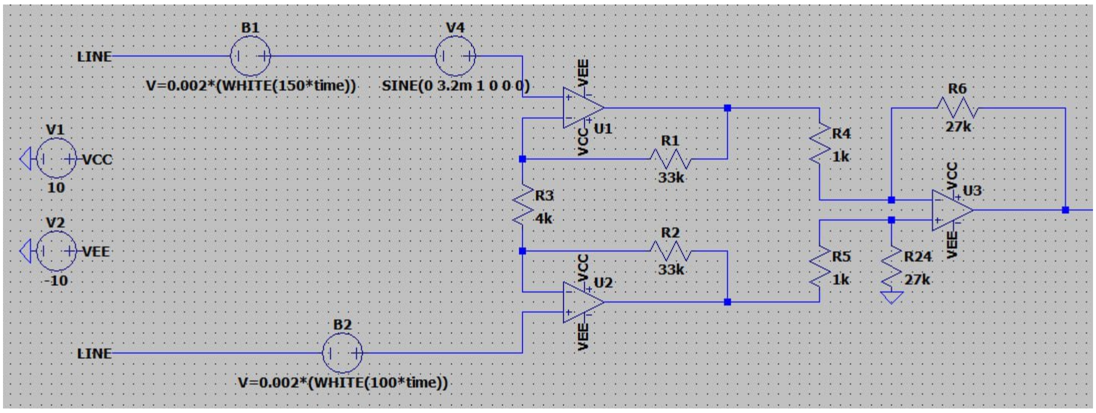

Figure 3.5: The instrumentation amplifier.

The instrumentation amplifier is designed to amplify the difference between the two voltages. The gain of the amplifier is given by:

$$A_d = \frac{V_o}{V_1 - V_2} = (1 + 2\frac{R_1}{R_3})\frac{R_6}{R_4} = (1 + \frac{33}{4}) \times \frac{27}{1} = 9.25 \times 27 = 250 \tag{3.9}$$

3.3.4 | The summing amplifier

The summing amplifier is shown below:

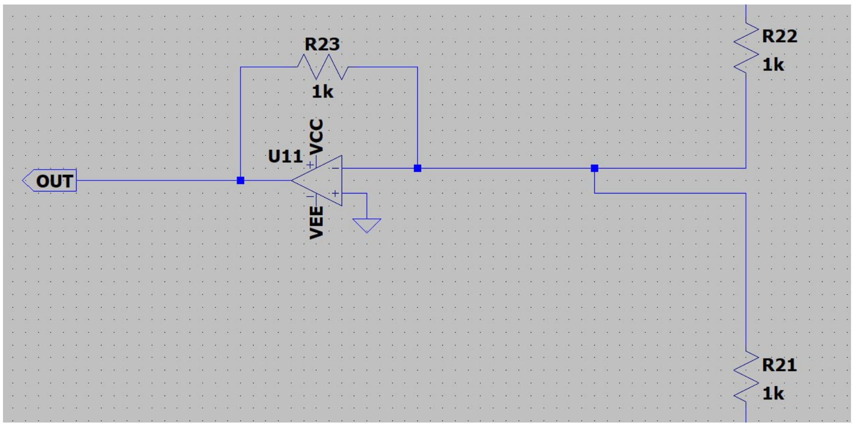

Figure 3.6: The summing amplifier.

The summing amplifier is designed to sum the output of the instrumentation amplifiers after passing through the low pass and high pass filters. The gain of the amplifier is given by:

$$A_d = \frac{V_o}{V_{in}} = -\frac{R_{23}}{R_{21}} = -\frac{1k\Omega}{1k\Omega} = -1 \tag{3.10}$$

3.3.5 | The circuit designed to measure the force applied to the foot

The circuit designed to measure the force applied to the foot is shown below:

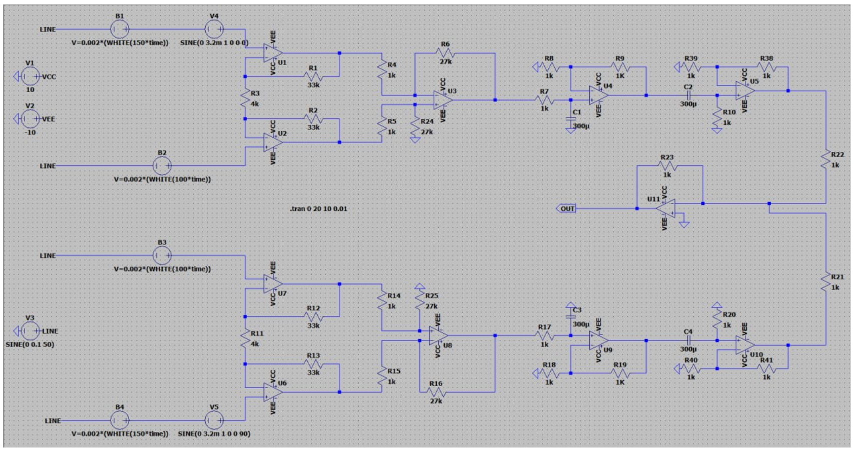

Figure 3.7: The circuit designed to measure the force applied to the foot.

The circuit is designed to measure the force applied to the foot. The output of the circuit is the voltage generated by the piezoelectric attached to the front of the foot and the piezoelectric attached to the back of the foot. The output of the circuit is given by:

$$V_o = -(V_{Front} + V_{Back}) \tag{3.11}$$

3.4 | The simulation

The simulation of the circuit is shown below:

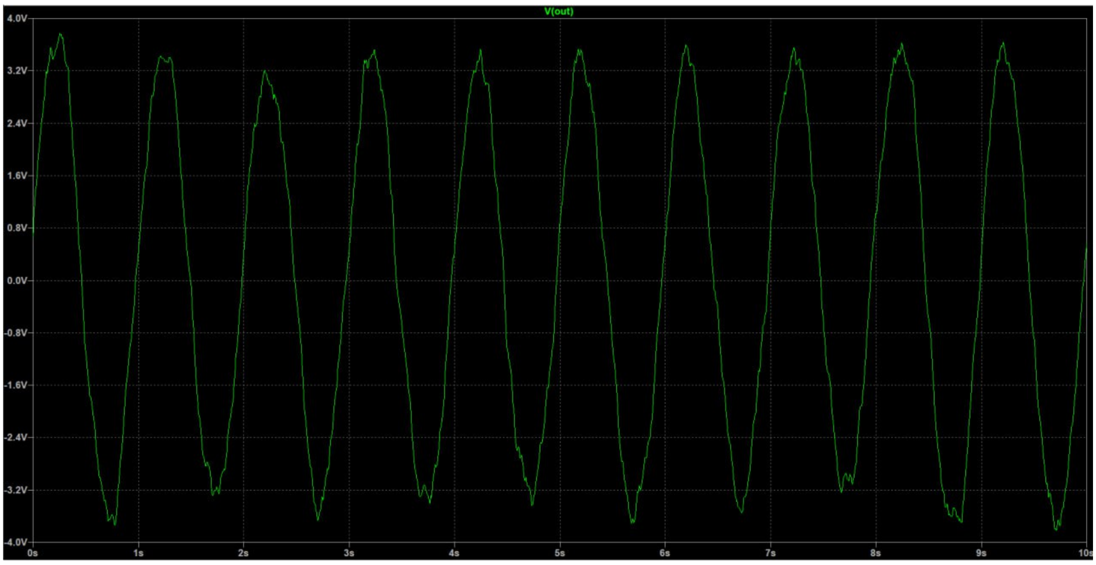

Figure 3.8: The simulation of the circuit.

Maximum output voltage is about 3.4 V and the minimum output voltage is about -3.4 V. The output voltage is the voltage generated by the piezoelectric attached to the front of the foot and the piezoelectric attached to the back of the foot for a man weighting 100 kg.

4 | Conclusion

Given the input signal, the circuit designed is able to measure the force applied to the foot; however, It's not for real-world application, the walking frequency is not exactly 1 Hz, and the maximum force applied to the sensor is not exactly 1000 N-people can apply more force on one foot than the other- and the urban electric noise amplitude is not exactly 0.1 V.
But for the purpose of this project, the circuit is able to measure the force applied to the foot. The output of the circuit is almost sum of the voltage generated by the piezoelectric attached to the front of the foot and the piezoelectric attached to the back of the foot. For real-world application, the circuit should be tested with real data and the parameters of the circuit should be adjusted to fit the real-world application.