Design & Simulation of a High-Gain EMG Amplifier

Mid Evaluation Presentation

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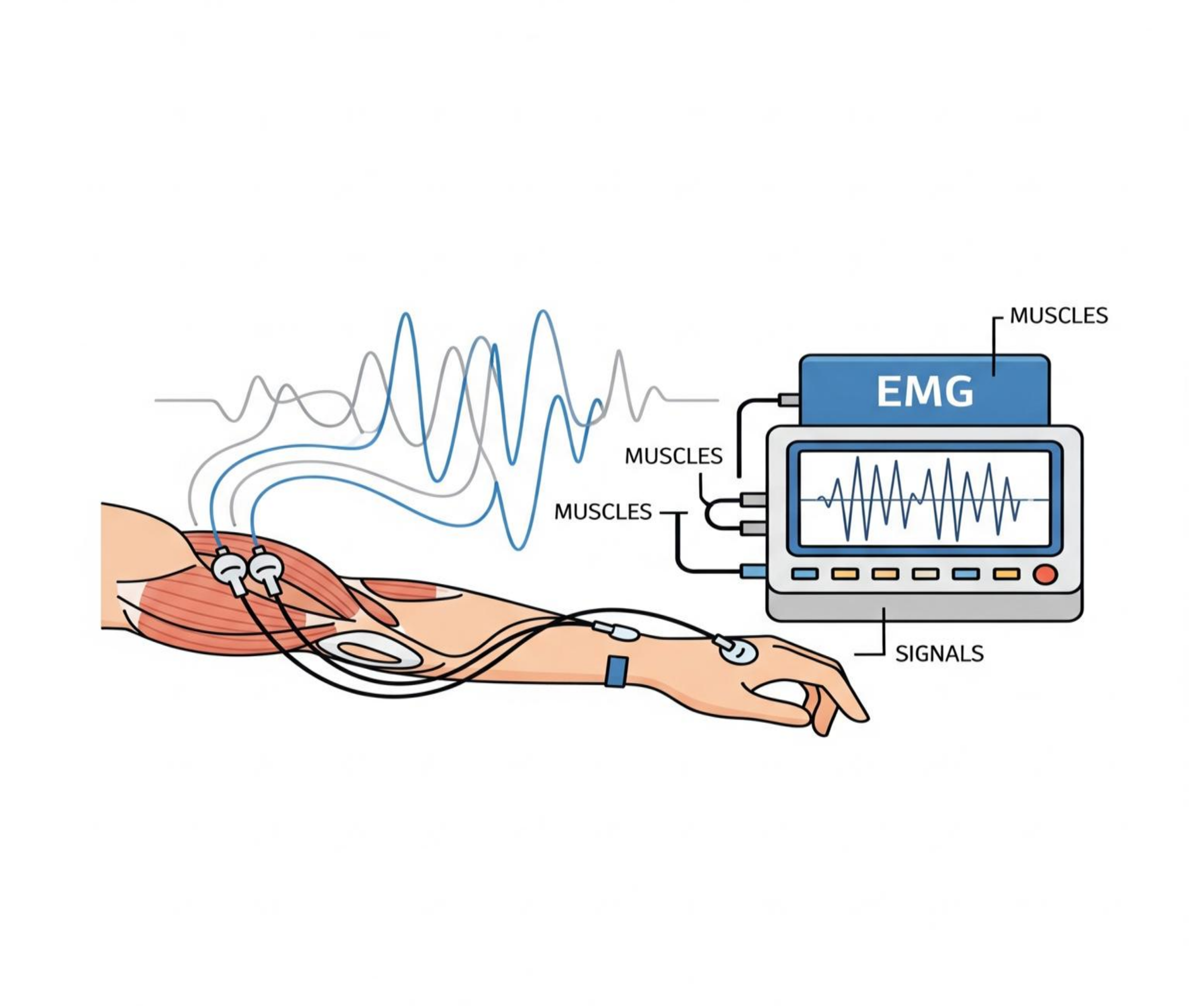
Presentation Outline

- **Introduction:** What is EMG?
- **The Challenge:** Signal vs. Noise
- **Design Goals:** General Objectives
- **Circuit Design:** A 3-Stage Solution
- **Component Analysis:** In-Amp, HPF, and LPF
- **Simulation:** Building Realistic Test Signals
- **Results:** Input vs. Final Output
- **Analysis:** Simulation vs. Reality



What is EMG and What Does It Do?

What is it?

"EMG" (Electromyography) is a technique used to record the electrical activity produced by skeletal muscles.

What does it do?

EMG is widely used for:

- Medical diagnosis of nerve and muscle disorders.
- Controlling advanced prosthetic limbs.
- Analyzing performance in sports and rehabilitation.

The Signal: When a muscle contracts, it generates tiny electrical signals. The EMG signal is the sum of thousands of these, characterized by a low amplitude (microvolt to millivolt range) and a specific frequency band (typically 10-500Hz).

The Challenge: Signal vs. Noise

The Weak Signal

The raw signal from a muscle signal is incredibly small, often in the 0.1-10 mV range. Our test signal is 1mV.

The Overwhelming Noise

The human body acts as an antenna, picking up electrical noise (like 50/60 Hz mains hum) that can be many orders of magnitude stronger than the biological signal

Design Goals for an EMG Amplifier

High Amplification (Gain)

Provide very high gain (typically 500x-2000x) to boost the weak microvolt/millivolt signal into a usable volt-level range.

High Noise Rejection (CMRR)

Aggressively reject strong common-mode noise (like 50/60Hz mains hum) to achieve a high Common-Mode Rejection Ratio.

Selective Filtering (Bandwidth)

Isolate the useful 10-500Hz EMG band by removing low-frequency motion artifacts and high-frequency electronic noise.

Standard EMG Amplifier Design

Stage 1: In-Amp

Provides high gain & rejects common-mode noise (e.g., 50/60Hz hum).

Stage 2: High-Pass

Removes low-frequency motion artifacts and DC drift.

Stage 3: Low-Pass

Removes high-frequency noise (anti-aliasing).

Final Output

A clean, amplified, and filtered signal.

Key Components in the Design

Active & Passive Components

- **Op-Amp (LM324):** The "workhorse" of the circuit. Used to build all three active stages (In-Amp, HPF, LPF).

- **Resistors:**
  - Rg1 (200Ω): Sets the In-Amp gain to 221x.
  - R_a1, R_b1 (82kΩ): Set the HPF cutoff.
  - R_c1, R_d1 (33kΩ): Set the LPF cutoff.

- **Capacitors:**
  - C1, C2 (100nF): Block DC and set the HPF cutoff.
  - C3, C4 (10nF): Remove HF noise and set the LPF cutoff.

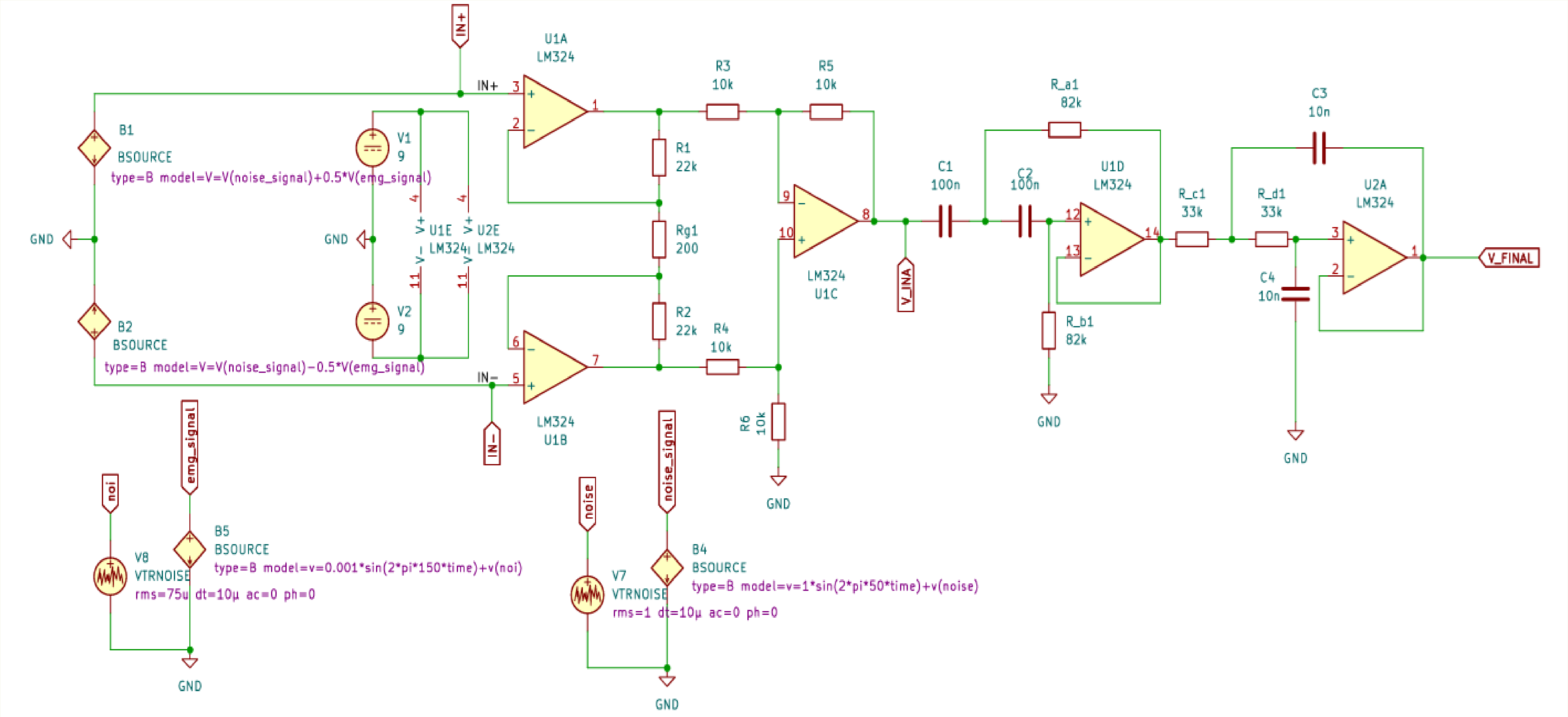
Simulation Sources

- **EMG Signal (B5):** A behavioral source (bv) creating a 1mV, 150Hz *bursting* signal to simulate a muscle flex.

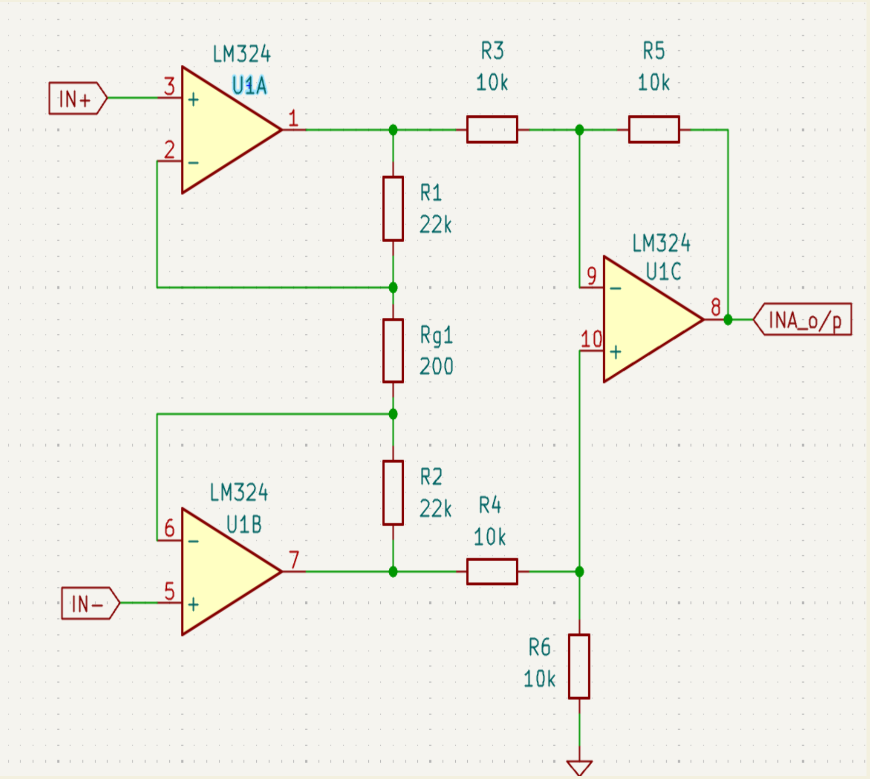
- **Noise Signal (B4):** A behavioral source (bv) creating a "dirty" 1V, 50Hz signal with harmonics and drift.

- **Test Mixers (B1, B2):** Behavioral sources that combine the "good" signal and "bad" noise to create the realistic 'IN+' and 'IN-' inputs.

Full Circuit Schematic



Stage 1: The Instrumentation Amplifier



Theory & Calculation

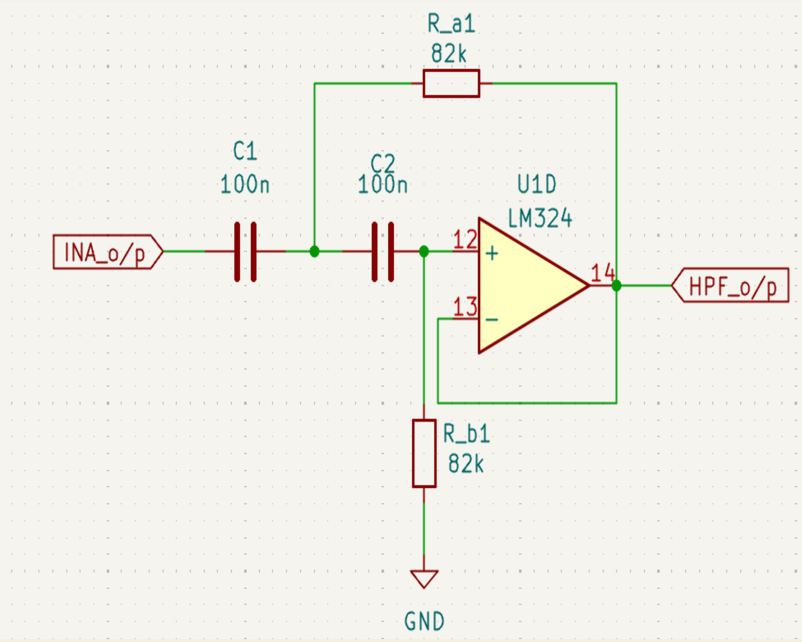
The In-Amp is the heart of the circuit, built from three op-amps to solve two problems at once:

1. **High Input Impedance:** The inputs connect to op-amps (U1A, U1B), which "listen" to the skin's voltage *without drawing significant current*. This is vital as the weak 1mV signal would collapse if "loaded" down.
2. **High CMRR (Common-Mode Rejection Ratio):** This is the In-Amp's most important ability. It measures how well the circuit rejects the "common" 1V 50Hz noise while amplifying the "differential" 1mV muscle signal.

```
G = 1 + (R1 + R2) / Rg1
G = 1 + (22k + 22k) / 200Ω
G = 221
```

Stage 2: The High-Pass Filter (HPF)

Theory & Calculation



This stage is **2nd-Order Sallen-Key active High Pass filter**, which serves two critical functions:

1. **Steep Roll-off:** Being 2nd-Order (using two capacitors), it has a steep **-40dB/decade** roll-off. This is twice as sharp as a 1st-order filter and is crucial for aggressively removing the strong, low-frequency "motion artifact" noise (from breathing or cable movement) that is below our 19.4Hz cutoff.
2. **Active Buffering:** The op-amp (U1D) acts as a buffer, isolating this HPF from the LPF stage that follows. This prevents the stages from interfering with each other and ensures our calculated cutoff frequency remains accurate.

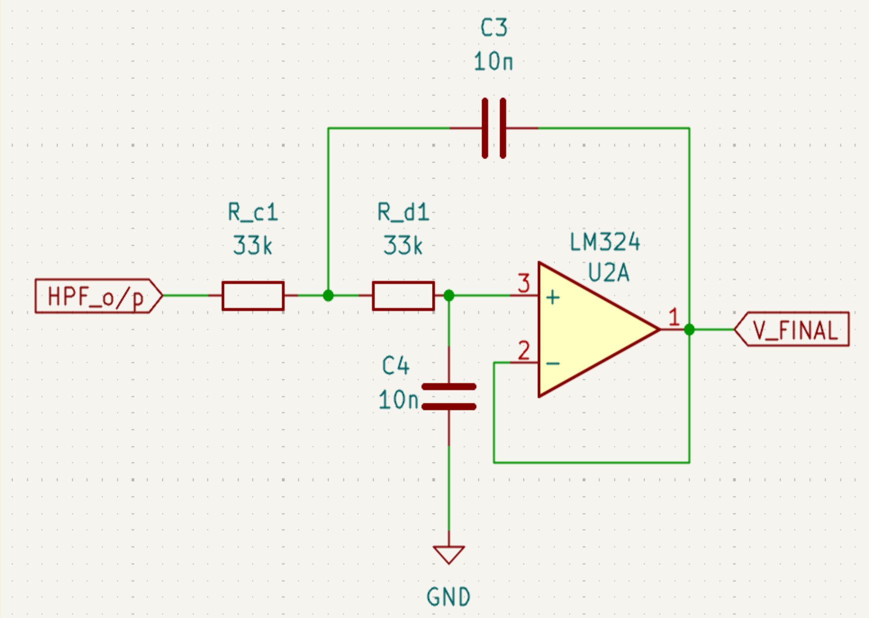
The cutoff frequency (f_c) is set by R_a1, R_b1, C1, and C2.

$$f_c = 1 / (2\pi RC)$$

$$f_c = 1 / (2\pi * 82k\Omega * 100nF)$$

$$f_c = 19.4 \text{ Hz}$$

Stage 3: The Low-Pass Filter (LPF)



Theory & Calculation

This final stage is another **2nd-Order Sallen-Key active Low Pass filter**, which serves two critical functions:

1. **High-Frequency Noise Removal:** Just like the HPF, its 2nd-Order design provides a steep **-40dB/decade** roll-off. This effectively removes high-frequency noise (e.g., from other electronics) that is above our 482 Hz cutoff, "cleaning up" the signal.
2. **Anti-Aliasing:** By guaranteeing that no signals *above* 482 Hz get through, this LPF acts as an **anti-aliasing filter**. This is a critical step to prevent signal distortion (aliasing) if the output is later sampled by a digital-to-analog converter (ADC) for a microcontroller, ensuring data integrity.

The cutoff frequency (f_c) is set by R_c1, R_d1, C3, and C4.

```
f_c = 1 / (2πRC)

f_c = 1 / (2π * 33kΩ * 10nF)

f_c = 482 Hz
```

Total System Specifications

Parameter	Value	Description
Total Gain	~221x	Set by ‘Rg1 = 200Ω’ in the In-Amp stage.
Bandwidth	19.4 Hz – 482 Hz	This is the "passband" for our EMG signal.
Input Signal	1mV @ 150 Hz	Sits perfectly inside the passband.
Noise Signal	1V @ 50 Hz (+white noise)	Rejected by the In-Amp (CMRR).
Expected Output	1mV * 221 = 221mV	A clean, amplified version of the input signal.

Simulation: Our Realistic Test Signals

EMG Signal (B5)

We created a realistic bursting signal: a 1mV, 150 Hz sine wave that turns on and off to simulate a muscle flexing and relaxing.

Noise Signal (B4)

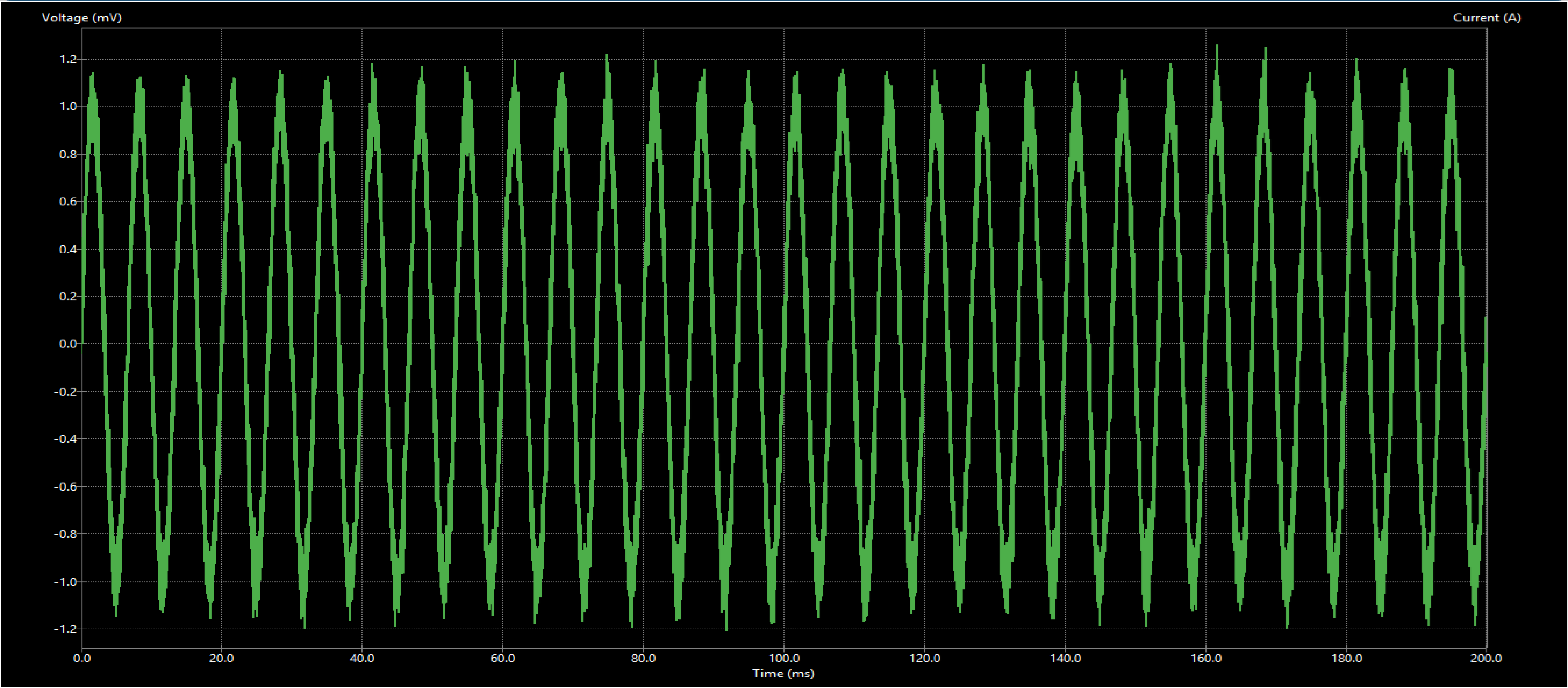
We built a "dirty" noise signal: a 1V, 50Hz hum combined with White Noise for a worst-case test.

The Test (B1, B2)

These sources mix the "good" and "bad" signals, creating the final 'IN+' and 'IN-' inputs that are fed to our amplifier.

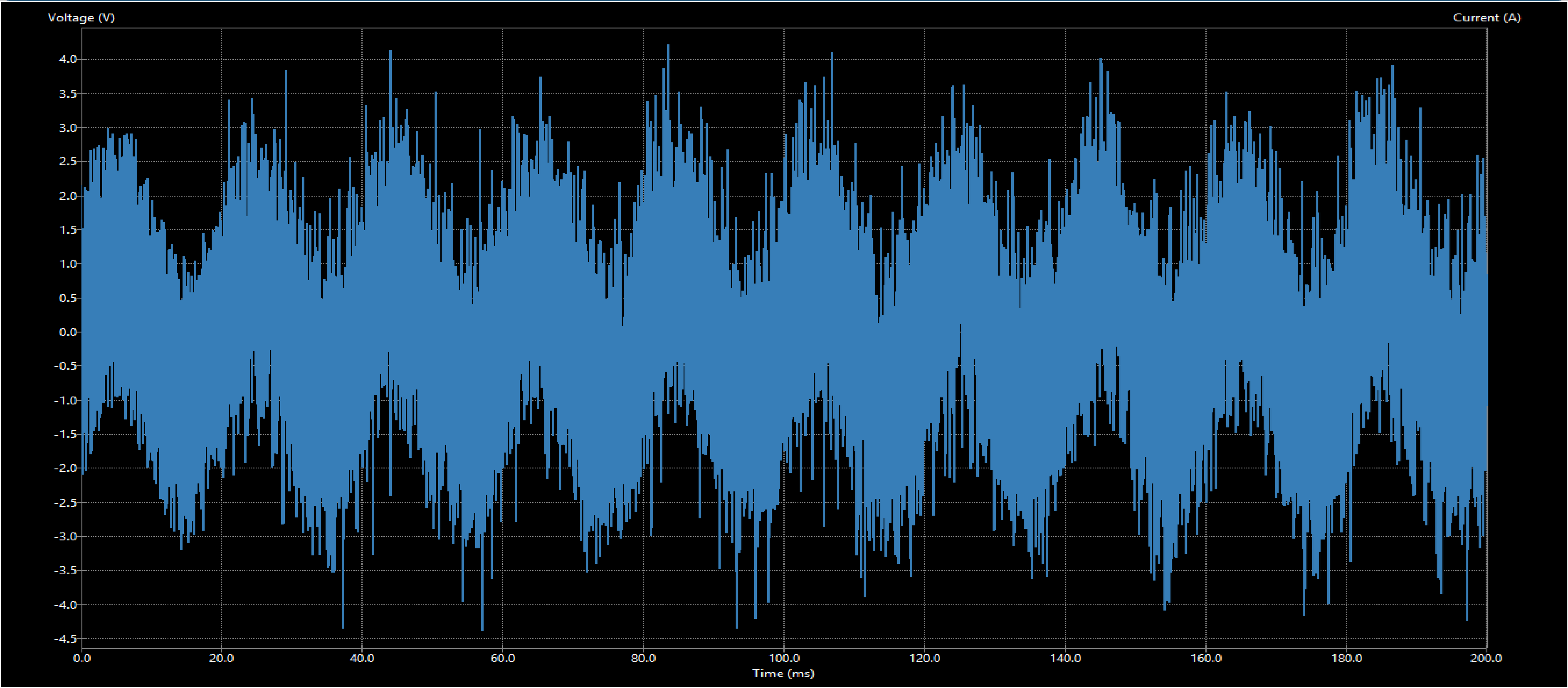
Simulation: EMG Signal

This is 1mV muscle signal with 150Hz frequency



Simulation: The Input

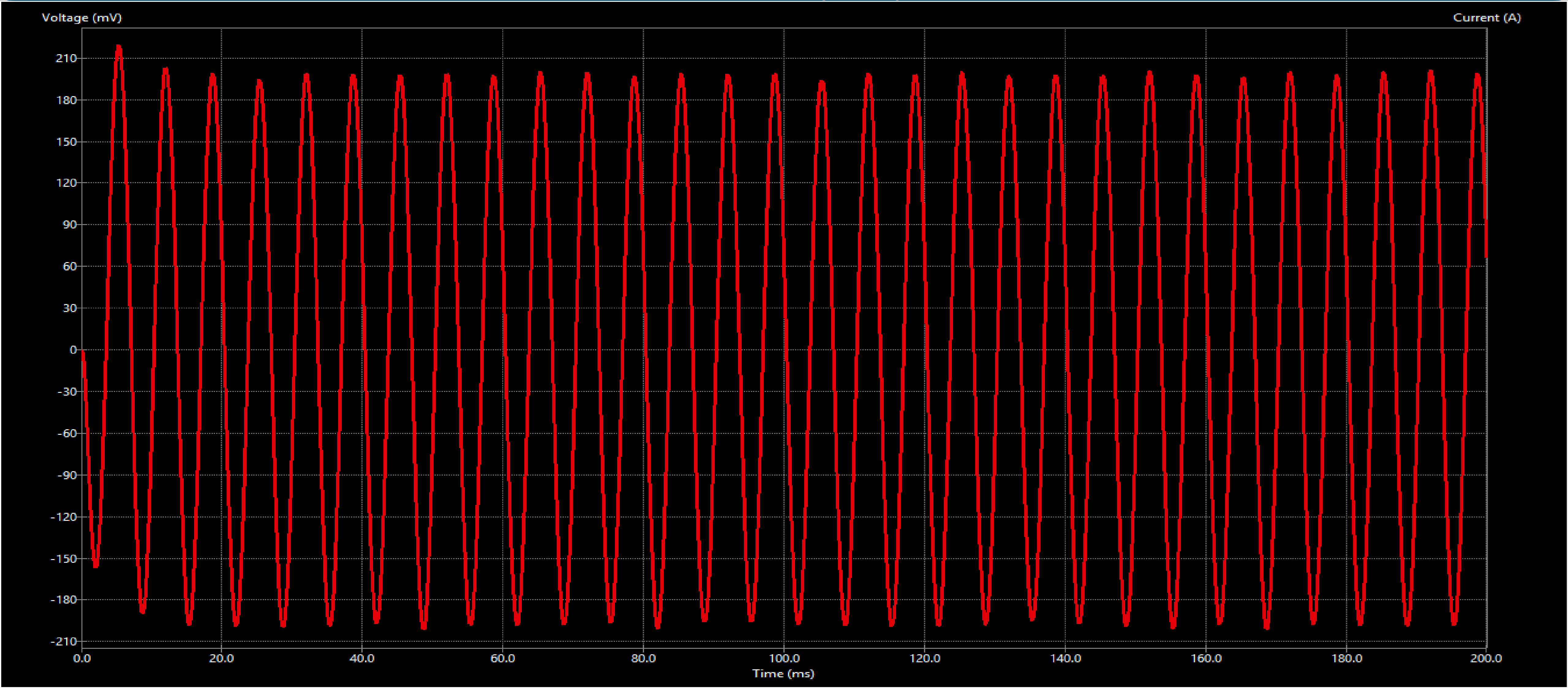
This is what the amplifier sees at ‘IN+’. The tiny 1mV muscle signal is completely invisible, buried inside the 1V 50Hz noise.



Simulation: The Output

Success! The final output at ‘V_FINAL’ shows the clean, amplified 150 Hz signal (at ~220 mV).

The 1V noise has been completely filtered out.



Analysis: Ideal Simulation vs. Real-World Signals

Our Ideal Simulation Model

- **Simplified Signal:** Uses a predictable 1mV,150 Hz sine wave to represent the signal's dominant frequency.
- **Controlled Noise:** Uses a known 1V, 50Hz wave (with harmonics) to test and validate noise rejection (CMRR).
- **Perfect Components:** Assumes ideal op-amps and perfect, exact values for all resistors and capacitors.

Real-World Considerations

- **Stochastic Signal:** The real EMG signal is non-periodic (stochastic), with its energy spread across a wide frequency band.
- **Complex Noise Floor:** Reality includes thermal noise, electrode "pop" noise, and crosstalk from nearby muscles.
- **Component Tolerances:** Real components have tolerances (1-5%), and op-amps have internal noise and offset voltages.

References

- **Instrumentation Amplifier Design:**
  Chowdhury, M. Z. A., & Roy, D. P. "Circuit Design and Analysis of an Electromyography (EMG) Signal Acquisition System." (IEEE).
  (This paper provided the core 3-op-amp instrumentation amplifier design used in this project.)

- **EMG Signal Characteristics (Amplitude):**
  De Luca, C. J. (1997). "The use of surface electromyography in biomechanics." *Journal of Applied Biomechanics*.
  (Validates our 1mV test signal as a realistic amplitude for EMG.)

- **EMG Filtering Standards (Bandwidth):**
  Merletti, R., & Di Torino, P. (1999). "Standards for reporting EMG data." *Journal of Electromyography and Kinesiology*.
  (Provides the basis for our 19.4Hz – 482 Hz filter bandwidth, which aligns with the 10-500Hz standard.)

Future Work: Hardware Implementation

- **PCB Design:** The next step is to move from the schematic to a physical Printed Circuit Board (PCB) using KiCad PCB editor. This involves component placement and routing traces.
- **Prototyping:** Soldering the components onto the PCB and addressing real-world hardware challenges, such as creating a proper RF-shielded enclosure.
- **Real-Signal Testing:** Test the physical board using Ag/AgCl electrodes on a human subject to validate its performance outside of simulation.
- **Digital Integration:** Connect the final analog output to an Analog-to-Digital Converter (ADC) of a microcontroller (like an Arduino or ESP32).
- **Signal Processing:** Once digitized, the signal can be processed to control prosthetics, analyze athletic performance.

Thank You

Questions?