Application Report

Driving Piezoelectric Loads With the OPA462 Precision Amplifier

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ABSTRACT

Piezo actuators are used in applications where precise, minute mechanical movements are required to be performed by a machine or apparatus. Precise voltage levels are applied to the actuator to produce very specific and controlled movements. The maximum voltages required by a piezo actuator may be several hundred volts and in some cases the polarity may need to be reversed.

High-voltage operational amplifiers such as the OPA462 precision op amp from TI, with (V+) – (V–) = 180 V, may be used to directly provide the controlling voltage and load current provided the actuator maximum voltage does not exceed approximately 175 V. If the actuator maximum voltage requirement is closer to 200 V, a unique, bridged-output op amp configuration consisting of an OPA462 and a lower voltage OPA192 can be employed to meet the required output voltage range.

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1 Semi-Bipolar Piezo Actuator Driven by a Single Op Amp

A piezo transducer or actuator can make use of the inverse piezoelectric effect to take an electrical signal and turn it into a mechanical signal, or actuation. The voltage across the piezo actuator determines how much it expands or contracts, often on the order of micrometers (µm). This facilitates extremely precise displacement of the actuator via a drive or control apparatus. These actuators are commonly used in test and measurement applications, for precise control of probes or for sample positioning; in aerospace and defense, for active vibration dampening; and even in optical applications, for minute tuning and adjustments to lasers. While commercial off-the-shelf piezo drive units are available, a piezo actuator may also be controlled by a precision operational amplifier (op amp) drive circuit. The specific circuit design is highly application-dependent, with the capacitance of the actuator, its resonant frequency, and its supply voltage range all playing a role; however, this document explores a general case of a low-to-medium supply semi-bipolar actuator that is operating below its resonant frequency, allowing it to be modeled as a capacitive load.

Consider first the case of a semi-bipolar piezo actuator driven by a single op amp, with the non-driven terminal of the actuator tied to the system ground. The input of the op amp can be controlled via a digital-to-analog converter (DAC); the amplifier will then gain up this control signal and drive the piezo, as shown in Figure 1-1A.

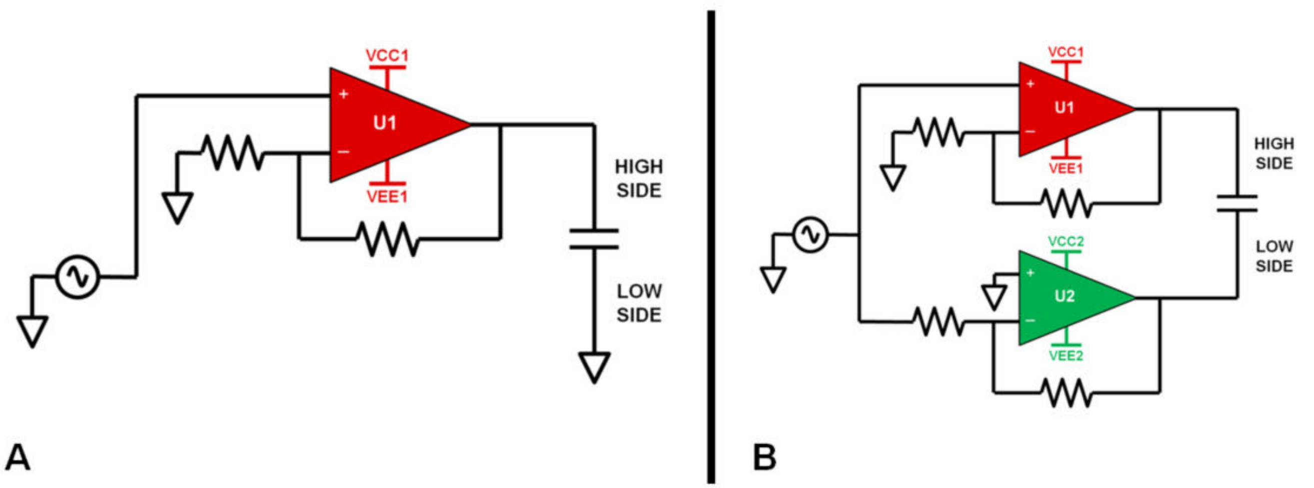

Figure 1-1. Driving a Piezoelectric Load With a Single Amplifier (A) and Bridge Arrangement (B)

Another way to drive a piezo actuator is to treat it as a floating load, “bridging” the outputs of two different op amps as shown in Figure 1-1B. The difference in the outputs of the amplifier is the effective voltage across the actuator. This means that by carefully selecting the supply voltages of the two amplifiers, a much greater effective voltage can be achieved. The “high” side of the load, driven by U1, can swing approximately as high as VCC1 and as low as VEE1, depending on the output swing limitations of U1 and the required current. In a similar fashion, the “low” side of the load can swing approximately as high as VCC2 and as low as VEE2, although some headroom is necessary due to the output swing limitations of U2. The greatest effective voltage across the load occurs when U1 swings high and U2 (which is 180° out of phase) swings low – the effective voltage across the load is thus:

Vpiezo = (VCC1 – U1 output swing to positive rail) – (VEE2 – U2 output swing to negative rail)

For example, if U1 and U2 can each swing within 5 V of either rail, and the supplies are VCC1 = VCC2 = 90 V and VEE1 = VEE2 = –90 V, then the greatest voltage across the load is (90 V – 5 V) – (–90 V – [–5 V]) = 170 V. Likewise, the lowest effective voltage across the load occurs when U1 swings low and U2 swings high. The effective voltage across the load is thus:

Vpiezo = (VEE1 – U1 output swing to negative rail) – (VCC2 – U2 output swing to positive rail)

For the supplies given in our prior example, this means a voltage of (–90 V – [–5 V]) – (90 V – 5 V) = –170 V is possible. Thus, the piezo load can swing from +170 V to –170 V, or 340 V pk-pk.

Most piezo actuators, however, are not intended to be driven in this fashion – rather, the "high" voltage across the load is intended to be higher than the "low" voltage, such as 150 V to 0 V, or 120 V to –30 V rather than 75 V to –75 V. We can achieve an offset, non-zero-centered output by shifting the supplies of the U1 and U2 op amps. For example, assume VCC1 = 175 V, VEE1 = –5 V, VCC2 = 5 V, and VEE2 = –175 V. The voltage across the load is now (175 V – 5 V) – (–175 V – [–5 V]) = 340 V when "high", and (5 V – 5 V) – (–5 V – [–5 V]) = 0 V when "low". The peak-to-peak voltage is unchanged, but the output is now centered on 170 V instead of 0 V. Thus, achieving a desired output swing range for a given piezoelectric load is simply a matter of shifting the supplies accordingly.

When driving a large capacitive load such as a piezoelectric actuator, two major concerns for the designer are output current requirements and circuit stability. The piezo load is constrained by the same i = C dv/dt equation that covers typical capacitive loads (there is a small intrinsic resistance due to electromechanical losses, but the actual value will depend on the actuator used). Thus, an actuator with a high capacitance or one that is excited at a high frequency will have correspondingly high current demands. In some cases, an external output stage after the op amp may be required to achieve high output current. This output stage, and any related compensation adjustments to meet stability requirements will be highly application specific. The stability of the circuit will depend on the load, the AC characteristics of the op amps employed, and when applicable the presence of an added output stage. Even if the U1 and U2 op amps are from the same fabrication lot, their gain-bandwidth product (GBW) may differ slightly, resulting in somewhat different gain and phase roll-offs. Therefore, it is suggested that a feedback capacitor (CF) be added across each op amp feedback resistor (RF) to reduce any excessive system bandwidth. Reducing the bandwidth reduces the circuit noise, which is especially important if the noise falls near the resonant frequency of the actuator. Additionally, the capacitors can help force the frequency roll off of the two amplifier circuits to be more closely matched.

Piezo actuators are comprised of specially formulated ceramics that exhibit piezoelectric properties similar to natural quartz. The actuators are designed to produce a particular mechanical response where they are able to extend or contract in response to the applied voltage. An electric field is developed across the internal dielectric of the actuator as charge collects on the actuator plates. The actuator reacts in the physical realm, in a mechanical manner as a response to the electric field developed. Conversely, a mechanical shock to the actuator can result in a momentary generation of a high-voltage output spike. This response is attributed to the forward piezoelectric effect that produces a very strong field manifested as a high voltage at the terminals of the actuator. This is commonly observed in the piezo strikers found on many gas stoves, which deliberately utilize this principle to generate an electrical arc that ignites the gas burners.

If a shock to an actuator that is driven by an amplifier circuit occurs, this high voltage spike will be applied directly to the output pin of the op amp, and to the internal output stage circuitry connected to the pin. The voltage levels of the spike can exceed the safe operating voltages of the output transistors and other components, possibly leading to voltage breakdown and circuit damage. In applications where a mechanical shock to the actuator might occur, the addition of electrical over-stress (EOS) protection is required to protect the op amp from being damaged. One common protective method to prevent such overvoltage damage is to include a transient voltage suppressor diode (TVS) directly across the piezo actuator. A TVS diode is similar to a Zener diode in that it turns on at a specified voltage, and then clamps the voltage to that level. They differ from a Zener in that they are designed specifically for clamping an EOS event, are very fast, and are made to handle repetitive surges without degradation. The TVS diode may be specified for either unidirectional single polarity clamping, or bidirectional dual polarity clamping. The simple TVS diode connected across the piezo actuator is sufficient for a single op amp driver actuator circuit. However, in a bridged output a different TVS clamp scheme is suggested, as will be shown.

2 Bridged Output Piezoelectric Actuator Driver

Consider an example case where the target voltage range of a hypothetical actuator extends from –30 V to +170 V. While this is a relatively “low voltage” in the field of piezo actuators, it still requires a “high-voltage” op amp circuit to drive it. The OPA462 precision op amp can use an 180-V supply, but on its own would still be unable to drive this particular actuator to its maximum expansion. However, by employing an additional lower voltage
(36 V) op amp such as the OPA192 along with the OPA462 in a “bridge” configuration, the full 200 V needed for full actuator response can be achieved. In the bridged output design the OPA462 (U1) serves as the “high side” driver, while the OPA192 (U2) serves as the “low side” driver.

We can determine the supplies needed to power the OPA462 and OPA192 as follows:

High piezo voltage = (VCC1 – U1 output swing to positive rail) – (VEE2 – U2 output swing to negative rail)

170 V = (VCC1 – 3 V) – (VEE2 – –1 V) → VCC1 – VEE2 = 174 V

Low piezo voltage = (VEE1 – U1 output swing to negative rail) – (VCC2 – U2 output swing to positive rail)

–30 V = (VEE1 – –5 V) – (VCC2 – 1 V) → VEE1 – VCC2 = –36 V

Observe that output voltage of U2 (VF2) does not actually need to swing –36 V below ground. VF2 simply needs to be 180° out of phase relative to the output voltage of U1 (VF1). It is the reversal of the maximum output voltages of U1 and U2 that result in the maximum voltage of 200 V being applied to the actuator. Simply stated, VF1 – VF2 = 170 V – (–30 V) = 200 V. Since both U1 and U2 are driven by the same input voltage source, different DC biases and gains are required for each amplifier. This is accomplished by establishing a unique DC input voltage at each non-inverting input, and setting the closed-loop gain of each op amp to the appropriate level.

The next step is actually selecting the supply rail voltages. To do this, first consider the input common-mode range of the two op amps. The OPA192 can accommodate a common-mode input as low as –100 mV below the VEE2. However, for the OPA462 this value cannot be lower than +1 V above the VEE1. The negative supplies VEE1 and VEE2 are set to –1 V to reduce the number of supply voltages needed. That allows the minimum common-mode input voltage applied at U1 to be 0 V. Although a –1-V supply is not common, –1.2 V can be easily provided from a linear, low-dropout regulator such as the TI TPS723, which accepts a –2.7 to –10 V input. For the positive supply, VCC1 should be at least 173 V. It can be as high as 179 V, and 175 V is selected for simplicity. VCC2 will be set to 35 V. If the VCC supply voltages differ by a few volts from +175 V and +35 V, then the resistor circuits used to set the voltage at the non-inverting inputs of U1 and U2 will need to be adjusted to maintain the correct bias levels.

Figure 2-1 shows a TINA-TI schematic for the bridged output piezo driver. The piezo load is modeled as a 400-nF capacitor, with 100 mΩ of series resistance to model the loss component. Figure 2-2 shows the results of a transient simulation of the system when source VG1 is a 5 Vpp, 100-Hz sinusoidal waveform. The system is compensated using a dual feedback, resistive isolation technique (R_{ISO}) to maintain stability even with the very high 400-nF load. The op amp drive currents peak at about ±25 mA, which both the OPA462 and OPA192 can provide. The bias voltage at the U1 non-inverting input (labeled as Vi1 in Figure 2-1) is +2.59 Vdc. The corresponding voltage Vi2 at U2 is +2.67 Vdc. The closed-loop gains for the U1 and U2 signal paths are labeled as well. As a result of the DC input biases and the gains shown, the output swing of U1 is 169 Vpp centered on a DC level of +89.06 Vdc, and the output swing of U2 is 31 Vpp centered on +19.25 Vdc.

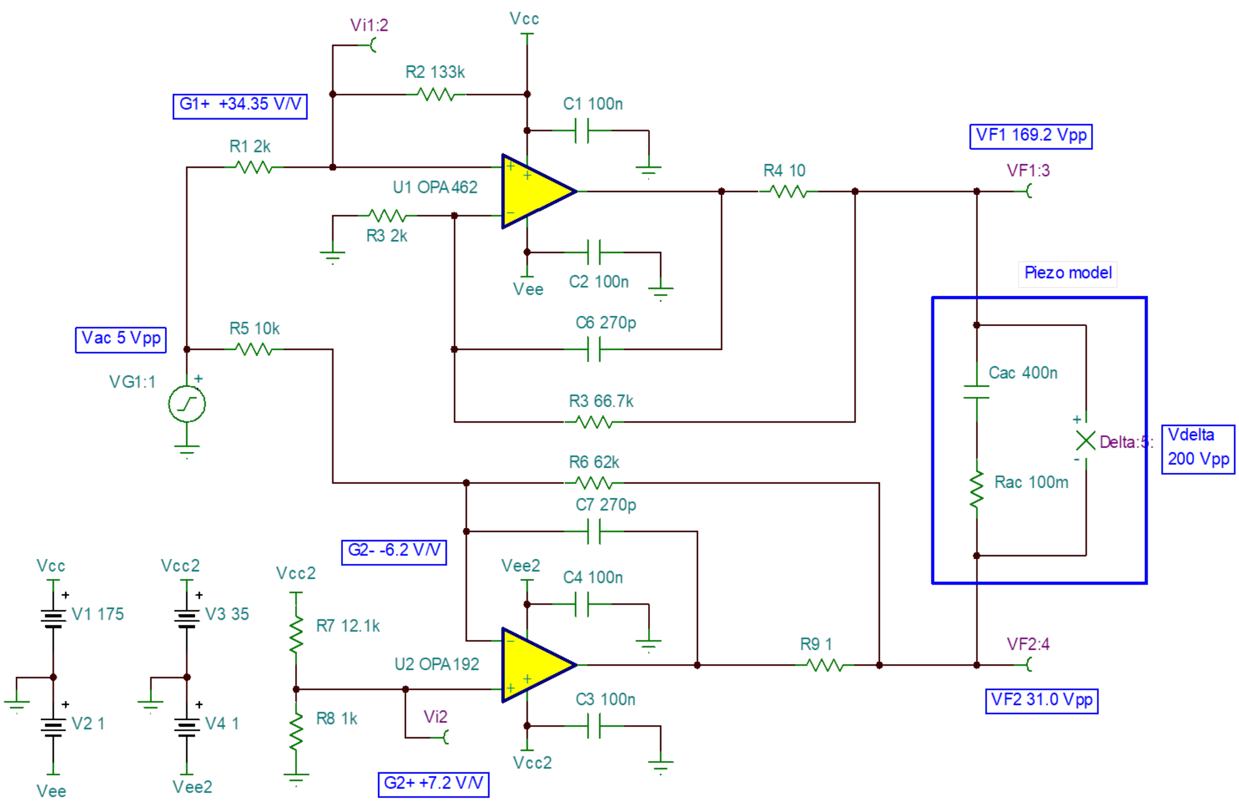

Figure 2-1. Schematic for 200-V Bridged-Output Piezo Driver

Figure 2-2, Marker A, shows that when VG1 is at –2.5 V, VF1 is +4.53 V and VF2 is +34.72 V, for a difference of 4.53 V – 34.72 V, or –30.19 V effective. At Marker B, VG1 is +2.5 V and VF1 is now +173.49 V with VF2 as +3.77 V, for a difference of +173.49 V – 3.77 V, or +169.72 V effective. The actuator thus detects an effective voltage that swings from –30.19 V to +169.72 V, close to the design goals of –30 V and 170 V. The total voltage change across the actuator is +169.72 V – (–30.19 V) = 199.91 V. Other than the 66.7-kΩ feedback resistance, all the resistor values used are standard values – however, for better precision, non-standard resistor values may be needed.

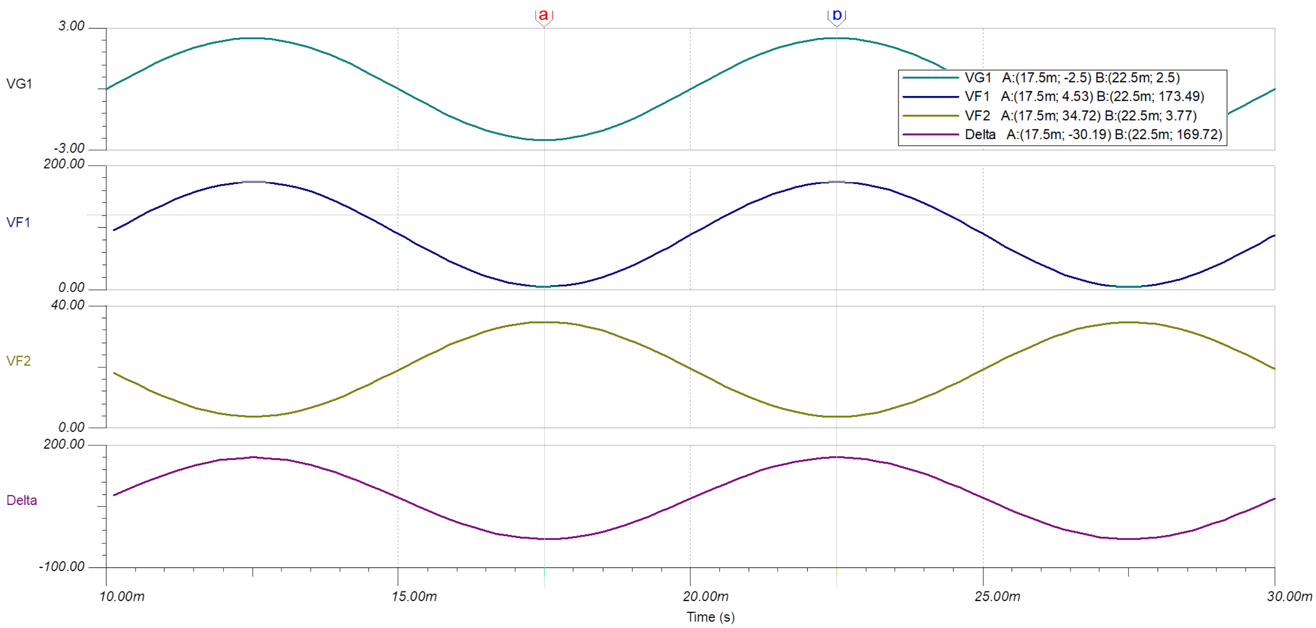

Figure 2-2. Transient Simulation Results for Bridged Output Circuit With 5-Vpp, 100-Hz Sinusoidal Input

Piezo actuators are most often controlled by a DC level, or sometimes by a low frequency AC voltage. Ideally, the output phase difference between the outputs of the two op amps (VF1 and VF2) should be 180°. In practice, because the two op amps have different gain bandwidth products and are operated with different closed-loop gains, their gain and phase responses will deviate from each other as the frequency increases. The amplitude changes and phase changes across frequency can cause waveform distortion. For example, a sine wave shows distortion from ideal which is detectable by the human eye on an oscilloscope screen when it becomes a few percent. Distortion is a source of error and will affect the actuator response accordingly. The output phase difference for this design holds very close to 180° at very low frequencies (< 10 Hz). The phase difference between VF1 and VF2 is approximately –0.064° at 10 Hz, –0.64° at 100 Hz, increasing to –6.4° at 1 kHz. There is a corresponding gain error as well.

Previously, it was mentioned that piezo driver circuits should include protection from a mechanically induced voltage transient. The bridged output circuit presented uses both the high-voltage OPA462 op amp, and much lower voltage OPA192 op amp. A safe plan is to apply individual op amp protections to each op amp that activate just outside their individual output and supply ranges.

Figure 2-3 shows the output sections for two well-protected op amp piezo drivers. In each case, a TVS diode having a voltage just above the operating supply voltage is added at VCC1 and VCC2 pins. Zener diodes are shown in the schematic for illustrative purposes; a 180-V diode for the OPA462, and a 39-V diode for the OPA192. Fast recovery 1-A/300-V rectifier diodes are then connected from each op amp output pin to the supply pins. These diodes are normally off, but one or more may become forward biased and turn on during a voltage transient event. The ON rectifier diode will direct the current generated during the event to the corresponding TVS diode. The forward voltage of the rectifier diode will clamp the voltage across the output transistor of the op amp to a safe, low voltage, while the TVS clamps the supply voltage at its rated breakdown voltage.

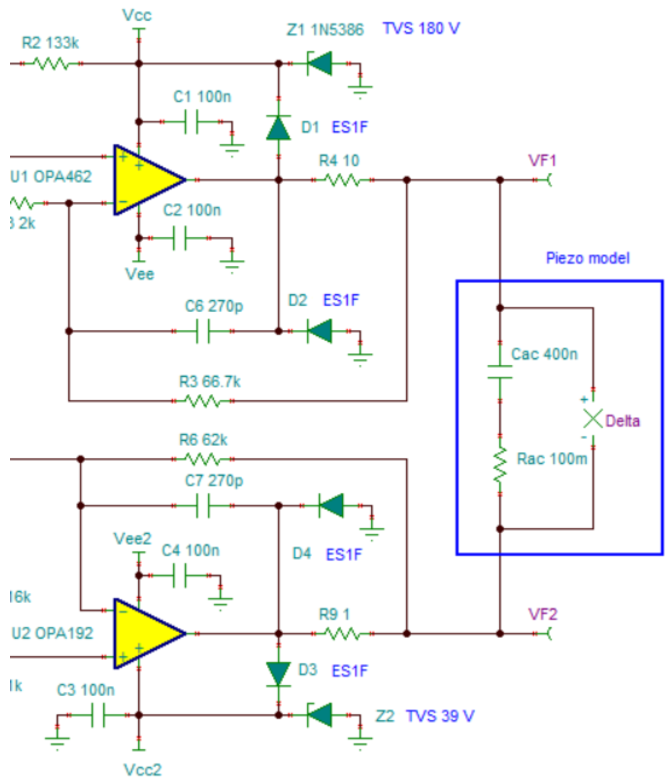

Figure 2-3. Fast Rectifier Diodes D1 – D4 and TVS Diodes Z1 and Z2 Added to Protect U1 and U2 Outputs

3 Conclusion

While the bridged circuit topology is well suited to driving piezoelectric loads, as has been shown, it can also be used to drive other floating loads provided the limitations of the output drivers are observed. It allows for a high effective voltage across the load without the complexity and cost of using a bootstrapped configuration, or other related circuit method.

When driving large capacitive loads at high voltage levels or high frequencies (or both), high output currents can be demanded from the op amps. Often a dedicated output stage following the op amps used as drivers would be required. In this case, good power management and heatsinking practices are essential because the two op amps will source and sink current from each other through the load. Ensure that both op amps are properly selected to handle the current requirements. This is especially important when using two different models of op amps, as were applied here.