

# Driving Piezoelectric Actuators

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Extraordinarily fast devices that can produce precise motions in subnanometer increments, piezoelectric actuators make unusual demands on the power op amps required to drive them.

Though the understanding of piezoelectrics is more than a century old, there is, of late, a rapidly expanding interest in piezoelectric actuators, because they are so extraordinarily fast and can produce motions in precisely controlled, subnanometer increments. Already well entrenched in industrial inkjet printers, their use is migrating into several other diverse applications, ranging from medical electronics to antivibration controllers for helicopter rotor blades.

Piezoelectric actuators require specialized drive circuits with high-speed and high-voltage capabilities. These circuits can be implemented using IC-style power op amps configured according to specific actuator requirements.

The three typical piezoelectric actuator drive circuits described in this article address actuators over a wide range of equivalent capacitance with different demands for voltage, current and slew rate. But before discussing drive circuit operation, one must

understand the principles behind piezoelectric actuator operation.

## Piezoelectric Operation

The word *piezo* is Greek for push. The effect known as piezoelectricity was discovered by brothers Pierre and Jacques Curie in 1880. They discovered that if a force was applied to a quartz crystal, an electric field was developed. Later they learned that the inverse was also true; that is, if a voltage was applied across the crystal, the electric field that developed would cause it to deform.

Crystals that exhibit these phenomena are said to be piezoelectric, and barium titanate, lead zirconate and lead titanate are a few of the ceramic materials employed today in industrial applications that exhibit these characteristics.

Within the cylindrical piezoelectric actuator illustrated in Fig. 1a, when a voltage is applied longitudinally, a displacement  $\Delta L$  occurs along the axis of the device. Typically, a piezoelectric material can withstand a strain, or change in length, of 0.1%. This means an actuator that is 100 mm long that is poled (energized) along its axis can be elongated by 0.1 mm. The displacement, or change in length, of an unloaded single-layer piezoelectric actuator can be closely approximated by:

$$\Delta L = (S)(L_0) \approx \pm(E)(d_{33})(L_0) \quad (\text{Eq. 1})$$

where  $\Delta L$  is the change in length (m),  $S$  is the strain per unit length or relative length change (meters/meters, therefore, dimensionless),  $E$  is the electric field strength (V/m) and  $L_0$  is the length of the actuator (m). The term  $d_{33}$  is the piezoelectric coefficient (m/V), where the first subscript identifies the axis of the field and the second subscript identifies the axis of the displacement.

The maximum electric field that most ceramic piezoelectric actuators can withstand is on the order of 1 kV/mm to 2 kV/mm. To extend travel beyond the approximately 0.1% maximum of a single slice, and to avoid applying too large an

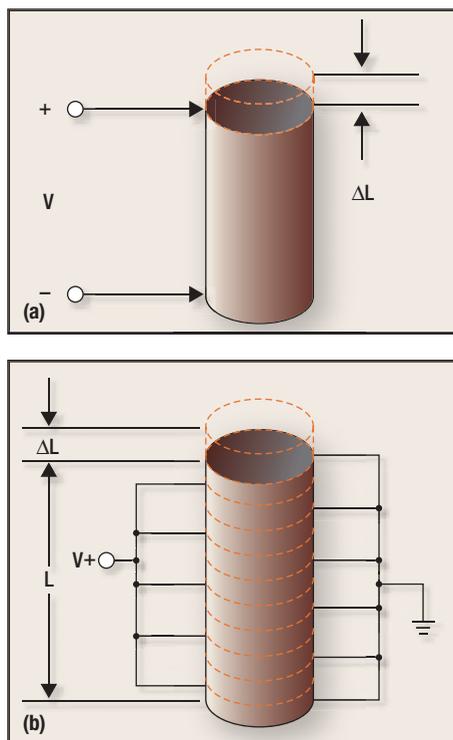


Fig. 1. Two linear piezoelectric actuators: A single stack (a) and a multilayer (b) in which the displacement is amplified by the number of slices.

applied field, a multilayer actuator can be fabricated by gluing thin layers of the piezo material together to form a stack. A voltage is then applied to each layer individually (**Fig. 1b**), so that each is powered independently. The voltage applied to each slice is still the same, but the total displacement is simply the sum of the individual displacements:

$$\Delta L_{\text{TOT}} = (N)(\Delta L). \quad (\text{Eq. 2})$$

When a piezoelectric actuator is driven by an ac voltage, the equivalent circuit becomes quite complex.<sup>[1]</sup> However, when a piezoelectric actuator is driven by a periodic voltage source whose frequency is below the resonant frequency of the piezoelectric actuator, which is often the case in inkjet driving circuits, then the device can be modeled by a single capacitor. Therefore, the impedance presented to the driving source is, to a good approximation, simply:

$$Z_{\text{LOAD}} = \frac{1}{2\pi f C_{\text{PA}}} \quad (\text{Eq. 3})$$

where  $f$  is the frequency of the driving source and  $C_{\text{PA}}$  is the equivalent capacitance of the piezoelectric actuator.

When designing systems that employ piezoelectric actuators, keep in mind some essential concerns. One such concern is an actuator's limited strength in tension. The tensile strength of a cylindrical actuator is approximately 10% of its strength in compression. Specific values can be obtained from data sheets from piezoelectric actuator manufacturers.

Boundaries on acceleration also must be considered. When driven by a periodic waveform, the acceleration will increase exponentially with frequency. Therefore, it is important to identify the upper limit of the device's ability to withstand high acceleration forces.

Another issue is power consumption. Though piezoelectric actuators consume virtually no power, the power dissipating demands upon the operational power-amplifier circuits employed to drive them are significant indeed. Follow sound principles in designing the driving circuits. This means making sure that the driving power op amps are operating in their safe operating region and that current limiting is provided to protect the circuitry from an inadvertent short circuit. Also, select a satisfactory heatsink, flyback diodes and compensation capacitors.

## Drive Circuits

What follows are circuits for driving actuators, as well as for driving the deflection plates employed in a continuous-drop inkjet application. The principal distinctions among these circuits are the equivalent capacitance of the actuator being driven, the voltage and currents required, and the slew rates necessary. The three circuits we will look at range from one that drives a 500-nF load down to one that drives almost no capacitance (a deflection circuit with a few pico-farads of distributed capacitance).

The design shown in **Fig. 2** is intended for piezoelectric actuators such as those employed in large-format, billboard-type printing. In this application, the 500-nF capacitor repre-

sents the load impedance of a large number of piezoelectric-driven individual inkjets that are connected in parallel. In this particular circuit, a slew rate of approximately 20 V/ $\mu$ s is required, which is well within the slew rate capabilities of Apex Microtechnology's PA69. This power op amp can deliver 200 V/ $\mu$ s.

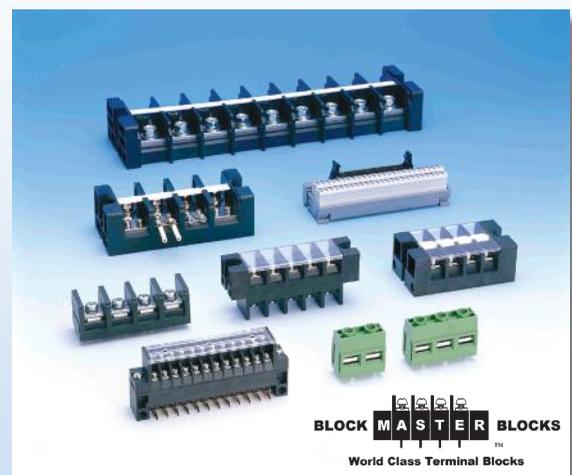
If the circuit was driven at this slew rate, it would be delivering 100 A given that  $I = CdV/dT$ , so it is important to keep

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the slew rate within bounds. The way this is done is with the compensation networks formed by the 4.7-pF capacitors (C3 and C4) and the 3-k $\Omega$  resistors (R3 and R4). These values are chosen from graphs in the data sheet. Since the PA69 is unable to deliver the required 10 A, it drives the MOSFET pair comprising X1 and X2, which deliver the current.

As depicted in **Fig. 2**, this is a pulse-type application with the driving source delivering a symmetric square wave that swings between +5 V and -5 V, thereby providing the pulse train as the input to the noninverting (+) terminal of the

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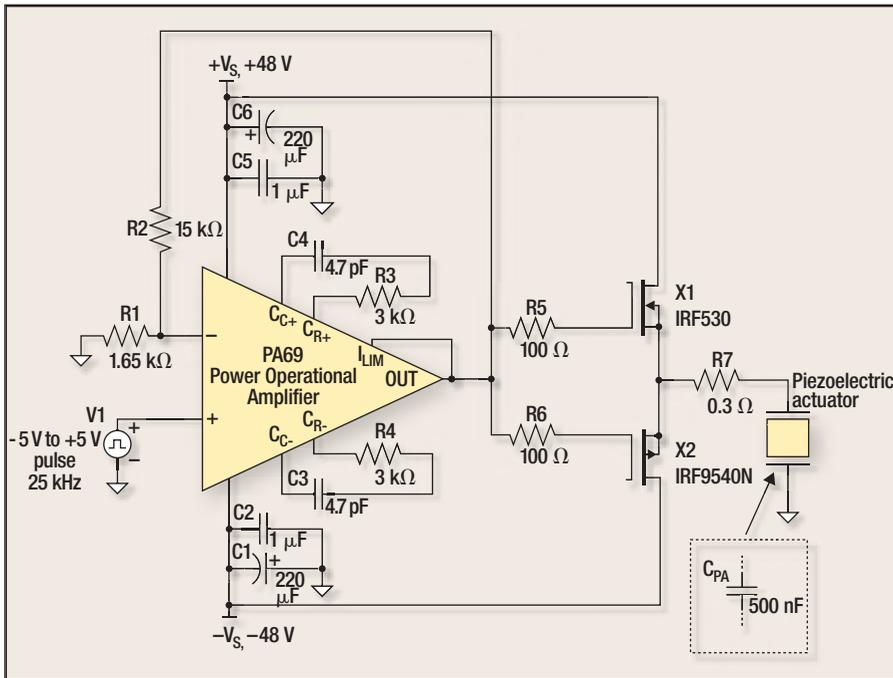


Fig. 2. This piezoelectric driver circuit can deliver 10 A at slew rates of 200 V/μs.

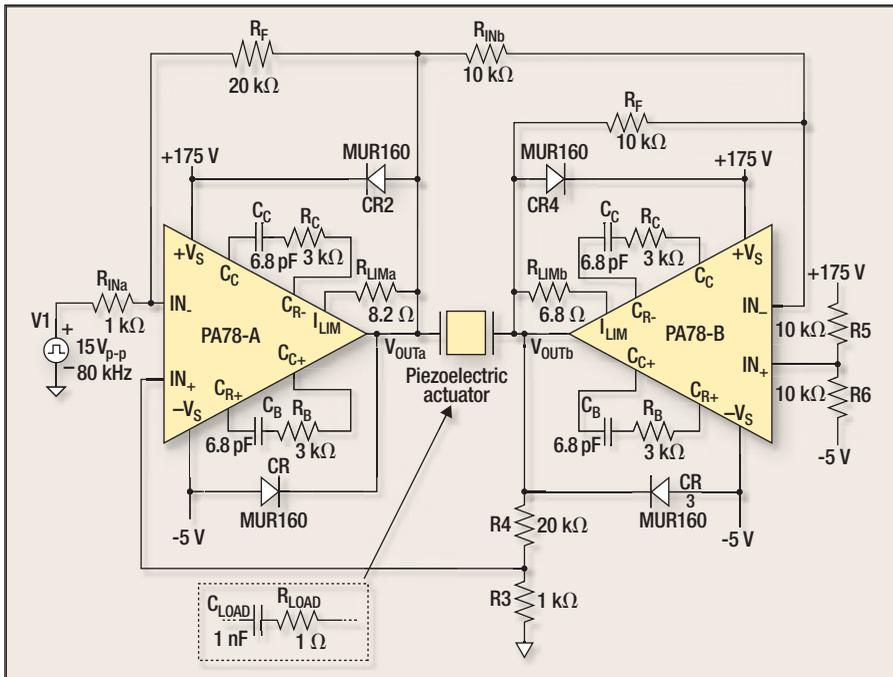


Fig. 3. A pair of bridge-connected Apex PA78 power op amps drive the piezoelectric actuator and are powered by asymmetric power supplies at +175 V and -5 V.

PA69. The source can be an FPGA, a microcontroller or some other source. The compensation network of the PA69 controls the slew rate, which in turn controls the current through the external MOSFETs.

The 100-Ω resistors (R5 and R6) are the gate resistors for the MOSFETs that prevent oscillations that might other-

wise occur, given that the MOSFET gates are capacitive and that the circuit-board layout contributes a distributed inductance due to the routing of the traces on the epoxy-glass substrate. Without these resistors, ringing might otherwise occur due to the various inductance-capacitance combinations.

The gain of the PA69 is 10 as gov-

erned by resistors R1 and R2, so that the output of the PA69, which is being driven as hard as it can be, is swinging between -48 V and +48 V. Therefore, the PA69 is acting as the gate driver for the MOSFETs (X1 and X2). The output of these devices swings all the way to the supply rails, +48 V and -48 V, as depicted in Fig. 2. The 0.3-Ω resistor (R7) is an isolation resistor modifying the output load so that it is not completely reactive, which thereby contributes to stability.

The power-supply bypass capacitors need to be hefty. The 1-μF capacitors C2 and C5 are ceramic, whereas the 220-pF C1 and C6 are electrolytics, which requires care that their polarity is observed.

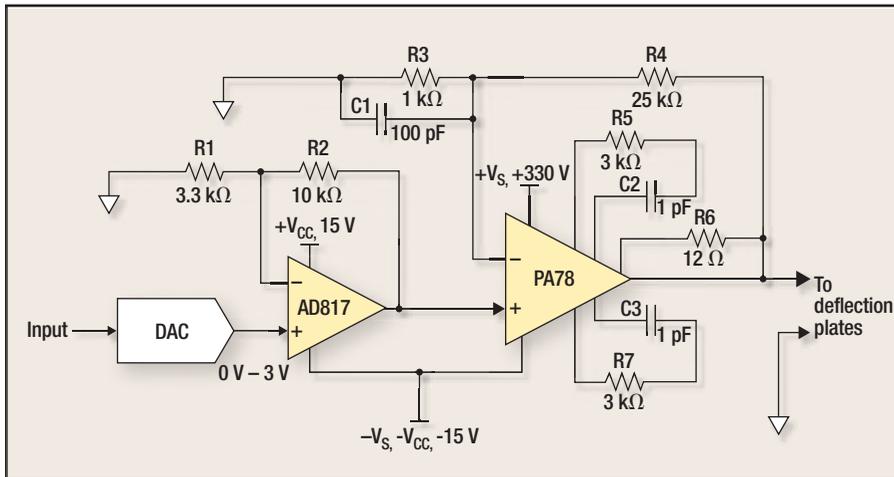
### Bridge-Connected Driver

Fig. 3 shows a circuit for a piezoelectric actuator that requires a high-voltage driver capable of delivering hundreds of volts, peak-to-peak (p-p). Since a typical actuator looks like virtually a pure capacitance to the driving amplifier, almost all the power dissipation becomes the burden of the driving amplifier. The source voltage V1 delivers 15 V<sub>p-p</sub> at 80 kHz. The circuit drives the actuator, which is represented by the 1-nF capacitance, in series with a 1-Ω resistance (Fig. 3).

In this example, two power operational amplifiers are connected in a bridge circuit.<sup>[2]</sup> When configured in this way, these ICs are able to deliver an output voltage swing that is twice that of a single device. Also, this configuration doubles the single-device slew rate while making any nonlinearities symmetrical, thereby reducing second-harmonic distortion when compared with a single amplifier circuit.

To say the load is floating is to say it is not ground-connected at all. When the left output (V<sub>OUTA</sub>) swings from 10 V to 160 V and the right output (V<sub>OUTB</sub>) descends from 160 V to 10 V, a voltage swing of 300 V (-150 V to +150 V) develops across the load.

In Fig. 3, the outputs of the two amplifiers are now out of phase. The overall gain of the two bridge-configured power op amps is +20, so that



**Fig. 4.** Deflection plates amplifier circuit. The fast op amp, an AD817 in cascade with the PA78, provides a gain of approximately 100 enabling the output voltage to the deflection plates to be changed instantaneously to any potential between 0 V and 300 V.

300 V<sub>p-p</sub> is delivered to the piezoelectric actuator, as required. As shown in Fig. 3, a dual-source, asymmetric power supply delivers +175 V and -5 V to the two amplifier modules.<sup>[3]</sup>

The values of +V<sub>s</sub> and -V<sub>s</sub> have been chosen so that there will be sufficient head room during the positive and negative excursions of both V<sub>OUTA</sub> and V<sub>OUTB</sub>. This, as well as computing the maximum dissipated power per module, is discussed in reference 4.

In the Fig. 3 circuit, the principal passive components are resistors R3 and R4 and diodes CR1 through CR4. The feedback circuit comprising resistors R3 and R4 centers the output of the two power op amps around 85 V. The diodes protect the amplifiers as follows.

In any piezoelectric actuator circuit, it is essential to prevent signals from inadvertently feeding back to the amplifier. A piezoelectric transducer can convert mechanical energy into electrical energy just as easily as it can convert electrical energy into mechanical energy.

So if something were to bump the transducer, it could create a lot of energy that would travel backward into the output of the amplifier, which could be destructive. However, by connecting several ultrafast MUR160 diodes (CR1 – CR4) from the output of each amplifier to its corresponding power-supply rails, as shown in Fig. 3,

each amplifier is protected. Ultrafast rectifiers typically have reverse recovery times of 100 ns or better, which offers good flyback protection.

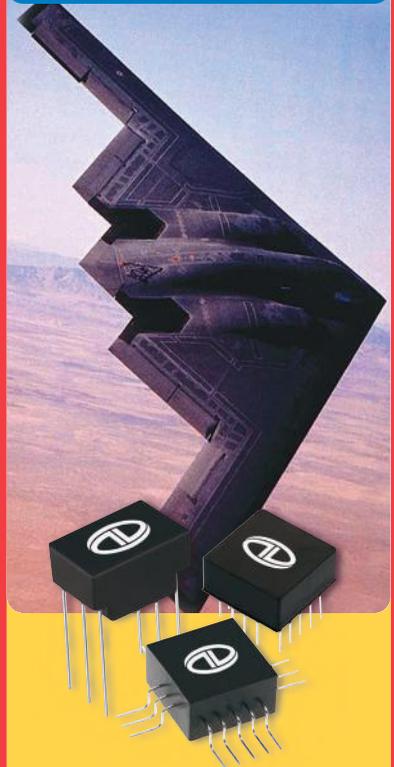
### A High-Speed Drive Circuit

The design goal of the circuit shown in Fig. 4 is to drive a pair of deflection plates. This circuit design is suitable for driving a piezoactuator that presents a load of approximately 10 pF. This circuit was actually developed for continuous-drop printing applications. In this circuit, the PA78 power op amp connects directly to the deflection plates.

Electrostatically charged ink droplets, typically 50 microns to 60 microns in diameter, are emitted by the ink source at a high velocity and are then passed through the electrostatically charged region between a pair of deflection plates. Each droplet is thereby deflected, as required to form the ink characters deposited on the printed surface.

The programming information, arriving as a digital data stream at the digital-to-analog converter (DAC), is converted into a sequence of square waves of differing voltages ranging from 0 V to 3 V. This wave-train sequence is then fed to a fast op amp, such as Analog Devices' AD817 (Fig. 5). In turn, the output of this device drives the Apex PA78 power operational amplifier.

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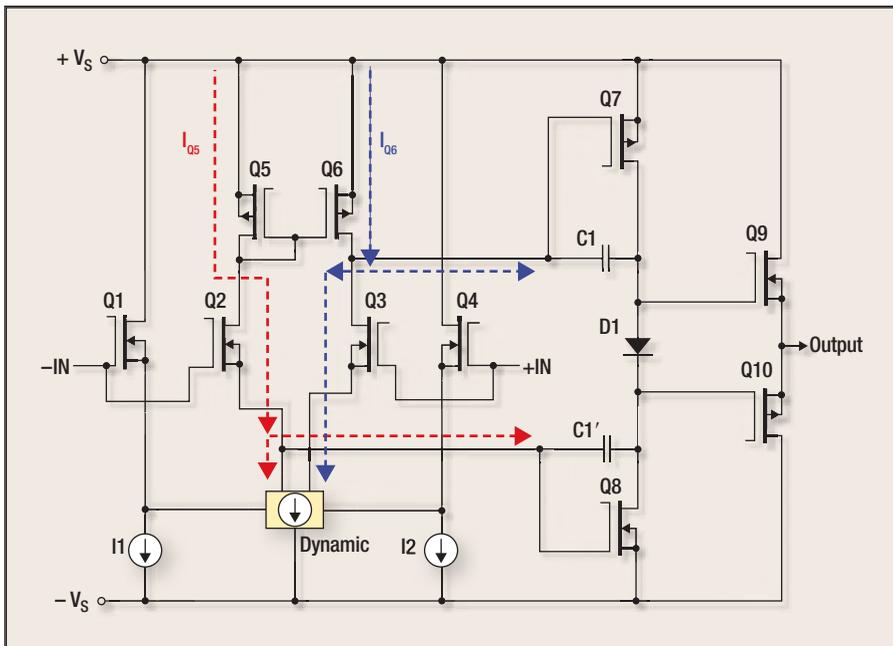


Fig. 5. The output of the PA78 supports high voltages and slew rates, and can directly drive the deflection plates of an inkjet printer.

The AD817 has a slew rate that fits very well with the 300-V/ $\mu$ s design goal. A slower pre-amplifier will not

reach the design goal and a faster amplifier may increase cost and power consumption. The PA78 achieves

higher slew rates when the output is overdriven, so this two-stage amplifier approach provides better high-voltage step response than a PA78 driven directly from the DAC.

The output of the PA78 is applied to the deflection plates, as a sequence of square waves, differing in magnitude and varying between 0 V and 300 V at a repetitive rate of 100 kHz. At the beginning of each programmed voltage value, the square wave must reach its programmed voltage within 1.5  $\mu$ s. This is essential because the programmed voltage must remain constant throughout the final 8.5  $\mu$ s, for that is the time span for the next droplet to pass through the deflection-plate field.

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### Acknowledgement

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