New Product Release

PUI Audio is excited to announce our Haptics Phase 3 launch to introduce piezo-based actuators, complementing our existing electromagnetic offerings!

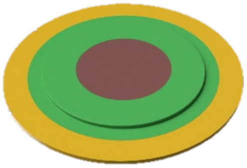
Innovations in piezoelectric materials and manufacturing processes have driven significant growth opportunities for piezoelectric haptic actuators. Various applications can achieve higher displacement precision, faster response speed, more significant generating force, and longer life to improve user experience.

Piezoelectric material can produce a small voltage when impacted by a mechanical force - if this is reversed, and a *voltage* is applied to the material, physical motion is produced. This *reverse piezoelectric effect* is the fundamental principle behind using piezoelectric actuators to produce haptic feedback. Various voltage levels and driving signal patterns can cause a wide range of precise motion in the actuator; the resulting displacement can activate switches, create sound, release fluid, auto-break, or auto-focus, and more!

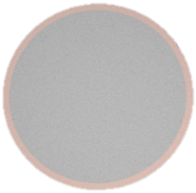
Typical application examples include smart displays, touchscreens, wearables, IoT devices, human-machine interfaces, health monitoring & diagnostic devices, medical imaging, minimally invasive surgery, micropumps, experiential learning, AR/VR, gaming controls, and precision motion controls.

These new devices are perfect when precise control and movement are required in a compact, thin profile- with a unique sense of touch for high-quality tactile effects. Visit our website today to learn more!

Piezoelectric Haptics – Discs



HD-PAB1501

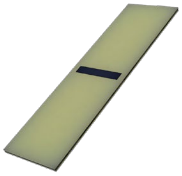


HD-PAB2701

Key Features

Part	Dimensions (mm) (Ø x H)	Max Voltage (V_{P-P})	Capacitance (nF)	Displacement (µm)
HD-PAB1501 ***NEW!***	15 x 0.31	300	6.5 ± 20%	55 ± 5.5
HD-PAB2701 ***NEW!***	27 x 0.5	155	55 ± 15%	65 ± 15

Piezoelectric Haptics - Strips



HD-PAS2507

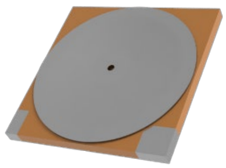
Key Features

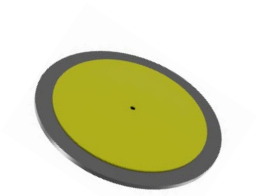
Part	Dimensions (mm) (L x W x H)	Max Voltage (V_{P-P})	Capacitance (nF)	Displacement (µm)
HD-PAS2501 ***NEW!***	25 x 7.1 x 0.5	50	75 ± 15%	50

Piezoelectric Haptics – Cymbals


HD-PAC0904


HD-PAC1204


HD-PAC1212

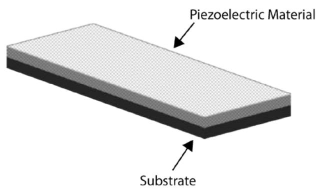

HD-PAC2102

Key Features

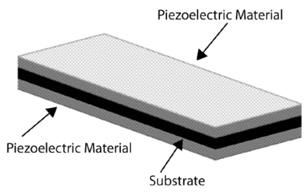
Part	Dimensions (mm)	Max Voltage (V_{P-P})	Capacitance (nF)	Displacement (µm)
HD-PAC0904 ***NEW!***	9 x 4 x 1.35 (L x W x H)	70	.16 ± 20%	12 ± 10%
HD-PAC1204 ***NEW!***	12 x 4 x 1.62 (L x W x H)	70	.24 ± 20%	25 ± 10%
HD-PAC1212 ***NEW!***	12 x 12 x 1.44 (L x W x H)	80	1000 ± 20%	45 ± 10%
HD-PAC2102 ***NEW!***	21 x 1.52 (Ø x H)	120	400 ± 20%	50 ± 10%

PIEZO CONSTRUCTION

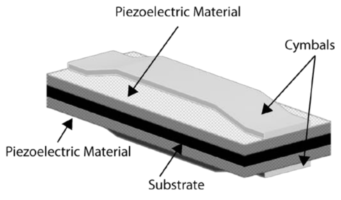
Piezoelectric haptic devices, also known as *piezo benders* or *piezo haptics*, are typically designed with either a bimorph or unimorph configuration. These actuators consist of flat layers of active piezoelectric material that bend and contract when voltage is applied, based on the reverse piezoelectric effect.



Standard Unimorph

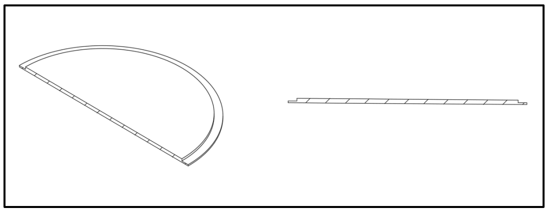


Standard Bimorph

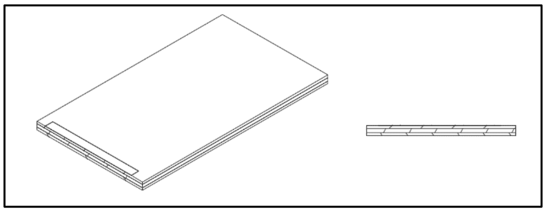


Bimorph w/ Cymbals

Bimorph (**HD-PAS2501**) benders consist of two active piezo layers, while unimorph benders (**HD-PAB1501** & **HD-PAB2701**) feature one active piezo layer, often attached to a passive substrate. The difference in polarization between the active layers and substrates causes one layer to contract and the other to expand during each voltage cycle, resulting in a bending motion.

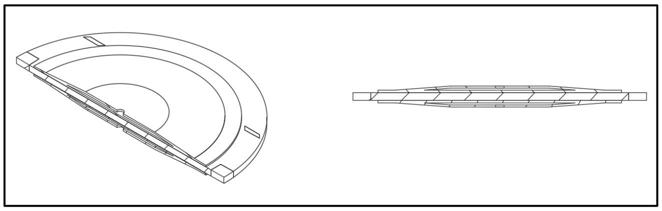


HD-PAB2701 Section View



HD-PAB2701 Section View

To enhance bender displacement and haptic performance, some piezo benders may be equipped with cymbals - additional metal plates that surround the actuator. These plates store potential energy when the bender deforms, further amplifying its motion. Implement the **HD-PAC0904**, **HD-PAC1204**, **HD-PAC1212**, or the **HD-PAC2102** today to feel the force!



HD-PAC2101 Section View

HAPTIC DISCS

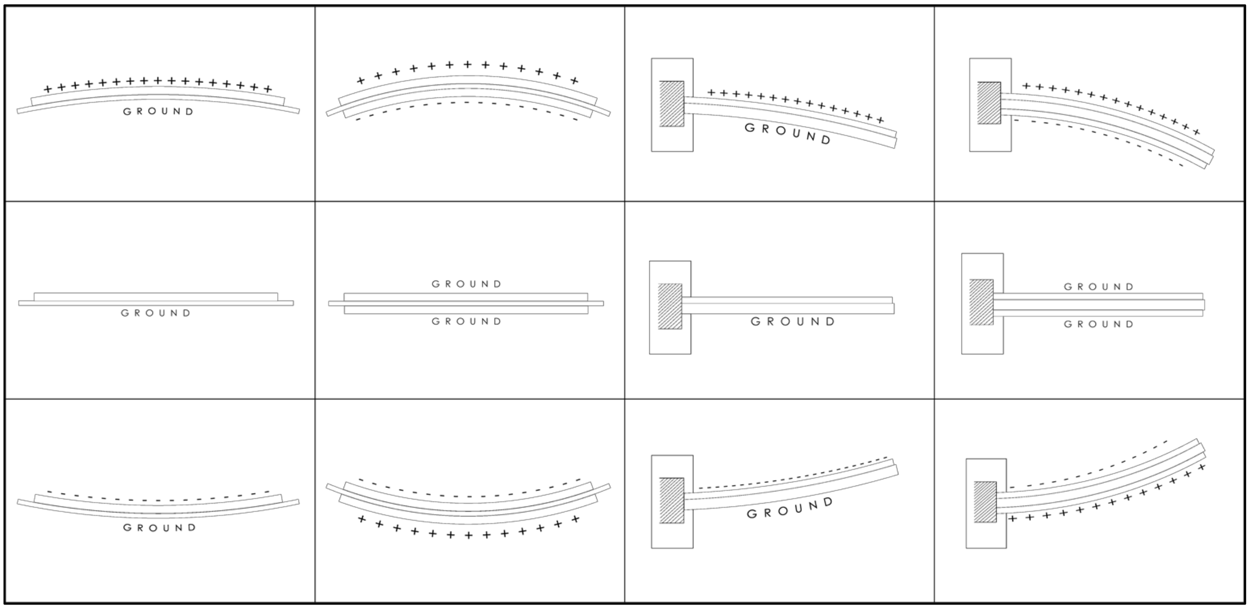
Piezoelectric Haptic Discs typically are unimorph devices. A polarized piezoelectric layer is bonded to a substrate layer, which provides stability to the piezo, and returns the bender back to the original shape after deformation. Applying a voltage causes the piezoelectric material to expand, with the largest amount of displacement appearing near the center of the disc (when mounted by only the disc edges).

This causes bending near the center of the substrate layer as the piezoelectric material deforms, creating a concave shape with stored potential energy. Removing the previously applied voltage will cause the piezoelectric material to no longer attempt to expand, and the concaved substrate layer will use its potential energy to "snap" the piezoelectric material back to its original position.

HAPTIC STRIPS

Piezoelectric Haptic Strips are typically constructed as either unimorph or bimorph devices. Applying opposite voltages to the two strip electrodes causes deformation in the ceramic material, resulting in a "bowed" shape in the strip. The flat, rectangular form benefits from use in a cantilevered orientation- fixing one end of the strip to a surface allows the opposing end to actuate freely when voltages are applied.

The bimorph construction typically includes multiple layers of varying polarization piezoelectric ceramics and may or may not have the metal substrate. The displacement of the haptic strip tends to be greater than that of the haptic disc at the cost of actuator stiffness, speed, and force.

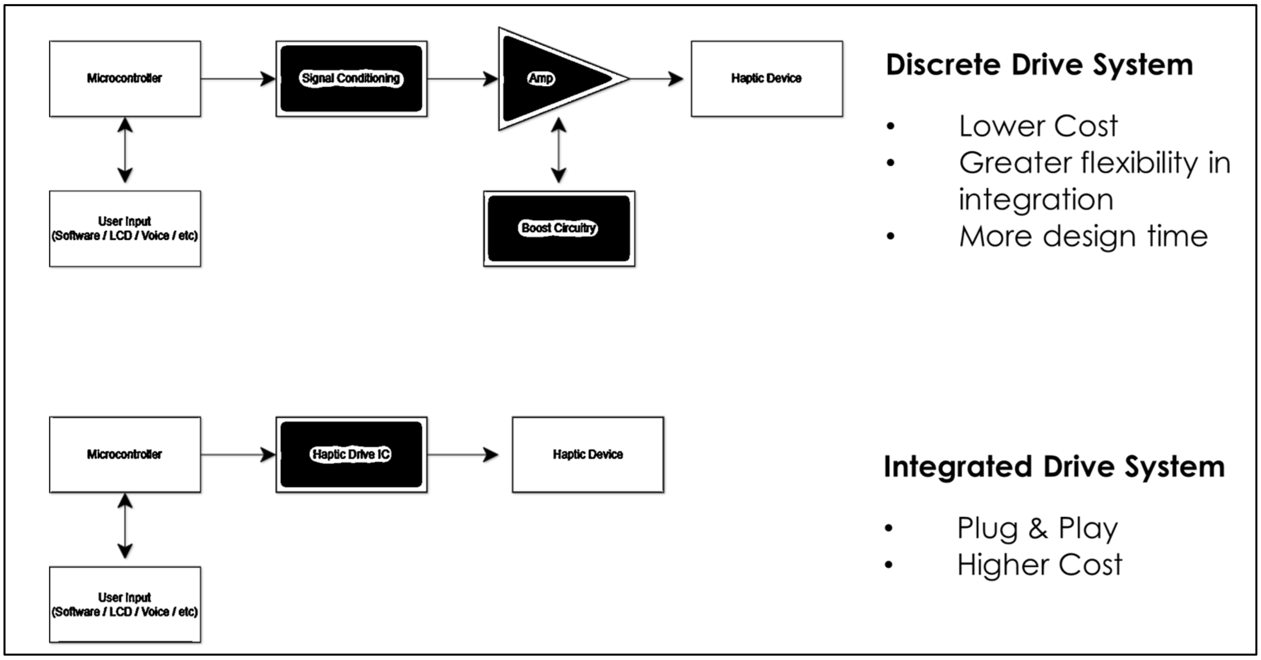


Drive Circuits

When integrating a piezoelectric haptic device into an application, deciding which method of driving the actuator will be necessary, as there are various options for driving piezoelectric actuators- the best of which is determined by the needs of the application itself.

Integrated drive circuits are available, which simplify the process, allowing for automatic optimization, dynamic vibration strength, and stored vibration patterns. These are popular in applications that require dynamic haptic effects- such as handheld devices and wearables. Users of these applications may encounter new haptic responses following device updates; therefore, an integrated drive circuit incorporating flexible waveform memory, signal conditioning, and amplification into a single chip is desirable.

A discrete drive circuit may be developed for applications that do not require dynamic responses but repetitive motion and precision. The advantages of this are often a lower cost when scaled for production and greater flexibility when integrating the actuator into applications. The image below illustrates some system-level differences between discrete and integrated drive circuits.



Discrete Drive System

- Lower Cost
- Greater flexibility in integration
- More design time

Integrated Drive System

- Plug & Play
- Higher Cost

DISCRETE DRIVE EXAMPLES

	Texas Instruments DRV2667	Analog Devices MAX77501	Microchip MTCH810	Boreas BOS1901
Operating Voltage	3.3 – 5.5	2.3 - 5.5	2.5 - 5.5	2.7 - 5.5
Output type	Differential	Differential	Single-ended & Differential	Differential
Interface	I2C	I2C	I2C	I2C / SPI
Feedback Mechanisms	Yes (Feedback Input Pin for Impedance Matching)	Yes (Auto Resonant Frequency Tracking with Adaptive Frequency Range)	No	Yes (CapDrive™ Technology with Low Voltage Tracking)
Boost Converter	Yes	Yes	No	Yes
Waveform Generation	Yes, integrated RAM	No	No	No

Haptic Driver References

DRV2667 Piezo Haptic Driver

High-Efficiency Piezo Haptic Actuator Boost Driver

MTCH810 Haptics Controller

BOS1901 Piezo Driver

AMPLIFIER DESIGN

The amplification stage for a piezoelectric Haptic actuator is affected by the fact that piezoelectric material has a capacitive element, which, like a capacitor, is proportional to the driving frequency, voltage, and temperature. Typically, these values are between 10 and 500 nF, depending on the actuator. When operating below the resonance point, the piezoelectric actuator can be viewed as a purely capacitive load; to begin the motion, the amplifier must supply a charge to the actuator, then remove the charge to cause movement in the opposite direction. When operating at or near the resonant frequency, the actuator can be viewed as a small resistive load in parallel with the capacitance of the actuator (generally no more than 100 Ω). The amplifier's output must be sufficient at this frequency to continually supply the piezoelectric actuator's required voltage across the resistive element.

For most piezoelectric actuators, this current draw is minimal (typically <10 mA), resulting in piezoelectric material being almost entirely capacitive, as discussed earlier. With a rated voltage generally between 100 and 200 Vpp, most devices will dissipate only a small amount of power across the actuator itself (specifically, across the resistive element appearing near resonance). Most of the power dissipation will occur across the driving IC and resistors of the amplifier system. Additionally, the capacitive behavior of piezoelectric material means that the actuator can store a charge- but without a true internal resistance, it cannot internally dissipate charges provided by the amplifier. When energized (and extended), the piezoelectric element will effectively stay in position until the charge is removed- when it is, the actuator will return to its initial position.

Suppose one terminal of the actuator is tied to the system ground. In that case, the initial position of the actuator is restricted by the ground reference, and any DC bias present– charge will not be removed past this level, meaning that the actuator may not contract fully in the opposing half of each cycle of the driving signal. While this may be desirable in some applications, using a piezoelectric element in an application such as a microfluidic pump often requires an equal positive (expansion) and negative (compression) cycle.

To solve this, a differential amplifier may be constructed so that the actuator is floating with respect to the system ground. When an alternating signal is applied, one side of the amplifier provides an actuator terminal with a positive voltage. In contrast, the opposite provides the remaining actuator terminal with an identical negative voltage. This allows for a positive charge to be fully applied to the actuator in a half-cycle (causing the piezoelectric material to expand) and a negative charge to be fully applied in the other half-cycle (causing the piezoelectric to contract in the opposite direction). Differential amplifiers also often provide higher voltages required by piezoelectric devices more efficiently than single-ended designs.

To achieve maximum displacement between the alternating cycles, the amplifier rise time must also be significantly faster than the response time of the actuator; it is recommended that the amplifier's bandwidth be 3-4 times the resonant frequency of the actuator.

Determining Minimum Current

Assuming the actuator can be considered a capacitive load at low frequencies, and the resistive element of the piezoelectric does not appear until close to the resonant frequency, the *average current* required to drive an actuator under continuous sinusoidal operation can be found by neglecting the resistive element and driving frequency (assumed to be below the resonant frequency), then applying the standard equation for a sinusoidal current through a capacitor.

$$I_{AVG} = C * \frac{dV}{dt} \qquad \textbf{(1)}$$

Where I_{AVG} = average current required for the actuator, C = capacitance of the piezoelectric actuator, and dV/dt = the rate of change of the voltage signal corresponding to the actuator's rated voltage and driving frequency.

The resulting value of I_{AVG} should be the *current required for the actuator to function at its rated voltage*.

Verifying Operation Near Resonance

To verify that the value calculated for I_{AVG} in (1) is still viable when driven closer to the resonant frequency (at frequencies where the piezoelectric resistive element appears), the following formula may be used:

$$I_{MAX} = C * V_{PP} * 2 * \pi * f \qquad \textbf{(2)}$$

Where I_{MAX} = the maximum (peak) current driving the actuator, V_{PP} = the rated voltage of the actuator in volts, C = capacitance of the piezoelectric actuator, and f = the maximum driving frequency.

This equation calculates the *required maximum current* that the amplifier must be able to provide over one full cycle of the driving signal, considering the effects of driving frequency. This is distinctly different from the previous calculation, as the effects of driving frequency are included.

By comparing the values obtained from equations (1) and (2), it is possible to assess the current requirements for driving the piezoelectric haptic actuator near its resonant frequency.

Maximum Operating Frequency

Suppose the average drive current calculated in (1) (I_{AVG}) is substituted in place of the maximum allowable drive current (I_{MAX}). In that case, the resulting value of f should equal the *maximum operational frequency* which meets the actuator's minimum driving current and rated voltage.

Equation (2), substituting I_{AVG} and rearranged to find this value of f_{MAX}:

$$f_{MAX} = \frac{I_{AVG}}{Vpp * \pi * C} \qquad \textbf{(3)}$$

Since $\mathbf{f_{MAX}}$ was found using the average current determined in formula (1), it can be inferred that the current draw increases when operating near resonance and that the maximum current draw appears at resonance.

To adjust this maximum frequency of operation, (1) and (2) may be applied with different initial parameters- by increasing the initial driving voltage value in formula (1), the resulting value of I_{AVG} is increased, therefore increasing the resulting maximum drive frequency in (3). Many piezoelectric actuators allow for variable frequency and driving voltage if the current provided by the amplifier is sufficient; check the specification of the actuator to determine a range of acceptable values.

This series of calculations assumed that the driving signal for the actuator was sinusoidal. Driving the actuator with other waveforms, such as a triangle wave, will require appropriate substitutions to reflect the change in the driving waveform.

Formula (2) for triangle waveform: $$I_{MAX} = Vpp * C * f \qquad \textbf{(4)}$$

Formula (2) for square waveform: $$I_{MAX} = \frac{Vpp}{\Delta t} * C \qquad \textbf{(5)}$$

<u>Summary</u>

- Piezoelectric material can be considered primarily capacitive, but a resistive element appears when the actuator operates near resonance.
- The amplifier must provide sufficient voltage to maintain the rated current of the actuator across this resistance at resonance

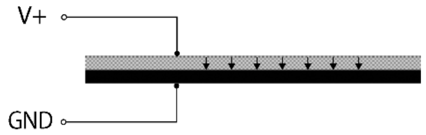
ELECTRICAL CONSIDERATIONS:

Ensure secure and reliable electrical connections between the actuator and the driving circuitry. Use flexible connecting wires to prevent any unwanted stress or distortion on the actuator during operation. Proper cable routing and strain relief techniques must be employed to maintain robust connections over time.

Wiring Configurations

Unimorph Series Wiring:

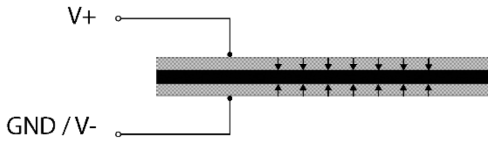
In this configuration, the unimorph bender is connected to the voltage source, with one terminal connected to the active piezo layer and the other terminal connected to the passive layer.



Unimorph Operation

Bimorph Series Wiring:

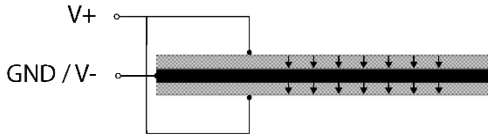
For bimorph actuators, the series wiring configuration connects the two active piezo layers in series. One terminal of the voltage source is connected to an active layer, while the other terminal is connected to the second active layer through a conductive middle shim. This results in a stronger bending effect due to the increased voltage difference across the two active layers.



Bimorph Series Operation

Bimorph Parallel Wiring:

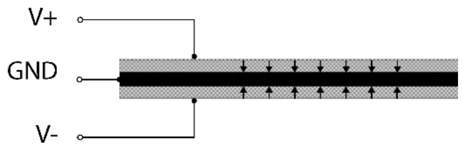
In the parallel wiring configuration, both active layers are connected to the voltage source simultaneously. This arrangement enables the layers to respond more quickly to the applied voltage, enhancing the response speed of the actuator at a cost of decreased displacements.



Bimorph Parallel Operation

Bimorph Differential Operation:

This configuration utilizes two separate voltage sources to drive the bimorph actuator. Each active layer is connected to an independent voltage source, with opposing polarity. As a result, it can better control the motion, allowing for more precise haptic feedback.



Bimorph Differential Operation

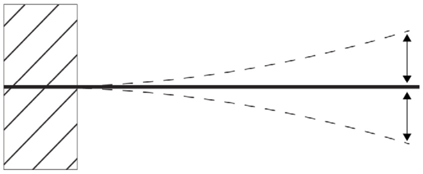
MOUNTING CONSIDERATIONS

Proper mounting of piezoelectric actuators is crucial in various applications to ensure optimal performance. Different mounting techniques are used for non-cymbal and cymbal actuators.

NON-CYMBAL ACTUATORS

Cantilever Mounting:

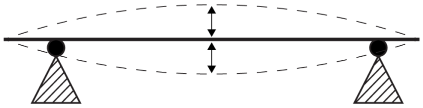
In this configuration, one end of the bending strip or disc is fixed while the other end is free to move. This allows the piezo actuator to create maximum displacement. Cantilever mounting is especially beneficial for applications requiring repetitive motion or precise positioning.



Cantilever Mounting Example

Edge/Beam Mounting:

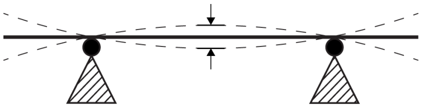
Edge or beam mounting involves attaching the piezo actuator to a rigid structure by its edges. This type of mounting allows the actuator to produce its maximum deflection in the center while maintaining stability. Edge mounting is commonly used for bending discs.



Edge Mounting Example

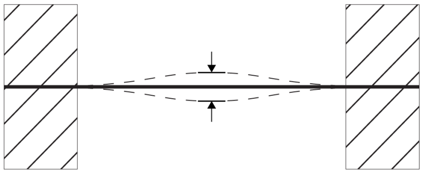
Nodal Mounting:

Nodal mounting refers to fixing the piezo actuator at its nodes, the points where the actuator exhibits minimal displacement. This mounting style ensures that the actuator remains stationary while the rest of the piece undergoes motion. Nodal mounting is ideal for applications requiring precise control over vibration and movement.



Nodal Mounting Example

Clamped Mounting:
This mounting configuration involves securing all edges of the piezo actuator to a surface, completely restricting deformation. Clamped mounting limits the actuator's movement and is typically used in applications where stability is essential, and vibration must be minimized.

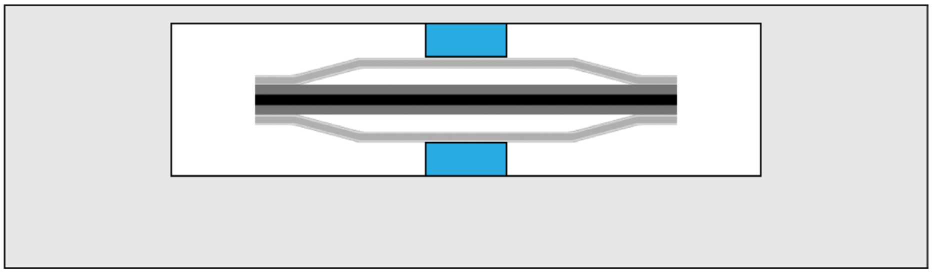


Clamped Mounting Example

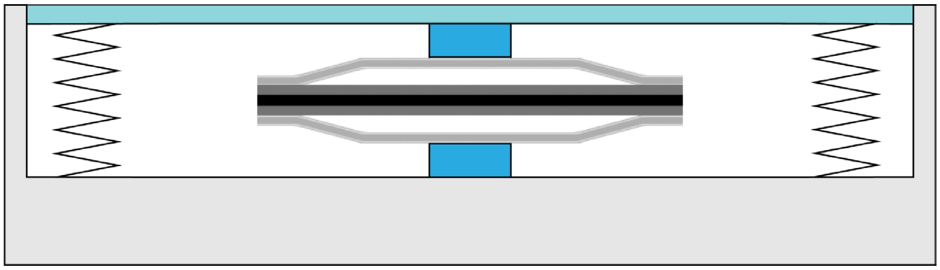
CYMBAL ACTUATORS

Piezoelectric actuators with cymbals are designed to deliver high-quality haptic feedback through surfaces, such as touchscreens or control panels. Proper mounting of these actuators ensures optimal transmission of vibrations and maximizes user experience.

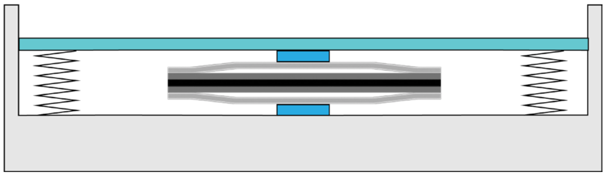
Surface Alignment and Attachment:
Ensure that the cymbal actuator is aligned correctly with the surface it will be transmitting vibrations to. The actuator must be placed in direct contact with the surface to achieve optimal haptic feedback. Use adhesive materials, such as double-sided tape or conductive epoxy, to attach the cymbal actuator to the surface. Ensure that the adhesive creates a consistent bond without any gaps between the cymbal and the surface. It is recommended that the surface opposite the desired haptic effect be significantly stiffer than the haptic surface, so that only the desired surface will flex.

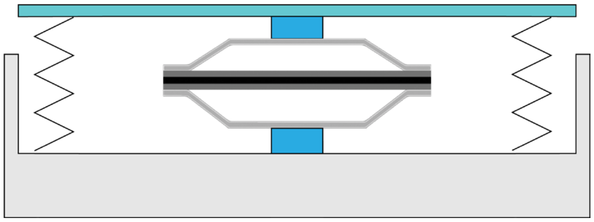


Often, the haptic surface in an application is not flexible- for instance, when the actuator is located behind a touchscreen or digitize. To accommodate this, the upper surface of the device may be isolated, requiring an elastic connection between the haptic surface and backing surface. This configuration emphasizes the importance of a stiff backing surface; increasing the difference in stiffness between the haptic surface and the backing will decrease the energy lost to the movement of the load and the resulting movement of the backing surface.



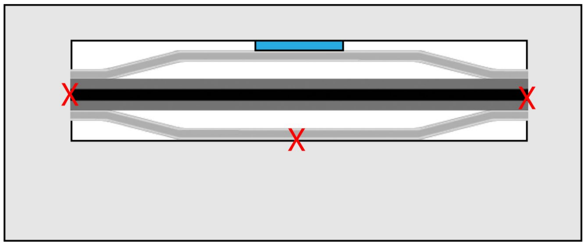
Selecting the Appropriate Pressure:
For effective haptic feedback, the cymbal actuator needs to exert adequate pressure on the surface. Too much pressure can cause discomfort to the user or even damage the actuator, while insufficient pressure can lead to weak haptic feedback. Test various pressures during the mounting process to determine the optimal pressure level.

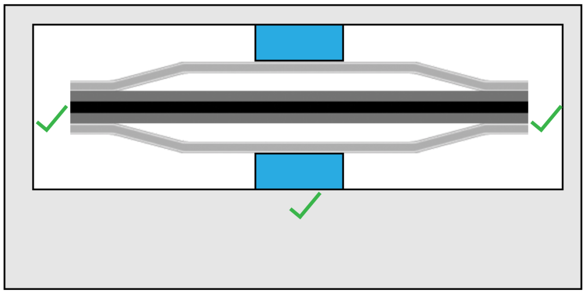




Space and Enclosure Considerations:

When mounting a cymbal actuator in a confined space, such as behind a touchscreen, ensure that there is adequate space for the actuator to bend and vibrate. Also, consider the surrounding structure and potential interference from any other components in the system.





CONCLUSION

Our new piezo-based haptic actuators are perfect when precise control and movement are required in a compact, thin profile- with a unique sense of touch for high-quality tactile effects.

View our available Piezo Haptics offerings here!