Piezoelectric Technology Enhances Haptics

Piezoelectric Materials Are Key to Enhanced Haptic Experience

By Jean-Jacques DeLisle for Mouser Electronics

Source: K-MookPan/stock.adobe.com; generated with AI

MOUSER ELECTRONICS | TDK

Discovering and Developing the Piezoelectric Effect

Figure 1: *Natural piezoelectric crystals, engineered piezoelectric ceramics, and non-piezoelectric structures demonstrate the variety of materials used in piezoelectric applications. (Sources: (a) Ekaterina/stock.adobe.com, (b, c) Mouser Electronics)*

In the late 1800s, French scientists discovered that applying pressure to specific naturally occurring crystalline structures, such as quartz and tourmaline (**Figure 1**), produces an electric charge. This phenomenon became known as the piezoelectric effect. Deeper exploration led to the discovery that many crystalline structures exhibit piezoelectricity, including topaz, Rochelle salt, sugars, and even wood.

Further studies based on theoretical analysis proved that exposing these crystalline structures to an electric field induces stress in the materials, causing deformation. Over the years, the understanding and application of this electrical deformation concept, the inverse piezoelectric effect, and the piezoelectric effect have evolved from an interesting material property to a fundamental means of realizing transducers and actuators—from advanced audio equipment to inertial sensors and piezosurgery equipment.

A major breakthrough in this area was the discovery and development of piezoelectric ceramics, such as barium titanate, which exhibit a higher piezoelectric response compared to naturally occurring crystalline structures. More growth in industrial- and engineering-grade piezoelectric materials has led to substantial improvements in responsiveness and miniaturization. Now, one of the significant modern use cases of piezoelectric materials is in haptic devices (**Figure 2**).

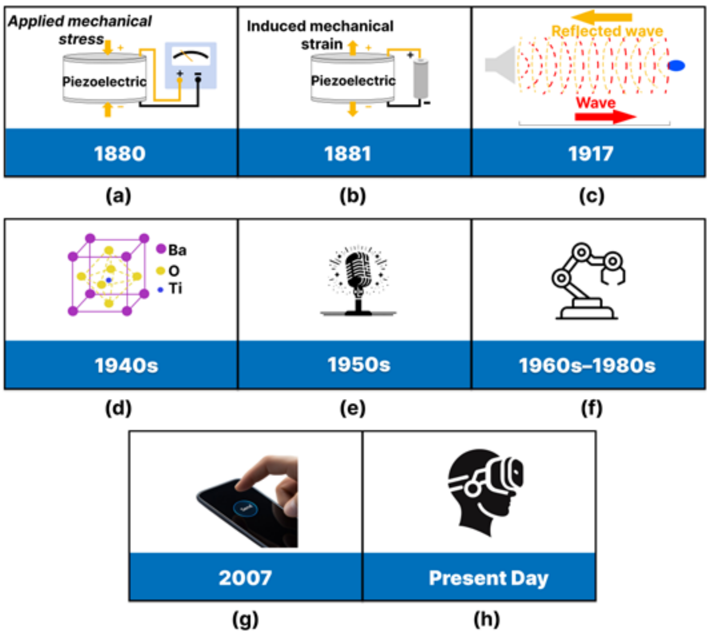

Figure 2: *Timeline of piezoelectric advancements, from discovery to modern innovations. (**a**) Discovery of the piezoelectric effect; (**b**) Prediction of the inverse piezoelectric effect; (**c**) First practical application, sonar; (**d**) Development of synthetic piezoelectric ceramics; (**e**) Commercial applications of quartz; (**f**) Piezoelectric transducers in industry; (**g**) Haptic feedback in smartphones; (**h**) Modern innovations such as gaming headsets*

This white paper provides an overview of the basic principles of piezoelectric materials and how they pertain to modern haptic technology. This paper will also share insights into how piezoelectric actuators and sensors are essential to modern haptics and the nuances of leading new haptic actuators. Finally, it will briefly discuss additional advanced material science concepts for piezoelectric devices, haptic feedback design, power management, and piezoelectric device integration into other systems.

Basic Principles of Haptics

Haptics is a wide area of study that covers the sensations of physical touch and physical object interaction. This sense can be expanded in haptics to the complete experience of sensory feedback, including tactile and force feedback. Additional haptic considerations pertain to emulating features such as surface texture, weight, shape, temperature, and the dynamic effects of 3D objects. Haptic technology utilizes kinesthetic communication and uses induced kinetic forces to convey information to a user. Haptic devices are generally composed of tactile sensors—measuring the forces exerted by a user—and haptic actuators—imparting kinetic forces to a user. Examples of haptic experiences include the rumble vibration systems in gaming controllers and gloves that accurately simulate the sensations of interacting with 3D objects in augmented reality (AR) and virtual reality (VR) environments.

The two main categories of haptic feedback are kinesthetic feedback and tactile feedback (**Figure 3**). Kinesthetic feedback refers to how a user perceives the size and density of an object through physical experience. This feedback can either be passive or active. When only a user's movements are impeded, this is called passive kinesthetic feedback. Active kinesthetic feedback involves imparting force and motion to a user.

Tactile feedback involves the perception of touch when interacting with an object. This feedback can be either non-spatial or spatial. Non-spatial tactile feedback uses methods such as vibration patterns to convey the sense of textures or physical ambiance from non-localized sources. Spatial tactile feedback involves communicating information about an object's edges and shape. This type of tactile feedback is generally realized using contact haptic feedback or even electrical stimulation.

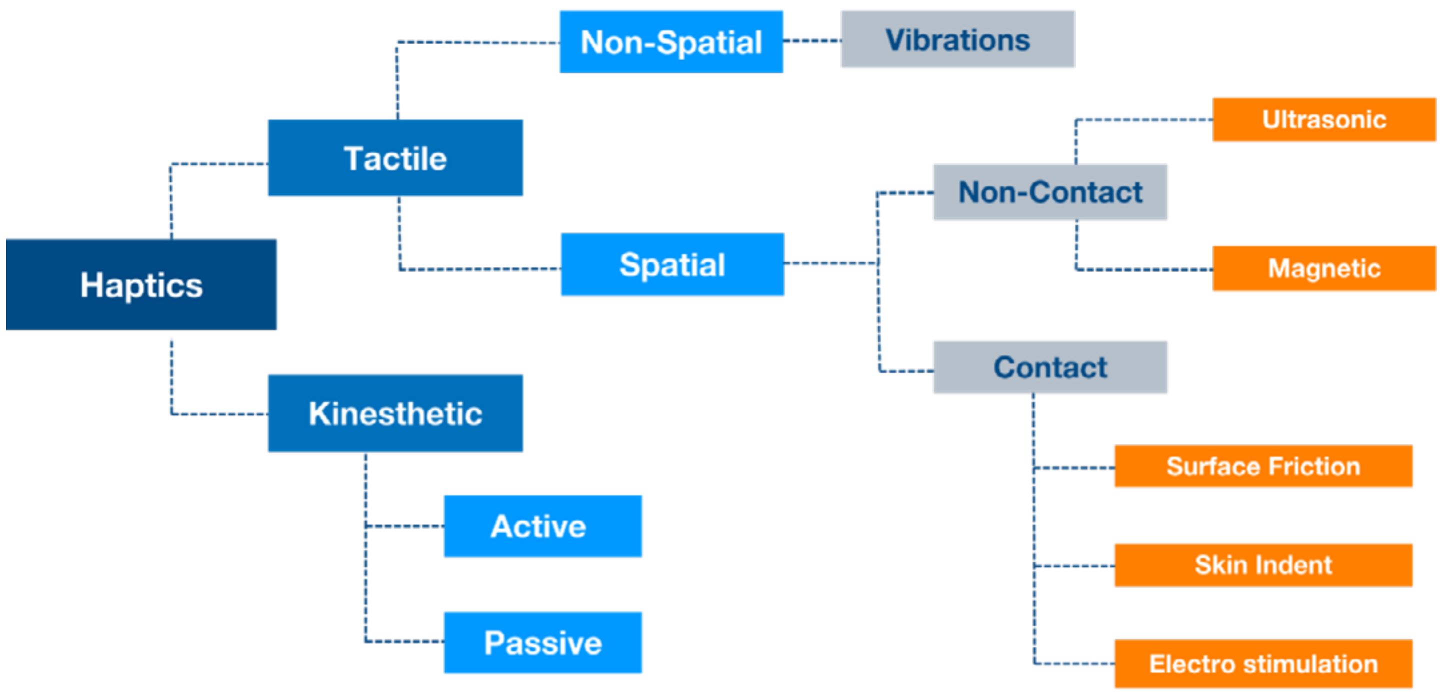

Figure 3: *Types of haptic feedback. (Source: Mouser Electronics)*

Main Types of Haptic Devices

A diverse range of haptic technologies use mechanical, electromechanical, or magnetic stimuli to impart sensations to users. Vibrotactile, electrotactile, and force feedback devices are more common, while ultrasonic, pneumatic, or hydraulic devices are used for specific applications.

Vibrotactile Feedback

The most common type of tactile feedback is vibrotactile feedback, such as vibrational feedback from smartphones, wearables, and other interfaces. These devices use vibration-inducing components to convey information to a user. Components for this type of feedback include vibration motors used in gaming controllers and sonic haptic transducers used in entertainment immersion enhancement systems.

Electrotactile Feedback

Electrotactile devices use electrical stimuli to induce nervous system effects on the body, replicating the nerve sensations that a user would feel if physically interacting with an object or environment.

Ultrasonic

Air-based ultrasonic haptics devices use ultrasonic generators to impart physical sensations to users. Also known as ultrasonic tactile feedback devices, these systems provide a touchless haptic experience by generating noticeable pressure regions to a user's skin. Examples include arrays of ultrasonic generators with advanced control algorithms that allow for multi-point ultrasonic feedback and a wide range of intensities.

Force Feedback

Force feedback kinesthetic devices—mechanical or electromechanical—simulate motion and resistance to motion. For instance, some gaming steering wheels use force feedback electromechanical motor systems to emulate the resistance an actual driver would feel while operating a race vehicle. Another example is using springs or pulleys to simulate the forces needed to manipulate virtual objects.

Pneumatic & Hydraulic

Possibly the oldest types of haptic feedback, pneumatics use air pressure actuators and hydraulics use non-compressible fluid actuators to replicate interactions with virtual objects.

Piezoelectric Technology for Haptics

Piezoelectric technology plays a pivotal role in modern haptic systems, offering precise and energy-efficient solutions for delivering tactile feedback in various applications.

Fundamentals of the Piezoelectric Effect

Piezoelectric materials generate electric charge (i.e., an electric field) when exposed to mechanical stresses and vice versa with the inverse piezoelectric effect. When mechanical stress is applied to a piezoelectric material, the reorientation of the electric dipoles within the crystal lattice causes the spontaneous separation of charges from within a crystalline structure and generates a measurable surface charge. The presence of a static electric charge generates an external electric field (**Figure 4**). Meanwhile, the inverse piezoelectric effect functions in reverse, where an external electric field causes stress within a piezoelectric material.

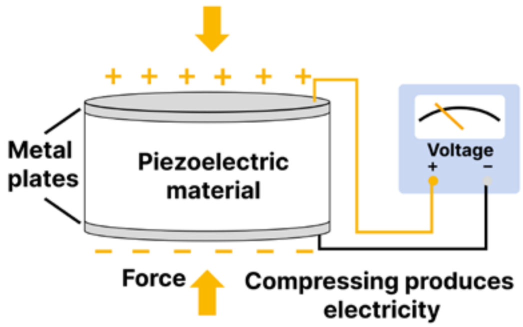

Figure 4: *Applying mechanical stress to a piezoelectric material reorients electric dipoles within the crystal lattice, causing charge separation and generating a measurable surface charge. (Source: Mouser Electronics)*

Polycrystalline ceramics that exhibit piezoelectric phenomena—called piezoceramics—are some of the most effective piezoelectric materials and can be cleverly designed to create a wide range of haptic feedback devices. Piezoceramics' ability to act as both haptic actuators and sensors can enable devices to produce vibrotactile or surface effects, depending on the application. This dual functionality allows piezoceramics to convert electrical energy into mechanical vibrations and vice versa. Key performance parameters for such piezoelectric haptic devices include the vibration frequency range, acceleration, force, displacement, response time, actuation and sensing electronics complexity, and power consumption. Other factors to consider are the size, weight, and cost of such devices, as this will also dictate their viability for specific haptic applications.

Mechanisms of Vibration & Displacement

A piezoelectric actuator experiences stress and physical deformation when exposed to an external electric field. This can be seen as an elongation or contraction of the shape and geometry of a piezoelectric material. Hence, a mechanical system can be designed around this electrically actuated material that allows for mass displacement, mechanical motion, and even vibration if a mass can be moved over adequate displacement fast enough to be perceived. A simple piezoelectric actuator is a cantilever, a floating beam of piezoelectric material that, when exposed to an electric field across the thickness of the material, causes the beam to bend along its length to achieve displacement of the beam's end. If this beam were weighted at the end, that weight could be rapidly displaced, which would induce vibrations along the beam and the support structure for the beam. More complex mechanical systems can be made that allow for a wide range of motion and vibration capabilities from piezoelectric actuators, which can also be used as sensors with the appropriate electronics.

Enabling Technologies in Piezoelectric Devices

The development of advanced enabling technologies has expanded the possibilities for piezoelectric devices, enhancing their functionality in haptic systems and beyond.

Actuators

Piezoelectric actuators, also called piezo actuators, can be fabricated in virtually any 3D arrangement with mechanical structures that allow for simple motion to complex mini-motor actuator systems. The most common types of piezo actuators are stack, shear, and bimorph. Stack actuators are stacks of thin piezoelectric disks, typically piezoceramics, that all expand as a function of the voltage applied. This piezo actuator can be used for simple linear displacement or combined with mechanical systems to enable vibration and even "amplified" displacement. A shear piezo actuator is also constructed as a stack, but when voltage is applied, its layers undergo shear deformation. Shear actuators are useful for precise XY positioning and, in combination with other piezo actuators, they can achieve XYZ positioning. A bimorph actuator is a piezo actuator in combination with a thin metallic disk and results in a simple and repeatable "amplified" motion. Given the degrees of freedom enabled by piezo actuator design, an extremely diverse range of piezo actuator types is available (**Figure 5**), each with advantages and applications.

Sensors & Transducers

Leveraging the inverse piezoelectric effect, piezo actuators and specifically designed piezo transducers can be used along with signal-conditioning electronics to create piezo sensors. A few common piezo sensors, such as accelerometers and force sensors, are widely used in everyday electronics and advanced scientific research applications. Piezoelectric ultrasonic sensors are also increasingly common in robotics, such as autonomous mobile robots (AMRs) used in the latest automated factory technology. These piezo sensors are often used to detect touch, pressure, and motion.

Microcontrollers & Signal Processing

Signal processing, driving, and control electronics are needed for piezo actuators and sensors to function. These electronics process and transmit the signals generated by piezo sensors and provide the necessary drive voltages for piezo actuators.

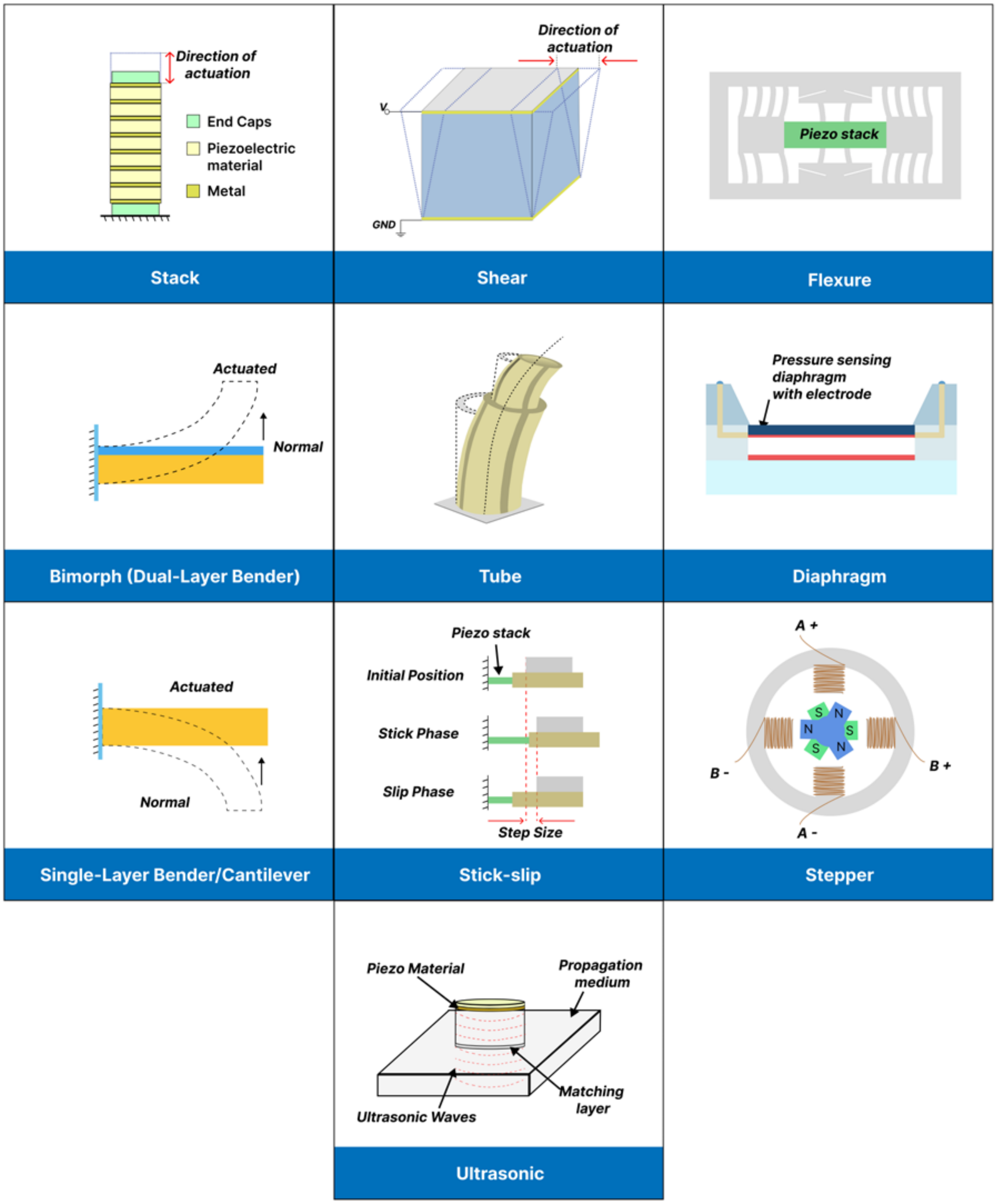

Figure 5: *Overview of piezoelectric actuator types, illustrating the various capabilities and applications of piezoelectric technology in motion control and haptic feedback systems. (Source: Mouser Electronics)*

TDK Piezoelectric Actuators for Haptics

Today, piezoelectric actuators for haptic applications are integrating these enabling technologies for enhanced performance and optimal user experience. Here are examples of the latest advances in this technology.

PowerHap Actuators

TDK PowerHap piezoelectric actuators are made with multilayer piezoceramics and mechanical displacement amplification, providing fast and precise displacement that is well suited to delivering crisp and sharp active haptics. Stainless steel bows are used in conjunction with the multilayer piezoceramic sections to augment the displacement of weighted sections far beyond the displacement of the piezoelectric sections. This arrangement results in vibrotactile and force feedback in a single device over a wide bandwidth of frequencies. With a range of frequencies and force outputs, these actuators can replicate a wide range of sensations with control of the frequency, signal characteristics, and signal strength.

Moreover, applying pressure or vibrations to PowerHap devices generates signals that can be extracted from the device. A force sensor and vibrotactile or force feedback system in a single package allows for enhanced optimization with no additional cost or footprint. Example use cases include vibrotactile and surface haptics for automotive displays, accurate button-like feedback emulation for scientific and medical devices, compact tactile effects for wearable AR/VR, and enhancing the sensation of a stylus to mimic drawing with various tools.

For quick haptics prototype design, TDK offers the **PowerHap development starter kit**. Featuring both seamless and round buttons plus additional PowerHap devices, the plug-and-play kit introduces engineers to incorporating haptic feedback into their designs.

PiezoHapt Actuators

TDK PiezoHapt actuators are thin vibrotactile devices composed of multilayer piezoelectric elements and a vibration plate. Their highly optimized design enables low-voltage operation, allowing for low power consumption. In addition to being highly efficient and compact, PiezoHapt actuators can provide near instantaneous, real-time response with an energization time that is a fraction of that of eccentric rotating mass (ERM) and linear resonant actuator (LRA) devices.

A unique feature of PiezoHapt actuators is that they provide a much more uniform vibrotactile response than traditional vibrotactile technologies (**Figure 6**). This means that if a PiezoHapt actuator is mounted within a smartphone or wearable, the user will experience the vibrotactile response more uniformly across the display without extreme high spots and low spots. The unimorph structure, with ceramic piezoelectric elements bonded to a metal plate, allows for efficient vibrations by warping the plate into “mountain” and “valley” shapes when AC voltage is applied, enhancing tactile feedback.

PiezoHapt actuators’ multilayer design allows greater displacement at the same thickness as other vibrotactile technologies, enabling low-voltage operation (as low as 24V) with strong vibration performance. This design also eliminates solder joints, reducing stress and improving efficiency. Moreover, using more advanced control systems and multiple actuators, PiezoHapt actuators can deliver vibrotactile responses toward a targeted region or in response to interactive control algorithms. With a thickness of just 0.35mm, PiezoHapt actuators are easily integrated into slim devices with limited vertical headroom.

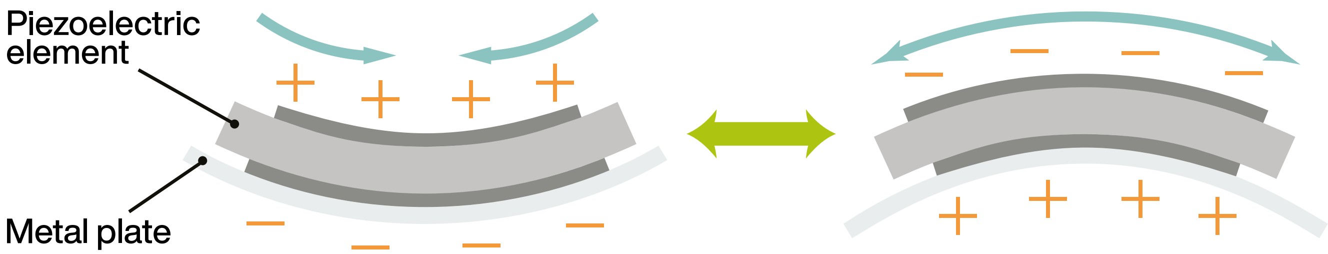

Figure 6: *The PiezoHapt actuator features a unimorph structure where ceramic piezoelectric elements with electrodes on both sides are bonded to one side of a metal plate. When an AC voltage is applied, the piezoelectric elements expand and contract, causing the metal plate to warp and generate vibrotactile feedback. (Source: TDK)*

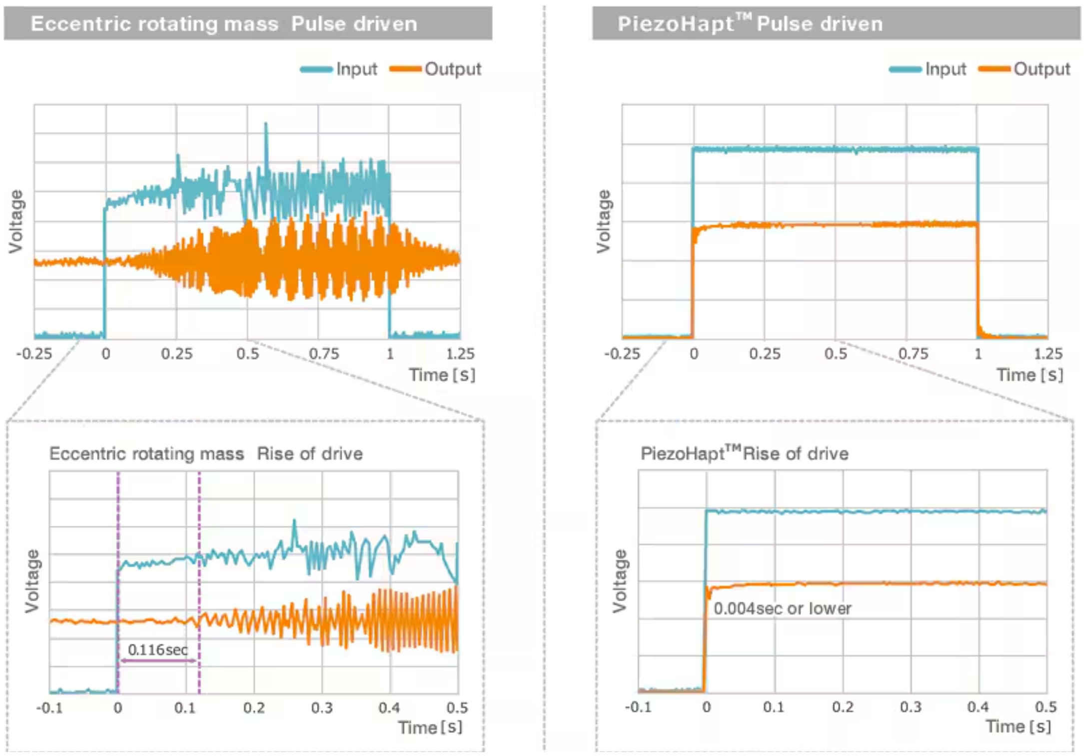

Figure 7: *Comparison of vibration amplitude and drive voltage patterns between ERM actuators and PiezoHapt actuators. (Source: TDK)*

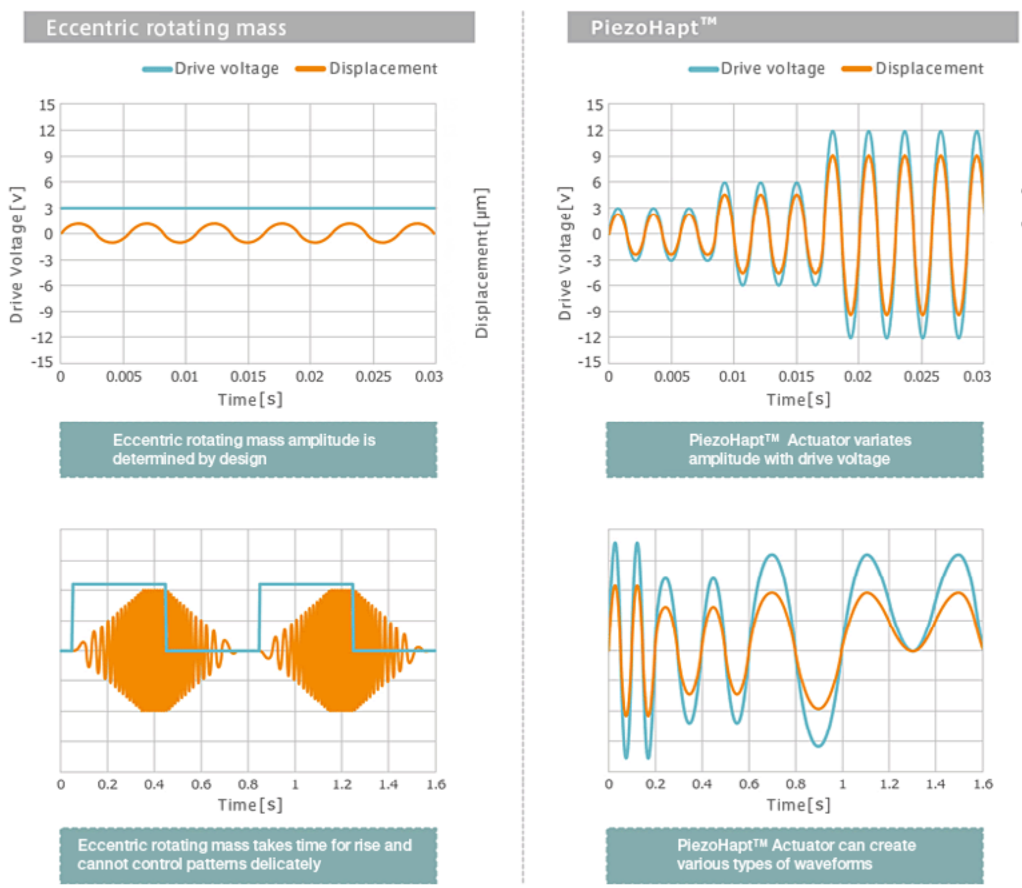

Figure 8: *Rise time comparison between ERM actuators and PiezoHapt actuators. (Source: TDK)*

The response speed and flexibility of PiezoHapt actuators set them apart from traditional ERM actuators. For example, while ERMs are limited to predefined vibration amplitudes, PiezoHapt actuators vary their amplitude with drive voltage, allowing for precise and dynamic haptic patterns (**Figure 7**).

PiezoHapt actuators rise 1/25th faster than ERMs, achieving a rise time of 0.004 seconds or less, compared to 0.116 seconds for ERMs (**Figure 8**).

These actuators' ability to create delicately controlled vibration patterns with lower power consumption further expands the possibilities for haptic feedback utilization (**Table 1**).

Figure 9 and **Table 2** compare PiezoHapt and PowerHap actuators, highlighting the strengths and parameters of each type.

Table 1: *Summary of performance metrics comparing ERM actuators with PiezoHapt actuators (Source: TDK; *Measurement by TDK)*

	Eccentric Rotating Mass	TDK PiezoHapt Actuator
Rise*	0.116 seconds	0.004 seconds (or lower)
Response	Slow	Fast
Vibration Uniformity	Transmits vibration partially	Vibrates the desired area uniformly
Displacement	Medium	Large
Vibration Patterns	Monotonous	Vibration is formed by pulse control
Power Consumption	15mW	5mW

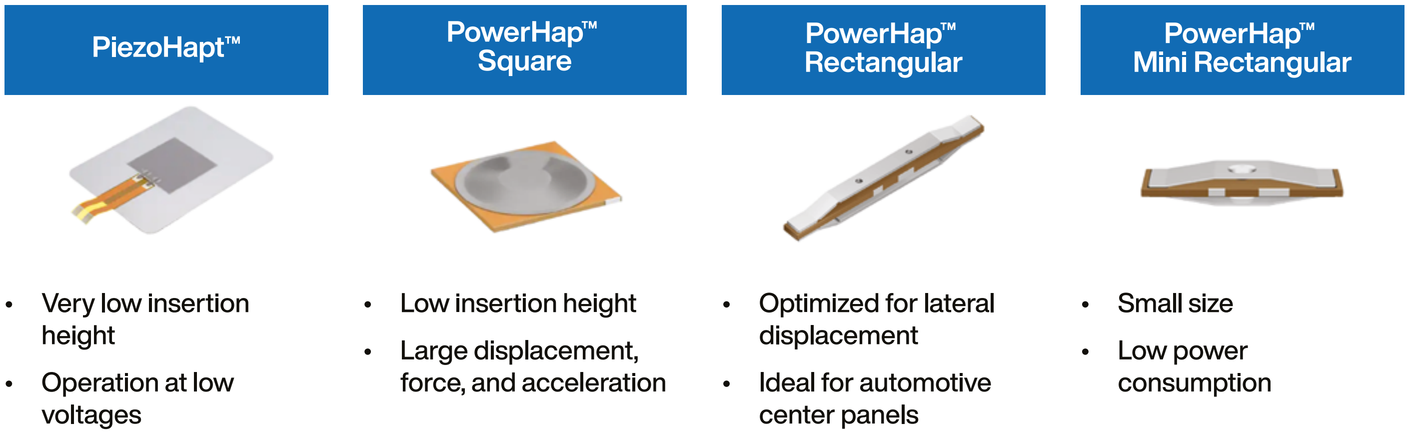

Figure 9: *Strengths comparison of PiezoHapt and PowerHap actuators. (Source: TDK, recreated by Mouser Electronics)*

***Table 2:** Detailed comparison of PiezoHapt and PowerHap actuators (Source: TDK)*

	PiezoHapt		PowerHap						
Shape	L-Type	L-Type	Square	Square	Square	Rectan-glular	Rectan-glular	Rectan-glular	Mini Rect-angular
Size (x, y, z) [mm]	80 × 60 × 0.35	30 × 15 × 0.30	26 × 26 × 2.3	19.4 × 19.4 × 2.1	12.7 × 12.7 × 1.8	60 × 5 × 7	60 × 5 × 9	12 × 4 × 1.8	9 × 3.75 × 1.4
Acceleration [G] (20g mass) peak	1.5	1.6	NA	NA	7	8	NA	4.8	2.4
Acceleration [G] (100g mass) peak	0.2	0.3	35	25	7	2.5	36	5	3.3
Acceleration [G] (500g mass) peak	NA	NA	6	6	1.2	NA	9	NA	NA
Rise Time [ms]	<1	<1	<1	<1	<1	<1	<1	<1	<1
Voltage [V] p-p	24	12	120	120	120	120	120	60	60
Energy per click [mJ]	5	1	8	6	3	1	6	3	1
Custom Waveforms	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Force Sensing	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Material Science for Piezoelectric Devices

Piezoelectric materials are often broadly categorized into three types: crystalline, ceramic, and polymeric. Piezoceramic materials, such as lead zirconate titanate (PZT), barium titanate, and lead titanate, are among the most common piezoelectric materials used in modern applications. Semiconducting ceramics, such as semiconducting materials and zinc oxide, are also used as piezoelectric devices for integrated circuit applications. Unlike single-crystal materials, inorganic ceramic piezoelectric materials allow for more degrees of freedom for fabrication and do not need to comply with crystallographic directionality.

Organic polymer piezoelectric materials tend to have a lower Young's modulus than inorganic materials, meaning they are easier to stretch or bend. However, they often have a higher piezoelectric stress constant than ceramic materials. Polymer materials can also be more readily manufactured into various shapes and films and can even be made larger than other piezoelectric materials. Where piezoelectric ceramics tend to be brittle, piezoelectric polymers, such as polyvinylidene difluoride (PVDF), demonstrate higher impact resistance and strength with lower elastic stiffness, dielectric constant, and density. Hence, polymeric piezoelectric materials are more suited to applications where voltage sensitivity and low acoustic or mechanical impedance are desirable.

Piezoceramic materials often exceed other piezoelectric materials in sensitivity and exhibit good piezoelectric stress constants. Typically, piezoceramics exhibit a low Curie temperature, which limits their applications. However, it is possible to build piezoceramic and polymer composites with promising capabilities. As flexible electronic systems are widely being explored, part of this trend includes the development of flexible and stretchable piezoelectric devices (**Table 3**).

Table 3: *Comparison of key properties among crystalline, ceramic, and polymeric piezoelectric materials.*

Property	Crystalline (e.g., Quartz) Rotating Mass	Ceramic (e.g., PZT)	Polymeric (e.g., PVDF)
Piezoelectric Constant	~2–5pC/N	~200–700pC/N	~20–30pC/N
Young's Modulus	~70GPa	~50–100GPa	~0.1–0.5GPa
Curie Temperature	N/A (Non-polarized crystals)	~120–350°C	N/A (No Curie point)
Elasticity/Impact Resistance	Low	Moderate	High
Key Advantages	High stability, natural piezoelectricity	High sensitivity, strong output	Flexible, lightweight, large-area fabrication
Application Areas	Clocks, RF filters, oscillators	Medical ultrasound, industrial sensors	Wearables, flexible sensors, robotics

Haptic Feedback Design

Haptic feedback design can be as simple as providing a control signal for a single vibration frequency in response to a touch or as complex as emulating the physical sensation of touching various textures. The complexity of the haptics depends on the advancement of the control algorithms of the haptic devices (including feedback), the haptic actuator's capabilities, and the haptic rendering's limitations. To provide real-time and realistic haptics, a haptic system needs to have a wide frequency bandwidth (~50Hz to 500Hz for vibrotactile feedback), very low latency time (milliseconds or fractions of a millisecond), and wide amplitude range for vibrotactile or force feedback. Such a system also needs to include feedback from the interface device to ensure the haptic response closely follows the control algorithms from the haptic rendering system simulating the virtual environments or objects. The most accurate control systems for this are closed-loop control systems, which use real-time feedback from sensors to adjust control algorithms for precise actuation of the haptic devices. Increasingly, machine learning (ML) and artificial intelligence (AI) algorithms are incorporated into haptic rendering and control algorithms to provide more realistic responses to virtual environments.

Power Management for Piezoelectric Devices

Many piezoelectric devices for haptic systems run on battery energy storage or energy-harvesting systems. This means that haptic devices in portable electronics, wearables, or medical devices often have a limited power supply capability. Consequently, these need high-performance piezoelectric actuators and sensors that are extremely energy efficient and can provide enhanced user experiences with minimal power draw. Advancements in battery and ultra-capacitor technologies mean that future piezoelectric systems built into portable devices may benefit from higher energy-density storage systems.

Integrating Piezoelectric Devices with Other Systems

Piezoelectric devices and audio systems are becoming essential for haptic feedback. The rise of AR/VR, the ubiquity of portable electronic devices, and the growing adoption of wearables for personal and medical use provide an expanding opportunity for piezoelectric technology.

The latest piezoelectric technology can deliver better performance in much more efficient and compact packages than legacy vibrotactile, force feedback, and pressure sensors. This means that more capable haptic feedback devices and systems can be integrated into emerging technologies. Denser and more capable haptics can create a more realistic experience. As response time is critical for this real-world feel, this is another crucial area for optimizing piezoelectric actuators and sensors.

Comparative Analysis and Future Trends

Currently, the most widely used vibrotactile haptic devices are ERMs and LRAs. ERMs can only oscillate using a sine wave of a singular frequency. LRAs can be controlled by frequency and amplitude to some degree, but with a resonant frequency of around 150Hz to 300Hz, they have a limited range of operation to convey refined tactile information. On the other hand, piezo actuator elements can be designed to resonate at tens of kHz, far beyond the frequency that humans can sense (50Hz to 500Hz). As a result, piezo actuators can offer precise control across the entire effective touch frequency range, accurately replicating the tactile sensations of touch (**Figure 10**).

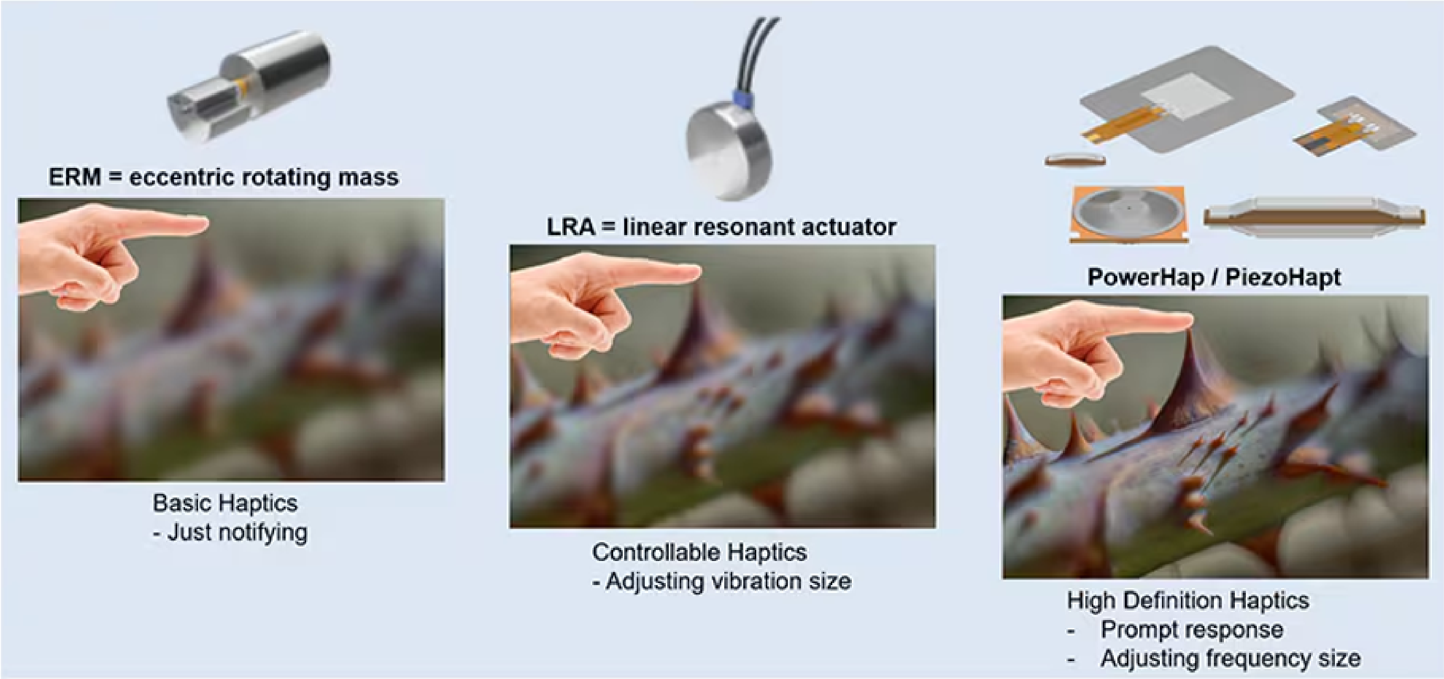

Figure 10: *Conceptual comparison of standard haptic feedback devices. (Source: TDK)*

Table 4: *Summary of performance metrics comparing ERM actuators with PiezoHapt actuators (Source: TDK; *Measurement by TDK)*

Metric	Piezo Actuators	LRAs	ERMs
Frequency Range	50Hz–100+kHz	150–300Hz	120–200Hz
Latency	<1ms	~10–20ms	~50–100ms
Power Consumption	Low (efficient)	Medium	High (inefficient)
Amplitude	High (precise)	Moderate	Low
Form Factor	Small, lightweight	Medium	Large, bulky

Where ERM devices can merely convey an on/off sensation of touch and LRAs provide only a limited tactile experience, piezoelectric devices can convey the full range of a touch sensation. Moreover, piezo actuators with this capability can be made smaller, thinner, and lighter than ERM and LRA devices (**Table 4**). Piezo actuators are ideal for future devices that require more complex, smaller, and lighter haptic components that provide a seamless AR/VR experience.

Conclusion

The future of AR/VR, wearables, and portable electronic devices lies in piezoelectric actuators and sensors. The latest piezoelectric devices provide advanced vibrotactile and force feedback capabilities to accurately emulate the sensations of touch and feel necessary to provide a desirable user experience. Legacy vibrotactile and force feedback devices are comparatively bulky, have slow response times, and provide only a limited range of possible sensations. As such, many engineers and product designers need to become familiar with piezoelectric actuators and sensors to bring the next generation of haptic feedback systems to life for the increasingly demanding and competitive landscape of modern electronic systems.