Ongoing Research and Advancements in Ceramic Piezoelectric Transducers: Comprehensive Review

ABSTRACT

This paper provides a comprehensive review of ceramic piezoelectric transducers, their applications, merits and demerits, and ongoing research and current advancements in these transducers.

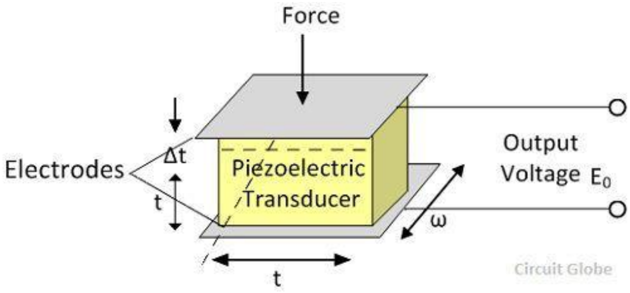
1. Introduction

Ceramic piezoelectric transducers, also called piezoceramics, belong to a class of electronic components that are distinguished by their exceptional capability of converting mechanical motion from electrical energy and vice versa. This feature results from the inherent ability of some ceramic materials to produce an electrical charge in response to mechanical stress or, on the other hand, to mechanically deform in response to an applied electrical voltage. This phenomenon is known as the piezoelectric effect.

These transducers are crafted from ceramic materials possessing a perovskite structure, with lead zirconate titanate (PZT) and barium titanate being prominent choices due to their robust piezoelectric characteristics. The fundamental principle behind their operation is relatively straightforward: when an electrical voltage is applied across the ceramic material, it triggers a change in its shape, leading to mechanical deformation. Conversely, when mechanical force or pressure is applied to the ceramic, it generates an electrical charge. Lead zirconate titanate (PZT) is a common ceramic used for its strong piezoelectric properties. Typically, the ceramic is sandwiched between electrodes to facilitate the electrical connection.

2. Working Principle

Piezoelectric Transducer works with the principle of piezoelectricity. The faces of piezoelectric material, usually quartz, are coated with a thin layer of conducting material such as silver. When stress is applied the ions in the material move towards one of the conducting surfaces while moving away from the other. This results in the generation of charge. This charge is used for the calibration of stress. The polarity of the produced charge depends upon the direction of the applied stress. Stress can be applied in two forms Compressive stress and Tensile stress as shown below.



3. Applications

Piezoelectric transducers power ultrasonic cleaners, where high-frequency vibrations remove dirt and contaminants. In ultrasound devices, these transducers emit and receive ultrasonic waves for imaging internal body structures. They are used in various sensors for detecting sound, pressure, and vibrations. These transducers are applied in nano positioning devices for accurate positioning in manufacturing and research. Piezoelectric transducers are used in gas appliances like lighters and grill starters for generating sparks. These transducers are also applied in underwater sonar systems for navigation and communication. They are Used to detect flaws or defects in materials without causing damage.

4. Ongoing Research and Advancements in Ceramic Piezoelectric Transducers

1) Pb-based ferroelectrics and piezoelectric in the form of bulk polycrystalline and textured ceramics, single crystals, and composites, have been used in sensors, actuators, and other electromechanical devices. However, the toxicity of these materials has been a major concern around the globe for the past few decades. The report of high piezoelectric activity in the lead-free BaTiO3 (BT), (Bi0.5Na0.5)TiO3 (BNT), and (K0.5,Na0.5)NbO3 (KNN) and binary and ternary systems with other compounds has given high hopes for alternatives to Pb-based materials. Recent modifications of KNN-based compositions with BaZrO3 in combination with

(Bi0.5,K0.5)HfO3 result in excellent electromechanical properties. Therefore, increased research and development in Pb-free materials brings hope for practical applications closer to reality. So, the recent developments on BT, BNT, and KNN reproducible soft and hard Pb-free piezoelectric compositions with a range of electromechanical properties for low- and high-power transducer applications will be reviewed.

2) Lead-based piezoelectric ceramics with a perovskite structure such as lead zirconate titanate (PZT) are most widely used in the fabrication of ultrasonic transducers for medical diagnosis and industrial non-destructive evaluation (NDE) applications due to their relatively high electromechanical coupling factor and piezoelectric constant. However, the use of lead-based ceramics would cause serious environmental problems. High lead content (more than 60% lead in PZT by weight) creates hazards in the fabrication process (lead is released into the atmosphere), which may cause lead poisoning. Therefore, it is necessary to develop more environmentally friendly piezoelectric materials to replace lead-based ones. The solid solutions of (1−x) Na0.5Bi0.5TiO3–xBaTiO3 (NBT–xBT or NBT–BT) are recognized as a leading candidate among lead-free materials. The piezoelectric constant d33 of NBT–BT ceramics and single crystals has been reported to be as high as 205 pC/N and 450 pC/N, respectively. As the NBT–BT material system has relatively high piezoelectric constants and Curie temperatures, various applications have been proposed. The reported NBT–BT single crystal-based ultrasonic transducer with a bandwidth of 46%. has shown the potential applications of lead-free materials in ultrasonic transducers. For enhancing the resolution in medical ultrasonic imaging and the performance in NDE applications for detecting highly attenuative materials the PZT/epoxy composites with 1–3 connectivity were generally utilized to further improve the electrical and acoustic properties. With a modified dice-and-fill technique, the 1–3 composites have been fabricated successfully using the very fragile NBT–BT single crystal. Based on this lead-free piezoelectric composite, ultrasonic transducers of single-element and linear array types were designed, fabricated, and characterized.

3) Recently, energy harvesting through the means of piezoelectric transducer technology has increasingly attracted the attention of engineers and scientists in producing/generating electricity for human consumption. However, understanding piezoelectric materials for application in piezoelectric transducer devices in energy harvesting remains important in today's energy systems engineering. lead zirconate titanate materials were shown to be the most common piezoelectric material with a high energy-generating performance but possessed more mechanical failure and compromised in a harsh environment compared to lead-free piezoelectric materials. lead-free piezoelectric materials, such as zinc oxide and barium titanate, remain the most conducive piezoelectric material over lead zirconate titanate, which basically affects the human environment due to its toxicity. Thus, to widen the use of lead-free piezoelectric materials in energy harvesting, owing to their improved properties and environment-friendly nature, the scientists have further enhanced the lead-free piezoelectric material properties via nanodielectric filler incorporations using the spark plasma sintering technique. However, there is a need for future study in the improvement of piezoelectric properties of lead-free piezoelectric materials, for example, BaTiO3, for better performance during service. As such, the scientist recommends the incorporation of nanoparticles with a high strain output, high strain (charge) constant and permittivity, low mechanical quality factor, and excellent thermal stability in lead-free piezoceramics in the design of piezoelectric

transducer components using the Taguchi design of experiment and spark plasma sintering processing methods.

4) Structural Health Monitoring (SHM) is an upcoming technology, which combines disciplines of smart materials, structural dynamics, structural engineering, Non-Destructive Testing (NDT), sensor and actuator development, signal processing, and more. Piezoelectric materials have been explored and applied in many fields since its first discovery. Recently, with the rapid growth of piezoelectric transducers, they have become an essential part of an SHM system due to many of their prior advantages, for instance, lightweight, low cost, ability to be integrated into a structure, easy to apply, and so forth. Generally, the conventional piezoelectric transducers used in SHM are discrete piezoelectric ceramic sensors. They are widely accepted in many SHM applications due to the above-mentioned features. However, they are also known for their brittleness, and hardness, unable to be applied on a single or multi-curved structural surface, difficult covering a large area, as well as error performance due to bonding layer failure. These drawbacks compromise the reliability of a SHM system. The research focuses on the investigation and development of a new type of smart material - the distributed piezoelectric transducer, with a target application in SHM fields where traditional piezoelectric ceramics are not suitable anymore. One of the main focuses is the development of a piezoelectric ceramic and polymer-based flexible piezoelectric composite: the piezoelectric paint. The production of a high-quality piezoelectric paint is investigated, and its material properties are characterized. To enhance the low piezoelectricity, which is the main drawback of piezoelectric paint, its improvement is studied.

5) With the rapid development of sensing and information technologies, smart flexible electronics have become a popular research topic, especially concerning cutting-edge technologies like artificial intelligence (AI) and human-machine interactions (HMIs), which greatly facilitate and enrich people's lives. Nevertheless, conventional electronic devices are often rigid and unwieldy, restricting their wearability and conformability with human skin, which severely affects the sensing accuracy and user experiences. On this basis, many researchers globally have investigated flexible electronic devices with more eminent stretchability and flexibility for applications such as health monitoring and gesture interactions. These flexible devices can be fixed to any shape of the object, such as skin, gloves, and rackets, to continually monitor human behavior in real time. HMIs serve as a bridge for information exchange between users and machines and represent an indispensable link for next-generation applications, such as virtual reality (VR). Among them, human-machine interfacial sensors based on the piezoelectric effect, which can generate an electric displacement in response to an applied mechanical stimulus, have been widely used for tactile sensing, due to their outstanding performance with high sensitivity, fast response time, and self-powered operation. Furthermore, due to the inverse piezoelectric effect, piezoelectric materials can be deformed under an external electric field, which facilitates the preparation of an all-in-one device with both sensing and actuation functions.

6) The advancement of next-generation bioelectronics and the powering of consumer and medical devices necessitate soft, flexible, extensible, and biocompatible power sources. Traditional energy storage devices like batteries and supercapacitors are rigid, unrecyclable, have short lifetimes, contain hazardous chemicals, and lack biocompatibility, limiting their use in wearable electronics. Consequently, there is a genuine demand for innovative energy-harvesting materials that are soft, flexible, biocompatible, and biodegradable. Piezo Gels, a type of smart crystalline gel with polar ordered structures within the broader family of piezoelectric materials, generate electricity in response to mechanical stress.

Structurally resembling hydrogels, Piezo Gels offer intrinsic chirality, crystallinity, ordered structures, mechanical flexibility, biocompatibility, and biodegradability, making them suitable for applications ranging from power generation to biomedical uses, including energy harvesting, sensing, and wound dressing. Recent efforts have explored Piezoelectric Generators (PEGs) or piezoelectric energy harvesters (PEHs), utilizing supramolecular organic and hybrid organic–inorganic materials. These materials boast facile synthesis, lightweight nature, mechanical flexibility, tunable structure, adaptability, multifunctionality, low temperature processability, easy orientation of molecular dipoles, efficient charge transport, and straightforward device fabrication. These qualities are crucial for developing cost-effective and versatile powered devices.

7) In high-power ultrasonics and underwater acoustics, composite piezoelectric ceramic transducers, such as the well-known Langevin piezoelectric composite ultrasonic transducer, are widely used as large-power sound radiators. In the present ultrasonic liquid processing applications, such as water treatment and sonochemistry concerning very large ultrasonic power, to improve the sound radiating efficiency and the distribution of sound field in liquids, some new kinds of large power radial vibration ultrasonic transducers and radiators are developed and attracted more and more attention. The electro-acoustic transducers are excited to vibrate in synchronism to supply longitudinal vibration from both ends to the round tube in which the longitudinal vibration is converted into radial vibration so that ultrasonic energy is emitted radially. A composite piezoelectric ceramic transducer consists of two metal thin circular rings and a thickness-polarized piezoelectric ceramic thin ring which is sandwiched between the two metal rings in the radial direction. The piezoelectric ceramic thin ring is excited to vibrate in the radial direction by the electric field in the thickness direction. Compared with the tubular radiator, the sound-radiating area of the ring-type radial composite piezoelectric ceramic transducer is smaller. A kind of cylindrical radial composite piezoelectric ceramic transducer consisting of a metal thin-walled cylindrical shell and a radially polarized piezoelectric ceramic thin-walled circular tube, which is composed in the radial direction, was made. Compared with the ring-type radial composite piezoelectric transducer, it has a larger sound radiating area, and therefore, more high radiation efficiency of sound in the radial direction. The radial vibration characteristics of the cylindrical radial composite piezoelectric ceramic transducer are studied, and its electro-mechanical equivalent circuit is derived. Based on the electro-mechanical circuit, its radial resonance frequency and the anti-frequency equations are obtained.

5. Advantages

The piezoelectric transducer has a good frequency response. It is small. It is easy to handle because of its small dimensions. It has a rugged construction. It is available in the desired shape. It has a negligible phase shift. Natural quartz and barium titanate can be made in any desired form and shape. It offers high output that is measured in the electronic circuit.

6. Limitations

It has high-temperature sensitivity. Some crystals are water soluble and dissolve in a highly humid environment. The piezoelectric transducer is used for dynamic measurement only, not suitable for static conditions. It needs a high piezoelectric cable for the electrical interface because the device operates with a small electric charge. The output obtained from the piezoelectric transducer is low, so the external electronic circuit has to be connected.

7. Future Prospects of Ceramic Piezoelectric Transducers

The outlook for ceramic piezoelectric transducers is optimistic, driven by ongoing research and technological progress that contributes to their continuous advancement. Prospective developments and applications include efforts to enhance the performance of ceramic piezoelectric materials, targeting increased sensitivity, a broader frequency response, and greater energy conversion efficiency. These improvements hold the potential for more efficient transducers across various applications. Progress in microfabrication techniques may lead to the creation of smaller and more compact ceramic piezoelectric transducers, paving the way for integration into diminutive devices like medical implants, wearables, and Internet of Things (IoT) devices. Researchers are investigating methods to impart flexibility and stretchability to ceramic piezoelectric materials, enabling their integration into curved surfaces and flexible structures. The exploration could expand their utility in areas such as flexible electronics and wearable devices. In the medical field, there is the prospect of expanded use for ceramic piezoelectric transducers in biomedical imaging, drug delivery systems, and therapeutic devices. Their compatibility with biological tissues and capacity to generate controlled vibrations render them suitable for diverse medical applications. Innovations in manufacturing processes, such as additive manufacturing and precision engineering, have the potential to contribute to the cost-effective production of ceramic piezoelectric transducers, facilitating broader adoption across industries. Future designs may involve transducers capable of harvesting energy from multiple sources concurrently, including vibrations, acoustic waves, and thermal fluctuations, offering a versatile and efficient energy-harvesting solution. Integration with smart materials, such as shape memory alloys or self-healing materials, has the potential to enhance the functionality and adaptability of ceramic piezoelectric transducers, possibly leading to the development of self-monitoring and self-repairing systems.

8. Conclusion

In conclusion, ceramic piezoelectric transducers present a promising avenue for technological advancement, with ongoing research and innovation driving their evolution. The future of these transducers is marked by several key developments and applications. Researchers are dedicated to improving the performance of ceramic piezoelectric materials, focusing on factors such as sensitivity, frequency response, and energy conversion efficiency. This pursuit holds the potential to create more effective transducers for a wide range of applications. The exploration of flexible and stretchable ceramic piezoelectric materials opens new possibilities for integration into curved surfaces and flexible structures, expanding their applications in flexible electronics and wearable devices. Overall, the versatility, adaptability, and ongoing technological advancements in ceramic piezoelectric transducers position them as key components in the future landscape of various industries, from healthcare to energy harvesting and beyond.

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