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INVERSE PIEZOELECTRIC EFFECT AS A FOUNDATION FOR INNOVATIVE APPLICATIONS
(Application of specialized composite materials in the further development of innovative applications based on the inverse piezoelectric effect, including applications for intelligent automotive transportation systems)

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Abstract

This article examines the application of the inverse piezoelectric effect as a fundamental physical principle for the development of innovative engineering applications in precision mechanics, automation systems, and advanced electromechanical devices. Particular attention is devoted to the design and development of piezoelectric motors intended for high-precision positioning systems, miniature actuators, and next-generation lighting and intelligent transportation technologies.

The publication analyzes the engineering principles of piezoelectric motors operating on the basis of the inverse piezoelectric effect and considers their advantages in achieving high positioning accuracy, compact dimensions, low weight, and enhanced operational reliability. The study further examines the influence of structural design solutions on the functional characteristics of precision stepper motors and other miniature electromechanical systems.

Special emphasis is placed on the application of advanced composite materials as structural elements of piezoelectric motors. The article discusses the contribution of specialized composite materials to reducing the weight and dimensions of electromechanical devices while improving their mechanical strength, durability, dynamic characteristics, and manufacturing flexibility.

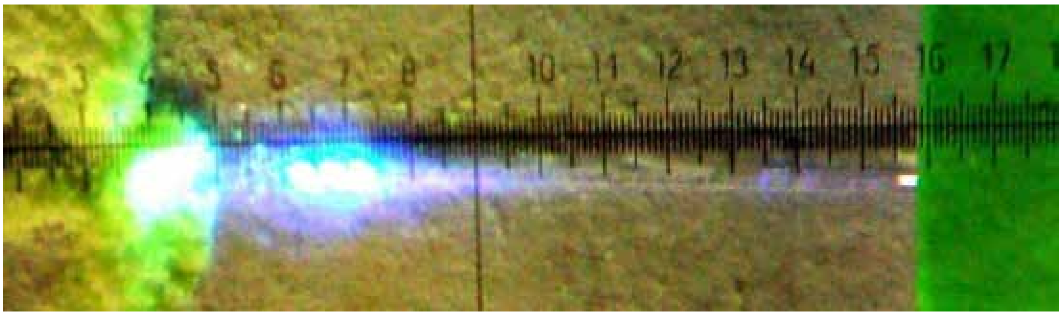
The publication further examines prospective directions for the development of innovative applications based on the inverse piezoelectric effect, including intelligent automation systems, precision mechanical equipment, miniaturized electromechanical devices, advanced lighting technologies, and intelligent automotive transportation systems. The study concludes that the integration of inverse piezoelectric technologies with modern composite materials represents a promising direction for the development of next-generation precision engineering products and high-performance electromechanical systems.

Keywords: *Inverse piezoelectric effect; piezoelectric motor; composite material; piezoelectric motor rotor*

Introduction

The continued development of innovative applications based on the inverse piezoelectric effect represents one of the most promising directions in modern precision engineering, automation, and intelligent electromechanical systems.

Figure 1.



Experimental investigations of piezoelectric motors operating on the basis of the inverse piezoelectric effect, together with attempts to employ them as precision stepper motors, have revealed the need to address a number of important engineering challenges. Many of these challenges arise from the incompatibility between the capabilities of modern control processors and their advanced software functions and the structural limitations of existing piezoelectric motor designs, which were originally developed using conventional engineering materials. Although these materials performed satisfactorily within previous generations of electronic components and control systems, they no longer fully satisfy the performance requirements imposed by contemporary high-precision electromechanical applications.

These circumstances create a need for the development of new structural concepts based on advanced composite materials capable of improving the mechanical, dynamic, and operational characteristics of piezoelectric motors while ensuring compatibility with modern digital control technologies. Such an approach provides opportunities for reducing weight and overall dimensions, increasing positioning accuracy, improving operational reliability, and expanding the practical application of inverse piezoelectric technologies in intelligent automation systems, precision engineering, and smart transportation.

Figure 2.

Figure 3.

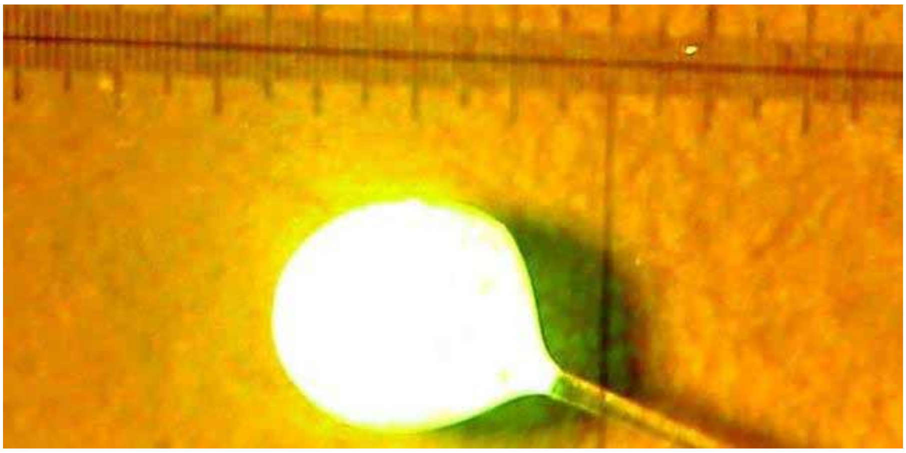


Figure 4.

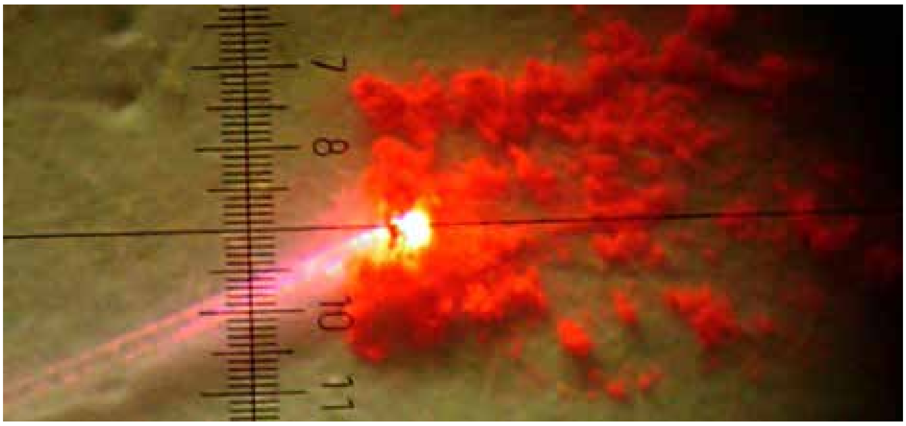


Figure 5.

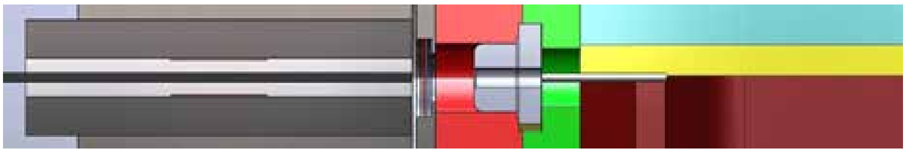
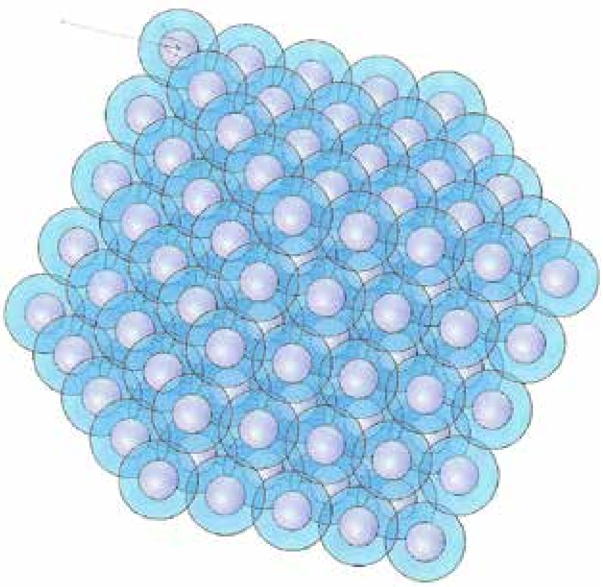


Figure 6.

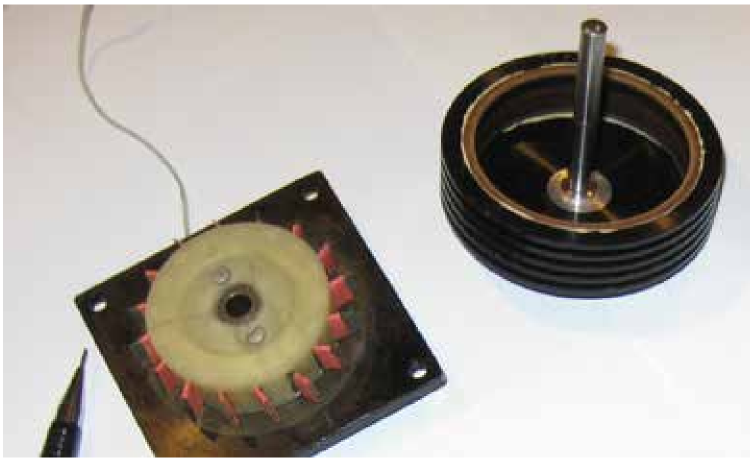


As can be seen from the photograph of one type of piezoelectric motor, its construction incorporates conventional engineering materials, including anodized aluminum, bronze, stainless steel, laminated plastics, and similar structural materials.

Testing of these types of piezoelectric motors, together with attempts to employ them as precision stepper motors, has revealed the need to address a number of important engineering challenges. Many of these challenges arise from the incompatibility between the capabilities of modern control processors and their advanced software functions and the structural limitations resulting from the use of traditional engineering materials, which performed satisfactorily with previous generations of electronic components but no longer fully meet the requirements of modern digital control systems.

Furthermore, the programmable control and drive management system, particularly when the motor operates in stepper motor mode, has highlighted the critical need to ensure that the mechanical properties of these structural materials are fully compatible with the stability requirements governing their response to piezoelectric excitation pulses. This compatibility is essential for achieving the positioning accuracy, dynamic stability, repeatability, and operational reliability required of modern high-precision piezoelectric drive systems.

Figure 7.



The positioning accuracy required of stepper versions of piezoelectric motors, combined with programmable control provided by modern monitoring and control systems, necessitated stable coordination between the output characteristics of the motor and the parameters of the electrical pulse signals applied to the piezoceramic ring.

Analysis of the kinematic transmission chain extending from the plain bearing to the piezoceramic ring, from the spring-steel elastic elements soldered to the piezoceramic ring to the friction ring, and subsequently from the friction ring to the motor rotor, demonstrated that the principal cause of the wide variation in the motor's output characteristics is the limited responsiveness of the elements comprising this transmission chain to changes and even short-term fluctuations in the control and feedback pulse signals.

Analytical investigations further demonstrated that the principal limitation of the system lies in the absence of an effective mechanism for the nearly instantaneous distribution or dissipation of the excitation pulses applied to the piezoelectric ring.

As an initial step in the optimization process, it was decided to replace the conventional piezoelectric ceramic used in the piezoelectric ring with a composite piezoceramic material containing specially selected components that are substantially insensitive to the excitation pulses applied to the piezoelectric ring.

Previous experimental investigations indicated that such performance may be achieved through the uniform incorporation of synthetic diamond microspheres into a specially formulated piezoceramic matrix.

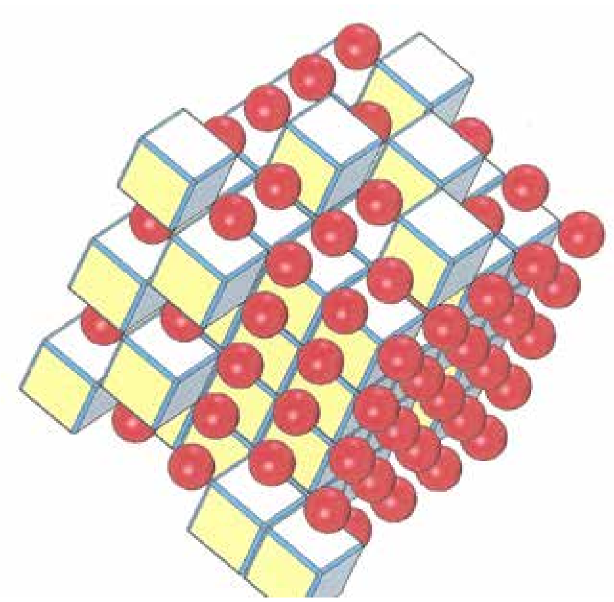
Figure 8.

A model of such a material illustrates its three-dimensional structure, consisting of a large number of spherical capsules arranged in at least two structural levels.

The first structural level consists of microspheres manufactured from synthetic diamonds. Modern production technologies make it possible to manufacture these microspheres with extremely high dimensional accuracy, minimal production costs, and a comparatively low cost of the raw material itself.

Furthermore, the requirements imposed on synthetic diamonds for this application do not include the stringent specifications for optical transparency or crystal purity that are characteristic of gemstones intended for jewelry applications.

Figure 9.

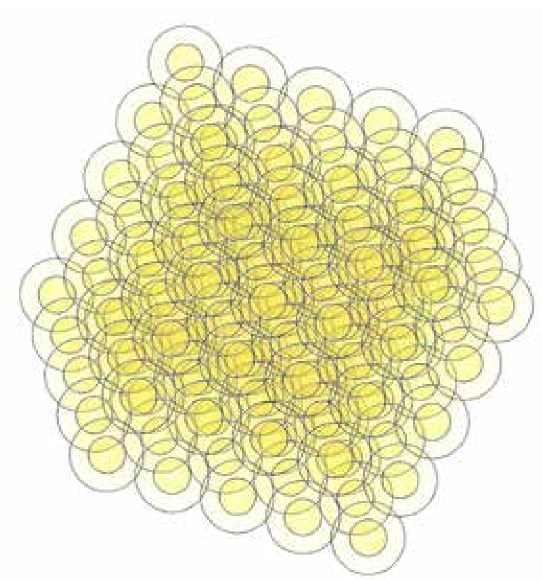


The following photograph illustrates the structure of the proposed composite material.

Following the fabrication of the synthetic diamond microspheres, they are coated with a moist ceramic composition and subsequently placed into a molding die. During the pressing process, the ceramic material surrounding the diamond microspheres undergoes volumetric deformation, forming a large number of cubic microstructures, each containing a synthetic diamond microsphere located at its geometric center.

The resulting structure may be described as pseudo-porous, since the synthetic diamond microspheres, being practically insensitive to the excitation pulses, promote the nearly uniform distribution of electrical signals or excitation pulses throughout the surrounding ceramic microcubes. This structural configuration provides exceptionally high stability and homogeneity of signal propagation within the pseudo-porous piezoceramic ring, thereby improving the dynamic response and operational stability of the piezoelectric motor.

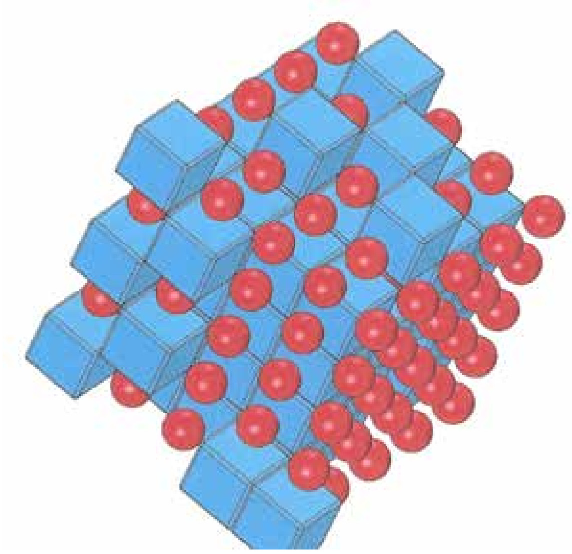
Figure 10.



It should also be noted that, because spring-steel elastic elements are soldered to the outer cylindrical surface of the piezoelectric ring, the uniform distribution of the excitation pulse throughout the piezoelectric ring makes it possible to satisfy the principal requirements for the stability and homogeneity of the driving vibration pulses transmitted from these elastic elements to the rotor in frictional contact with them.

As a result, the force impulses acting on the rotor become more uniform in both magnitude and temporal distribution, thereby improving the positioning accuracy, repeatability, dynamic stability, and operational reliability of the piezoelectric motor, particularly when operating in precision stepper motor mode under digital control.

Figure 11.



It is now appropriate to return to the issue of rotor wear resistance.

Considering that the ends of the spring-steel elastic elements remain in continuous dynamic contact with the inner surface of the rotor, and assuming that the excitation pulses are distributed non-uniformly throughout the three-dimensional structure of a rotor manufactured from conventional engineering ceramic, it can be assumed that the force transmitted from the ends of the spring elements to the rotor surface is likewise non-uniform. Such non-uniform loading results in uneven wear of the rotor's inner surface and, consequently, in radial runout of the motor output shaft.

If the conventional piezoelectric ring material is replaced with the proposed pseudo-porous composite piezoceramic, the dependence of rotor wear on the non-uniform distribution of excitation pulses within the ceramic material is expected to decrease significantly. This improvement should have a positive influence on the output characteristics and operational performance of the piezoelectric motor.

The principal performance parameters expected to benefit from this modification include:

- reduction of radial runout of the motor shaft;

- improved synchronization of all mechanical interfaces between the structural components of the motor;
- increased service life of the motor;
- simplified simultaneous synchronization of the operating characteristics of multiple motors used in systems converting rotary motion into the linear displacement of machine tool carriages or positioning stages;
- improved uniformity and stability of the rotor rotational speed.

It should also be noted that, in the existing motor configuration, the vibration characteristics of the entire electromechanical system are directly influenced by the non-uniform and cyclic transmission of mechanical forces from the special ceramic material to the rotor and, ultimately, to the motor output shaft.

System-level analysis and computer modeling have further demonstrated that replacing the conventional rotor material with a composite material analogous to the pseudo-porous structure proposed for the piezoceramic ring may also provide significant advantages.

In this case, the structural architecture of the composite material remains unchanged, while only the constituent materials are modified.

For example, to improve the durability of the structural components of the motor, the core material may be changed from synthetic diamond to beryllium, while the surrounding matrix is formed from aluminum.

Aluminum possesses sufficient ductility to ensure the required cold-flow characteristics during volumetric plastic calibration of the geometric configuration of the motor elements and structural components.

Numerous combinations of core and matrix materials may be selected for the composite capsules, thereby providing maximum flexibility in the design of control and monitoring systems employing piezoelectric motor drives.

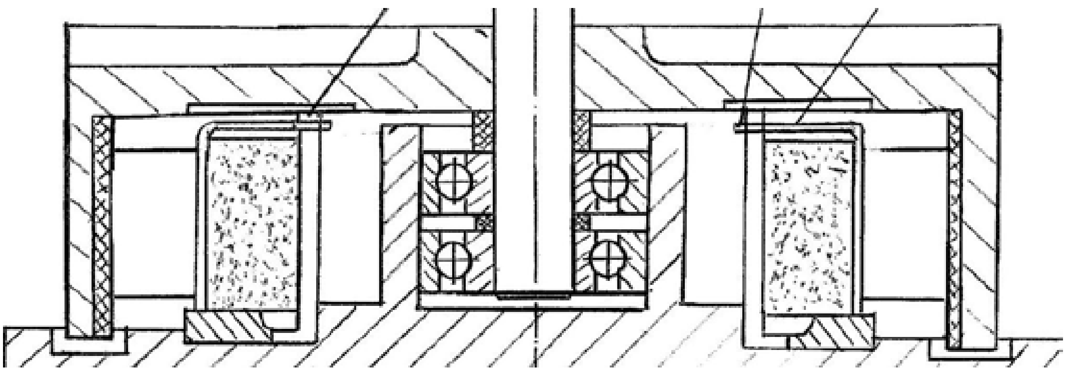
It is also appropriate to address the design of the spring-steel elastic elements.

When these elements are attached to the piezoceramic ring by soldering, an additional group of engineering problems arises, primarily associated with the inability to achieve the required levels of dimensional accuracy, mechanical strength, and long-term durability. These limitations are well known and result from the inherent characteristics of conventional soldering materials.

Particularly complex are the technological issues associated with preparing the outer surface of the piezoceramic ring for soldering and with applying a metallic or equivalent intermediate layer capable of providing a reliable soldered joint between the ring and the spring-steel elastic elements.

The author of the present publication proposes solving this problem by eliminating soldered joints entirely and replacing them with an optimized spring-element assembly manufactured as a continuous spring band incorporating the required elastic fingers.

Figure 12.



This spring band is mechanically clamped around the outer diameter of the piezoceramic ring, providing several additional advantages for optimizing the performance of the piezoelectric motor, including:

- uniform circumferential distribution of the spring elements around the piezoceramic ring;

- the ability to adjust the clamping force between the spring band and the outer surface of the piezoceramic ring;
- simple, rapid, and reliable replacement of the spring band in the event of wear of the elastic fingers;
- substantial reduction in manufacturing cost while simultaneously improving the efficiency, reliability, and overall quality of the piezoelectric motor.

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