ISSN: 2476-6909; Modares Mechanical Engineering. 2024;24(09):575-581.

Tarbiat Modares University

Multi-Mode Bulk Magnetostrictive Actuator for Precision Positioning System

ARTICLE INFO

Article Type
Original Research

Authors
Ansari S.[1],
Karafi M. R.[1],

How to cite this article
Ansari S, Karafi M R, Multi-Mode Bulk Magnetostrictive Actuator for Precision Positioning System. Modares Mechanical Engineering; *2024;24(09):575-581*.

[1] Faculty of Mechanical Engineering, Tarbiat Modares University, Tehran, Iran

***Correspondence**
Address: Faculty of Mechanical Engineering, Tarbiat Modares University, Tehran, Iran.

karafi@modares.ac.ir

Article History
Received: November 7, 2024
Accepted: December 2, 2024
ePublished: December 14, 2024

ABSTRACT

This paper presents an innovative bulk magnetostrictive actuator made of a 2V-Permendur alloy rod, capable of functioning across multiple deformation modes—longitudinal, torsional, and flexural. In longitudinal mode, displacement is produced by the Joule effect, where a magnetic field applied along the rod's axis, generated by a surrounding coaxial coil, induces deformation along its length. Torsional mode activation follows the Wiedemann effect, wherein an electric current passed directly through the rod produces a circumferential magnetic field that twists the material. Additionally, flexural deformation is achieved by a special designed magnetic core that directs a magnetic field to the rod's surface, producing bending movements along the rod's length. The actuator operates using controlled DC magnetic fields. Experimental results demonstrated outstanding performance, with maximum displacements reaching 12 microns in longitudinal mode, 7 microns in flexural mode, and 0.15 degrees in torsional mode. Such multi-functional performance highlights the actuator's potential in precision positioning systems, with particular suitability for advanced microscopy, optical instrumentation, and other fields requiring sub-micrometer positioning accuracy.

Keywords Magnetostrictive Actuator, Permendur Alloy, Longitudinal-Torsional-Flexural Modes, Precision Mositioning, DC Magnetic Fields.

CITATION LINKS

1- Ferroic Materials for Smart Systems: From Fundamentals to Device Applications. 2- Review of Modeling and Control of Magnetostrictive Actuators. 3- Characterization of Terfenol-D for Magnetostrictive Transducers. 4- Hybrid Piezoelectric-Magnetostrictive Actuator. 5- Study on Control of Giant Magnetostrictive Piezoelectric Hybrid Actuator. 6- Nonlinear Giant Magnetostrictive Actuator and Its Application in Active Control. 7- Experimental Study on Dynamic Load Line for Magnetostrictive Actuator. 8- A Novel Magnetostrictive Torsional Resonant Transducer. 9- Design and Fabrication of a Novel Vibration-Assisted Drilling Tool Using a Torsional Magnetostrictive Transducer. 10- A New Hybrid Longitudinal–Torsional Magnetostrictive Ultrasonic Transducer. 11- Introduction of a Hybrid Sensor to Measure the Torque and Axial Force Using a Magnetostrictive Hollow Rod. 12- Development of a Novel Ultrasonic Drill Using Longitudinal-Bending Hybrid Mode. 13- Design and Experiments of a Novel Rotary Piezoelectric Actuator Using Longitudinal–Torsional Convertors. 14- Development of a Planar Piezoelectric Actuator Using Bending–Bending Hybrid Transducers. 15- A Two-DOF Ultrasonic Motor Using a Longitudinal–Bending Hybrid Sandwich Transducer. 16- An Introduction to a Bulk Magnetostrictive Bending Actuator Using a Permendur Rod.

1- Introduction

The advancement of high-precision positioning technology has driven extensive research and development in actuator designs, especially those incorporating smart materials that enable precise mechanical responses under controlled magnetic fields. Among these, magnetostrictive actuators have emerged as powerful candidates due to their unique ability to convert magnetic fields into mechanical movement, positioning them as ideal components for high-precision tasks. Actuators made from smart materials have become widely used in applications such as microscope platforms, optical systems, positioners, and other electromechanical devices[1]. Magnetostrictive materials, primarily structured in either bulk or thin-film forms, leverage properties that enable complex modes of deformation, including longitudinal, torsional, and bending motions, each serving distinct applications in smart structural components, underwater sensors, and ultrasonic devices[2]. Typically, these actuators are built from three core components: a magnetostrictive material, a magnetic field-generating circuit (usually consisting of coils and magnetic core), and a mechanism to transfer or amplify the resultant displacements. This structure allows for design versatility, making these actuators well-suited to highly demanding applications[3]. By carefully optimizing the magnetic properties and geometry, engineers can adapt these actuators for precise and efficient movement across various modes, positioning magnetostrictive actuators as critical tools for innovation in precision-based technologies. In 2005, Anil made significant strides by creating a combined actuator system that integrates piezoelectric and magnetostrictive components. Rather than being directly connected, these two actuators are separated but linked by an intermediary structure. This linkage, featuring fine microgrooves on its connecting end, allows precise engagement with corresponding microgrooves on an attached rotating shaft[4]. Hui et al. developed an advanced hybrid actuator system that integrates a giant magnetostrictive actuator (GMA) to drive displacement, paired with piezoelectric stacks that provide secure clamping[5]. Inspired by inchworm locomotion, this design allows the actuator to achieve highly precise, incremental positioning.Yang et al. conducted an in-depth study on giant magnetostrictive actuators (GMAs), focusing on their fundamental role in enhancing vibration control technologies[6]. Yoo and Jones explored the dynamic load line characteristics of Terfenol-D magnetostrictive actuators, which are distinguished by their remarkable magnetostriction levels exceeding 1000 ppm[7]. Their investigation aimed to define the actuator's peak stroke and force output, both of which are fundamental for effective implementation in real-world applications. Karafi et al. designed a torsional transducer utilizing bulk magnetostrictive materials[8]. This novel device features magnetostrictive elements as the core, allowing it to produce effective torsional vibrations. They used the Wiedemann effect to generate shear deformation within the material. This actuator has been successfully implemented to achieve torsional movements in vibration-assisted drilling techniques[9]. Furthermore, in 2013, Karafi et al. presented a longitudinal-torsional ultrasonic transducer that incorporates a horn-shaped design made from magnetostrictive material[10]. The transducer incorporates a horn-shaped structure meticulously designed to synchronize the primary longitudinal and torsional vibration modes at a frequency of 20,288 Hz. This design has been used to develop a hybrid sensor which can measure torques and axial forces simultaneously[11]. In 2017, Xintian Tang et al. presented an ultrasonic drilling method that employs a hybrid mode of longitudinal and bending vibrations to enhance the machining process for hard and brittle materials[12]. This technique integrates both longitudinal and bending vibrations, moving away from the traditional reliance on a single vibration type. In 2019, Deen investigated a newly engineered piezoelectric actuator designed to facilitate rotary motion through a hybrid mechanism that combines longitudinal and torsional vibrations[13]. This actuator features a piezoelectric stack, along with a leftward bending longitudinal-torsional converter (LBLTC) and a rightward bending longitudinal-torsional converter (RBLTC). In the same year, Deng developed a planar piezoelectric actuator designed for extensive travel ranges[14]. The actuator integrates four uniform piezoelectric transducers, each capable of independently bending in horizontal and vertical directions. In 2019, Yingxiang Liu introduced a two-degree-of-freedom ultrasonic motor utilizing a hybrid sandwich transducer that combines longitudinal and bending vibrations to generate linear movement in both horizontal and vertical directions[15]. This design ensures precise, multi-directional movement driven by ultrasonic vibrations within the hybrid transducer structure, making it well-suited for high-precision applications requiring control in two axes. In 2020, Karafi et al. designed a bulk magnetostrictive bending actuator utilizing a permendur rod[16]. By applying a magnetic field along the cylinder's surface, tensile deformation was induced, leading to bend the magnetostrictive material.

This article introduces an innovative bulk magnetostrictive actuator that integrates longitudinal, flexural, and torsional deformation modes, utilizing a permendur rod for a precision tip positioner. By applying distinct magnetic fields—axial, circumferential, and surface—this actuator is capable of generating longitudinal, torsional, and flexural displacements within the magnetostrictive material. Specifically, the flexural mode is induced through a surface-applied magnetic field via a magnetic core. The axial magnetic field is generated using a coaxial coil surrounding the rod, while the circumferential field is achieved by passing an electric current through the wire inside the rod. Operating under constant magnetic fields, this actuator enables control across four degrees of freedom, making it highly suitable for high-precision positioning tasks. Experimental findings demonstrate its effectiveness, particularly in applications requiring meticulous control, such as microscopy and optical instrumentation.

2- Principle

The magnetostrictive actuator presented in this study features three distinct modes of operation: longitudinal, torsional, and flexural. The longitudinal mode is activated by the Joule effect, facilitated by a coaxial coil wrapped around the magnetostrictive material, which generates a uniform magnetic field within the coil. This field induces elongation in the material, thereby stimulating the longitudinal motion. An axial hole is drilled into the material, through which a wire is passed. When electrical current passes through the wire, it produces a circumferential magnetic field. Furthermore, a coupler fixed to the surface of the material generates a magnetic field that induces elongation in the surface layer, resulting in flexural motion. The material utilized in this actuator is 2V permendur, characterized by a chemical composition of $Co_{49}Fe_{49}V_2$, which exhibits isotropic magnetic properties. Its Curie temperature is 940 degrees Celsius, and at room temperature, the material demonstrates an approximate saturation strain of 60 ppm. Additionally, its saturation magnetic flux density is 2.3 Tesla, while the saturation magnetic field is around 20 kA/m.

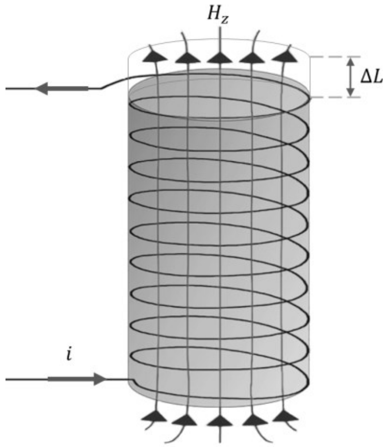
Figure 1 illustrates the schematic representation of how circumferential and axial fields are applied to induce torsional, longitudinal, flexural deformations. In the figure, i represents the electric current (A), and H denotes the magnetic field (A/m), which is generated by the applied electric current. The arrows in the figure indicate the direction of the electric current or the magnetic field vectors, depending on the context. Additionally, in part C of the figure, the dotted lines represent the actuator's position when it undergoes displacement due to the applied magnetic fields.

To activate the actuator in the flexural mode, an axial magnetic field must be applied to one side of the material, specifically at its surface. This stimulation of the magnetic field results in both an increase in the length and the flexural deformation of the material.

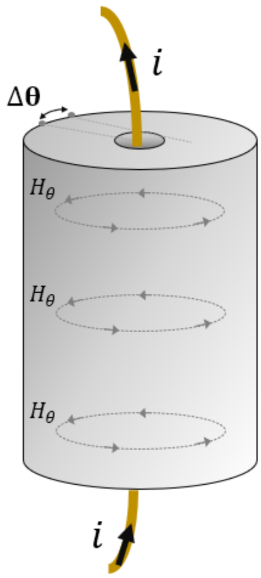
Figure 2 presents the magnetostrictive actuator. In this arrangement, the core of the flexural coil causes the generation of magnetic flux on the surface of the magnetostrictive material.

The end of the rod is connected to the base plate, restricting all degrees of freedom. A coaxial coil, made with 1mm diameter wire and consisting of 95 turns, is employed. The coupler, made from CK45, features an additional 150 turns of wire wound around it to facilitate the induction of magnetic flux, which is then bonded to the material. Additionally, a circumferential magnetic field is produced by a wire running through the center of the material.

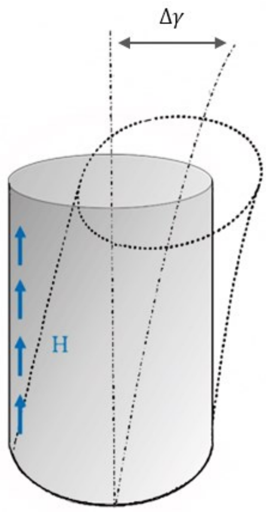
The coaxial coil generates a magnetic field intensity of approximately 12,000 A/m, which is sufficient to saturate the material. In the torsional mode, a current of about 30 amperes flowing through the internal wire achieves saturation. However, full saturation is not attained in the flexural mode, as only a section of the material is subjected to the magnetic field. Enhanced concentration of magnetic flux at the surface of the material leads to increased flexural deformation. When combining magnetic fields, it is essential to ensure that the magnetic flux vectors of the flexural and longitudinal modes are aligned correctly. Incorrect alignment may result in interference between the modes, hindering the desired flexural response of the material.



A) Generating axial magnetic fields throughout the material's volume (longitudinal mode)



B) Applying circumferential magnetic fields (torsional mode)



C) Applying axial magnetic fields on the surface of the material (flexural mode)

Fig 1.) Magnetic fields for longitudinal, torsional, and flexural modes

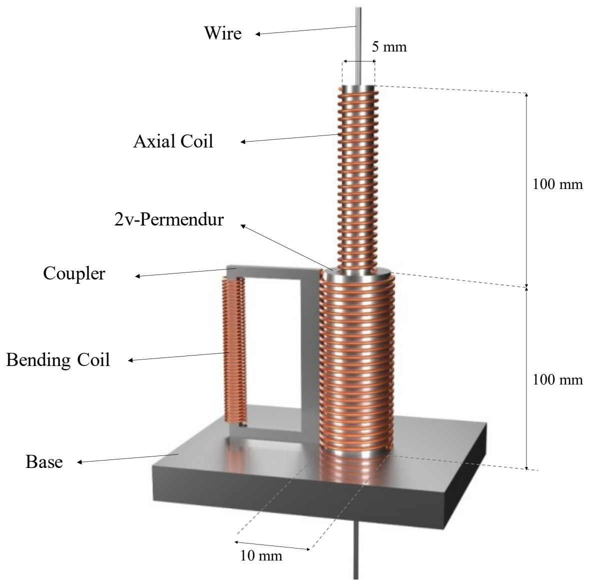


Fig 2.) Excitation coils and dimensions of the Magnetostrictive actuator

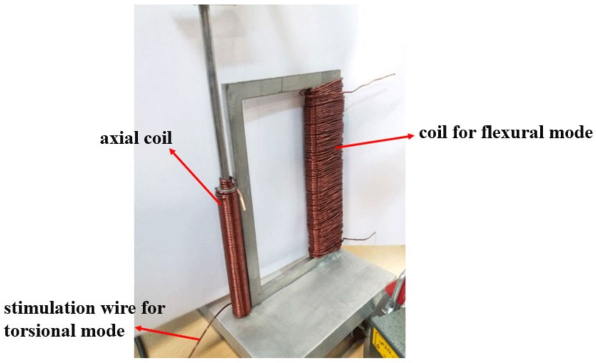


Fig 3.) Assembled multi-mode magnetostrictive actuator

3- Experimental results and discussions

Figure 3 presents the assembled magnetostrictive actuator. The full length of the magnetostrictive material is covered with a coil specifically designed to excite the longitudinal mode. To achieve the desired magnetic characteristics, a coupler made of CK45 is chosen and attached to the longitudinal coil. Since the magnetostrictive material operates in multiple modes, the longitudinal coil is deliberately positioned slightly apart to prevent any restriction on its movement.

Measurements were performed using Omron ZX-LD40 laser displacement sensors, which provide analog output and have a precision of 2 microns. The setup included three laser sensors functioning independently to capture the three unique types of deformations. One of these sensors was placed above the magnetostrictive material to measure longitudinal displacement. Additionally, a mechanical arm was used to enhance the measurements of flexural and torsional deformation while minimizing noise interference. Figure 4 displays the configuration of the experimental setup for the magnetostrictive actuator.

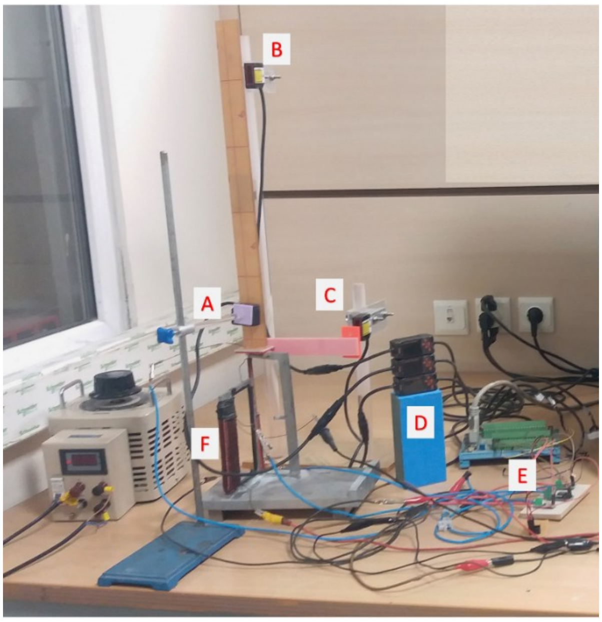


Fig 4.) Experimental arrangement for the magnetostrictive actuator; **A)** Laser sensor for measuring longitudinal displacement **B)** Laser sensor for detecting bending deformations **C)** Laser sensor for measuring torsional displacement **D)** sensor's amplifier and transmitter E) Data acquisition card and current sensors F) Magnetic Coupler

The analog outputs from the sensors were captured using an Advantech 1716 DAQ card, which was linked to a computer. MATLAB Simulink software handled the data acquisition and storage. In Simulink, the signals were filtered through a low-pass IIR filter and then amplified by a factor of 10,000. The filter was set with a 100 Hz sample rate, a 0.1 Hz passband frequency, and an 8 Hz stopband frequency.

Three separate electrical current sources were used to activate the different modes of the actuator. Real-time current measurements were obtained using three ACS 712 current sensors, which were connected to the DAQ card for continuous monitoring. The system logged data from both the current and laser sensors simultaneously. Furthermore, a Hall effect sensor (A3503) was used to quantify the magnetic flux.

When assessing each mode individually, the corresponding current source and laser sensor were engaged to determine the displacement related to that particular mode. Data on electrical current and displacement were recorded concurrently. The same methodology was followed when analyzing two or three modes at once.

Figure 5 presents the results of the test, demonstrating the correlation between axial displacement and the axial magnetic field. The error bars represent the standard deviation, calculated from multiple repetitions of the corresponding experiments, and are shown as vertical lines at each data point. The experiments were repeated four times to ensure the reliability of the results. The same procedure, with four repetitions of each experiment, is done for figures 6 and 7.

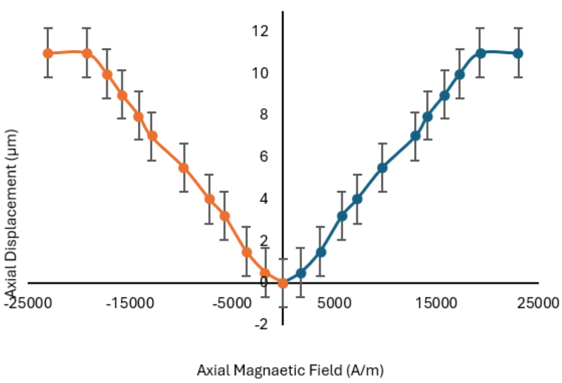
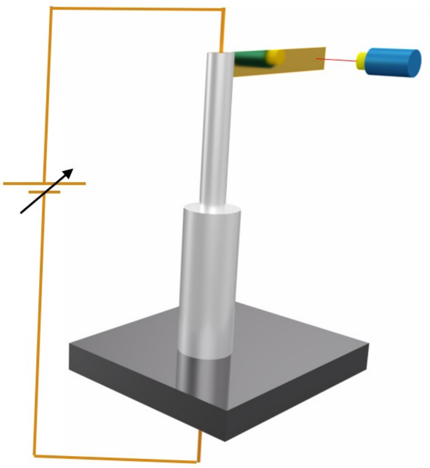
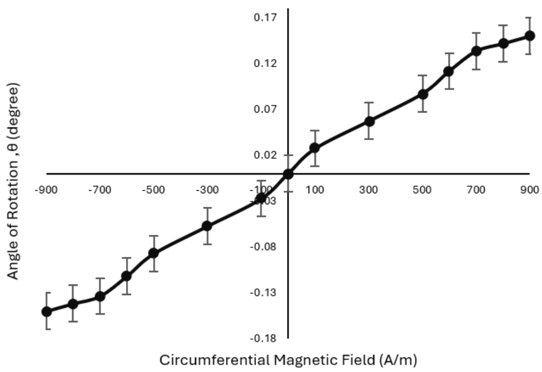


Fig 5.) Axial displacement in relation to the axial magnetic field



A)



B)

Fig 6.) (A) Measurement of torsional displacement; **(B)** Torsional angle versus circumferential magnetic field.

To activate the torsional mode, it is essential to apply a circumferential magnetic field (H_2) to the magnetostrictive material. Figure 6 provides a schematic representation of this testing process.

By energizing the bending coil, the magnetic field passes through the coupler and the surface of the magnetostrictive rod. This magnetic field at the rod's surface induces bending. Figure 7 illustrates the bending deflection of the actuator in relation to the excitation current of the bending coil.

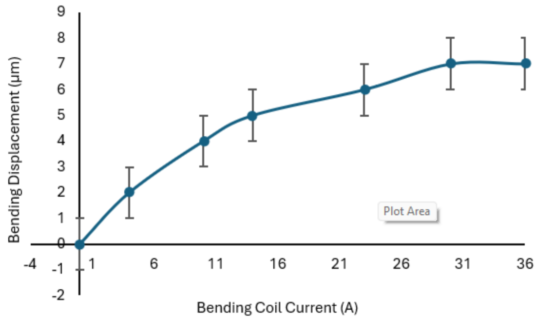


Fig 7.) Bending displacement vs bending coil's current

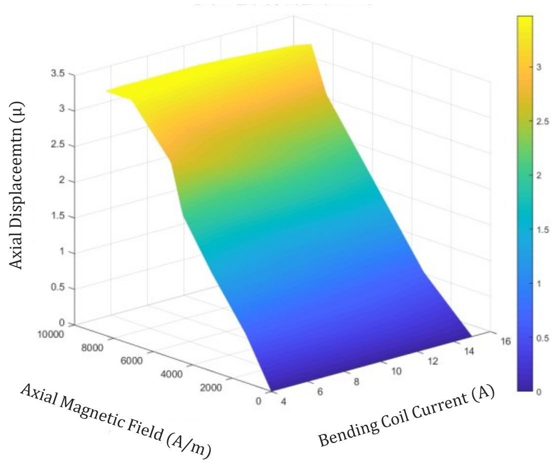


Fig 8.) Longitudinal displacement with an axial magnetic field applied under varying excitation currents for the bending coil, with a torsional wire current of 10 A.

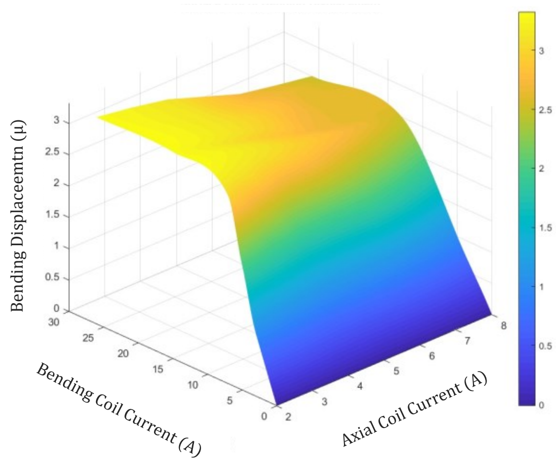


Fig 9.) Bending displacement with excitation of axial and bending coils at a constant wire current of 5 A.

In the preceding experiments, the modes were investigated separately to evaluate the impact of individual magnetic fields on magnetostrictive deformations. The subsequent tests focused on assessing the combined effects of two and three magnetic fields on deformation measurements.

Figure 8 demonstrates the axial displacement of the actuator when both the flexural and axial coils are excited. The displacements are shown for varying excitation currents in the bending coil, with a constant torsional wire current of 10 A.

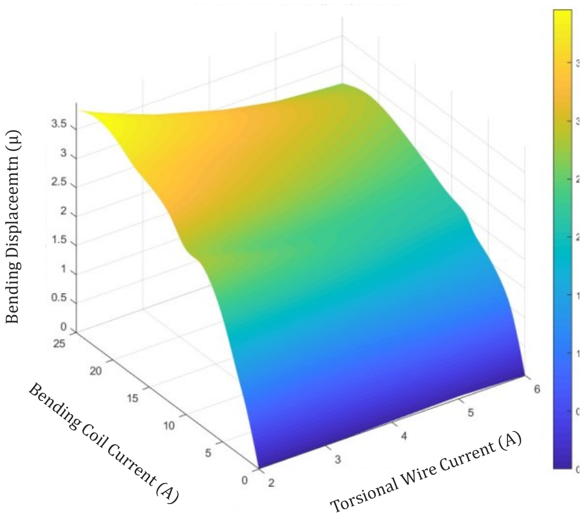


Fig 10.) Bending displacement with excitation of bending coil and wire at a constant axial current of 5 A.

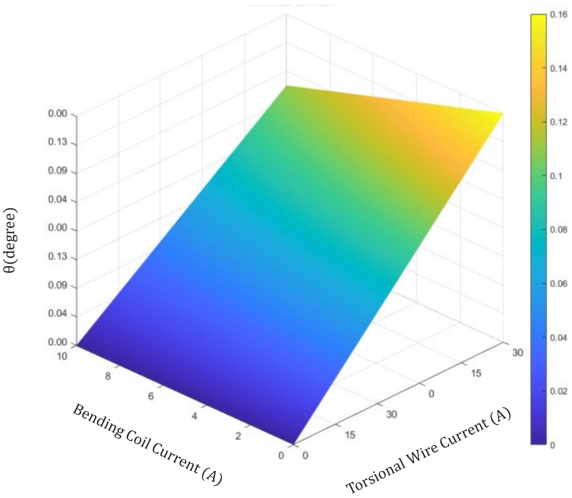


Fig 11.) Graph of torsional displacement measurement while exciting the wire and axial coil with a constant bending coil current of 5 A.

Figure 9 illustrates the bending displacement of the actuator when the longitudinal and flexural coils are excited. The graph shows results under different current levels in the axial and bending coil, with a constant torsional current of 5 A.

Figure 10 shows the bending displacement of the actuator when the flexural coil and wire are excited, with a constant axial coil current of 5 A.

Figure 11 illustrates the actuator’s torsional displacement while exciting the wire and axial coil at a constant bending coil current of 5 A.

When comparing the magnetostrictive actuator presented in this study to other existing technologies, there are several notable distinctions. Piezoelectric actuators, widely used in precision applications, offer excellent displacement resolution and high speed. However, they are typically limited by their relatively small displacement ranges. Additionally, piezoelectric actuators require high-voltage operation. In contrast, the magnetostrictive actuator presented here, utilizing the 2V-Permendur alloy, provides a much larger displacement range, making it ideal for high-precision positioning tasks in micrometer ranges. Furthermore, magnetostrictive actuators do not require high voltages. The multi-mode functionality—longitudinal, torsional, and flexural—adds to the actuator's versatility, enabling more complex positioning tasks than most other actuators, including piezoelectric and mechanical types, which typically operate in a single mode. Mechanical actuators, while effective for larger displacements, are often larger and less precise than the magnetostrictive actuators described in this study. Their performance can be limited in high-precision applications where fine, repeatable movements are required. Moreover, they tend to have slower response times compared to the quick adjustments achievable with magnetostrictive materials. Thus, this study demonstrates that magnetostrictive actuators present a promising alternative to both piezoelectric and mechanical actuators, offering superior displacement, precision, and versatility, making them particularly well-suited for applications like advanced microscopy and other fields requiring highly accurate positioning.

4- Conclusion

This study presents a novel bulk magnetostrictive actuator designed to achieve deformation across longitudinal, torsional, and flexural modes when subjected to magnetic excitations. The flexural mode is activated through a coupler that directs magnetic flux onto the surface of the Permendur material. In contrast, the torsional mode is induced by passing a wire through the magnetostrictive material and applying an electric current, using the principles of the Wiedemann effect. The actuator demonstrates impressive displacement capabilities, achieving a maximum of 12 microns in the longitudinal mode, 7 microns in the flexural mode, and 0.15 degrees in torsion. The research covers an in-depth exploration of both individual and combined operational modes, highlighting the actuator's versatility in functioning autonomously in each mode or in various combinations. This versatility enables the exploration of various promising research opportunities.

Ethical Statement

The content of this manuscript is original, based on the authors' research, and has not been published or submitted elsewhere, either in Iranian or international journals.

Conflict of interest

The authors declared that they have no conflicts of interest to this work.

References

1- Dai J. Ferroic Materials for Smart Systems: From Fundamentals to Device Applications. John Wiley & Sons; 2019 Dec 19.

2- Apicella V, Clemente CS, Davino D, Leone D, Visone C. Review of modeling and control of magnetostrictive actuators. InActuators 2019 May 29 (Vol. 8, No. 2, p. 45). MDPI.

3- Moffett MB, Clark AE, Wun-Fogle M, Linberg J, Teter JP, McLaughlin EA. Characterization of Terfenol-D for magnetostrictive transducers. The Journal of the Acoustical Society of America. 1991 Mar 1;89(3):1448-55.

4- Mavanur A, Cormier J, inventors; Energen Inc, assignee. Hybrid piezoelectric-magnetostrictive actuator. United States patent US 7,352,112. 2008 Apr 1.
5- Hui Z, Meng W, Chengxi W. Study on control of giant magnetostrictive piezoelectric hybrid actuator. In2011 International Conference on Mechatronic Science, Electric Engineering and Computer (MEC) 2011 Aug 19 (pp. 657-660). IEEE.
6- Yang L, Zhang H, Jiang H, Liu S, Wu H, Li H, Farsangi EN. Nonlinear Giant Magnetostrictive Actuator and Its Application in Active Control. InNoise and Vibration Control-From Theory to Practice 2019 Jun 18 (p. 1). IntechOpen.
7- Yoo JH, Jones NJ. Experimental study on dynamic load line for magnetostrictive actuator. InSensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2021 2021 Mar 22 (Vol. 11591, pp. 295-303). SPIE.
8- Karafi MR, Hojjat Y, Sassani F, Ghodsi M. A novel magnetostrictive torsional resonant transducer. Sensors and Actuators A: Physical. 2013 Jun 1;195:71-8.
9- Karafi MR, Korivand S. Design and fabrication of a novel vibration-assisted drilling tool using a torsional magnetostrictive transducer. The International Journal of Advanced Manufacturing Technology. 2019 Jun 19;102:2095-106.
10- Karafi MR, Hojjat Y, Sassani F. A new hybrid longitudinal–torsional magnetostrictive ultrasonic transducer. Smart materials and structures. 2013 Apr 30;22(6):065013.
11- Karafi MR, Ehteshami SJ. Introduction of a hybrid sensor to measure the torque and axial force using a magnetostrictive hollow rod. Sensors and Actuators A: Physical. 2018 Jun 15;276:91-102.
12- Tang X, Liu Y, Shi S, Chen W, Qi X. Development of a novel ultrasonic drill using longitudinal-bending hybrid mode. Ieee Access. 2017 Apr 21;5:7362-70.
13- Bai D, Quan Q, Tang D, Deng Z. Design and experiments of a novel rotary piezoelectric actuator using longitudinal–torsional convertors. IEEE Access. 2019 Feb 8;7:22186-95.
14- Deng J, Liu Y, Liu J, Xu D, Wang Y. Development of a planar piezoelectric actuator using bending–bending hybrid transducers. IEEE Transactions on Industrial Electronics. 2018 Oct 10;66(8):6141-9.
15- Liu Y, Yan J, Wang L, Chen W. A two-DOF ultrasonic motor using a longitudinal–bending hybrid sandwich transducer. IEEE Transactions on Industrial Electronics. 2018 Jun 21;66(4):3041-50.
16- Karafi MR, Nejabat RS. An introduction to a bulk magnetostrictive bending actuator using a permendur rod. SN Applied Sciences. 2020 Feb;2:1-0.