

Embedded Piezoelectric Shear Actuators as Inertial Systems for Vibration Control in Metallic Structures

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Abstract. This paper presents a novel approach to integrate piezoelectric shear actuators into thin metallic structures for active vibration control. Piezoelectric inertial mass actuators operate by utilizing the inertial forces generated by piezoelectric materials under dynamic motion. However, these actuators have several limitations, including the addition of mass to the structure, the need for preload, and high power consumption. Unlike traditional IMAs, the proposed inertial shear actuator is integrated within the thickness of the structure, with the inertial mass effectively extracted from the metallic structure itself, offering several advantages. This integration leads to a significant reduction in weight and size. In addition, the actuator features reduced capacitance, leading to a significant reduction in power consumption, as well as eliminating the need for preload. While piezoelectric shear actuators have been mostly applied to composite structures, this work extends their use to metallic structures. A comprehensive model is developed to characterize the proposed shear actuator concept, and its performance is validated through a simulation on a simple plate structure. Experimental results show a vibration reduction of approximately 34 dB, targeting the first bending mode of the plate.

Key words: Inertial Mass Actuator, Piezoelectric, Active Vibration Control, Smart Structures

1 INTRODUCTION

Active Vibration Control (AVC) systems are superior regarding adaptability and precision compared to passive methods. Their ability to respond in real time allows them to perform optimally in a wide range of operating conditions, making them ideal for many applications where dynamic stability is crucial.

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AVC systems rely on actuators, sensors, and control algorithms to generate forces that counteract vibrations in real time. Inertial Mass Actuators (IMAs) have gained significant attention in vibration control applications because of their unique ability to provide effective vibration suppression without requiring a fixed reaction point. Using the inertia of an internal mass to generate control forces, IMAs are particularly advantageous in applications where traditional reaction-based actuators are impractical.

Various actuator technologies, including piezoelectric, electrodynamic, magnetostrictive, electromagnetic, and dielectric elastomer actuators, have been employed in IMAs. Piezoelectric actuators are distinguished by their high blocking force, superior high-frequency performance, compact size, and reliability. These actuators operate based on the piezoelectric effect, where an applied voltage induces mechanical deformation, enabling precise displacements across a broad frequency range.

Several studies have explored the integration of piezoelectric actuators into IMAs. Herold et al. [1] developed a piezoelectric-driven IMA capable of adjusting resonance frequency through stiffness modification, demonstrating its effectiveness in AVC for lightweight structures. Zhao et al. [2, 3] introduced a novel concept utilizing two piezo-based rotating inertial actuators to suppress structure-borne noise in gearbox systems by intervening early in the transfer path. Further advancements include Cao et al. [4], who proposed a compact inertial piezoelectric rotary actuator with high load capacity, and Deng et al. [5], who developed a bipedal piezoelectric actuator with triple actuation modes, enhancing displacement linearity and load stability. Pan et al. [6] designed a piezoelectric inertial actuator with asymmetric inertial masses capable of operating in both quasi-static and resonant states.

Despite their advantages, traditional IMAs have several limitations, including the increase in system weight, high power consumption, and the need for preload. Additionally, the high capacitance reduces the operating frequency range, making the selection of low-capacitance actuators critical for optimizing energy efficiency and performance in AVC systems.

To address these challenges, this paper proposes an integrated inertial shear actuator with a compact design, low weight, and reduced capacitance. Unlike conventional piezo stack actuators, piezo shear actuators have significantly lower capacitance, which minimizes their power consumption and improves their power efficiency at high frequencies. The proposed design further reduces weight by using a cutout of the mechanical structure as the inertial mass, eliminating the need for additional components. The relationship between power consumption, capacitance, and operating frequency is governed by:

$$I_{max} = U_{pp}\pi fC \quad (1)$$

and the maximum power necessary for this mode of operation is given by:

$$P_{max} = U_{pp}^2\pi f_{max}C \quad (2)$$

Where I_{max} is the maximum amplifier current, f_{max} is the maximum operating frequency, C is the piezo actuator capacitance, and U_{pp} is the peak-peak drive voltage. It can be observed

that the consumed power relies on the capacitance of the actuator.

While piezo shear actuators are mainly used in positioning stations and composite structures, their application in IMAs remains underexplored. Senthil and Batra [7] developed a 3D state-space solution for laminated plates with embedded shear actuators. Trindade [8] investigated the use of both extension and shear piezoelectric actuators for active vibration control of clamped sandwich beams. His study showed that shear actuators, when embedded in the structure, provide reduced sensitivity to actuator position and improved durability compared to surface-mounted actuators. Baillargeon and Vel [9] experimentally demonstrated vibration suppression in sandwich beams using piezoelectric shear actuators with feedback control. Notably, Zech et al. [10] were the first to employ piezoelectric shear elements in an IMA for high-frequency AVC in planetary gearboxes as an add-on solution, demonstrating effective suppression of dominant vibration orders.

Building on these advancements, this paper presents a novel integrated inertial shear actuator designed for thin metallic structures, targeting localized vibrations in the high-frequency range. The following sections explain the actuator design, modeling, and experimental validation. The work presented in this paper stems from the research project LIVE-I [11].

2 METHODOLOGY

A small setup is constructed to test the new concept, the setup employs a metallic aluminum plate with a piezoelectric shear actuator that is fully integrated within the thickness of the plate. This innovative configuration connects the actuator to an inertial mass that is formed by strategically machining cutouts from the metallic structure itself, thereby eliminating the need for additional mass. The shear actuator has one side fixed to the main structure and the opposing side attached to the integrated inertial mass, as illustrated in Figure 1.

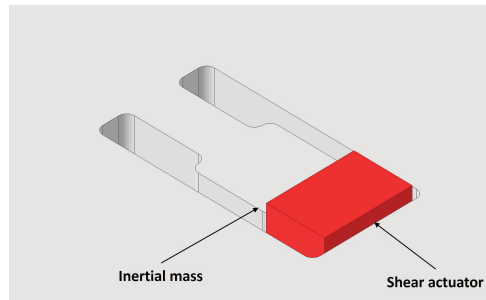


Figure 1: Integrated inertial shear actuator design.

A comprehensive numerical model is developed in MATLAB Simulink to simulate and validate the actuator's vibration control performance. The model incorporates four key components: the mechanical structure, the shear actuator, the inertial mass, and the controller, which employs a Filtered-x Least Mean Square (FxLMS) algorithm. The mechanical structure is simulated using a finite element analysis model conducted in ANSYS, which identifies the structure's modal

characteristics. The modal analysis shows that the first bending mode occurs at 2998 Hz, as shown in Figures 2 and 3.

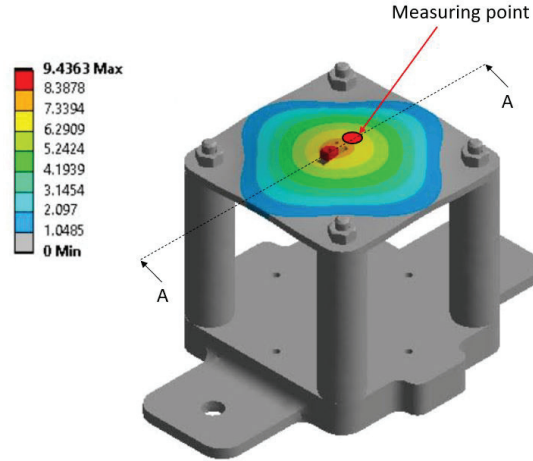


Figure 2: Modal analysis of the test setup.

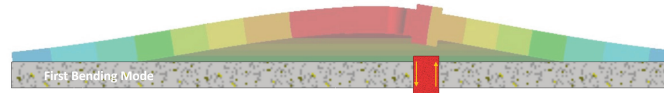


Figure 3: First bending mode (section A-A).

The finite element model is subsequently reduced to its first 22 modes, covering a frequency range up to 12.4 kHz, and converted into state-space representation for integration with the Simulink environment. The state space model has 44 states, having three input force points, which are the excitation point and the shear actuator influence points. In addition, there are three output points, which are the displacement, velocity, and acceleration of the measuring point. The modal damping is estimated and added to the State space matrices.

The mechanical modeling approach follows the framework established by Herold et al., employing alternating impedance and admittance formulations to describe the interaction between the mechanical structure and the piezoelectric actuator. In this representation, the plate structure is characterized by its admittance properties while the shear actuator is modeled as an impedance element. The coupling between these components occurs at discrete connection

points, with the actuator module receiving input voltages and connection point velocities as inputs and generating output forces. The piezoelectric actuator's behavior is implemented using the AdaptoSim™ toolbox from Fraunhofer LBF, which provides an analytical formulation incorporating the actuator's mechanical properties (stiffness and damping) and its electromechanical coupling characteristics. For this initial modeling phase, the electrical interaction between the actuator and power amplifier is simplified by assuming an ideal voltage source, though this aspect may be refined in subsequent development stages.

The model's inputs are the velocities v_1 and v_2 at both ends of the actuator as well as the driving voltage U . The block's outputs are the resulting forces F_1 and F_2 at the corresponding positions. Thus, the transducer is described in terms of impedance in the mechanical domain. The shear actuator is described by the following equation:

$$F_1 = -F_2 = \left(\frac{k}{s} + d\right)(v_2 - v_1) + \alpha U \quad (3)$$

The shear actuator stiffness and the coupling factor between the actuator input voltage and output force are determined experimentally. The damping parameter d is estimated for the shear actuator module. The excitation force is modeled as an ideal sinusoidal force supplied to the excitation point.

The complete Simulink model, depicted in Figure 4, integrates the reduced-order state-space representation of the plate structure with the shear actuator module, inertial mass, and controller. The power amplifier is modeled as a constant gain.

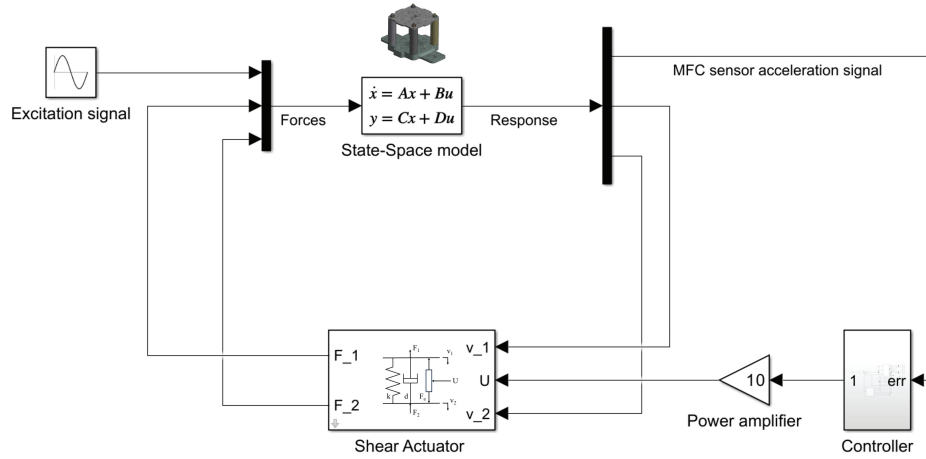


Figure 4: Developed setup Simulink model.

Simulation results demonstrate the system's effectiveness in vibration suppression, achieving approximately 60 dB of attenuation at the first resonance frequency when subjected to an ideal sinusoidal excitation, as shown in Figure 5.

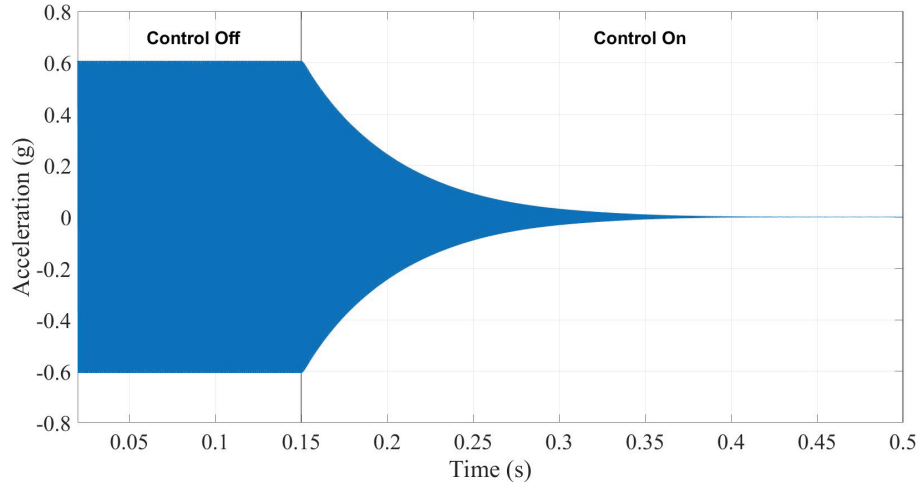


Figure 5: Simulink model acceleration levels before and after control of the shear actuator design.

Upon the completion of model construction and its subsequent successful evaluation, an experimental setup is developed to validate the newly developed concept. A test rig featuring an aluminum alloy plate, the shear actuator of type P-121.01 from Physik Instrumente (PI), an MFC (Macro Fiber Composite) [12] sensor for vibration monitoring, and an additional exciting inertial actuator that acts like a shaker. The test setup is shown in Figure 6. The piezo shear actuator is chosen due to its small size compared to the thickness of the plate, the shear actuator has a low electric capacitance of 1.4 nF. The size of the shear actuator is shown in Figure 7.

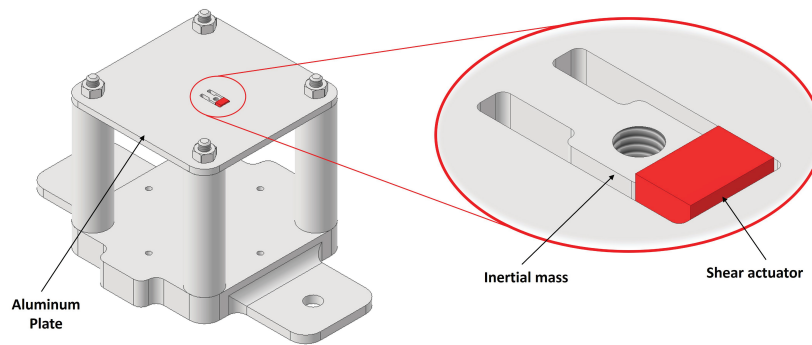


Figure 6: Developed plate structure with the integrated shear actuator design.

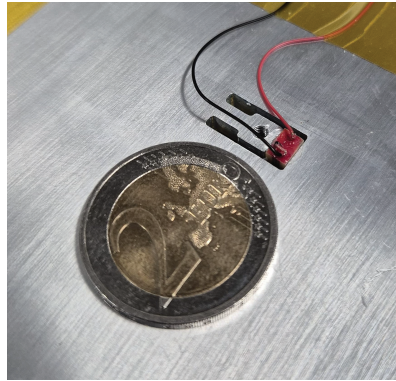


Figure 7: The developed inertial shear actuator size.

3 RESULTS AND DISCUSSION

Following the model evaluation, the test setup is assembled successfully with the integrated shear actuator, as illustrated in Figure 8.

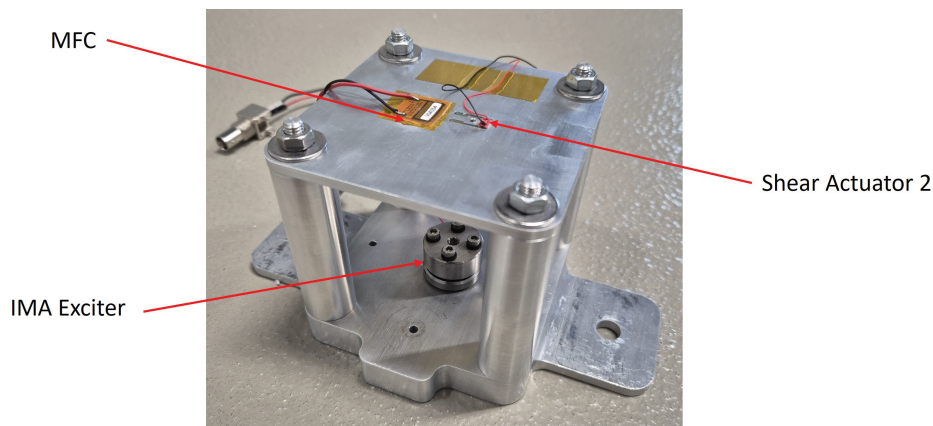


Figure 8: Test setup of the shear actuator utilizing the shear actuator.

The experimental procedure involves exciting the plate to induce its first bending mode and subsequently applying a control signal to the shear actuator. A sine chirp signal is applied at the excitation point to identify the resonant frequencies, revealing a first bending mode at 2990 Hz—closely matching the finite element model prediction of 2998 Hz. Following the resonance identification, a sustained sinusoidal excitation at this frequency is applied to generate steady-state vibrations.

The control system is activated after a 0.15-second initialization period, achieving convergence within 0.2 seconds of engagement. As shown in Figure 9, the time-domain response demonstrates effective vibration suppression of 34 dB reduction in acceleration amplitude.

The experimental results show strong agreement with the Simulink model, confirming the actuator's real-time mode identification and suppression capabilities. Although the achieved 34 dB reduction in vibration amplitude is lower than the 60 dB shown in simulation. This difference is likely due to small misalignments in actuator placement that affect force coupling efficiency, as well as unmodeled damping effects in the physical system. Nevertheless, the 34 dB suppression level proves highly effective for practical implementation, especially considering the actuator's compact dimensions and negligible weight addition, demonstrating the design's viability for real-world vibration control applications.

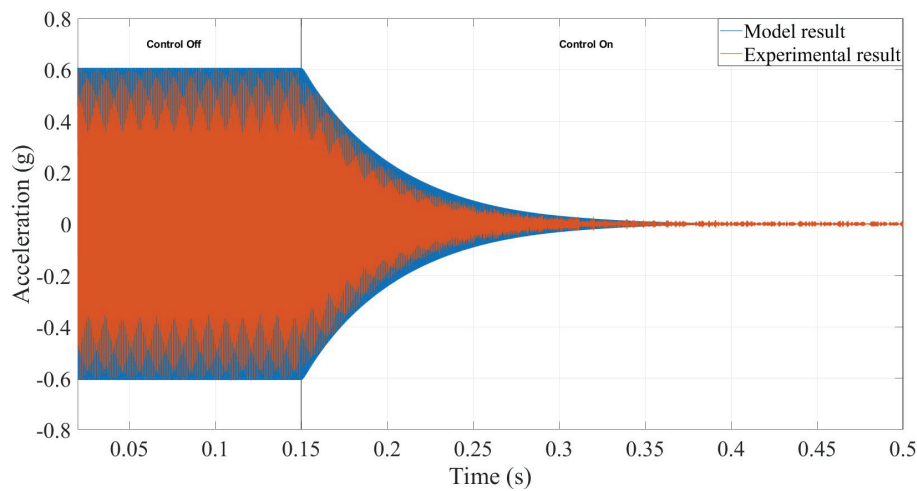


Figure 9: Time domain MFC sensor signal without and with activated control.

4 CONCLUSION

This study presents an innovative concept for integrating a piezoelectric shear actuator directly into a metallic structure, offering significant advantages over traditional IMAs. The newly developed actuator demonstrates better performance through reduced weight, lower power consumption, extended high-frequency operation, and improved structural integration. Numerical modeling in MATLAB Simulink confirmed the actuator's vibration suppression capabilities, which are subsequently validated through experimental testing on a simple plate structure. The system achieved a vibration reduction of 34 dB for the first bending mode of the plate.

The successful validation of the plate structure establishes a strong foundation for further development. Additional investigations should explore sensor dynamics optimization and power amplifier performance characterization to enhance the system modeling accuracy. Future work should also consider long-term reliability testing under operational conditions and potential adaptation for composite-metal hybrid structures to broaden the technology's applicability.

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REFERENCES

- [1] S. Herold, D. Mayer, T. Melz, and T. Röglin, "Design and test of a piezoelectric inertial mass actuator for active vibration control," *Vibration Engineering and Technology of Machinery: Proceedings of VETOMAC X 2014, held at the University of Manchester, UK, September 9-11, 2014*, pp. 587–597, 2015.
- [2] G. Zhao, N. Alujević, B. Depaetere, and P. Sas, "Active structural acoustic control of gear-box systems using a pair of piezo-based rotating inertial actuators," in *7th ECCOMAS Thematic Conference on Smart Structures and Materials SMART 2015*. IDMEC, 2015, pp. 1–16.
- [3] G. Zhao, N. Alujević, B. Depaetere, G. Pinte, J. Swevers, and P. Sas, "Experimental study on active structural acoustic control of rotating machinery using rotating piezo-based inertial actuators," *Journal of sound and vibration*, vol. 348, pp. 15–30, 2015.
- [4] Y. Cao, Z. Xu, L. You, Y. Wu, and H. Huang, "An inertial piezoelectric actuator with small structure but large loading capacity," *Review of Scientific Instruments*, vol. 92, no. 8, 2021.
- [5] J. Deng, W. Wang, S. Zhang, F. Lu, and Y. Liu, "An inertial bipedal piezoelectric actuator with integration of triple actuation modes," *Smart Materials and Structures*, vol. 31, no. 11, p. 115019, 2022.
- [6] C. Pan, C. Shi, A. Feng, M. Hu, S. Shu, and H. Xia, "Resonant-type piezoelectric inertial drive mechanism with asymmetric inertial masses," *Review of Scientific Instruments*, vol. 92, no. 1, 2021.
- [7] S. S. Vel. and B. R. C., "Exact solution for the cylindrical bending of laminated plates with embedded piezoelectric shear actuators," *Smart Materials and Structures*, vol. 10, p. 240, 4 2001.
- [8] M. A. Trindade, "Simultaneous extension and shear piezoelectric actuation for active vibration control of sandwich beams," *Journal of intelligent material systems and structures*, vol. 18, no. 6, pp. 591–600, 2007.
- [9] B. P. Baillargeon and S. S. Vel, "Exact solution for the vibration and active damping of composite plates with piezoelectric shear actuators," *Journal of Sound and Vibration*, vol. 282, pp. 781–804, 4 2005.

- [10] P. Zech, D. F. Plöger, T. Bartel, T. Röglin, and S. Rinderknecht, “Design of an inertial mass actuator for active vibration control of a planetary gearbox using piezoelectric shear actuator.” In Proceedings of ISMA2018 International Conference on Noise and Vibration Engineering, 2018, pp. 203–215.
- [11] H2020. Live-i. [Online]. Available: <https://livei.fr/>
- [12] S. M. GMBH. Macro Fiber Composites - Overview. [Online]. Available: <https://www.smart-material.com/fx/ms-product-mainV2.html>