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Design And Evaluation Of Piezoelectric-Based Passive Damping For High Frequency Noise Suppression

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ABSTRACT

This study focuses on developing a piezoelectric-based passive damper to mitigate high-frequency brake noise. The research investigates different designs of piezoelectric transducer elements to convert mechanical energy into electrical energy using a mass sliding belt test system that simulates real disc brake noise mechanisms. Integration of these electrical elements into the existing mass-sliding belt system is investigated. Five distinct piezoelectric transducer designs (Design-1, Design-2, Design-3, Design-4 and Design-5), each with unique technical specifications, boundary conditions, and scaling, are developed to suppress high frequency noise from friction-induced vibrations. To facilitate effective selection, a scoring method is employed, identifying Design-5 with a cylindrical model as the most efficient transducer design. Evaluation criteria include energy generation, compressive strength, operating temperature, weight, ergonomic usability, cost, and safety. In the scoring process, the designs respectively received 65, 56, 27, 44, and 89 points. Analyses are performed to assess potential stress-induced damage to the piezoelectric material resulting from the selected design. This study aims to contribute a novel perspective to noise reduction techniques and successfully demonstrates the integration of a piezoelectric transducer and an RLC circuit into a functional system.

Keywords: Piezoelectric-based passive damper, high-frequency noise suppression, transducer design, piezoelectric damping

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Introduction

Research in the area of energy damping of piezoelectric transducers has been ongoing for more than the last four decades. The ability of piezoelectric materials to convert mechanical energy into electrical energy has been particularly studied in the conversion of energy from mechanical vibrations into electrical energy. It is important to analyze how the electrical energy obtained in this conversion process can be effectively distributed to an RLC circuit [1]. Detailed studies in the literature revealed the existence of the energy damping potential of piezoelectric transducers. Forward's inductor experiments in 1979 and Hagood and Von Flotow's contributions to analytical formulas for resistive and inductor (RL) circuits in 1991 was notable [2]. As research progressed, the concept of damping was differentiated and Hollkamp's work on the RLC circuit in 1994 and Wu's work on the use of resonant circuits (LC) in 1998 also attracted attention [3, 4]. Studies on energy dissipation of piezoelectric transducers through RLC circuits revealed practical applications of the piezoelectric material's capacity to convert its mechanical energy into electrical energy. Moreover, the structural behavior of R and RL shunts has also been studied in detail in the literature [5-7]. Studies on vibration damping methods have demonstrated the effectiveness of using piezoelectric passive vibration damping. It has been observed that piezoelectric transducers can be integrated into electrical RL circuits to provide passive vibration damping [3]. Various studies have been conducted, ranging from conceptual designs to applied tests. Structural tests were conducted using

RC and LRC circuits in a piezoelectric damper weighing 0.5 kg in a structure weighing 5000 kg to absorb vibration in the test system of the ASTREX space structure, aiming at improving vibration in designs through piezoelectric passive energy damping [2]. The use of R and RLC circuits in this study demonstrates the potential applicability of a similar approach within the scope of design projects. Focused on mitigating excessive vibrations in turbomachinery blades, this study examined passive vibration damping methods implemented using piezoelectric transducers, particularly investigating the feasibility of resonance damping control through the use of piezoelectric materials in plate geometries, employing both passive and active control techniques. The results obtained indicate that, with passive damping circuits, bending resonance vibration at the third highest energy point could be reduced by 50%, and with the most suitable inductive circuits, this vibration could be reduced by 90% [8]. Neubauer and Oleskiewicz pioneered the development of a controller utilizing piezoceramic networks, wherein piezoactuators are autonomously controlled and operate concurrently employing a straightforward proportional and derivative feedback signal [9,10]. Park et al. introduced an active noise control system incorporating piezoelectric patches, deploying said system within the practical context of a vehicle's braking mechanism. Notably, this endeavor encompassed simultaneous management of active actuators and damping through a passive resonance shunt methodology [11]. Furthermore, Jearsiripongkul and Hagedorn advanced distinct methodologies for the active modulation of brake noise [12,13]. Literature review indicates that the application of a piezoelectric-based passive damping element to a mass-spring test system for suppressing high-frequency noise can play an effective role in passive damping applications of piezoelectric transducers. Therefore, this study demonstrates the effective utilization of designs through passive damping with piezoelectric transducers.

This study focuses on the design of a piezoelectric-based passive damper for the suppression of high frequency brake noise. Piezoelectric-based passive damping design studies are carried out on a mass-sliding belt test system that can mimic the high-frequency noise generation mechanism of the real disc-brake test system. Various designs of piezoelectric transducer elements which are used to convert mechanical energy into electrical energy and their integration into the current mass-scale tape system are performed. In this study, 5 different piezoelectric transducer designs with different technical specifications, boundary conditions and scaled are developed. These designs aim to provide damping by transmitting friction-induced vibrations to the transducers. In order to make an effective selection between the designs, a scoring method is applied and the most effective transducer design is identified. These 5 designs are evaluated in terms of energy generation, compressive strength, operating temperature, weight, ergonomic use, cost and safety criteria. This study aims to add a new aspect to the research on noise reduction techniques and demonstrates the successful implementation of a system combining a piezoelectric transducer and an RLC circuit.

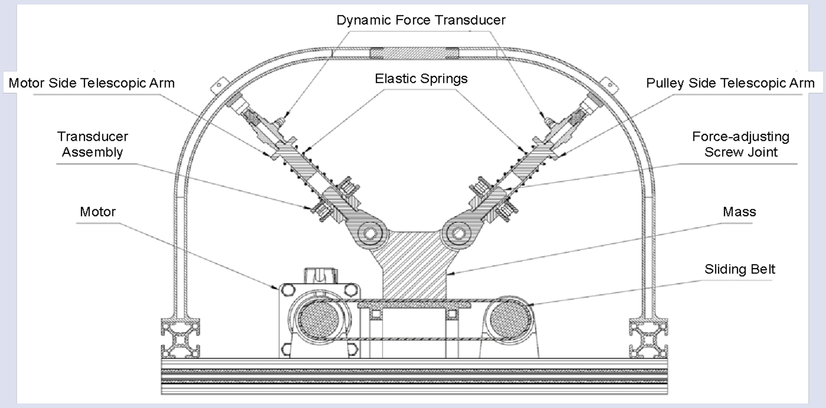

Figure 1. Mass-sliding belt test setup.

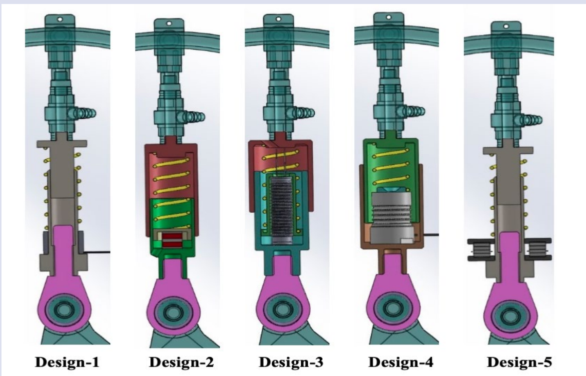

Figure 2. Transducer designs.

Design Options and Selection Criteria

The study focuses on resolving resonance problems caused by mechanical vibration on a specific design. The design, representing a real disc-brake test system, involves a sliding belt in contact with an angularly positioned telescopic cylinder between a mass and a spring creating pressure on top. This test system investigated the noise generated by the mass representing the pad on the sliding band representing the disc at various forces and speeds [14]. The mass-sliding belt test system is demonstrated in Figure 1. The preferred piezoelectric method for vibration damping in the study examined three fundamental methods for damping mechanical vibrations using transducers. These methods can be listed as active vibration damping, piezoelectric energy harvesting, and passive vibration damping. Active vibration damping involves applying counter vibrations with piezoelectric transducers to prevent the system from resonating. However, prior knowledge of the system's natural frequency is required for this process. The control system intervenes when the natural frequency of the system approaches a certain level and prevents resonance formation. This active vibration damping method involves electrical, electronic, and automation system circuits. The cost of hardware and software design is higher compared to others.

Vibrations generated in piezoelectric energy harvesting are converted into electricity and stored through piezoelectric transducers. Energy losses in this system negatively affect the energy storage efficiency of the system. Electrical and electronic auxiliary products are used to convert the high voltage and low current generated in the transducers from alternating current to direct current for storage. In passive vibration damping, the resistance to vibration generated through transducers allows vibration to be converted into heat and dissipated into the environment using inductor and capacitor circuits. This method aims to convert mechanical energy into thermal energy while minimizing automation and storage needs. In the comparison, mechanical energy is converted to thermal energy using RLC circuits as the fastest and most economical solution.

When these three methods are considered, passive vibration damping emerges as a more optimal solution, as active vibration damping and piezoelectric energy harvesting methods require more control systems and integrations. With passive vibration damping, vibration is converted into heat using transducers without the need for complex control algorithms and energy management systems. With this feature, it has the advantage of dealing with less complexity and lower costs in the design process. Parameters such as dimensions, voltage, capacitance, resonant frequency, compression force and temperature are critical in selecting the preferred transducers for the chosen passive vibration damping method for design implementation.

Industry brands such as Kemet, Noliac, PI, Piezosystem Jena and Thorlabs are identified for transducer brand selection. To better observe the differences between each brand's products and make appropriate choices, a material library has been created using technical information obtained from shared datasheets. The listing includes 1250 transducers with different specifications.

Geometric shapes play a significant role in transducer selection. Transducers can have various geometries such as stacked single-piece, rectangular prism, cube, cylinder, and hollow cylinder. In the design, transducers can be positioned both inside and outside the telescopic cylinder. The selected transducer designs (Figure 2) are respectively modeled as Design-1, Design-2, Design-3, Design-4, and Design-5.

In the modeling of ***Design-1*** in Figure 3, Kemet AER20x15.4x13.5DF model ring-stack transducer is utilized. The transducer is chosen for external mounting according to its geometric structure. The outer diameter, inner diameter, and height dimensions of the transducer are 20 mm, 15.4 mm, and 13.5 mm, respectively. The operation is carried out with two cable connections for positive and negative voltage outputs on the transducer. The accessibility of the design from the outside facilitates the control of connection accents. The operation of R and RLC circuits, which will convert electrical energy into heat, can be observed. This positively affects the operational safety of the system. Being exposed to the external environment enhances heat transfer, enabling rapid cooling at ambient temperature. The transducer, with a capacity of 5300 nF and a voltage output of 150 V, is able to facilitate the transfer of high wattages. The PZT piezo material used is highly resistant to impact, capable of withstanding compression strength up to 4200 N. The mass value on a single piston in the design is 7.65% heavier than the default design. This change in weight may result in a variation in the natural frequency of the design. Despite the shocks that cause vibrations in the mechanism, the transducer resonates at a frequency of 102 kHz. It can suppress friction induced vibrations at frequencies below 102 kHz. The transducer can effectively operate within a temperature range of -25°C to 85°C. Exceeding these temperature values may lead to the loss of strength properties of the PZT material inside and render it unusable.

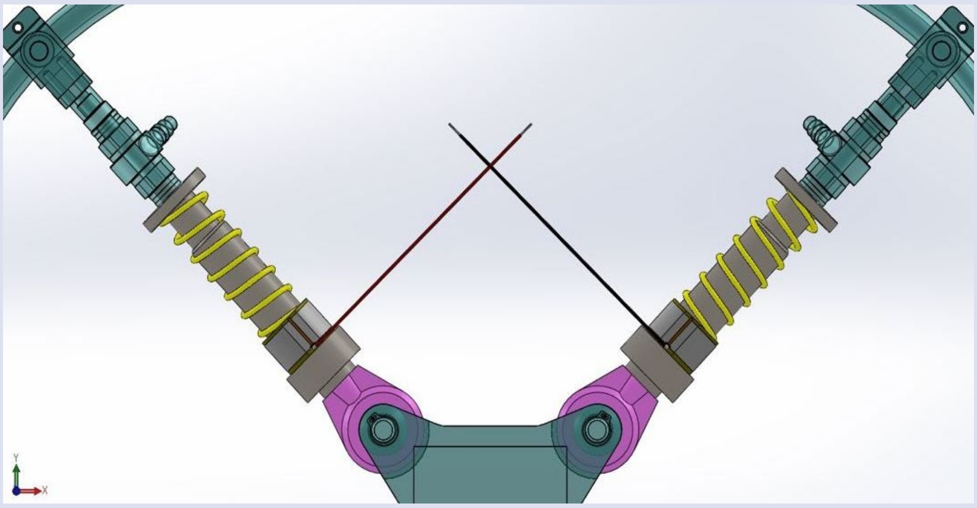

Figure 3. Design-1

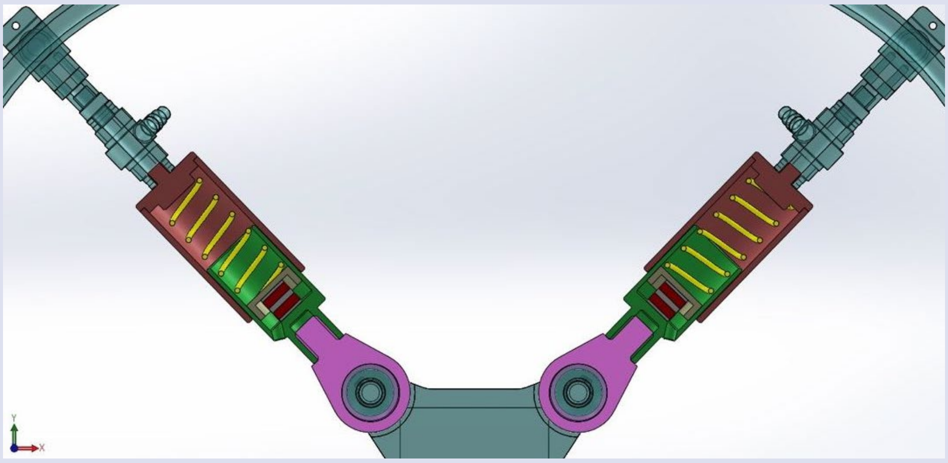

Figure 4. Design-2

In the modeling of ***Design-2*** in Figure 4, Noliac NAC2015-H08 model stack transducer is selected. The transducer has a cubic geometric shape. The stack is formed by soldering transducer parts, each 2 mm thick, in parallel layers. The dimensions of Design-2 transducer are 10 x 10 x 10 mm for width, length, and height, respectively. The design is made according to the closed inner part based on the geometric shape of the transducer. To enable a healthy comparison of analyses, the design is made based on the dimensions of the springs used in the default design. A sleeve is used as an intermediate support to ensure the pressure of the spring on the transducer. The compression spring, sleeve, and transducer are located inside the inner-outer telescopic bodies. To reduce mass and avoid obstruction to the transducer, the threaded portion of the ball joint connection is shortened by cutting. The telescopic outer body, shown in red, is planned to be welded to a seamless steel drawn tube using a welded disc for connection to facilitate production. After welding, slag will be turned to obtain a clean surface and reduce mass. The telescopic inner body, shown in green, is aimed to be produced from a single piece without any welding process. The cable input and output for the transducer are made through the hole drilled at the fixing end of the green part. Design-2 has a 20.07% higher mass difference compared to the default design. The transducer, with electrical properties of 150 volts and 2740 nF capacitance, can operate up to 150 degrees Celsius. It withstands a compression strength of 4200 N. It is the transducer with the highest resonant frequency, 248 kHz.

In ***Design-4*** depicted in Figure 6, Piezosystem Jena brand P18-S22 model transducer is housed in a large cylindrical volume. The transducer, placed in the brown outer telescopic body, has a diameter of 22 mm and a length of 30.5 mm. To prevent displacement of the spring during vibration and to ensure better grip, a special washer with a hexagonal head screw is attached to the M4 guide hole located at the top of the transducer. The inner and outer telescopic bodies of the transducer, with large dimensions, are constructed by welding flanges to seamless steel drawn tubes according to DIN2448 standard. The cable connection of the transducer is routed outside through a hole drilled in the outer body. The energy generated by the transducer, with a maximum applied force of 130 volts and 5400 nF capacitance in the enclosed volume, is 45.63 mJ. Assuming the system operates at 10 kHz frequency, the theoretical heat generated would be 456.3 J/s. Despite this performance, the recommended operating temperature range for the transducer is -20°C to 80°C, and using it above or below this range may cause permanent damage. It is 88.28% heavier compared to other designs. The inconsistency in natural frequency resulting from the volumetric differences in the design significantly affects the validity of the design. However, a sleeve design was not preferred due to the transducer diameter being larger than the compression spring. The reduction in distance between the transducer and the inner telescopic body due to this aspect increases the force applied by the spring, potentially hindering the achievement of the appropriate compression force for testing in the experiment. The compression strength of design-4 is 3400N.

In ***Design-5*** depicted in Figure 7, the transducer used is the cylindrical model PK25LA2P2 from Thorlabs. It is a design with two transducers placed between two plates. The transducers have a diameter of 8.2 mm and a length of 9.2 mm. The compression force between the spring and the body is transmitted to the transducers through the black metal plate. The transducers are planned to be used by adhering them to the metal plate used as a transmitter without being glued to it and can be glued with Thorlabs' recommended epoxy, 353NDPK. Since the transducers in the design are positioned externally, they contribute to increased heat dissipation, aiding in the cooling of the transducers. The recommended operating temperature range for the transducers is between -25°C and 130°C. Their compressive strength is 1800 N. As two transducers are used on a telescopic arm, this compression strength value is considered as 3600 N. Although the capacitance value of a single transducer is the lowest in the comparison, at 2200 nF, it has the highest voltage value of 200 volts, enabling it to operate at the highest voltage. These values result in a higher energy value compared to other designs when evaluated as two transducers on a single telescopic arm. Designed externally, it is 17.90% heavier than the default design, allowing for the use of fewer parts.

The developed designs have different advantages and disadvantages in terms of their ability to dissipate heat. Transducer selections and designs were made with simplicity and ease of use in mind. Among these options, the most suitable one will be evaluated and chosen. The transducers used in the designs discussed in terms of their technical specifications are listed in Table 1.

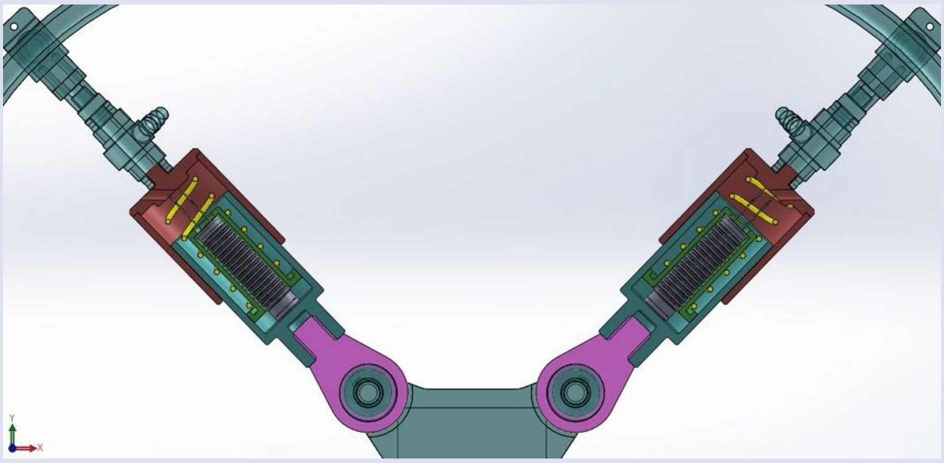

Figure 5. Design-3

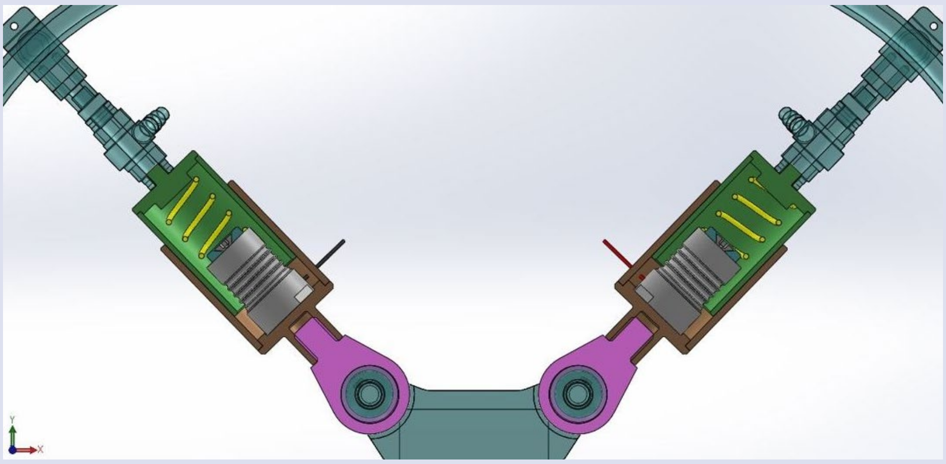

Figure 6. Design-4

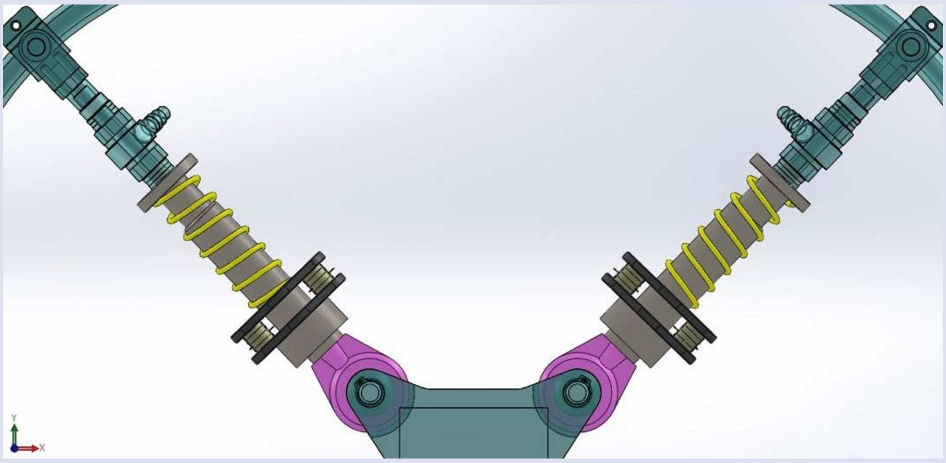

Figure 7. Design 5

Table 1. Transducer specifications used in the designs.

	Design-1	Design-2	Design-3	Design-4	Design-5
Brand	Kemet	Noliac	Physik Instrumente	Piezosystem Jena	Thorlabs
Model	AER 20x15.4 x13.5DF	NAC2015-H10	P-885.95	P18-S22	PK25LA2P2
Location	Outer	Inner	Inner	Inner	Outer
Geometry	Hollow Cylinder	Cube	Cylinder	Cylinder	Cylinder
Dimensions	ØD20 x Ød15.4 x 13.5 mm	10 x 10 x 10 mm	ØD11.2 x 40.5 mm	ØD22 x 30.5 mm	ØD8.2 x 9.2 mm
Voltage	150 VDC	150 VDC	120 VDC	130 VDC	200 VDC
Capacitance	5300 nF	2740 nF	3100 nF	5400 nF	2200 nF
Resonance Frequency	102 kHz	248 kHz	35 kHz	24 kHz	125 kHz
Compression Strength	4200 N	4200 N	900 N	3400 N	3600 N
Operating Temperature	-25/85°C	150°C	-40/150°C	-20/80°C	-25/130°C

Determination Of Optimal Design With Appropriate Selection Criteria

The criteria for the designs vary internally. These designs need to be evaluated by eliminating them based on the established criteria to select the best one. The time involved in the production and procurement of designs is a significant factor that can affect a study. The transducers used in the designs are not widely available in the market, making it difficult to find the products. Suppliers do not maintain product inventory and instead source them from abroad based on the orders they receive. This situation may prolong the process in case of product purchase or malfunction, necessitating an evaluation of the timing of design production and procurement. The prolongation of the process and additional tax payments affect its cost. The difficulty in finding the product adversely affects its cost due to the supply-demand relationship. It is necessary to classify the preferred products economically. It is important for the designs to be user-friendly. The difficulty of part replacement during maintenance and repair reduces the preference for the design. Simple and ergonomic designs are preferred for user and performance aspects.

Considering that the aim of the study design is to convert existing vibration into heat, the transducers and the associated R and RLC circuits should have a design model that allows heat conduction. Thus, the ability to dissipate heat into the surroundings will significantly affect the system's performance. Therefore, open systems will always be more effective. The information in Table 1 provides details about the positions of transducers on the assembly. The position boundaries are examined in two categories: internal and external. If the transducers are positioned internally, it adversely affects heat conduction. Transducers positioned externally are more advantageous in dissipating heat to the outside environment compared to internal positioning due to being in an open environment.

Table 2. Weights of parts required for transducer connection (grams)

	Default	Design-1	Design-2	Design-3	Design-4	Design-5
Transducer	-	14.75	7.80	26.27	77.10	10.90
Outer Body	42.99	42.99	88.06	93.99	121.35	42.99
Inner Body	59.40	59.40	46.79	97.58	80.75	59.40
Spring	8.52	8.52	8.52	8.52	8.52	8.52
Sensor	31.24	31.24	31.24	31.24	31.24	31.24
Joint Connection	50.20	50.20	39.17	39.17	39.17	50.20
Bolts	-	-	-	-	4.03	-
Hive	-	-	9.38	23.79	-	-
Plate	-	-	-	-	-	23.54
TOTAL	192.35	207.10	230.96	320.56	362.16	226.79
Difference [%]	-	7.67	20.07	66.65	88.28	17.90

Table 3. Natural frequency change of telescopic arm mounting in designs.

Design Name	Natural Frequency [Hz]	Natural Frequency Change [%]
Default	1623.72	-
Design-1	1564.81	3.63
Design-2	1481.68	8.75
Design-3	1257.64	22.54
Design-4	1183.28	27.13
Design-5	1495.22	7.91

Table 4. Energy calculation in transducers exposed to vibration at a frequency of 10kHz

	Design-1	Design-2	Design-3	Design-4	Design-5
Voltage (V)	150	150	120	130	200
Capacitance (nF)	5300	2740	3100	5400	2200
Energy (Joule)	0.0596	0.03083	0.02232	0.04563	0.0880
Power (Watt)	596.25	308.25	223.20	456.30	880.00

Table 5. The scores of the designs.

	Design-1	Design-2	Design-3	Design-4	Design-5
Energy Generation	20	5	1	13	35
Compression Strength	20	20	1	15	17
Operating Temperature	2	6	6	2	5
Weight	10	9	3	1	9
Ergonomics	4	2	1	2	3
Supply Time	4	2	3	1	4
Cost	1	7	6	3	10
Safety	4	5	6	7	7
Total Score	65	56	27	44	89

Advantages of Selected Design 5

Changes in the mass of the designs will result in differences in the natural frequency of the default system; therefore, it is important to select a design with minimal weight variation to ensure that the experiment can be conducted accurately again. The weight values are shown in Table 2, where the total weights of the designs are listed along with their percentage differences in the bottom row.

The value of the natural frequency is one of the fundamental calculation parameters for all systems. In this study, the aim is to minimise mass changes so that the natural frequency remains unchanged. Any change in the natural frequency could lead to discrepancies in the data compared to previous experiments. There could be many variables involved, but the vibration in the design should be limited to ensure that the weight at the point of measurement remains constant. The calculated natural frequencies of the system are shown in Table 3.

The ergonomic design of the system allows for easy observation during experiments and access to cables due to the positioning of the transducers. While the likelihood of any risk of ignition in the system is low, there should be effective intervention in case of a short circuit that could disrupt the operation of the system. The ability to observe the system from the outside allows for intervention and observation in possible situations. The safety of the system is evaluated based on these limitations.

Considering the purpose of the design to expel heat, it is important to consider the data of the transducers that will be connected to the R and RLC circuits. The energy produced by the transducers determines the performance of the design. The calculation in the Table 4 is based on the power (Watt) value corresponding to the 10 kHz vibration frequency in the mechanism.

The maximum theoretical energy production achievable through passive vibration damping in the designs is provided in the table above. The use of two transducers in Design 5 allows for higher energy production compared to other designs, making it considered as the design with the highest energy output. The energy generated by the designs is crucial in terms of the intended usage of the design. The operational temperature value is important for the effective operation of the design. Since it needs to generate heat for energy conversion, the use of heat-resistant transducers is more critical.

Compression strength comparison is an important part. Since each transducer has its own material and structure, it can withstand different force values. These strength values were taken from the datasheets shared by the manufacturers and evaluated. For scoring, the lowest score was given to the one with the lowest strength, while the highest score within the determined limit was given to the one with the most durability.

Evaluations will be based on energy production, compression strength, operating temperature, weight, ergonomic usage, supply time, cost, and safety. The designs are evaluated based on a total score out of 100. The highest score is given to the value showing the best performance in comparison. The product with the lowest performance receives a score of 1. The scoring of technical specifications with intermediate values is done according to the established linear equation. A comparison of the scores of the 5 different designs is provided in Table 5. As a result, Design-5 received the highest score of 89, followed by Design-1, Design-2, Design-4, and Design-3, with scores of 65, 56, 44, and 27 respectively. Design-5, with a score of 89, achieved the highest score. In the final, work continues with Design-5, which is made with the Thorlabs brand PK25LA2P2 model transducer for noise reduction through passive vibration damping.

In accordance with the established criteria, the design made with Thorlabs transducers has been identified as the most effective model with a score of 89. The prominent features of the design include the positioning of the transducers in an open configuration and their advantageous mass properties. Among the designs, this is the only one that utilizes two transducers. It has been observed that this system generates a high level of energy, as shown in Table 4. The dimensions of the transducers, with a diameter of 8 mm and a length of 9 mm, contribute to a lightweight product. This lightness helps maintain an acceptable level of change in the system's natural frequency. Being in an open environment facilitates the temperature regulation, maintenance, and potential interventions of the transducers. It is the transducer model with the lowest cost among the designs. The specifications of Design-5 made with Thorlabs transducers are listed in Table 6.

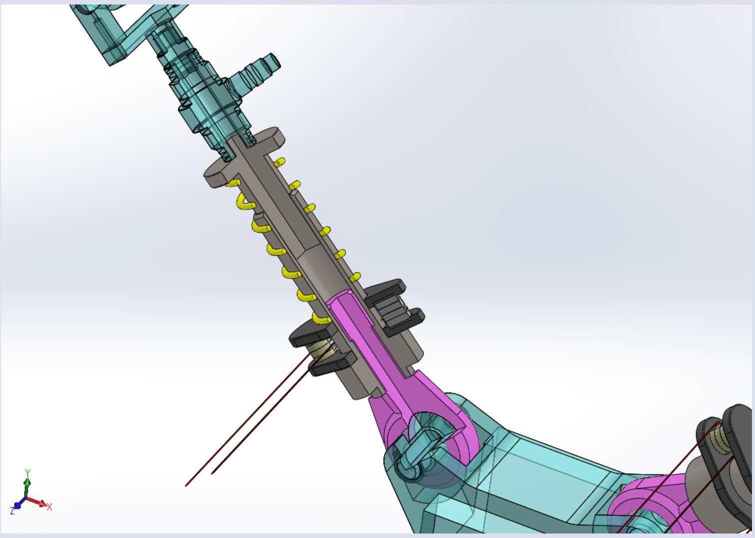

Figure 8. Half-section perspective view of Design-5

Table 6. Characteristics that make the choice of Design-5 important

Parameters	Design-5
Weight	226.79 grams
Natural frequency change	7.91%
Maximum energy that can be collected	880 W
Temperature resistance	-20°C/150°C
Compression Strength	3600 N

Conclusion

In this study, various passive vibration damping methods have been proposed to attenuate the high-frequency noise induced by friction-induced vibration. Within this scope, five different piezoelectric transducer designs are suggested. The mass-spring test system used in the study is modified for the purpose of converting mechanical energy into heat energy using different piezoelectric transducer designs. A market survey is conducted by listing five different products selected from existing transducer brands. Various designs are made with five different transducers in accordance with the dynamics of the mass-spring test system. Through a comparative scoring method, designs are eliminated, and the most suitable model, Design 5, was selected. Following the selection of Design 5, development analyses aimed at increasing efficiency within the boundaries of the design are applied.

This study aims to provide a new dimension to research on noise reduction techniques and demonstrates the successful applicability of a system involving a piezoelectric transducer and an RLC circuit. The results obtained have the potential to shed light on further research in acoustic control systems.

The application area of this study focuses on experimental studies aimed at reducing vibration-induced noise by dissipating vibration as heat energy. It contributes to research aimed at eliminating noise associated with vibration. The design developed in the study contributes particularly to research aimed at effectively controlling friction-induced noise in environments such as laboratories and research centers.

Friction-induced noise can be ubiquitous in human surroundings. This design aims to convert vibration-induced noise into electricity using passive vibration damping methods. According to experimental results, the areas of application for this design may include machines that produce noise from vibration. This study has opened a door towards reducing noise originating from friction using piezoelectric transducers. In the future, providing an applicable solution for noise elimination through further analysis and examination of parametric values is planned.

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