Investigating Kangaroo Legs as Bioinspired Vibration Damper for Heavy Load Machinery

Abeer Gosain [a], Reetu Jain[b]

(a) Class of 2026, The Shri Ram School, Moulsari Avenue, Gurgaon, Haryana, India
Email id: abeergosain0912@gmail.com

(b) Supervisor, On My Own Technology Pvt. Ltd., Lokhandwala, Oshiwara, Mumbai, India.

ORCID: 0000-0002-7199-2823

Abstract: *Heavy machinery vibration dampening presents many difficulties that frequently result in mechanical breakdowns, decreased efficiency, and higher maintenance costs. To address the demand for more efficient damping systems, this study investigates a bioinspired method based on the structural architecture of kangaroo legs, which are well-known for their innate capacity to absorb shock. The study evaluated the performance of different damper designs using experimental testing and finite element analysis (FEA), with an emphasis on a front-and-back opposite (FAB OPP) orientation. The flexibility and durability of thermoplastic polyurethane (TPU) made it the ideal material for the damper. According to FEA models, the FAB OPP orientation had the best damping performance with the least amount of deformation under dynamic stress. These results were corroborated by experimental testing, which demonstrated that compared to conventional cylindrical dampers, the kangaroo leg-inspired damper absorbed vibrations faster and reduced acceleration amplitude more successfully. The findings imply that in heavy load situations, bioinspired designs such as the kangaroo leg damper can offer better vibration absorption, less deformation, and increased stability. This study shows how bioinspired solutions can be integrated into mechanical systems, providing a viable substitute for traditional damping techniques with wide-ranging industrial consequences.*

Keyword: **Seronegative Spondyloarthropathies (SSA), IMU Sensor, Riemann Sum, Rib cage**

I. INTRODUCTION

During consistent and intense use, heavy machinery is likely to start producing oscillations i.e. back and forth movements. This motion by heavy machinery and components is known as vibration in motorised equipment. Vibrations in machinery can indicate deterioration and lead to greater and more permanent damage to equipment if ignored. They may be caused by a manufacturing defect, which causes certain machinery to have heavy points creating unbalanced weight throughout the machine when it rotates and creating centrifugal force. This imbalance has caused greater vibrations and hence greater damage to the equipment as the speed of the machinery increases.

Furthermore, wear and tear can also play a factor in vibrations since they can give rise to unsmooth surfaces and bumps in the surface. Then, when the speed of the components is increased, these bumps cause vibrations in the machinery in contact with other components. Additionally, a loosely attached component may cause vibrations. However, the looseness could also be caused by the chain effect of underlying vibrations. This means that this cause of vibration is far more dangerous and harmful for machinery as these vibrations could increase quickly and become destructive.[1]

A. Novelty

As a result, researchers have used various methods to mitigate the effects of these vibrations. Firstly, a strategy known as dynamic balancing has been employed, where mass distribution is continuously adjusted within a roto or other rotating equipment. It aligns the machine's centre of gravity with its axis of rotation. Secondly, the use of dampers enables researchers to reduce the vibration energy in machinery by distributing, changing, or absorbing the vibration energy. Thirdly, isolators are components that reduce the amplitude of vibration and hence reduce the magnitude of vibration passed on to other machinery in the event of a vibration forming in one of the components. They can be made out of any elastic material such as rubber or springs.[2]

Another way in which the amplitude of vibrations is reduced is through antivibration pads, which are placed underneath the machinery and slightly deform in response to receiving a vibration. This reduces the after-shock on the next machinery as the vibration's kinetic energy is converted to a small amount of thermal energy. [3]The final method researchers use is precision alignment, where the various components in motion are correctly aligned with the main system. When they aren't correctly aligned, there may be a disbalance in forces, causing a vibration to form. [4]

By looking at different types of dampers available in the market, this research investigates a new damper design that overcomes the disadvantages of currently available dampers like costly heavyweight, etc. To perform this, the inspiration from the kangaroo's leg has been drawn and then the kangaroo leg type damper has been 3D modeled, which is further analyzed using ANSYS - structural module considering various parameters. Finally, to validate the damping study, an experimental test was performed between kangaroo and traditional damper. The complete procedure is mentioned in the various sections of this research paper.

B. Project timeline

To ensure the successful completion of myproject, the research was divided into four distinct phases. The first phase involved conducting a comprehensive literature review and surveying relevant research papers. This phase spanned from March 23, 2024, to April 12, 2024, taking approximately 20 days. It was essential in identifying existing research gaps and providing the foundation for the project's direction. The second phase commenced on April 12, 2024, and focused on hardware design, which concluded on May 16, 2024, after 35 days. During this period, the necessary components were selected and the initial design of the hardware was completed.

In the third phase, the simulation model was developed, beginning on May 16, 2024, and concluding on June 7, 2024, after 22 days. This phase involved building a simulation environment to test the design. Finally, the fourth phase focused on testing the simulation and troubleshooting any issues, which lasted from June 7, 2024, to July 28, 2024, covering 51 days. This critical phase ensured that the project was functioning as intended and any errors were resolved.

My research work was divided into 4 phases.

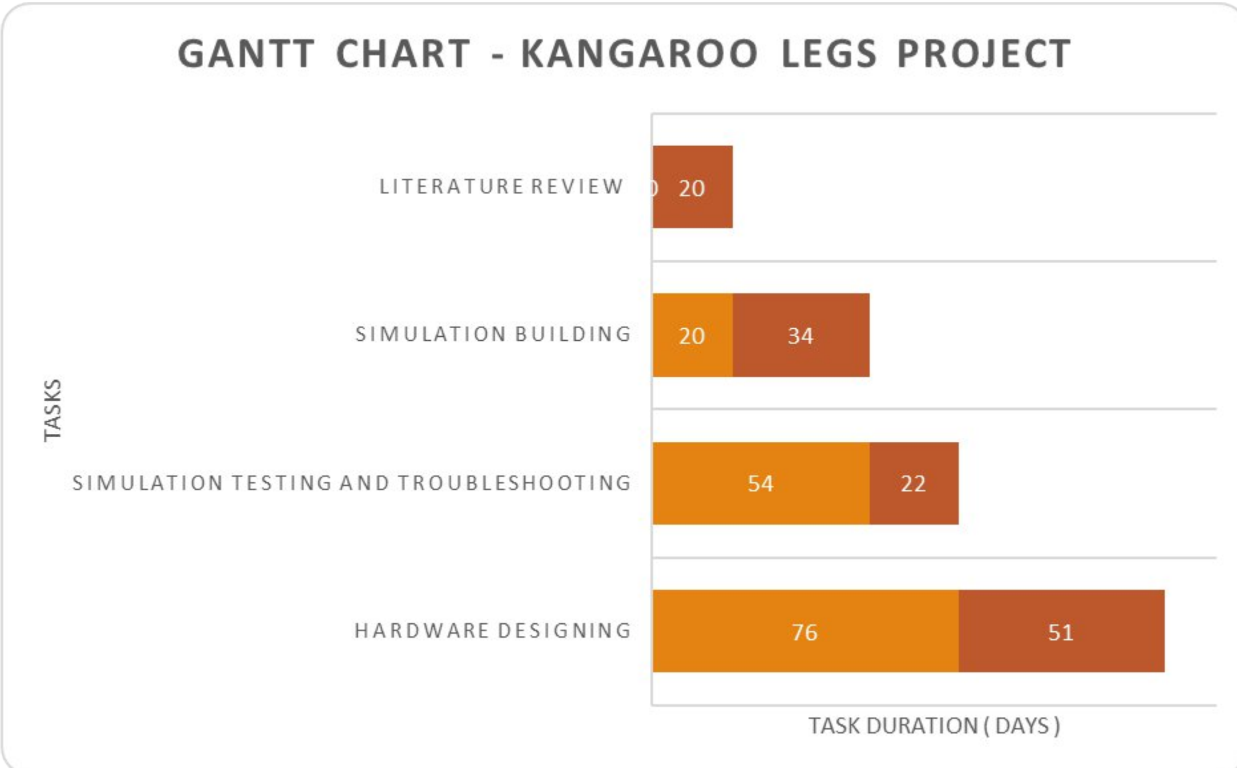

Figure 1 : Gantt chart with Four Task sections

Table 1: Timeline and Duration of Project

Task	Start Date	End Date
Literature review	23 March 2024	12 April 2024
Simulation building	12 April 2024	16 May 2024
Simulation testing and troubleshooting	16 May 2024	07 June 2024
Hardware Designing	07 June 2024	28 July 2024

II. Literature Review

The literature review highlights the different types of damping used in the machinery. It also shows the advantages and disadvantages of the various dampers. It is also observed from the literature that there are only a few researchers who have explored the bioinspired damper in small robotics. It was also found that kangaroo legs mimic design to give optimum performance with a viable cost-to-weight ratio. Based on the above literature review it was concluded that there is a research gap in exploring the kangaroo legs as a better damper in case of heavy machinery.

Yujun Hu et al. [5] aimed to enhance the damping performance of tuned mass dampers using an analytical method, which can be beneficial for studying tuned mass damper's nonlinear characteristics. The complex variable averaging method was employed to analyze and design a nonlinear tuned mass damper. This method was validated by comparing its results with traditional numerical methods, ensuring correctness and accuracy. The analysis led to the derivation of a nonlinear restoring force equation, incorporating stiffness terms up to the fifth order. Through the study, it was noted that the complex variable averaging method was approximately 69 times faster than another method known as the Runge-Kutta method in generating frequency response curves under the same conditions for each. This method facilitated obtaining structural steady-state solutions swiftly, saving time for system designers and improving efficiency in practical engineering. There is not data publicly available regarding the limitations in this study.

Jia Fu et al.[6] looked to investigate and solve the various difficulties related to the nonlinearity of rubber and how its affected by high temperatures while accurately simulating rubber shock absorbers and using them in various practical methods. To do this, the team first analyzed the rubber's hyperelasticity by analyzing the correlation data that was brought up while conducting tests on the rubber material, which helped them build an overarching model. To verify this model, they conducted various experiments along with numerical simulations on UAVs using a robber shock absorber. Additionally, to recognize rubber material's parameters, another model known as the Mooney-Rivlin model was utilized, along with the complex number method to solve various equations. As a result, the model's simulation provided acceleration response curves which were similar to test results, validating the accuracy of the simulation which showed that rubber shock absorbers can be used for vibration reduction.

Viktor Berbyuk et al. [7] aimed to explore the possibility of using a dual mass flywheel for heavy-duty truck drivetrain systems. This was done by examining the third engine vibration harmonic, which was an important cause of these systems' oscillatory responses. To do this torsional vibration absorbers with an engine speed range from 600 to 2000 rpm were developed by the Global Sensitivity Analysis and Pareto. This optimization by the GSA and Pareto aimed to maximize the vibration absorber's energy efficiency while reducing torque oscillations at the gearbox input shaft. GSA made it possible to simultaneously explore all of the design parameters in great detail, which improved the effectiveness of the design process. The results were positive, with them showing optimized mass inertia, stiffness, and damping parameters for a DMF. These results seemed to show that there is a solution for the bi-objective optimization problem - torsional vibration absorbers, presenting Pareto fronts that showed a trade-off between the absorber's energy efficiency and the attenuation of torque oscillations. Lastly, these results also helped conclude that the outcomes demonstrated in installing two mass flywheels in heavy-duty truck drivetrain systems are feasible and could lead to better system performance.

Qi Wang et al.[8] aimed to increase the load capacity and driving speed of small robots, while also trying to operate them at a lower voltage. To do this, the researchers made use of a biological feature of a kangaroo - its hop - and an electromagnetic drive, which helped create two soft mass-structured robots. To replicate a kangaroo's hop technique, the researchers enabled the robot to use a coil and magnet connected to a conductive body - in this case silicone - with a cavity structure. The results were quite positive, with the robot shrinking down to a length of only 2 cm, with its body weight dropping to a mere 1.46 g. Along with this significant change in dimensions and weight, the robot reached appx 21.5 body lengths per second. This high speed seemed to be irrespective of the surface, be it slopes, rough or even underwater. Despite its smaller size, the robot could lift a higher 32.5 times its body weight. However, a few of the limitations should be noted. Firstly, the robots might become unstable at lower frequencies of vibration, hence the experiment had to be conducted at a higher 75 Hz rather than 50 Hz. Due to this, there are a few doubts regarding the long-term durability of the robot, along with whether the robot is capable of real-world applications

Tian Wang et al. [9] utilized Shape memory alloy in a Semi-Active Damper Oscillator to observe how much the frequency of engineering structures can be adjusted, along with the vibration attenuation of the structures and damping. To do this, the researchers aimed to control and change the stiffness and frequency of the structures. This was done by managing the smoothness parameter of the SMA-SD oscillator which was achieved by changing the SMA springs to their austenite phase. Additionally, by changing the intensity of the current, the researchers evaluated the trend between current and temperature. They used this for accurate conversion of frequency. The results were positive, with it first being noted that a structure known as a VFVVDA could reduce vibration in various conditions(temperature variations)as it was noted that conversion of frequency did happen through changing the current. Furthermore, the results of this experiment showed that the SMA oscillator was capable of having negative, positive, and neutral stiffness when the temperature was changed. The results also showed that researchers could influence the current differently, using the VFVVDA which controls damping. The VFVVDA was made by using an MRF and the oscillator.

Y H Zhang et al. [10] created a bionic kangaroo robot known as Z bot to improve the jumping abilities and amount of load their previous robots were carrying. To simulate the bionic performance of a kangaroo for the robot, the researchers used a system using five gears that detached the knee and ankle joints. This detachment system was improved by an enumeration method. The results were very positive, with a great improvement in the jumping ability and load capacity of the robot being noticed, showing a successful bionic performance. The researchers also noticed a pattern in the movement of the ankle joint and knee joint when the robot jumped, showing that while jumping, the robot had similar acceleration performance to a kangaroo. This was discovered when the results of the previous experiment were substituted onto the ankle angle in the knee angle expression. However, while the results more or less showed constant imitation of kangaroo jumping ability, there were slight variations in optimisation results due to parameter gaps and constant/discrete testing points.

John Trautwein et al.[11] explored whether the scope of the hopper spacecraft could be influenced/increased using metal bellows. This meant that the vertical movement of the hopper would be initiated by the mass of the hopper being influenced by the shock absorber. This makes the hopper a single-degree-of-freedom system. To do this, the researchers needed to analyze the practicality of increasing the capsule range, which was done by comparing the surface area of various metal bellows and differentiating them. The results of this methodology would show the researchers the effectiveness of using metal bellows as part of a landing gear system for space and aircraft. However, the limitation of this study is that the results were only obtained based on simulated models and using past results and understandings. This lack of practical experimentation could reduce the applicability of the results in a real-world scenario.

Zhongjie Li et al.[12] explored the issues related to gathering useful energy from suspension vibrations, with some of the issues relating to efficiency, impact forces, and unproportionate voltage readings. Firstly, at higher than normal frequencies, typical regenerative vibrations don't have an efficiency of more than appx 45%, which is relatively low. Additionally, the vibrations portrayed on the oscilloscope show unconventional voltage readings, which means diode forward voltage significantly reduces and affects the efficiency further. Lastly, since the vibrations are bidirectional i.e. in both directions, there is a significant amount of strain put on mechanical components, causing them to deteriorate. To test and find solutions to these issues, a new type of shock absorber was developed which converted the aforementioned bidirectional oscillations to unidirectional through the use of a mechanical motion rectifier. This prototype was then tested by inputting a range of frequencies and observing the voltage output through a DSA. The results of efficiency and power output were then analyzed. They showed promising signs, such as an efficiency increase of 60%

III.CASE STUDY

3.1. Problem Statement

Heavy industrial machinery often faces challenges related to vibration-induced wear and tear, leading to reduced equipment lifespan and efficiency. Traditional dampers, while effective, may not offer the optimal balance between cost, weight, and performance. This case study explores a bio-inspired approach to addressing these issues by designing a vibration damper based on the structural characteristics of kangaroo legs. Kangaroos are known for their exceptional ability to absorb impact and manage energy efficiently during motion, making them an ideal model for developing a damper capable of handling heavy vibrations in machinery. This study investigates how the kangaroo leg-inspired design can be used to create an efficient, cost-effective damper that enhances the lifespan of heavy machinery.

The main issues identified include:

- Inadequate vibration damping by conventional dampers leading to frequent maintenance and reduced machinery life.
- High cost and complexity of existing damping solutions for heavy machinery.
- The need for a durable, high-performance damper that balances cost, weight, and vibration absorption efficiency.

3.2. Assumptions

Several assumptions were made throughout the design and testing phases of this case study:

- **Bio-inspired Efficiency**: It was assumed that mimicking the kangaroo leg structure would provide a superior energy absorption and vibration damping capability compared to traditional dampers.
- **Material Uniformity**: The assumption was made that the materials chosen for the damper (TPU, TPC, PP) would behave uniformly during both the simulation and real-world testing phases, ensuring consistency in the results.
- **Simulation Accuracy**: It was assumed that the finite element analysis (FEA) simulations conducted in the ANSYS workbench would accurately reflect the performance of the damper under real-world conditions, minimizing the need for additional physical prototypes.
- **Environmental Control**: The assumption was made that external factors like temperature and humidity would be controlled or have a negligible impact on the damper's performance during testing.

3.3. Problem Formulation

The problem formulation defines the objectives, constraints, and approach to developing and testing the kangaroo leg-inspired damper for heavy machinery:

Objectives:

- **Improve Vibration Damping**: Design a damper that provides enhanced vibration absorption, reducing machinery wear and tear.
- **Increase Durability**: Develop a design that maximizes the life cycle of the damper while

minimizing maintenance costs.

- **Optimize Cost and Weight Ratio**: Ensure that the damper provides high efficiency at a reasonable manufacturing cost and weight.

Constraints:

- **Material Availability**: The selection of suitable materials such as TPU, TPC, and PP may be limited by availability and cost.
- **Complexity of Design**: The intricate structure of the kangaroo leg-inspired design may introduce manufacturing challenges and increase production costs.
- **Simulation Limitations**: While simulations provide a reliable first step, real-world testing may reveal discrepancies due to unaccounted-for environmental factors.

IV. THE METHODOLOGY

To investigate the kangaroo legs as a potential solution to damp heavy load machinery vibration, a methodical approach has been carried out, which is mentioned in the step below:-

Bioinspired design

In the first phase, a kangaroo leg design was identified using the literature, in that case, the design was used in an airless tyre structure for smooth movement of wheeled vehicles and also for vibration reduction. Figure number 1 shows the nomenclature of the kangaroo leg that was used in this study. The ratio shown in the figure, between different parts of the legs, is taken into consideration while preparing the design for the damper which can take the vibration of heavy machinery with optimum cost to weigh to ratio.

$$I_{AB} : I_{BC} : I_{CD} : I_{CE} = 1 : 2 : 1.3 : 0.76. \quad (2)$$

The spatial rotation angles of AB, BC, CD, and CE and the lengths of AB, BC, CD, and CE in the bionic flexible spoke support can be determined by the triangular cosine theorem as:

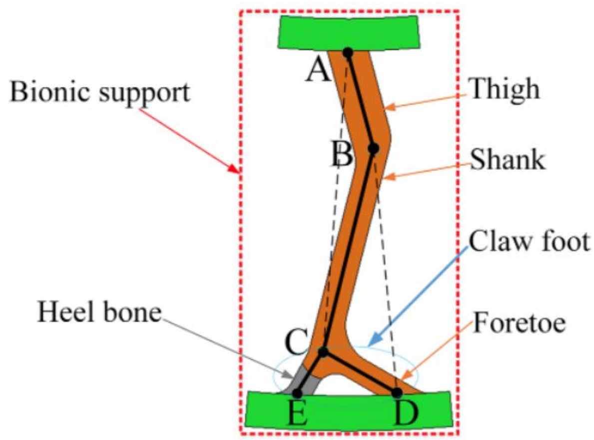

Figure 1: kangaroo leg nomenclature [13]

3D design of Kangaroo leg damper

Based on bio-inspired kangaroo leg a damper design was prepared with a different orientation. The main basic objective of arranging the legs in different orientations was to enhance the weight-loading capability of the damper as well as the life cycle. Sometimes the weight-to-cost ratio was first proprietary compared to the traditional damper. Figure 2 shows the different orientations of the kangaroo legs damper, which are further analyzed using the simulation technique.

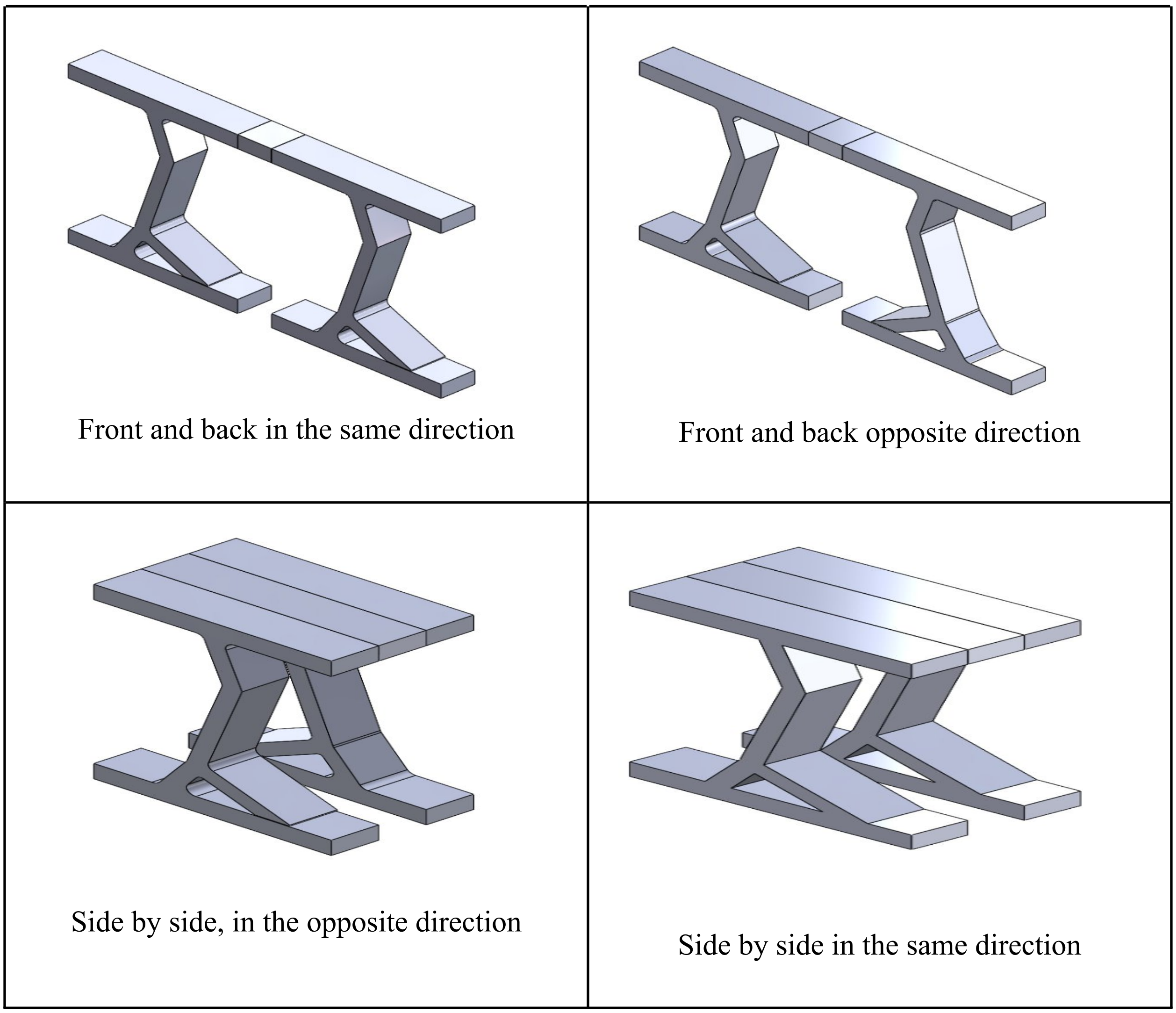

Figure 2: Different orientation of kangaroo leg damper.

Structural testing matrix

Once all orientations of the kangaroo-inspired damper are designed. In the next step, a simulation testing matrix has been prepared. Table 1 shows the testing matrix used while performing the FEA simulation. The matrix was prepared based on the material that can be considered for manufacturing the damper, the orientation of the legs design, and the corresponding analysis need to determine the damper's efficiency.

Table 1: FEA simulation testing matrix

Types of material	**Orientation of Kangaroo leg**	**Types of analysis**
TPU (Thermoplastic polyurethane)	FAB (Front and back) SBS (Side by side) FAB OPP(Front and back opposite direction) SBS OPP (Side by side opposite direction)	Static analysis Random vibration analysis
TPC (Tournament Players Championship)	FAB (Front and back) SBS (Side by side) FAB OPP(Front and back opposite direction) SBS OPP (Side by side opposite direction)	Static analysis Random vibration analysis
PP (Polypropylene)	FAB (Front and back) SBS (Side by side) FAB OPP(Front and back opposite direction) SBS OPP (Side by side opposite direction)	Static analysis Random vibration analysis

Structural analysis

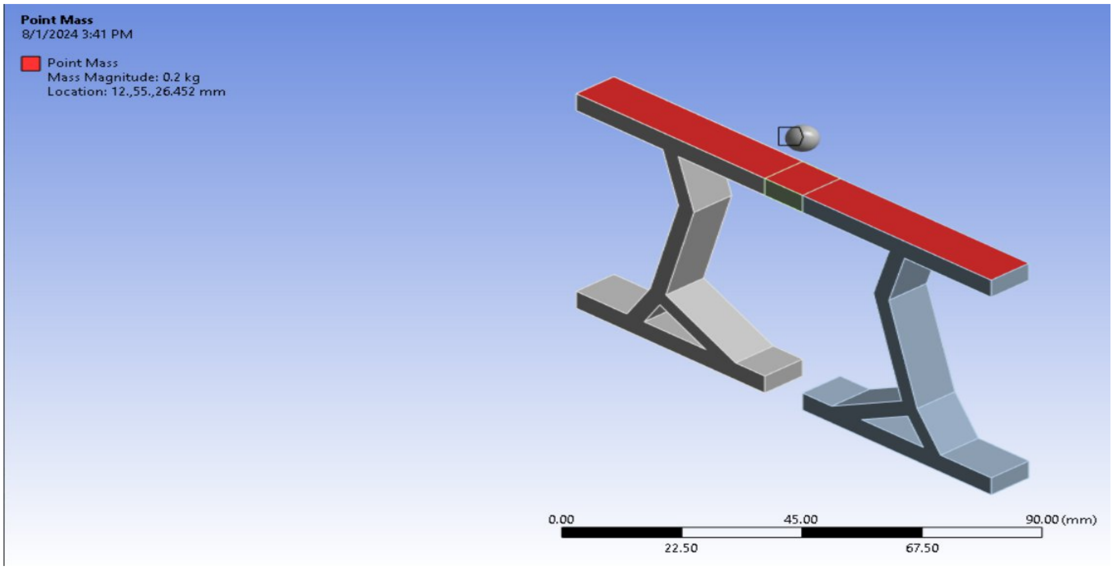

Figure 3: testing setup in ANSYS structural module

Based on the testing matrix prepared in the last section, the design was exported to the FEA structural model of the ANSYS workbench. Figure 3 shows the testing condition used while performing the simulation in the ANSYS workbench. To start with the simulation at first meshing was done, While performing meshing the mesh sensitivity analysis was done to find the optimum mesh element hence to save the simulation time, also not compromise the accuracy of results. A total of two types of simulation were carried out, The first was to test the deformation of the damper when dynamic loading was applied to the damper and the second was to test the vibrational frequency of the damper when the same type of loading was applied.

Testing:-

All the orientations of the damper were initially analyzed using the ANSYS, by changing the material. The orientation that was performed best in terms of low deformation and the oscillation frequency was further developed using the 3d printed techniques to do the experimental testing. Figure 4 shows the experimental setup of the kangaroo leg damper built using the 3D printed technique. The material used to build the damper was TPU because it performs better in the case of the simulation performed. The over-setup with one complete damper can be directly placed at one end of the machinery to dampen the vibration. Furthermore, the system was connected to the sensor to measure the vibration in terms of the acceleration frequency concerning time. The data is further analyzed and compared with the standard damper that is currently in use in the industry. The next section shows the results which are observed from the simulation and the experimental test.

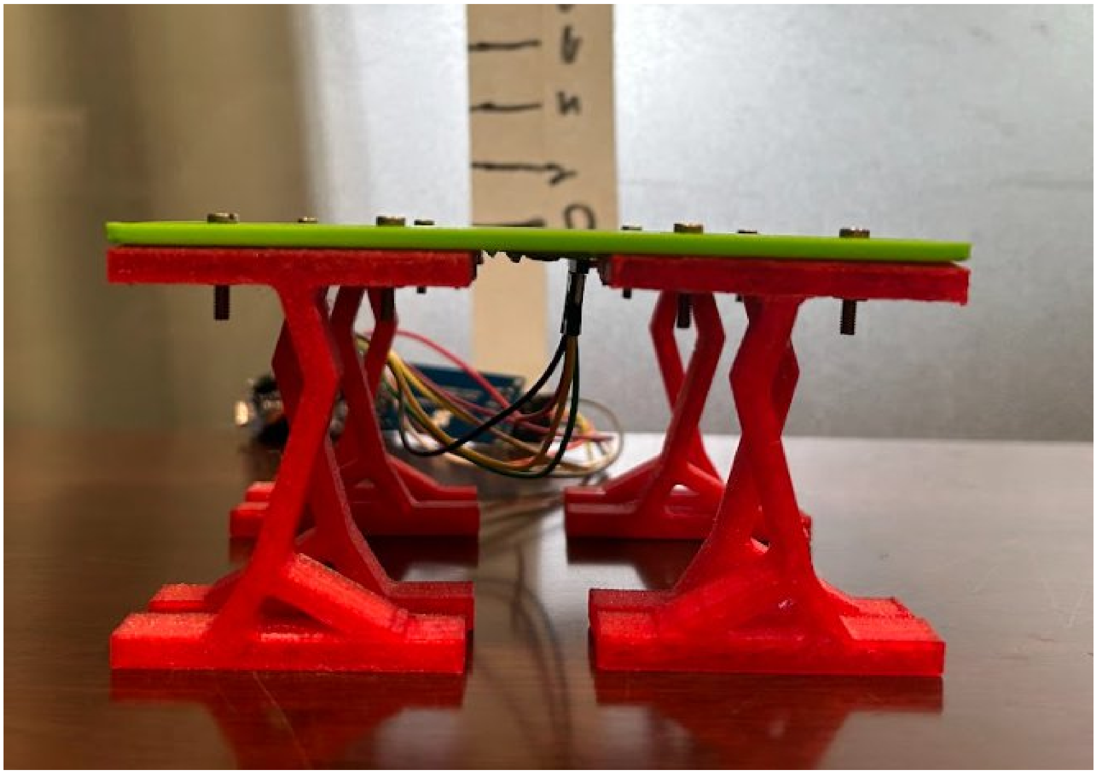

Figure 4: Experimental setup of kangaroo damper

Observation

To evaluate the damper efficiency created by the bio-inspired kangaroo legs, initially, the simulation test was performed. This test was performed to check the optimum material that can be used to create the damper and also the orientation with which the damper can be placed directly to make one complete damper that can be placed at the bottom of the machinery. Figure 5 shows one of the sample simulations performed on the ANSYS structural module to check the deformation of the damper when dynamic loading is applied to it. It is also evident from the image (figure 5) that the damper deforms max at the top corner whereas it shows very low deformation at the center and the fixed end of the damper. This represents that dampers have a very low chance of damage in the case of buckling.

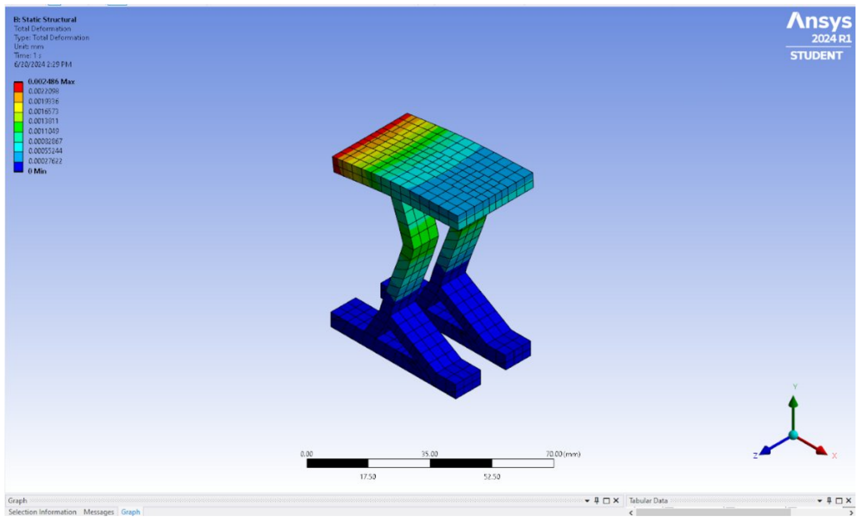

Figure 5: Deformation of the damper in ANSYS structural simulation

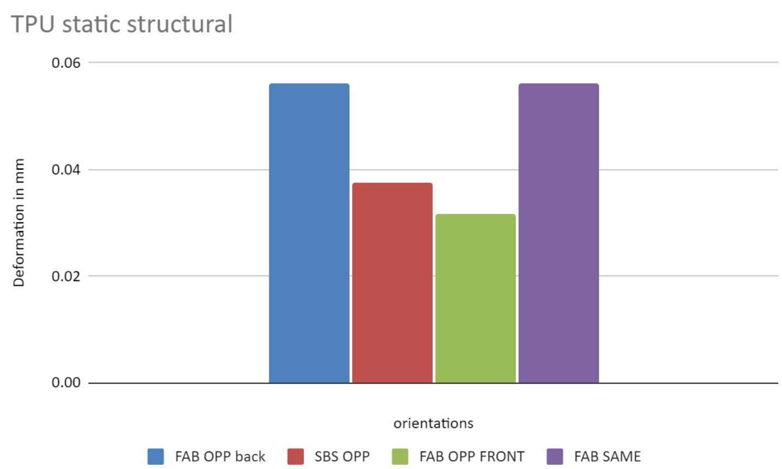

Figure 6: Deformation of various damper orientations using TPU material

While analyzing the various damper orientations in terms of deformation using TPU as material complete data was gathered using the ANSYS simulation. Figure 6 shows the relative deformation of all the orientations using the TPU material. From Figure 6 it is evident that the FAB OPP (Front and Back, Opposite mounting) orientation of the damper shows the lowest deformation among others. Whereas analyzing the random vibration that is shown in Figure 7, SBS OPP has the lowest random vibration and the second lowest orientation is FAB OPP. therefore the final experimental testing was conducted using the FAB OPP orientation.

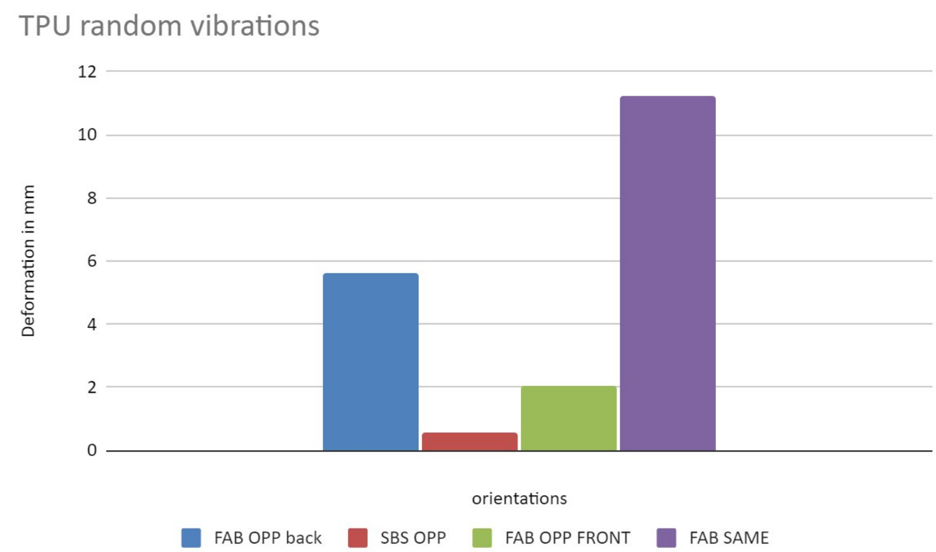

Figure 7: Random vibration of various damper orientations using TPU material

V.RESULTS

Based on the simulation result a small prototype damper was manufactured using the 3D printed technique and tested for vibration damping efficiency, this result was compared with the cylindrical damper which is traditionally used. Figure 8 shows the experimental results of a kangaroo leg vibration absorption graph concerning time. The pick of the graph represents the point at which the load falls onto the damper and the damper reacts by deforming itself. this deformation is collected in the form of the acceleration VS time. The graph shown in Figure 8 represents that the kangaroo leg damper absorbs the vibration in a faster time compared to the regular cylindrical damper

A regular cylindrical damper is represented in Figure 9.

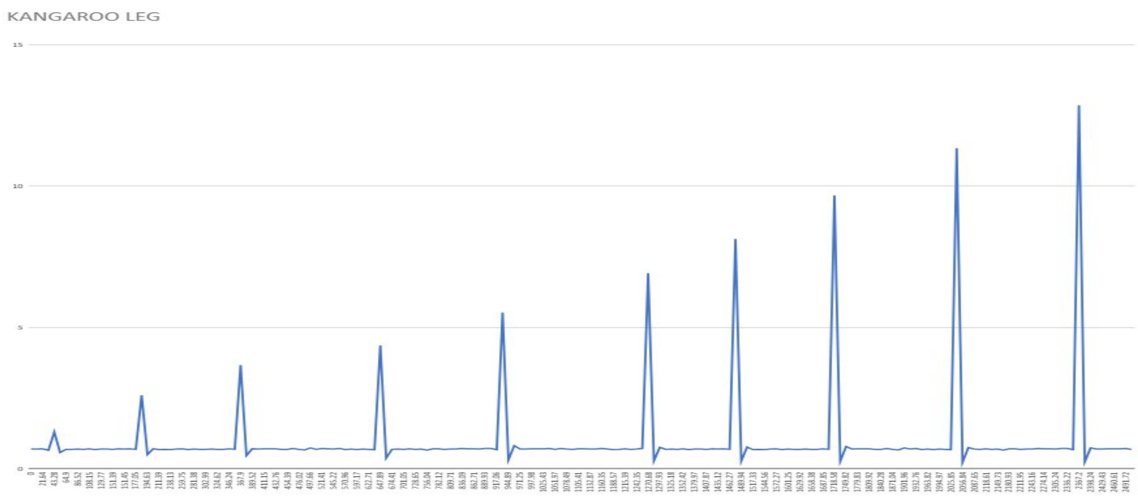

Figure 8: Experimental test result of kangaroo legs damper

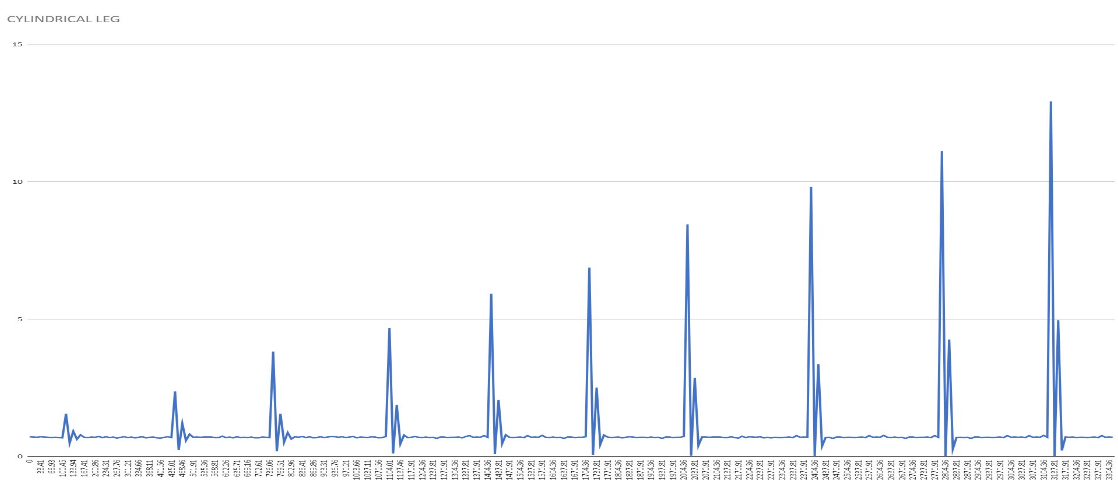

Figure 9: Experimental result of cylindrical damper

VI. CONCLUSION

To reduce vibrations in heavy machinery, this research examines a bioinspired design based on the structure of kangaroo legs. The study started with an in-depth, highlighting the need for more effective and efficient dampening systems in industrial settings and the possibility of using structures inspired by kangaroos as an innovative alternative. A thorough process was used to create, simulate, and test several orientations of dampers inspired by kangaroo legs using finite element analysis (FEA).

Based on the simulation phase results, the thermoplastic polyurethane (TPU) construction of the front-and-back opposite orientation (FAB OPP) kangaroo leg damper resulted in the least amount of deformation under dynamic loading and the least amount of random vibrations. Experimental testing confirmed these results, showing that the FAB OPP orientation outperformed conventional cylindrical dampers in terms of vibration absorption efficiency.

The experimental findings verified that, in comparison to the traditional damper, the kangaroo leg-inspired damper absorbed vibrations more quickly and efficiently, lowering the acceleration amplitude and stabilizing the system more quickly. This implies that by reducing the negative impacts of vibrations, the bioinspired damper could greatly increase the lifespan and dependability of heavy machinery.

In summary, the kangaroo leg-inspired damper presents a viable substitute for conventional damping systems, blending excellent vibration absorption efficiency and low deformation with a workable cost-to-weight ratio. Subsequent investigations may concentrate on enhancing the damper's performance in diverse industrial applications by improving the design and optimizing the material selection. Using the design principles found in nature, this bioinspired method opens up new possibilities for creative engineering solutions to address challenging mechanical problems.

A. Implications to the wider world

The bioinspired kangaroo leg damper presents significant advancements for industries reliant on heavy machinery. By reducing vibrations more efficiently than conventional dampers, this innovation has the potential to extend machinery lifespan and lower maintenance costs. The application of nature-derived designs could revolutionize not only mechanical engineering but also fields such as automotive, aerospace, and construction, where vibration control is critical. Moreover, this study highlights the broader importance of biomimicry in solving real-world engineering challenges, emphasizing sustainable and cost-effective solutions that could be adopted globally to improve industrial efficiency and resilience.

Acknowledgment:

I sincerely thank all of the instructors and mentors at On My Own Technology Pvt. Ltd. for assisting with this specific project. They have made it possible for me to carry out the research. I will always be appreciative of their assistance and kindness.

Ethical standards:

In the development and testing of the bio-inspired kangaroo leg damper for heavy machinery, ethical considerations play a crucial role in ensuring the integrity, safety, and environmental sustainability of the project.

The following ethical standards were adhered to throughout the design, simulation, and testing phases:

- ***Sustainability:*** *The materials selected for the damper (TPU, TPC, PP) were chosen based on their environmental impact, favoring recyclability and reduced carbon footprint.*
- ***Accuracy in Simulation:*** *All simulations were conducted with rigorously calibrated models to ensure reliable, honest reporting of results, avoiding misrepresentation or bias in data.*
- ***Fair Use of Resources:*** *The study utilized minimal resources and adhered to cost-effective practices, avoiding excessive material waste and ensuring efficient use of computational and physical resources.*
- ***Health and Safety:*** *Testing was conducted in controlled environments, adhering to strict safety protocols to prevent accidents or hazards related to heavy machinery vibrations.*
- ***Transparency and Accountability:*** *All design, testing, and results were documented transparently, with full disclosure of the methodology and assumptions, allowing for peer review and reproducibility of results.*

References

1. Wright, Jeremy. "What Causes Machinery Vibration?" *Machinery Lubrication*, 6 Aug. 2010, www.machinerylubrication.com/Read/25974/signs-tips-machinery-vibration.
2. https://rms-reliability.com/vibration/treatment-for-machine-vibration/

3. Munsell, Faith. “5 Strategies for Effective Vibration Control in Industrial Machinery - Mark Tool.” *Mark Tool*, 13 June 2024, www.marktool.com/5-strategies-for-effective-vibration-control-in-industrial-machinery/#:~:text=Precise%20alignment%20of%20machinery%20components,energy%20loss%2C%20and%20unexpected%20downtime.
4. Dm_Adm, and Dm_Adm. “Benefits of Using Anti-Vibration Pads for Machine.” *Dynemech*, 7 Sept. 2023, www.vibrationmountsindia.com/benefits-of-anti-vibration-pads-for-machinery/#:~:text=They%20protect%20equipment%20from%20damage,equipment%20replacement%20and%20repair%20costs.
5. Hu, Yujun, et al. "Analysis and Design of Nonlinear Tuned Mass Damper Based on Complex Variable Averaging Method." *Applied Sciences* 13.10 (2023): 6287.
6. Fu, Jia, et al. "Design and experimental study on vibration reduction of an UAV lidar using rubber material." Actuators. Vol. 11. No. 12. MDPI, 2022.
7. Berbyuk, Viktor. "Design optimization of torsional vibration absorbers for heavy-duty truck drivetrain systems." Vibration 2.3 (2019): 240-264.
8. Wang, Qi, et al. "Small-Scale Soft Robot with High Speed and Load Capacity Inspired by Kangaroo Hopping." Advanced Intelligent Systems 4.1 (2022): 2100129.
9. Wang, Tian, et al. "A novel dynamic absorber with variable frequency and damping." Shock and Vibration 2021.1 (2021): 8833089
10. Zhang, Y. H., et al. "Mechanism design and optimization of a bionic kangaroo jumping robot." IOP Conference Series: Materials Science and Engineering. Vol. 324. No. 1. IOP Publishing, 2018.

11. Trautwein, John. "Pressurized Metal Bellows Shock Absorber for Space Applications." (2015).

12. Li, Zhongjie, et al. "Energy-harvesting shock absorber with a mechanical motion rectifier." Smart materials and structures 22.2 (2012): 025008.

13. Zhang, Zifeng, et al. "Pattern design and performance analysis of a flexible spoke bionic non-pneumatic tire." Journal of the Brazilian Society of Mechanical Sciences and Engineering 43 (2021): 1-11.