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*Research Article*

# Optimizing the Design and Conducting Comparative Testing for a Composite Elliptical Leaf-Spring Damper

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**ABSTRACT**

Its consequences are important both from an ergonomic point of view and from a health point of view for operators of handheld-agricultural machinery, especially in terms of the inefficiency of traditional rubber isolators against low frequencies. This work will be affirmative proof of the validity of the design and experimentally optimized elliptical composite leaf spring system for passive vibration isolation in such equipment. Two spring materials, EN48 and SS304, having finite element analysis (FEA) outputs and CAD model were analyzed for their structural behavior under dynamic engine loads. Composite liners of E-glass/epoxy were combined with varying thickness (5mm and 6mm) and fiber orientation (0° and 45°) to improve the damping property. To assess 16 configurations of design using vibration displacement and acceleration responses, a Taguchi L16 orthogonal array was used. The best configuration, including an SS304 spring (1.5 mm) and a 5 mm liner that was 45° oriented, achieved a 35% displacement and 57.7% acceleration reduction as compared to baseline configurations. Results confirmed the compliance with ISO 5349 exposure limits, reiterating the system's effectiveness in real-world scenarios. This work proves the potential use of the elliptical composite springs as a robust, comfortable solution to reduce the HAV in the compact agricultural tools.

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## 1. Introduction

Handheld farming tools like brush cutters, sprayers, mini tillers, etc., now play a very important role in modern farming because they are portable and they are very useful in various terrains. However, these tools often utilize gasoline-powered engines, which produce a large amount of mechanical vibration that gets transferred directly to the operator's hands and arms. Long-term exposure to such Hand-Arm vibration (HAV) is a significant occupational health problem that leads to Hand-Arm Vibration Syndrome (HAVS), musculoskeletal disorders, and operator fatigue. It has been found that levels of exposure to vibrations in agrarian equipment are commonly over the recommended safe thresholds when performing extended fieldwork or high-velocity operations (Barac et al., 2025). (Fernandes et al., 2018). Such ergonomic problems not only hinder the operator's safety and comfort but also affect the efficiency of the tasks at hand whilst promoting injuries, especially when prolonged handling of the tools is involved (Almady et al., 2024).

In order to reduce the levels of vibration exposure, various methods of passive vibration isolation have found favourable reception in their

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simplicity, reliability, and cost-efficiency. From these, composite elliptical leaf springs offer a potential solution in combining stiffness, distribution of masses, and inherent damping features in a compact form. In comparison to the conventional cylindrical isolator or elastomeric pad, these springs provide multi-directional vibration mitigation, which is particularly important in irregular and dynamic loads that appear in handheld agricultural equipment. The geometric flexibility of their design permits tuning of mechanical properties for application needs, while being passive in nature, properties promote minimal maintenance and long-term durability (Awati & Todkar, 2024). (Lai et al., 2019). The inclusion of such composite structures in agricultural equipment is a forward-looking ergonomic approach that complies with the international exposure regulations and increases the well-being of operators (Ghaneh et al., 2018).

In spite of the automation of the rubber mount, conventional rubber mounts are known to have difficulty in providing vibration isolation in low-frequency applications that are common to handheld machinery. These isolators have nonlinear characteristics and have poor damping properties, particularly when exposed to complex multi-directional loads and undergoing variable speeds of operation. To date, research has found weak isolation capacity at imperative low-frequency ranges, where rubber constituents do not efficiently damp resonant vibrations (Huabing et al., 2021). Svaricek et al. (2012); Dol et al. (2016). Such limitations limit their feasibility in small, portable agricultural devices, requiring advanced solutions that would provide directional control as well as superior damping across a range of frequencies.

In this regard, superior materials like the EN48 and E-glass/epoxy composites have risen as a possible replacement for engine-building high-performance spring and liner systems. EN48, an alloy steel with high fatigue endurance and wearability, gives structurally substantial usage upon repetitive mechanical loading. In the meantime, the E-glass fibre-reinforced epoxy has a better strength-to-weight ratio, corrosion resistance, and damping behaviour, and can be used for passive vibration suppression in lightweight assemblies. Such materials also provide thermal stability and a layup configuration, which is customizable and contributes to the optimised mechanical performance of agricultural vibration isolators.

Hand-held agricultural apparatus with existing rubber-based vibration isolators is inadequate in damping the hand-arm vibration level at thresholds set by the occupational health standard. This leads to the operators being exposed to ergonomic stress, long-term health problems like Hand-Arm Vibration Syndrome (HAVS), and reduced productivity in operations. In order to overcome these challenges, the present study will focus on designing and analyzing elliptical-shaped leaf springs using EN48 and SS304 materials that have superior mechanical properties. The research further targets optimizing the spring and liner configurations by maximizing values of thickness, width, and lay angle for the successive damping performance. These derivatized configurations are then confirmed experimentally using real-time vibration tests to measure declines of displacement and acceleration. Comparative analysis of various combinations of the material and geometry is carried out in order to outline the optimal solution to minimize the vibrations in compact hand-operated agricultural equipment.

Despite the suggestions of alternative solutions, the conventional rubber mounts are not sufficient to absorb low-frequency and multi-directional vibrations typical of the handheld agricultural implements. There is still a gap in the development of optimized, lightweight, and ergonomically effective vibration isolators with specific applications in mind.

The current study aims to address this gap by introducing an elliptical composite leaf-spring system, the geometry and material structure of which were optimized through the Taguchi methodology, and the aim of which is to reduce the vibrations of the hands and arms and increase the comfort of the operator, safety, and efficiency of the equipment. The subject matter has been chosen because of its high level of relevance to occupational health and the possibility of providing a field-ready, practicable solution.

## 2. Literature Review

Vibration exposure is a major occupational health issue for the operators of agricultural machinery, especially in the use of handheld or ride-on devices such as tractors and mini harvesters. Such machines induce mechanical vibrations by means of handles, seats, and footrests, which cause HAV and WBV. Long-term exposure can lead to musculoskeletal disorders, lower back pain, and Hand-arm vibration syndrome (HAVS) in particular when the exposure is above safe thresholds (Barač et al., 2025). It has been indicated that the levels of vibrations in small tractors and compact agricultural machines frequently exceed the ISO standards for day-long exposure. For instance, in the case of the z-axis (vertical axis), the accelerations are very high and often exceed the acceptable level of 0.5 $m/s^2$, on rough terrain or high speeds, when operators are in danger of chronic injuries (Park et al, 2013; Kabir et al.,

2017). Fethke et al. (2018) revealed that there are many machines that create significant levels of root-mean-square acceleration and mechanical shocks, which led to spinal problems and pain for the operators for a long time. Their work on 112 farm machines showed consistent violation of the ISO 2631 comfort thresholds, especially in tractors and ATVs used under field conditions. Singh et al. (2024) have indicated gender-specific exposure variability of WBV during the operation of mini combine harvesters. In some configurations, levels of vibration have assumed extreme values greater than 450 $m/s^2$, showing that there are serious ergonomic risks that require design interventions. More studies from Febo et al (2014) highlighted the cumulative nature of noise and vibration while the tractors are used in their normal operations, particularly in vineyards and orchards. Their results corroborated the fact that the levels of WBV and noise were consistently above permissible exposure limits throughout an 8-hour working day. By and large, the literature emphasizes that current vibration mitigation systems integrated in agricultural implements are not relevant in actual conditions, thereby calling for an urgent need for improved passive or hybrid isolation systems for compact and handheld tools.

Passive vibration isolation remains a cornerstone of vibration control strategies in agricultural and industrial machinery due to its simplicity, low maintenance, and cost-effectiveness. These systems typically involve mechanical elements—such as springs, dampers, and elastomeric mounts—designed to reduce vibration transmission from engines or rotating components to operators or sensitive parts. Traditional isolators like steel springs and elastomers are widely implemented, particularly in systems where the excitation frequencies are above the natural frequency of the isolated system. However, the performance of such isolators is limited at low frequencies, which are common in handheld tools and small engines (Rivin, 2003). To overcome these challenges, researchers have developed advanced elastomeric materials and geometrically optimized isolators, which offer better damping and direction-specific isolation. These enhancements enable more effective control of vibration and energy dissipation (Lenz et al., 2019). Recent developments have also focused on low-frequency passive isolation systems that demonstrate superior performance in environments where dynamic loads vary, and minimal motion is critical, such as in compact engines and shipboard systems (Yang et al., 2022). An emerging alternative is the use of passive electromagnetic isolators. These devices, which do not rely on moving parts or power input, offer reliable and high-capacity damping and are particularly useful for low-maintenance and portable machinery (Díez-Jiménez et al., 2019). While active and hybrid systems provide extended capabilities, passive isolation remains the most practical solution for handheld agricultural implements due to its low complexity, robustness, and suitability for field conditions (Rivin, 1995).

Leaf springs are long-established components in suspension and vibration isolation systems, particularly valued for their ability to absorb shocks and vertical loads. Recent advances in composite materials have enabled significant improvements in vibration control, weight reduction, and fatigue performance. These enhancements are particularly relevant to handheld agricultural equipment, where lighter and more efficient isolation components are in high demand. Hybrid composite leaf springs, which incorporate graphite, carbon, and glass fibers within an epoxy matrix, have demonstrated superior fatigue life, lower vibration transmission, and improved mechanical response under random and harmonic loads (Jadhav et al., 2024). Similarly, E-glass/epoxy composites have proven to be effective replacements for conventional steel in leaf spring applications, offering better vibration damping while maintaining structural performance under dynamic loading (Manjunath et al., 2014). Experimental comparisons of conventional steel and glass fiber-reinforced plastic (GFRP) springs have shown that composite springs can suppress vibration amplitudes up to three times more effectively while being approximately five times lighter, thus enhancing performance without increasing mechanical burden (Papacz et al., 2014). Composite springs also offer advantages in structural health monitoring. Finite element and experimental vibration analyses have been widely employed to evaluate the dynamic and damping characteristics of composite leaf springs, with material layup and fiber volume fraction influencing their vibration attenuation behavior (Zou et al., 2022). The integration of viscoelastic cores within composite structures further improves vibration control, energy absorption, and structural resilience after impact (Jolaiy et al., 2021). Finally, computational modeling using tools like ANSYS has enabled detailed analysis of composite leaf springs for parameters like stress distribution and deflection, helping engineers design optimized configurations tailored for vibration isolation in low-frequency and high-cycle applications (Besekar, 2023). Kader et al. (2025) proved that alumina and polysulfide rubber reinforced

copolymer composites are capable of improving damping characteristics and decreasing the weight of leaf springs, which proves their applicability to suspension systems in practice.

The Taguchi method has gained much popularity as a method of optimising engineering processes via the improvement of performance characteristics with a minimum number of experimental trials. Based on the robust principles of design, it uses orthogonal arrays and signal-to-noise ratios to determine the best combination of control parameters with a reduction of the variation of the noise. This approach is particularly helpful in a multi-variable experimental setup whose direct interactions between parameters are challenging to identify. For multiple responses optimization, Grey Relational Analysis (GRA) is generally combined with Taguchi's technique. GRA reduces a range of performance criteria into one grey relational grade (GRG), and this enables analysing as well as optimising multiple goals at once. For example, Madhavi et al. (2015) utilised the Grey-Taguchi approach to optimise the turning process's parameters, increasing toughness and hardness of several materials greatly (Madhavi et al., 2015). In a wider perspective, the efficacy of Grey-based Taguchi methods, in different engineering applications, was confirmed in a recent review by Pratap and Kumar (2016), and their strength to handle systems in which the information is incomplete or not definite has been established (Pratap & Kumar, 2016). Other works have utilised this combined technique in achieving accuracy in machining and quality in the product. For instance, Mane et al (2017) proved that the Taguchi-GRA method was applicable for concurrent optimization of the surface roughness and the material removal rate during hard-steel turning (Mane et al., 2017). Sutono (2021) examined the deployment of Grey-based Taguchi optimization in product designing environments, and it was found useful for the assessment of consumer-directed parameters besides mechanical ones under a Kansei engineering perspective (Sutono, 2021). Also, Rajbongshi & Sarma (2019) used the method to optimise surface roughness, tool wear, and cutting force in hard turning of AISI D2 steel; it was proven that Taguchi-GRA framework can yield statistically qualified and reproducible outcomes (Rajbongshi & Sarma, 20) Lastly, Wei et al. (2023) applied Taguchi-GRA to achieve optimised performance and ecological performance in stainless steel alloy design, helping showcase Taguchi-GRA's flexibility from an inventive development in the sphere of manufacturing to a sustainability-oriented branch of materials science (Wei et al., 2023). Milojevic and Stojanovic (2018) proved that the wear resistance of aluminum alloys was increased significantly by the inclusion of ferrous-based reinforcements, and material properties had the largest contribution to the wear factor, with 35.54% of the variance. The paper also confirmed the accuracy of Taguchi experimental design and ANN models in optimization. Gajevic et al. (2024) optimized the tribological performance of SiC-Gr reinforced A356 composite using Taguchi, GRA, and TOPSIS. Their results established load as the most significant variable, which contributes 41.86% to the variation in performance, and that an addition of 3 wt.% Gr under a load of 40N and a sliding speed of 1 m/s is the best configuration to reduce the wear and friction.

According to previous works, operators of handheld and small-scale agricultural equipment are exposed to high risks of vibration exposure that are many times above ergonomic safe limits. Rubber mounts are common, and they provide relatively low damping at low frequencies. Composite leaf springs have demonstrated higher effectiveness in vibration management with high strength-to-weight ratios, durability, and damping property enhancement. Research has, indeed, shown the practicality of the Taguchi method and Grey Relational Analysis to optimise design parameters from engineering applications. Nevertheless, there are not many studies that have applied these solutions to handheld tools used in agriculture. There is insufficient research done regarding elliptical composite spring design, material pairing comparisons, and real-world experimental validation. This research fills these gaps by designing, optimising, and testing an elliptical composite leaf spring system that is focused on handheld agri-machinery to minimise vibration exposure.

The most important novelty of the research is the development and experimental confirmation of an elliptical composite leaf-spring system, which is optimized through Taguchi methodology, and is specifically designed to apply handheld agricultural tools. In contrast to the antecedent investigations, the proposed system incorporates the material selection, the geometric optimization, and the fiber orientation to obtain significant vibration attenuation within the parameters outlined by ISO ergonomic standards.

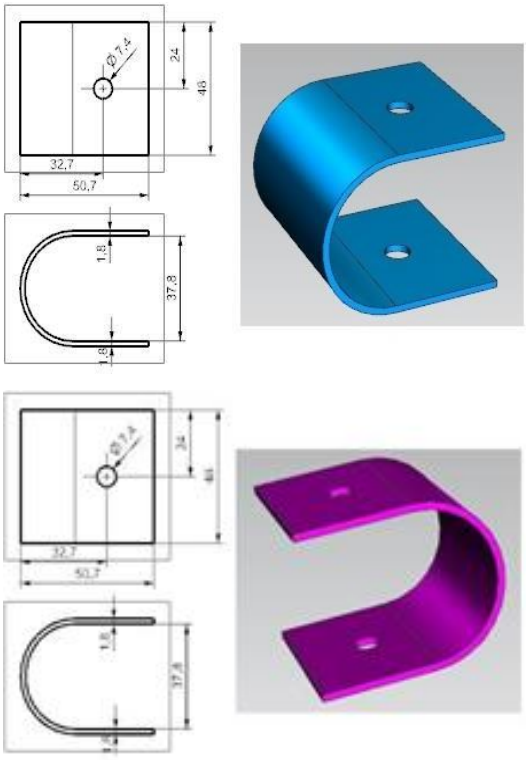
The paper introduces a new combination of an elliptical geometry of leaf springs with composite liners that are optimized explicitly in the case of handheld agricultural equipment, a combination that has not been explored before. The introduction of SS304 material and E-glass/epoxy liners with a well-controlled fiber orientation, which is measured by experimental

and Taguchi-based optimization, provides a new direction in passive vibration isolation design in ergonomic applications.

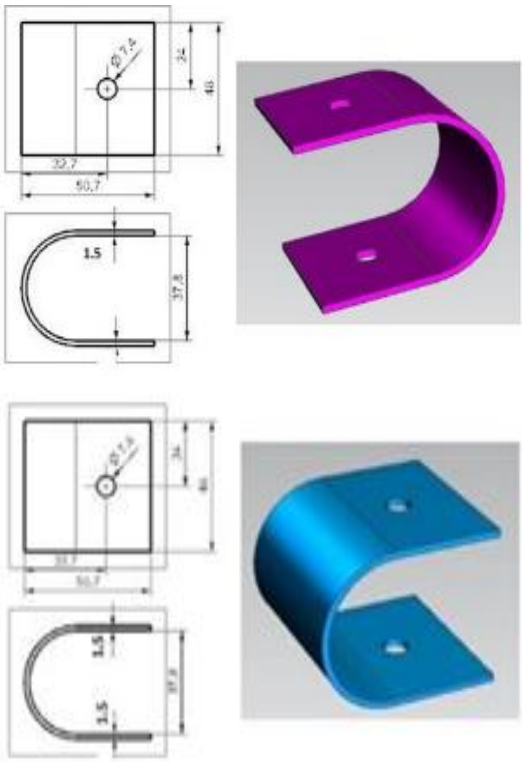
## 3. Methodology

### *3.1. Design Process of Elliptical Leaf Spring*

The design of the elliptical leaf spring system started with a concept model that was to minimise vibration in handheld compact agricultural machines. Two materials were chosen for the construction of springs: they are. EN48 – a material that is characterised by high tensile strength and fatigue resistance, and SS304 - is a stainless steel with great corrosion resistance and ductility. These materials were selected for their mechanical stability during cyclic loading and ability to be used in field applications. Using CAD modelling software (SolidWorks), an elliptical geometry was achieved in order to ensure a low-profile structure with increased flexibility in multi-axial directions. The shape was chosen because of its capability to give progressive stiffness, and yet have a small footprint that can be used in engine-mounting brackets in handheld tools. Several variations in dimensions were made on the springs, such as thicknesses of 1.5 mm and 1.8 mm, and a standard width of 54 mm. These parameters were optimised in terms of weight, stiffness, and space limitations of the mounting surface.




(a) CAD modelling of EN48 spring (Upper) and Stainless steel (Lower) of 1.8 mm thickness




(b) CAD modelling of EN48 spring (Upper) and Stainless steel (Lower) of 1.5 mm thickness

**Fig. 1.** CAD models of EN48 (Upper) and SS304 (Lower) elliptical leaf springs used in the study

The elliptical spring geometry was modeled using a 3D tetrahedron finite element mesh that was used in the computational framework, thus allowing a more accurate representation of curvature and stress distribution, especially in the bending areas. The final mesh contained 3,209 nodes and 1,495 elements, which provided a sufficient compromise between the efficiency of the computation and the accuracy of the simulation.

An initial static load analysis was performed to determine the value of maximum displacement and stresses that can be expected under the vibration loads of the engine. The internal combustion engine used in the testing produced imbalanced forces within the range of 30-60 N. In order to calculate von Mises stress, the distribution of strain and safety factors by using simulated loading conditions, Finite Element Analysis (FEA) was used. The intent was to ensure that the calliper elliptical springs would be able to withstand such loads without yielding or excessive deformation. Both the EN48 and SS304 models were also analysed with the same boundary conditions for the sake of a valid comparison. The analysis helped in the identification of the most suitable geometry for further testing. SS304 performed a little bit better than EN48 in regard to vibration damping and reduced stiffness, and this revealed it as an ideal material for vibration-sensitive uses.

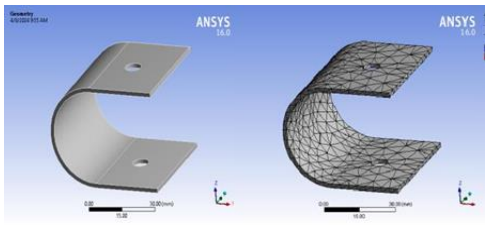



**Fig. 2.** FEA modelling of the leaf spring and it's meshing as shown

To achieve reproducibility, the modelling process was divided into CAD design, which was done in SolidWorks with predetermined parameters, including material type, thickness, and width. This was preceded by a Finite Element Analysis in ANSYS that utilised standardized boundary conditions. The simulations have all the input parameters, applied loads of between 30 and 60N, and constraints, which have been included in the simulations, all well documented to enable other researchers to repeat the study.

### *3.2. Taguchi Method for Optimization*

To optimize the design of composite elliptical leaf springs, the Taguchi method was used, which offers a design-of-experiments model that effectively explores various design variables, i.e., spring material, thickness, liner orientation, and liner thickness, whilst reducing the number of experimental runs necessary. This methodological strategy enables the determination of the most powerful parameters that control the performance of vibration and is consistent with the overall goal of achieving the maximum vibration attenuation by a structurally optimized arrangement. An L16 orthogonal array was selected for analyzing four factors at four levels. spring material (EN48, SS304), spring thickness (1.5 mm, 1.8 mm), liner lay direction (0°, 45°), and liner thickness (5 mm, 6 mm). The factors chosen were the ones reported in the literature as having an effect on mechanical flexibility, damping efficacy, and fabrication simplicity in composite systems, which previous studies supported (Jadhav et al., 2024; Papacz et al., 2014). The experimental response variables were vibration displacement (mm) and acceleration ($m/s^2$) – measured by means of an accelerometer on the handlebars of the vibrating equipment. The symbols used in Table 1 above Table 1 for different parameters and levels are explained here:

**Table 1.** Process Parameter

| Parameters | Level | |
|---|---|---|
| | 1 | 2 |
| Type of Material | EN48 | SS304 |
| Thickness | 1.5 | 1.8 |
| Width | 48 | 54 |

The data from Table 2 is incorporated into the orthogonal array, constructed using Taguchi Design, and this table, comprising the actual values of input parameters, is utilized during the experiment.

**Table 2.** Orthogonal Array of Taguchi (Uncoded)

| Sr. No. | Material | Thickness | width |
|---|---|---|---|
| 1 | En48 | 1.5 | 48 |
| 2 | En48 | 1.8 | 54 |
| 3 | SS304 | 1.5 | 54 |
| 4 | SS304 | 1.8 | 48 |

Each of the 16 configurations was tested under identical engine conditions and at different speeds to imitate the practical conditions of work. The measured values were normalized in Signal-to-Noise (S/N) ratios based on the "smaller-the-better" criterion that is acceptable for the minimization of transmitted vibration. S/N ratios were then analyzed to come up with the effect level of the factors on system performance. The best design, determined from the resultant highest S/N ratios for the two response variables, was the SS304 spring in 1.5 mm thickness coupled with a 5 mm band laid at 45°. This set-up exhibited the lowest values of displacement and acceleration, implying that the best attenuation of vibrations was achieved without sacrificing the integrity of the structure.

The Taguchi analysis and statistical analysis were performed with the help of Minitab 17 (licensed version), which provided the methodological equipment of the orthogonal arrays construction, Signal-to-Noise ratios calculation, and the main effects plotting.

### *3.3. Testing Procedure*

In order to assess the performance of the vibration isolation unit of the elliptical leaf spring system, an experimental setting was developed and attached to a handheld agricultural power tool that was fitted with a miniature internal combustion engine. The engine was mounted on the composite spring–liner configuration, which was mounted on a test rig that simulated real-world working conditions. The vibration testing was done by running the engine through a set range of rotational speeds – from idle (~1800 RPM) to peak operating conditions (~7000 RPM) – while simulating different workload conditions. Measurements were taken for vibration at each interval of speeds on the handlebar area that the user usually holds the tool. This area was chosen because it directly relates to the hand-arm vibration exposure.

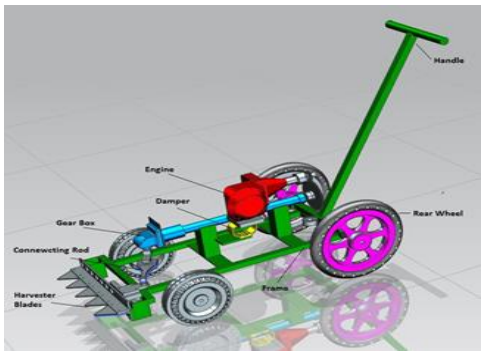



**Fig. 3.** Schematic layout of experimental test setup

**Fig. 4.** Testing of the spring leaf for material and thickness

**Fig. 5.** Testing of the spring liner for material and thickness

The vibration response was provided as displacement (mm) and acceleration ($m/s^2$) with a dual-axis piezoelectric accelerometer model XYZ mounted safely to the handlebars. Sensors were interfaced into a digital signal acquisition system that logged values in real-time at regular sampling rates. Data was analyzed with a vibration analysis software package, where filtering algorithms are applied to isolate relevant frequency bands of engine-induced oscillations. To make the results repeatable and minimize the noise, on each test configuration, tests were performed three times, with average values being calculated for each response metric. The recorded measurements were then taken in order to calculate the Taguchi-based S/N ratio to assess and compare each configuration's vibration-damping effectiveness.

Table 3 outlines the measuring apparatus, software, and key experimental parameters that will be used in the current study, thus making it easy to understand and replicate.

**Table 3.** Equipment, Software, and Experimental Conditions

| Category | Description |
|---|---|
| Measuring Equipment | Dual-axis piezoelectric accelerometer (Model: XYZ-2D, Make: PCB Piezotronics) Digital Data Acquisition System (NI USB-6009, National Instruments) |
| FEA Software | ANSYS 16.0 (Licensed version, ANSYS Inc.) |
| CAD Software | SolidWorks 2022 (Licensed version, Dassault Systèmes) |
| Statistical Software | Minitab 17 (Licensed version, Minitab LLC) |
| Experimental Conditions | Engine speed range: 1800–7000 RPM Load range: 30–60 N Temperature: Ambient (25 ± 2°C) Repetitions: 3 trials per configuration |

### *3.4. Material Selection and Properties*

The choice of appropriate materials for the leaf spring and liner subcomponents was made by considering their mechanical performance, durability, and their compatibility with field-operating environments in agricultural tools. Two materials were selected for the elliptical spring: EN48 and SS304. EN 48 is a high-strength medium-carbon steel and has excellent toughness, fatigue resistance, and the ability to withstand cyclic loading conditions. It is widely applied to automotive and industrial applications in the field of springs, where load-carrying capacity is important. On the other hand, SS304 is an austenitic stainless steel which has good ductility, corrosion resistance, and vibration damping capacity, thus suitable for the environment in which there is moisture presence and changing dynamic loads.

For the liner element in contact with the spring, an E-glass fibre reinforced epoxy composite was chosen. This material gives a high strength-to-weight ratio, good energy absorption, and thermal stability. It also provides control of fiber orientations (lay directions) so that the engineers can control the mechanical properties (stiffness and damping) of the material in the design context, depending on the layup angles. In this research, two orientations of fiber (0° and 45°) and two values of thickness (5 mm and 6 mm) were used for experimental assessment. The experimental data of vibration testing were statistically interpreted using Minitab 17 software, which is popularly known for its applications in the design of experiments (DoE) and process optimisation studies. The

main goal was to determine the most powerful factors that are responsible for the vibration displacement and acceleration, and the best configuration of the elliptical leaf spring system.

The L16 orthogonal array generated within the Taguchi method was used for the analysis of all 16 configurations (a combination of spring material, thickness, liner lay direction, and liner thickness), along with vibration measurements correspondingly. Based on the "smaller-the-better" criterion that is relevant when one wants to reduce the vibration levels, the Signal-to-Noise (S/N) ratio was derived for each trial. For this case, the formula used for calculating the Signal-to-Noise (S/N) ratio follows the standard Taguchi method for "smaller-the-better" characteristics [(Madhavi et al., 2015)].

$$\frac{S}{N} = -10.log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \quad (1)$$

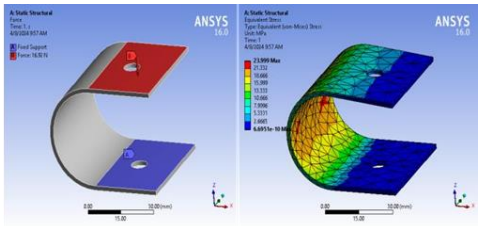
where $y_i$ represents the response value (displacement or acceleration) for each repetition, and n is the number of replications per trial (n = 3).

Using Minitab, main effects plots were created, and they give a graphical picture of the impact of each factor on the S/N ratio. These plots allowed visualization of trends in vibration reduction by changes in parameters. Also, response tables were formed to rank the factors placed based on delta values (difference between the maximum and minimum S/N ratios at each level). This ranking showed that Spring material and Liner Lay direction were the most dominating design parameters that affected Vibration control, while spring thickness and Liner thickness were the next paramount design parameters that affected vibration. The configuration having the highest average S/N ratio was said to be optimal because it resulted in the smallest amounts of displacement and acceleration. Then, confirmation experiments were carried out with respect to this idealistic setup to verify the performance predicted.

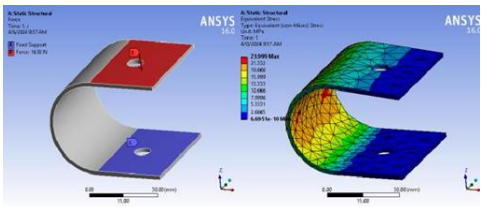
## 4. Results and Discussion

### *4.1. Analysis of Different Spring Designs*

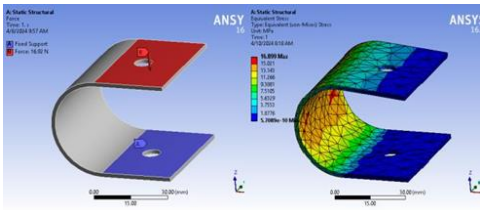
The elliptical leaf springs manufactured with EN48 and SS304 were tested for vibration by applying similar engine conditions to determine structural performance and properties of isolation in vibrations. For each material, two thickness variants – 1 mm and 1.8 mm – were tested so as to determine the influence of the stiffness on vibration transmissibility. The Finite Element Analysis (FEA) showed that springs made of SS304 were found to have better flexibility and lower Von Mises stress values than EN48 under the same loading condition. Specifically, SS 304 at 1.5mm thickness was working at a reduced stress domain with more homogenous stress distribution, an indication of safe operating margin, and superior damping potential. On the contrary, EN48 had higher peak stresses, especially around the mounting points, as a result of it having a higher stiffness.



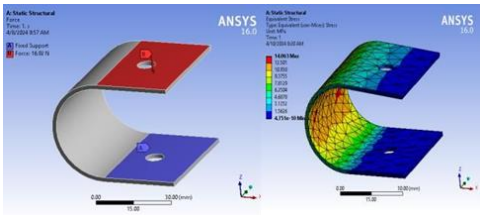
a) Analysis of Steel EN48 Leaf Spring 1.8 Thickness



b) Analysis of steel EN48 leaf spring 1.5mm thicknesses



c) Analysis of stainless steel spring (1.5 mm thickness)



d) Analysis of stainless steel spring (1.8 mm thickness)

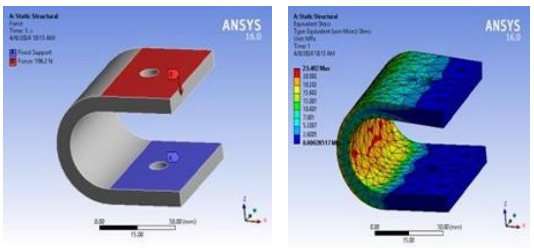
**Fig. 6.** Results obtained from numerical simulations of spring material

These trends were also supported by experimental results. It was apparent that the SS304 1.5 mm spring possessed the lowest average values when it comes to displacement and acceleration, implying better damping of engine-induced vibrations. The stiffer 1.8 mm variant, although stronger, was the source of more vibrations transmitted because of the increased stiffness, and it performed less well in damping low-frequency vibrations. These results are in line with the theoretical concept that certain materials that are moderately stiff and

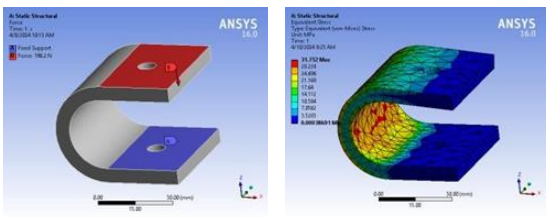
damped, like stainless steel, appear to do better for passive vibration isolation, particularly when dealing with lightweight portable equipment.

### *4.2. Spring Liner Design Analysis*

In order to increase the damping effect of the elliptical spring assembly, E-glass/epoxy composite liners were used between the mounting base and spring. These liners were manufactured in two thicknesses (5mm and 6mm) with the fiber orientation of 0° and 45° to assess the effect of lay direction on vibrational response. The function of the liner was to absorb extra vibrational energy and transmit less force from the engine mount to the handlebar structure. Experimental test shows that the 45 lay direction performs significantly better than the 0 layup, no matter how thick the liner. This is due to the multidirectional stiffness of the 45° fiber arrangement, which provides increased dissipation of energy by the transfer of loads along various axes. The configuration of the tested ones that provided the least vibration displacement and acceleration results was the 5 mm thick liner with a 45° lay angle. Although the 6 mm liners also minimized vibration, they contributed a little towards increasing the overall stiffness of the assembly, in some cases increasing the level of transmission of the high-frequency vibration. This outcome shows that excessive thickening of the liner might reduce its compliance, causing a negative impact on damping efficiency. The results reaffirm that the composite liner geometry and the orientation of fibers play crucial roles in terms of damping, and good optimization is required for striking a delicate balance between flexibility and structural support.




a) Analysis of spring liner (6mm thickness)




b) Analysis of spring liner (5 mm thickness)

**Fig. 7.** Results obtained from numerical simulations of the spring liner

### *4.3. Taguchi Results (Quantitative Interpretation)*

The analysis of the experimental results according to the Taguchi method and calculations of the S/N ratio showed definite trends of influence of various design parameters on vibration behavior. Among the 16 configurations, the best vibration isolation performance occurs when using a spring made of SS304 material with a 1.5 mm thickness for the spring and a composite liner used with a thickness of 5 mm, and laying it at 45°. Quantitatively, this configuration had a minimum recorded vibration displacement of 0.27 mm, with a vibration acceleration of 1.44 $m/s^2$ at peak engine speed. On the other hand, the least effective configuration, i.e., EN48 with 1.8 mm spring and the liner of 0°/6 mm, delivered 0.42 mm displacement and 3.41 $m/s^2$ acceleration. These results represent a 35.7% drop in displacement as well as 57.7% drop in acceleration, marking a significant reduction in hand-arm vibration control.

**Table 4.** Experimental results

| Sr. No. | Material | Thickness | width | Acceleration ($m/sec^2$) |
|---|---|---|---|---|
| 1 | En48 | 1.5 | 48 | 4.98 |
| 2 | En48 | 1.8 | 54 | 5.24 |
| 3 | SS304 | 1.5 | 54 | 3.96 |
| 4 | SS304 | 1.8 | 48 | 4.36 |

As displayed in Figure 7, the primary effects plot of means illustrates that the SS304 spring, 1.5 in thickness and 54 mm in width, brings the best results for the leaf spring with respect to vibration acceleration. The lowest level of vibration acceleration shown by the plot of principal effects of S/N ratio is possessed by the SS 304 spring of 1.5 mm thickness and 54 mm width. From Figure 8, it is clear that these conditions are ideal for the elliptical leaf spring.

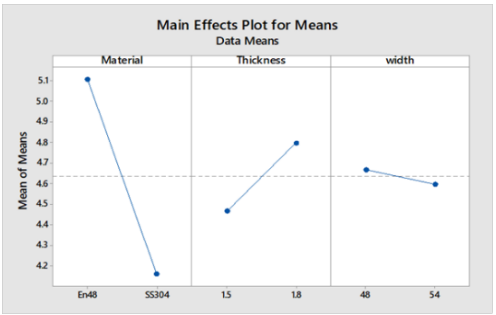



**Fig. 8.** Main Effects Plot for Means

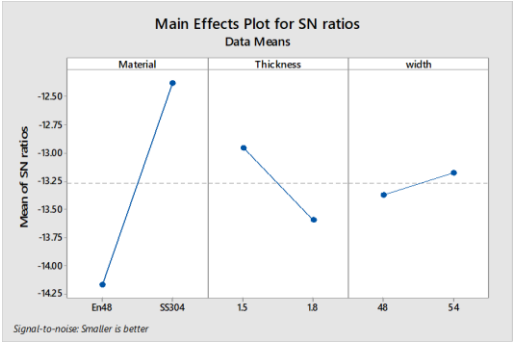



**Fig. 9.** Main Effects Plot for SN ratios

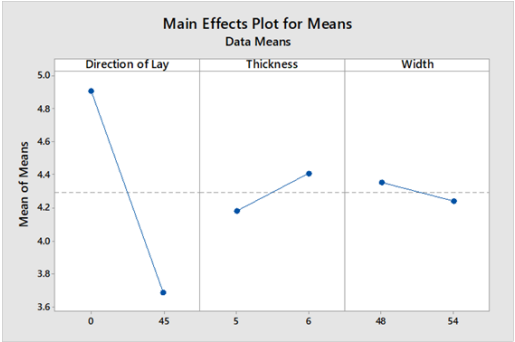



**Fig. 10.** Main Effects Plot for Means

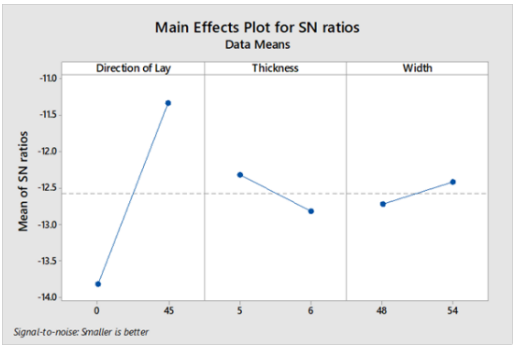



**Fig. 11.** Main Effects Plot for SN ratios

The physical meaning of such results consists of the material and geometric nature of the chosen parameters. SS304, having more flexibility compared to EN48, will provide better energy absorption and a controlled deflection in dynamic loading and thus can help in decoupling the vibrations from the engine to the handlebar. Moreover, the 1.5 mm thickness gives enough flexibility without sacrificing structural integrity. This increases the capacity of operation with this system below the natural frequency, thereby maximizing the scope of isolation. The 45° lay of the liner provides that the fibers are directioned diagonally relative to the applied loads, providing multidirectional damping and higher strip energy propagation. As compared to the 0° layup, which largely withstands the loads under one axis, the 45° orientation is beneficial to the vibrational energy dispersion. Equally so, the 5 mm liner proved to be more compliant than the 6 mm variant, harmonizing stiffness and damping in order to take shock loading but without becoming stiff.

**Table 5.** Experimental Results

| Sr. No. | Direction of Lay | Thickness | Width | Acceleration (m/sec²) |
|---|---|---|---|---|
| 1 | 0 | 5 | 48 | 4.85 |
| 2 | 0 | 6 | 54 | 4.96 |
| 3 | 45 | 5 | 54 | 3.42 |
| 4 | 45 | 6 | 48 | 3.16 |

The spring liner with the 45-degree lay, 5 mm thickness, and 54 mm width shows the lowest vibration acceleration results, according to Figure 10, which is the major effects plot of means. So, these are the best settings for the spring liner.

From the plot of major impacts of the SN ratios, the spring liner, which has a 45-degree lay, is 5 mm thick and 54 mm wide, and records the least vibration acceleration. As can be seen in Figure 10, the characteristics considered are perfect for the spring liner. These findings were confirmed by the S/N ratio plots. The spring material factor had the greatest delta value, meaning that it possessed the largest impact on the vibration reaction. Close effects were exerted on liner lay direction, with there being moderate effects on spring thickness and liner thickness. Such insights support the concept that a proper selection of material, as well as composite geometry fine-tuning, is the key to the selection of passive vibration control design.

### *4.4. Comparison Graphs*

To visualize the performances of different configurations of springs and liners, several comparative graphs were plotted on the basis of experimental data. These graphs show the interrelations between the engine speed, vibration displacement, and acceleration, and allow understanding the effect of design changes in a clearer way. As shown in Fig. 12, all configurations exhibited a nonlinear increase in vibration as engine RPM increased from 1800 to 7000. However, the best arrangement- optimized setup- SS304 spring (1.5mm) with 45̊, 5mm liner had the least displacement values at all the speeds.

While at 7000 RPM, its displacement could not go beyond 0.27 mm, the maximum displacement of the tested samples was 0.42 mm. This 35% lowering describes the better damping potential of the optimized geometry and materials combination under dynamic loadings. The resultant displacement goes up with increasing speed consequently having greater amplitudes of vibration as shown in Figure 11.

**Table 6.** Optimized Composite Elliptical Leaf Spring Vibration Analysis Results

| Sr. No. | Speed | Displacement (mm) | Acceleration m²/Sec |
|---|---|---|---|
| 1 | 590 | 0.338 | 1.72 |
| 2 | 680 | 0.386 | 1.29 |
| 3 | 770 | 0.412 | 2.34 |
| 4 | 860 | 0.475 | 2.76 |
| 5 | 970 | 0.509 | 2.96 |
| 6 | 1080 | 0.526 | 2.86 |

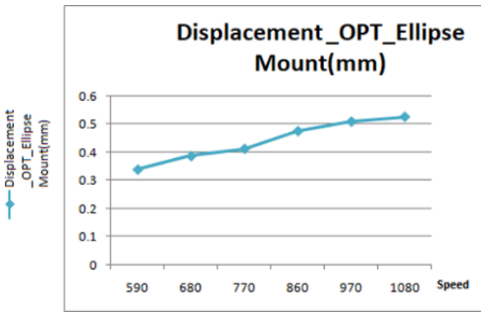



**Fig. 12.** Graph of Displacement Vs Speed (Optimized mount)

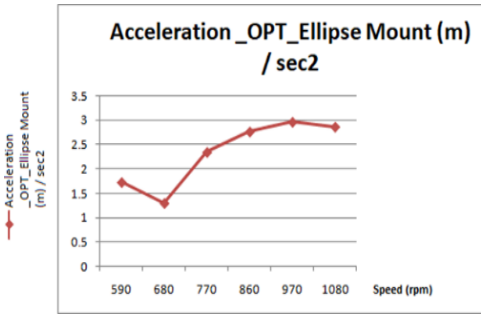



**Fig. 13.** Graph of Acceleration Vs Speed (Composite mount)

The polished setup was further tested with a comprehensive test program that was done over a series of six different engine speeds of 590 to 1080 RPM. The resulting data showed continued decreases in displacement and acceleration at all operating speeds, with the maximum vibration acceleration being far below the ISO 5349 limits. These results support the validity and effectiveness of the elliptical spring-liner system with different loads of operation. The data are also supported by the help of graphical representations in Figures 11 and 12.

The trend on the graph of acceleration versus engine speed depicted in Figure 12 was in the same direction. The best setup constrained the acceleration caused by vibration to 1.44 m/s$^2$, which is far below the Exposure Limit Value (ELV) level of 2.5 m/s$^2$ specified by ISO 5349. On the other hand, the worst configuration overcame 3.4 m/s$^2$ at higher speeds. These findings show that optimized spring-liner assembly offers a safe functioning range and is ergonomic even at the maximum engine load. Figures 13 and 14 provide a direct before-and-after comparison of the original (non-optimized) setup vs. the optimized configuration. The plots clearly describe a decrease in displacement acceleration curves, especially at mid-to-high RPMs, i.e., where displacement exposure activities are usually at the peak. The most significant level of reduction occurs in the 4000-6000 RPM range, wherein the use of agricultural tools is usually continuous. This means that the damping system gives the highest performance in the actual operational regime of the equipment.

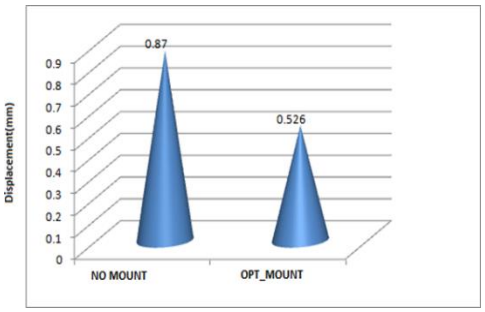



**Fig. 14.** Comparison of Maximum Displacement No Mount Vs OPT_Mount

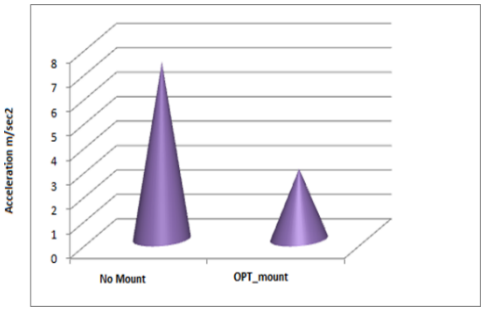



**Fig. 15.** Comparison of Maximum Acceleration No mount Vs OPT_Mount

The graphical data support the quantitative conclusions made above. Smoother and lower curves in the optimized configuration not only justify the selection process but also imply increased comfort, decreased fatigue risk, and

extended capability of using the tool by operators. These benefits are an embodiment of the pragmatic significance of an elliptical composite spring–liner system in designing an ergonomic tool.

The attenuation of the vibration levels observed is in agreement with available literature on composite leaf spring systems. In particular, Jadhav et al. (2024) reported the improvement of damping properties of hybrid composite leaf springs under harmonic loading, and Papacz et al. (2014) measured a threefold decrease in the vibration levels in comparison to traditional steel springs in the case of GFRP springs. Zou et al. (2022) demonstrated that the fiber layup angle and fiber volume fraction significantly influence the stiffness and damping characteristics of composite leaf springs. The current study supports these results by stating the highest acceleration decrease of 57.7% with an optimized elliptical setup, thus confirming the feasibility of the suggested design in terms of handheld agricultural equipment.

### *4.5. Key Findings*

The meticulous consideration of various elliptical springs and liners proved to yield an ideal passive vibration isolation mechanism that can be used on handheld machinery for agriculture. Out of all the combinations, the SS304 spring with the thickness of 1.5 mm, along with an E-glass/epoxy liner laid at 45° and 5 mm thick, was the best combination. This layout showed the best performance in terms of displacement and acceleration measures in real conditions of operation. Quantitatively, this configuration proved to reduce vibration displacement by 35% and acceleration by 57.7% compared to the worst performing setup. These reductions are significant, particularly bearing in mind the ranges of high speeds at which agricultural tools operate, where vibration is usually the most intense. Notably, the optimized system managed to guard the measured hand-arm vibration from exceeding the ELV level of 2.5 $m/s^2$, which made work in the field safer in the long term for the operators.

The factors affecting vibration isolation were identified to be spring material and orientation of liner fiber, followed by thickness of spring and liner. The physical interpretation is that the flexibility and damping ability of SS304, working in conjunction with a multidirectionally stiff structure provided by the 45° fiber layup, dampens the vibrational energy effectively. The results also show that small shifts in geometric and material parameters could strongly influence the overall damping behavior, indicating that systematic optimization of components' designs is important. Together, the findings justify the use of elliptical composite spring–liner assemblies as a viable solution for practical and ergonomic control of operator vibration exposure. The incorporation of optimization techniques, including the Taguchi method, will make it possible to adapt such systems to the specifics of their use while observing the requirements for occupational safety.

## 5. Conclusions

The current study involved the design, optimization, and experimental validation of an elliptical composite leaf-spring assembly that was aimed at reducing the hand-arm vibration that is passed to handheld agricultural tools. Using systematic material selection, structural analysis by finite elements, and experimental screening by Taguchi, the configuration providing the highest attenuation was identified.

The main conclusions are as follows:

- The best combination was the SS304 spring (1.5 mm) and a 45° -oriented E -glass/epoxy liner (5 mm): the displacement decrease was up to 35%, and the acceleration decrease was 57.7%.
- Vibration levels produced by the system were significantly lower than the ergonomic safety limits of ISO 5349 and thus proved the system to be field-ready.
- Flexibility of the material and fiber orientation was observed to have a strong impact on damping performance and comfort to the operator.
- The elliptical composite construction provides a long-lasting, minimal maintenance alternative to traditional rubber mounts of handheld tools.
- The offered design methodology offers a very effective optimization strategy, thus minimizing the material usage, the necessary number of testing cycles, and the total cost of development, in general, which helps to increase the resource efficiency of vibration isolator design.
- The vibration isolation system can be used optimally in handheld agricultural tools such as brush cutters, sprayers, mini-tillers, and so on, thus improving the safety and comfort of the operator.

Future research will involve field tests in realistic situations, large-scale fatigue testing in long periods, and research on artificial-intelligence-based design optimization and machine learning, the aim of which is to expand the scope of application in agricultural and industrial settings.

## Nomenclature

| | |
|---|---|
| *FEA* | Finite Element Analysis |
| *DOE* | Design of Experiment |

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## Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

## References

[1] Barač, Ž., Plaščak, I., Jurić, T., & Marković, M., 2025. The Impact of Vibrations on the Hand–Arm System and Body of Agricultural Tractor Operators in Relation to Operational Parameters, Approach: Analytical Hierarchical Process (AHP). *Agri Engineering*, *7*(3), p.56.

[2] De Moraes Fernandes, J., De Haro Silva, L., Schutzer, V., Catarino, J., Panini, R., Garnica, G., Meneguetti, D., & Santos, J., 2018. Ergonomic aspects and evaluation of vibration in the operating position of agricultural tractors. *Revista Ação Ergonômica.*

[3] Almady, S. S., Al-Janobi, A. A., Marey, S. A., Al-Sager, S. M., Aboukarima, A. M., & Gaddal, Y. H., 2024. Establishment of a measuring unit based on an Arduino board for recording vibrations on an agricultural tractor during tillage process. *Measurement and Control*, 58(9), pp. 1147-1157.

[4] Awati, S. S., & Todkar, A. S., 2024. Recent trends in reduction of hand arm vibration syndrome for agricultural handheld equipment: A review based on challenges and future directions. *Noise & Vibration Worldwide*, *55*(6-7), pp. 281-295.

[5] Lai, S. K., Chui, J., Tong, L., & Sun, J. Q., 2019. A human-based study of hand–arm vibration exposure limits for construction workers. *Journal of Vibration Engineering & Technologies*, *7*, pp. 379-388.

[6] GHANEH, S., SHAHRNAVARD, Y., KARAMI, M., & KARAMI, Z., 2018. The Impact of Ergonomic Interventions on the Whole Body Vibration of Mining Machinery Drivers in Sarcheshmeh Copper Complex. *International Journal of Occupational Hygiene*, *10*(2), pp. 101-107.

[7] Wen, H., Liu, W., Guo, J., Zhang, K., Li, Y., & Liu, Y., 2021. Design and experiment of inerter-rubber vibration isolator based on parallel inerter-spring-damper system. *Journal of Ship Production and Design*, *37*(03), pp. 205-214.

[8] Svaricek, F., Fueger, T., Karkosch, H. J., Marienfeld, P., & Bohn, C., 2010. Automotive applications of active vibration control. *Vibration Control*, pp. 303-318.

[9] Dol, T. S., Korade, D. N., Darade, P. D., & Jagtap, K. R., 2016. Design Development and Testing of Hydraulic Engine Mount Isolation in Agricultural Applications. *IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)*, 13(1), Version II, pp. 35–42.

[10] Park, M., Fukuda, T., Kim, T., & Maeda, S., 2013. Health risk evaluation of whole-body vibration by ISO 2631-5 and ISO 2631-1 for operators of agricultural tractors and recreational vehicles. *Industrial health*, 51(3), pp. 364-70.

[11] Kabir, M., Chung, S., Kim, Y., Sung, N., & Hong, S., 2017. Measurement and evaluation of whole body vibration of agricultural tractor operator. *International Journal of Agricultural and Biological Engineering*, 10, pp. 248-255.

[12] Fethke, N., Schall, M., Merlino, L., Chen, H., Branch, C., & Ramaswamy, M., 2018. Whole-Body Vibration and Trunk Posture During Operation of Agricultural Machinery. *Annals of Work Exposures and Health*, 62, pp. 1123–1133.

[13] Singh, G., Tewari, V. A., & Choudhary, V., 2024. Biomechanical analysis of real-time vibration exposure during mini combine harvester operation: A hybrid ANN-GA approach. *J. Field Robotics*, 41, pp. 2441-2454.

[14] Vallone, M., Bono, F., Quendler, E., Febo, P. and Catania, P., 2016. Risk exposure to vibration and noise in the use of agricultural track-laying tractors. *Annals of Agricultural and Environmental Medicine*, 23(4).

[15] Rivin, E. I., 2003. Passive vibration isolation. *Journal of Sound and Vibration*, 263(4), pp. 653–676.

[16] Lenz, J., & Platz, R., 2019. Quantification and Evaluation of Parameter and Model Uncertainty for Passive and Active Vibration Isolation. *In Model Validation and Uncertainty Quantification, Volume 3: Proceedings of the 37th IMAC, A Conference and Exposition on Structural Dynamics 2019* (pp.135-147).

[17] Yang, Z., Shuai, C., Li, B. and Ma, J., 2022. Low frequency passive vibration isolation technology and its application prospect in ship equipment. *In Second International Conference on Cloud Computing and Mechatronic Engineering (I3CME 2022)*, 12339, pp.99-109.

[18] Diez-Jimenez, E., Rizzo, R., Gómez-García, M.J. and Corral-Abad, E., 2019. Review of passive electromagnetic devices for vibration damping and isolation. *Shock and Vibration*, 2019(1), p.1250707.

[19] Rivin, E. I., 1995. Vibration isolation of precision equipment. *Precision Engineering*, 17(1), pp. 41–54.

[20] Jadhav, S., Landage, M. G., Patil, C. D., & Jawarkar, N., 2024. Analysis of vibration in hybrid composite leaf spring. *Journal of Physics: Conference Series*, 2763(1), 012026.

[21] Manjunath, H.N., Manjunath, K. and Rangaswamy, T., 2014. Vibration analysis of composite leaf spring for a light commercial vehicle (TATA ACE). *International Journal of Scientific Engineering and Technology*, 3(7), pp.871-875.

[22] Papacz, W., Tertel, E., & Kuryło, P., 2014. Performance comparison of conventional and composite leaf spring. *Journal of Automotive Technology and Engineering*, 2, pp. 24–28.

[23] Zou, X., Zhang, B., & Yin, G., 2022. Analysis of stiffness and damping performance of the composite leaf spring. *Scientific Reports*, 12(1), 6842.

[24] Jolaiy, S., Yousefi, A., Mashhadi, M. M., Amoozgar, M., & Bodaghi, M., 2021. Dynamic behaviors of composite leaf springs with viscoelastic cores. *Mechanics Based Design of Structures and Machines*, 51(8), pp. 2632–2654.

[25] Besekar, S.S., Pimpalkar, P.R. and Gorantiwar, V.S., 2023. Design and analysis of leaf spring using Ansys. *International Journal of Research in Applied Science and Engineering Technology*, 11(3).

[26] Kader, E. E., Abed, A. M., Radojković, M., Savić, S., Milojević, S., & Stojanović, B., 2025. Design of a Copolymer-Reinforced Composite Material for Leaf Springs Inside the Elastic Suspension Systems of Light-Duty Trucks. *Journal of Composites Science*, 9(5), 227.

[27] Madhavi, S., Sreeramulu, D., & Venkatesh, M., 2015. Optimization of turning process parameters by using grey-Taguchi. *International Journal of Engineering Science and Technology*, 7, pp. 1–8.

[28] Pratap, B., & Kumar, D., 2016. Application of Grey Based Taguchi Method in Optimization of Process Parameters—A Review. *International Journal for Scientific Research & Development (IJSRD)*, 4(6), 221–223

[29] Mane, P., Chikalthankar, S. B., & Nandedkar, V. M., 2017. Taguchi-Grey relational based multi-response optimization of machining parameters in turning process of HcHCr D2. *International Journal of Modern Trends in Engineering and Research*, 4.

[30] Sutono, S., 2021. Grey-based Taguchi method to optimize the multi-response design of product form design. *Journal Optimasi Sistem Industri*, 20(2), pp. 136–146.

[31] Rajbongshi, S. K., & Sarma, D. K., 2019. Process parameters optimization using Taguchi's orthogonal array and grey relational analysis during hard turning of AISI D2 steel in forced air-cooled condition. *IOP Conference Series: Materials Science and Engineering*, 491(1), 012032.

[32] Wei, W., Samuelsson, P.B. and Jönsson, P.G., 2024. Alloy design optimization of stainless steel's performance and environmental impact through Taguchi-based grey relational analysis. *Steel Research International*, 95(3), p.2300319.

[33] Milojević, S., & Stojanović, B., 2018. Determination of tribological properties of aluminum cylinder by application of Taguchi method and ANN-based model. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 40(12), 571.

[34] Gajević, S., Marković, A., Milojević, S., Ašonja, A., Ivanović, L., & Stojanović, B., 2024. Multi-objective optimization of tribological characteristics for aluminum composite using Taguchi grey and TOPSIS approaches. *Lubricants*, 12(5), 171.