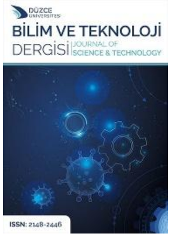

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Research paper

Experimental Investigation of Suspension Cord Material Influence on Modal Parameters in Free-Free Boundary Conditions

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ABSTRACT

During the design stage of engineering structures, determining their dynamic response is essential to ensure performance and long service life. Experimental Modal Analysis (EMA) is a widely used method for this purpose, as it provides critical modal parameters (natural frequencies, damping ratios, frequency response) and reveals the dynamic behavior of structures. In the EMA, structures are typically excited at single or multiple locations, and the responses are measured using sensors under various boundary conditions. One common approach is the free-free boundary condition, which involves suspending test structures using suspension cords to simulate unconstrained behavior. This study investigates how the material of suspension cords affects the dynamic characteristics of a structure. Two cord materials—nylon and rubber—along with four different combinations of these cords were tested. Results indicate that while the natural frequencies remain unchanged (%1-%2 difference) across different suspension materials, the damping ratio is notably affected. The measured damping ratios ranged from 0.95% (nylon) to 3.45% (rubber), demonstrating the significant influence of suspension material on energy dissipation. Additionally, harmonic response measurements confirm that differences in damping ratios due to the suspension material are clearly detectable.

Keywords: *Experimental Modal Analysis, Natural Frequency, Damping Ratio, Free-Free Boundary Condition*

I. INTRODUCTION

Experimental Modal Analysis (EMA) is a well-established method for identifying the dynamic characteristics of structures, including natural frequencies, damping ratios, and frequency response. It is widely employed in structural dynamics, aerospace, mechanical engineering, and civil engineering applications to validate numerical models and assess structural performance and long service life. The accuracy of the EMA heavily depends on the quality of excitation, measurement setup, and most critically, the boundary conditions imposed during testing.

Studies have shown that variations in suspension stiffness can significantly influence measured modal parameters. Even small changes in the mechanical properties of suspension elements may cause frequency shifts and alter damping estimations, highlighting the sensitivity of the EMA results to suspension design (Bahari et al., 2019).

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It is widely recognized that ideal free-free boundary conditions are rarely realized in practice. Instead, suspension systems introduce unintended stiffness and damping, distorting the dynamic response of the test structure (Carne et al., 2006; Munsi et al., 2002). This is particularly critical for lightweight or flexible structures, where boundary-induced effects may dominate the observed behavior (Chang & Hodges, 2007)

Damping measured during testing may not solely reflect the inherent damping of the structure but can also include contributions from the suspension system. If these contributions are not properly accounted for, damping values obtained from modal testing may be significantly overestimated (Geweth et al., 2021)

Efforts have been made to develop techniques for minimizing or correcting such external effects. For instance, methods have been proposed to eliminate the influence of transducer mass and suspension interference from frequency response functions, while specific post-processing techniques have been developed to compensate for boundary condition effects when ideal suspension cannot be achieved, (Cooley & Giunta, 1992; Cui et al., 2022).

Further studies emphasize the need for consistent and low-interference support systems in flexible structure testing. These include the design and evaluation of specialized suspension devices for large-scale or space-based structures, which demonstrated that suspension performance must align with the dynamic behavior of the test article to avoid distortion in modal results (Cooley & Giunta, 1992)

Recent developments also focus on the challenges posed by uncertainty in structural parameters, such as suspension-induced variability, which must be accounted for in vibration control systems (Cui et al., 2022). Additionally, fundamental resources on modal testing theory highlight the critical importance of minimizing boundary influence to ensure accuracy and repeatability in experimental data (Ewins, 2000)

Recent studies show that boundary conditions can affect modal analysis results, particularly damping estimations, while natural frequencies remain relatively stable. Even soft suspensions used to simulate free-free conditions can introduce measurable variations(Sahu & Kanchwala, 2024; Shen & He, 2024).

Despite this broad body of research, the specific role of suspension cord material—such as differences between rubber, nylon, and hybrid configurations—has not been systematically explored. Most prior studies have addressed generic suspension effects or applied to aerospace-scale components. There is a lack of experimental investigation targeting the direct comparison of suspension cord materials and their combinations on the modal parameters of metallic structures. The present study addresses this gap by experimentally evaluating how the choice of suspension cord material affects the identified modal properties of a stainless-steel beam under free-free boundary conditions (Huang et al., 2016; Jiang et al., 2024).

II. MATERIALS AND METHODS

A uniform AISI 304 stainless-steel beam (Young's Modulus=190 GPa, density= 7850 kg/m3 and Poisson's ratio= 0.29) with dimensions of 250 mm in length, 25 mm in width, and 5 mm in thickness was used as the test specimen. The beam was suspended using suspension cords to simulate a free-free boundary condition.

The experiments were carried out using the test setup shown in (Figure 1). An instrumented modal impact hammer (Type: Dytron, Model: 58001B3T) was used to excite the beam, while the dynamic response was recorded using a single-axis accelerometer mounted at the edge of the beam using a small amount of instant adhesive to reduce mass loading effects. A Dewesoft brandmark multichannel Data Acquisition (DAQ) device and software package DewesoftX were used during the data collection. A single accelerometer was selected to minimize mass loading effects and avoid altering the dynamic behavior of the lightweight beam.

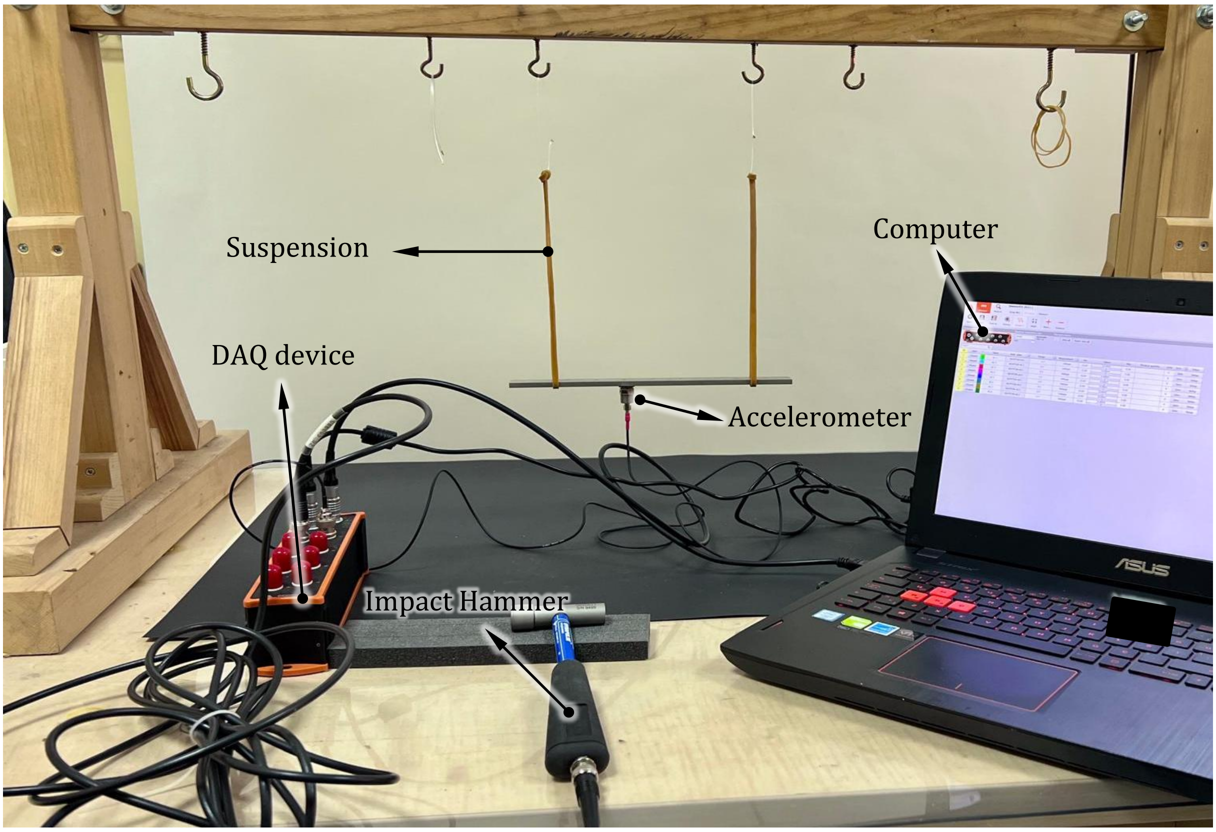

Figure 1. Test setup.

For modal testing, eleven excitation points were marked along the beam's span, each spaced 25 mm apart (Figure 2). At each point, the beam excited five times to ensure repeatability and reduce random errors. Thus, each transfer function was measured five times and averaged in order to ensure good measurements. The resulting time-domain data were processed to extract frequency response functions (FRFs), from which modal parameters were estimated. This setup allowed for a consistent comparison across all suspension configurations, isolating the influence of cord material on the beam's modal characteristics. Damping ratios were calculated using the half-power bandwidth method applied to the FRFs for each mode.

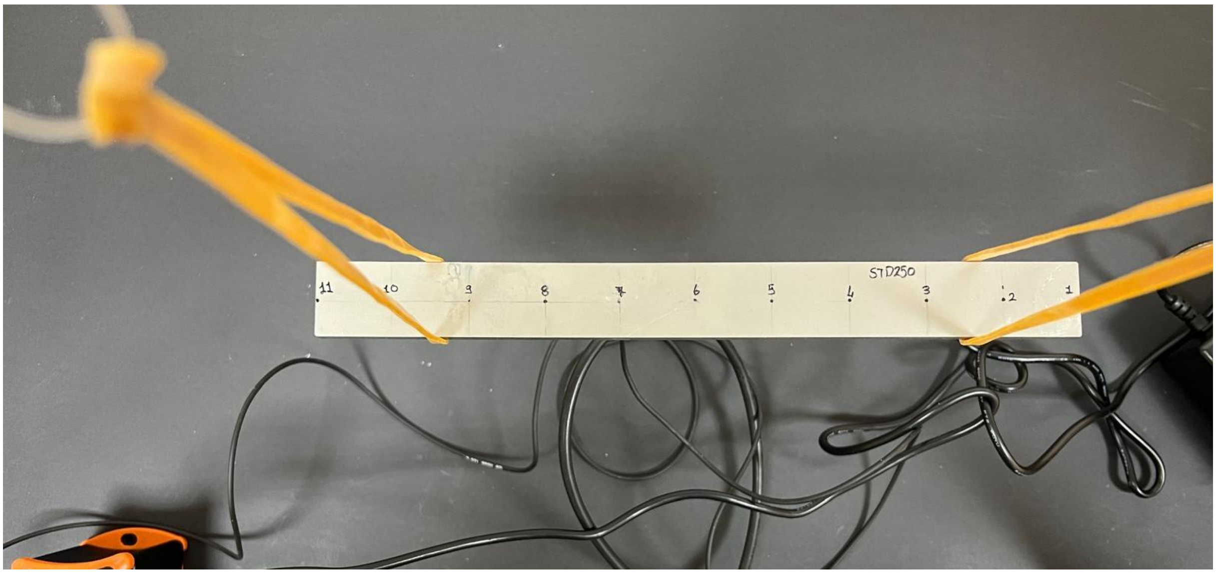

Figure 2. Test specimen and excitation points.

Four suspension configurations (Nylon, Rubber, Rubber-Nylon, and Nylon-Rubber) were used to assess the effect of suspension cord material on the beam's dynamic behavior, as shown in Figure 3. In hybrid combinations, the two cord materials Rubber and Nylon were tied together as Rubber-Nylon and Nylon–Rubber to form a single suspension line. The first mentioned material was connected to the beam, while the second was connected to the hook. These setups allowed evaluation of how material type and connection order affect damping and modal response. This arrangement enabled a controlled evaluation of both material properties and interface effects, allowing for the assessment of asymmetric damping contributions and variations in modal response due to suspension configuration. To ensure consistency, the suspension cords were attached at pre-defined nodal points with equal tension, and all tests were performed under identical environmental and boundary conditions

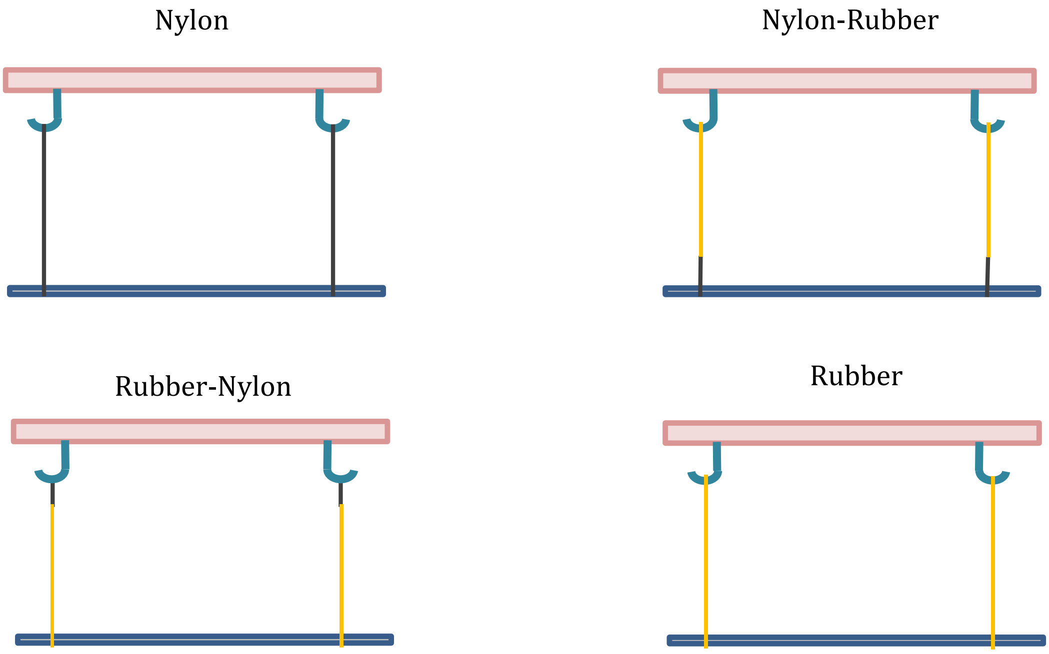

Figure 3. Test configurations.

III. RESULTS AND DISCUSSION

The testing was done using free-free boundary conditions. A variety of suspension cord configurations were used for the tests. This condition was simulated by hanging the beam by suspension cords. The effect of the suspension cord on both modal parameters, namely natural frequencies and damping ratio of the beam structure were assessed and illustrated.

Figure 4 presents the natural frequencies corresponding to the first four vibration modes of the beam under four different suspension cord configurations (Nylon, Rubber, Rubber-Nylon, and Nylon-Rubber). The results indicate that the choice of suspension cord material has a minimal effect on the natural frequencies.

In Mode 1, frequencies range from approximately 360 Hz to 390 Hz. The Rubber suspension cord yields the highest value, while the Nylon suspension cord shows the lowest, suggesting slightly increased effective stiffness with the Rubber suspension cord due to its lower compliance. A similar trend is observed in Mode 2, where frequencies span from 950 Hz to 1050 Hz. The Rubber suspension cord again produces the highest frequency, followed by the Nylon–Rubber and Nylon. The Rubber–Nylon cord exhibits a slightly lower frequency, potentially due to localized compliance at the beam–cord interface in hybrid arrangements.

Mode 3 shows negligible variation across all configurations, with frequencies centered around 2000 Hz, indicating that higher-order modes are less sensitive to small differences in suspension compliance. In Mode 4, the frequency ranges from approximately 3550 Hz to 3650 Hz. The Rubber cord again results in the highest natural frequency, while the Rubber-Nylon cord is the lowest. The hybrid setups fall between the pure-material results, consistent with the expected averaged stiffness behavior.

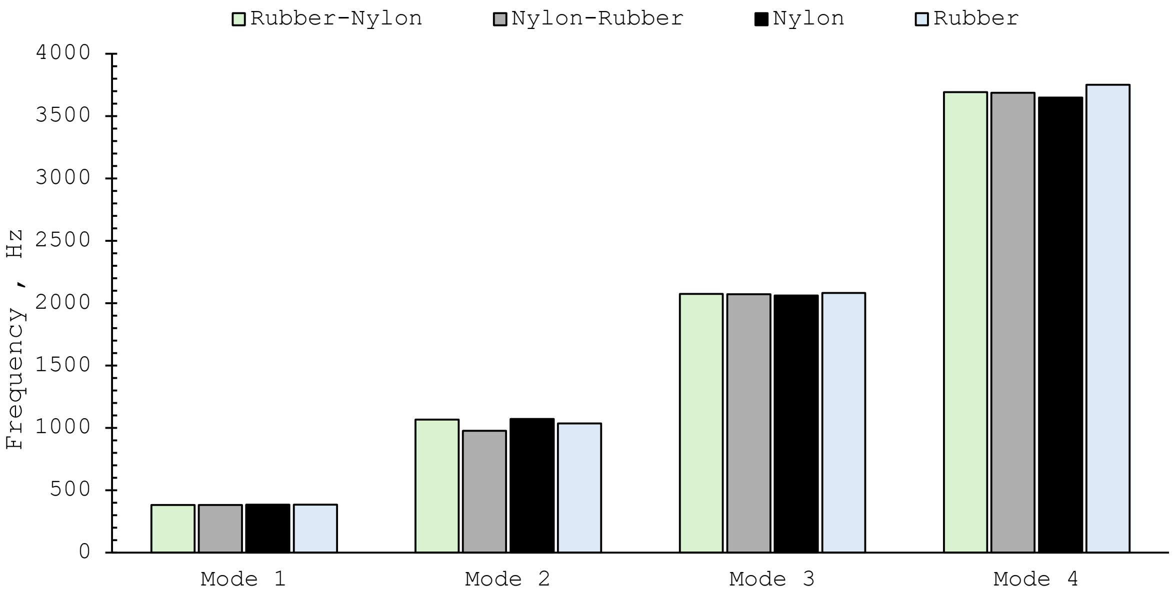

Figure 4. Natural frequencies

These findings are consistent with previous studies in the literature that reported natural frequency variations due to suspension stiffness remain within 1–2% across configurations [1], [3], [5]. Such small shifts are typically acceptable in experimental modal analysis, particularly when the primary focus is on damping estimation or mode shape comparison. However, in applications requiring high-frequency precision—such as model updating or inverse identification, these subtle effects should be considered.

Figure 5 shows the damping ratios for the first four vibration modes of the beam under different suspension cord configurations: the Rubber-Nylon, the Nylon-Rubber, the Nylon, and the Rubber.

The results revealed significant changes in measured damping ratios. In Mode 1, damping varies noticeably across suspension types. The Rubber cord and the Rubber-Nylon cord configurations yield the highest damping (~2.2% and ~2.05%, respectively), while pure the Nylon cord results in the lowest (~1.3%). This indicates that rubber's inherent viscoelastic properties significantly increase energy dissipation at lower frequencies.

In Mode 2, this trend continues. The Rubber cord again results in the highest damping (~2.3%), and the Nylon cord the lowest (~0.95%). Interestingly, the Nylon-Rubber cord and the Rubber-Nylon cord configurations show intermediate values, confirming that material layering and contact sequence influence how damping is transmitted through the suspension system.

In Mode 3, all configurations exhibit a drop in damping, but the overall ranking remains consistent: the Rubber cord is the highest and the Nylon cord is the lowest. This suggests that higher mode shapes may be less sensitive to boundary-induced damping due to reduced modal displacements at the suspension points.

Mode 4 shows the most significant spread. The Rubber cord again reaches the highest damping (~3.45%), and the Rubber-Nylon cord (~2.75%) and the Nylon-Rubber cord (~2.45%) follow. The Nylon cord remains lowest (~1.7%), reinforcing the conclusion that rigid, low-damping materials like nylon reduce artificial energy dissipation through the suspension system.

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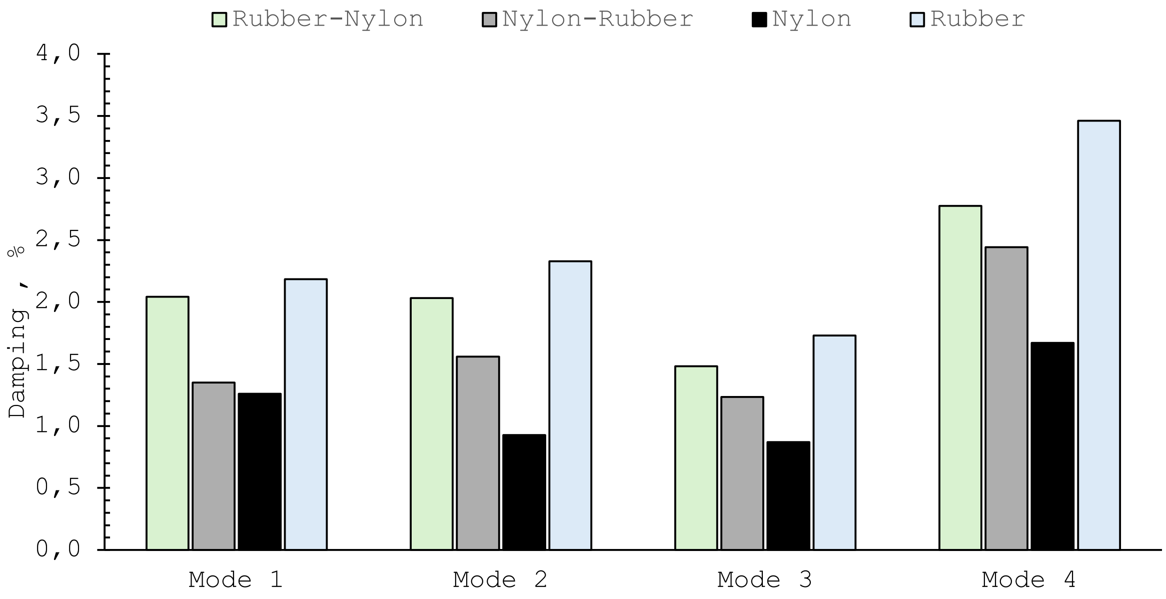

Figure 5. Damping Ratios.

Overall, these results confirm that suspension cord material substantially affects the measured damping ratios, particularly in higher modes. Rubber cords, due to their greater internal damping, introduce additional energy dissipation which may not originate from the structure itself—potentially leading to overestimation of structural damping if not properly accounted for. Conversely, nylon-based suspensions yield lower damping, which may more accurately reflect the true behavior of the structure but could also introduce more noise due to reduced vibration isolation.

These findings are consistent with literature highlighting how boundary and support conditions influence damping measurements in experimental modal analysis (Carne et al., 2006; Geweth et al., 2021). The results also support the importance of carefully selecting suspension materials when damping is a key parameter in system identification.

Figure 6 illustrates the acceleration-based frequency response functions (FRFs) of the stainless-steel beam suspended using four different cord configurations: Nylon, Rubber, Rubber-Nylon, and Nylon-Rubber. The FRFs represent the structural response to impact excitation in terms of acceleration over a frequency range up to 5000 Hz.

The FRF curves exhibit four prominent peaks, corresponding to the first four bending modes of the beam. Each peak varies slightly in both frequency location and amplitude depending on the suspension configuration, reflecting the influence of suspension cord materials on dynamic characteristics.

All curves exhibit similar resonance frequencies, with minor shifts. The Nylon-Rubber cord and the Nylon cord configurations tend to show slightly lower resonance frequencies compared to the Rubber cord and the Rubber-Nylon cord. This aligns with previous observations that rubber-based cords introduce additional stiffness, slightly raising the effective system stiffness and shifting natural frequencies upward.

The amplitude of each resonance peak is also influenced by the suspension material. The Nylon-Rubber and the Nylon cords generally produce higher peak amplitudes, especially in the 2nd and 3rd modes, indicating lower damping and more pronounced resonance behavior. In contrast, the Rubber and Rubber-Nylon cord configurations yield more damped peaks with lower amplitude, consistent with their higher energy dissipation capacity.

Peaks are sharper for the Nylon and the Nylon-Rubber cord suspensions, while broader peaks are observed with the Rubber and Rubber-Nylon cords. This further confirms that rubber contributes significantly to damping, causing more distributed energy dissipation and reducing peak sharpness.

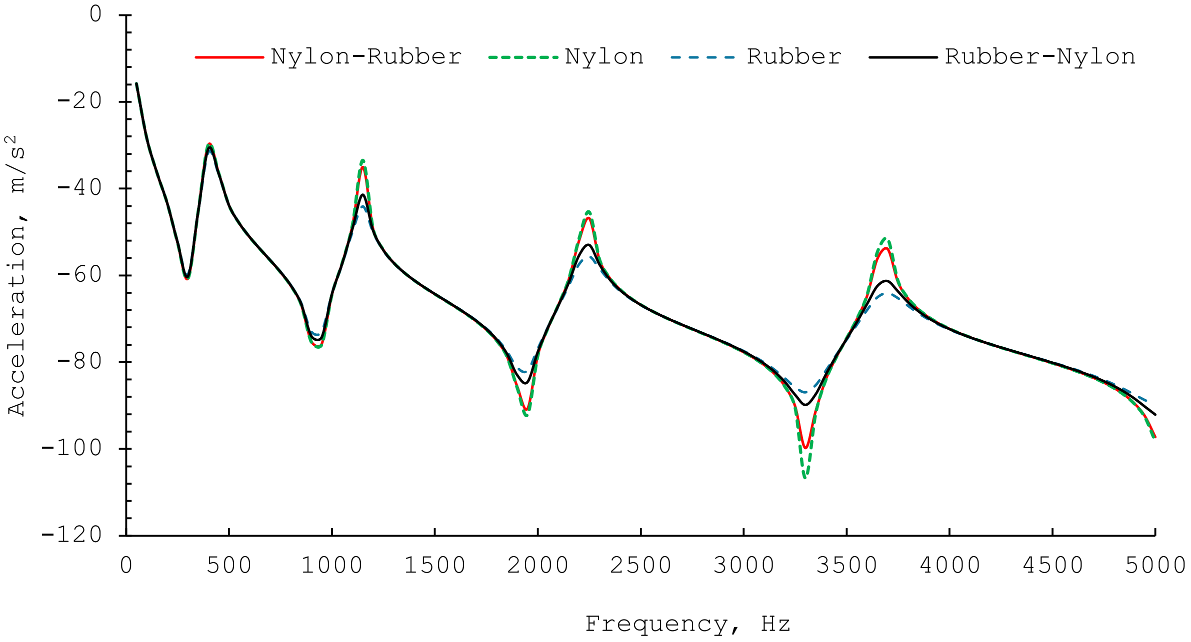

Figure 6. FRF curves.

Overall, the FRF results reinforce the conclusion that suspension material affects both the amplitude and frequency content of modal responses. The Nylon cord provides lower damping and more accurate reflection of the beam's inherent behavior, while the Rubber cord introduces artificial damping that may mask or shift modal features.

These observations are consistent with existing findings on boundary condition sensitivity (Geweth et al., 2021) and validate the importance of choosing appropriate suspension materials in experimental modal analysis.

IV. CONCLUSION

In this study, the influence of different suspension cord materials and their combinations on the modal parameters of a stainless-steel beam under free-free boundary conditions was experimentally investigated using the experimental modal analysis (EMA) method. Specifically, the effect of using rubber cords, nylon cords, and hybrid combinations (rubber–nylon and nylon–rubber) was analyzed in terms of their impact on natural frequencies and damping ratios.

The results showed that the natural frequencies of the beam structure were only slightly affected by changes in the suspension cord material. Across the tested configurations, the first four natural frequencies exhibited variations within approximately 1.5%, with the maximum shift observed in the first mode between the rubber and nylon configurations. For instance, in Mode 1, the natural frequency ranged from 368 Hz (nylon) to 374 Hz (rubber). This indicates that while suspension material stiffness influences the boundary conditions, its effect on global structural stiffness remains limited in the frequency domain.

In contrast, the damping ratios were significantly influenced by the suspension material. The measured damping ratios varied from 0.95% (nylon–nylon configuration) up to 3.45% (rubber–rubber configuration). This substantial variation is attributed to the viscoelastic nature of the rubber cords, which introduced additional energy dissipation during vibration. Hybrid configurations yielded intermediate damping values, typically ranging between 1.8% and 2.7%, demonstrating that both the material type and the sequence of materials in contact with the structure affect energy dissipation.

These findings emphasize that suspension cord material selection is a critical factor in experimental modal analysis, particularly when accurate estimation of damping parameters is required. The use of highly damping materials, such as rubber, can lead to an overestimation of structural damping, potentially masking the true dynamic characteristics of the tested structure. Conversely, using low-damping materials like nylon can provide more accurate damping estimations, closer to the intrinsic response of the beam.

Consequently, improper selection or inconsistency in suspension setup may result in misinterpretation of structural dynamic behavior, especially in comparative studies or model updating applications. To ensure repeatable and reliable modal parameter identification, it is recommended that suspension materials be carefully selected based on their mechanical properties, and that experimental setups maintain strict consistency across tests.

These findings are particularly relevant for practical applications where accurate dynamic characterization is essential. In aerospace structures, automotive components, and precision mechanical systems, reliable identification of damping behavior is critical for model updating, structural optimization, and fatigue life prediction. The results of this study can guide the selection of appropriate suspension materials during experimental modal analysis to minimize boundary-induced errors, especially in damping estimation. Furthermore, the methodology is applicable to vibration testing in structural health monitoring systems, vibration isolation studies, and the dynamic assessment of lightweight metallic structures, where free-free boundary conditions are commonly simulated. Ensuring proper suspension material selection helps avoid overestimation of damping and ensures the repeatability and reliability of modal testing results in these engineering applications.

For future work, analytical or computational correction methods could be developed to compensate for suspension-induced boundary effects. Additionally, the methodology can be extended to more complex structural geometries, such as plates or curved shells, and explored under multi-axis suspension configurations to assess the influence of three-dimensional boundary flexibility on modal parameters.

DECLARATIONS

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Ethical Approval and Participant Consent: This study does not involve human or animal participants. All procedures followed scientific and ethical principles, and all referenced studies are appropriately cited.

Plagiarism Statement: This article has been evaluated for plagiarism, and no instances of plagiarism were detected.

Use of AI Tools: The authors declare that no Artificial Intelligence (AI) tools were used in the creation of this article.

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