Vol 7 No 1 (2025) *e*-ISSN: 2682-8383

Journal of Engineering Technology and Applied Physics

Experimental and Numerical Study of Shape Memory Alloys for Vibration Amplitude Reduction in Mechanical Structures

Hyginus Chidiebere Onyekachi Unegbu*, Danjuma Saleh Yawas, Bashar Dan-asabe and Abdulmumin Akoredeley Alabi
Department of Mechanical Engineering, Ahmadu Bello University, Zaria, Nigeria.
**Corresponding Author:* chidieberehyg@gmail.com, *ORCiD*: 0000-0002-2016-4825
https://doi.org/10.33093/jetap.2025.7.1.9
Manuscript Received: 7 December 2024, Accepted: 23 January 2025, Published: 15 March 2025

Abstract — This study explores the effectiveness of Shape Memory Alloys (SMAs) for adaptive vibration control in mechanical structures through both experimental and numerical methods. SMAs were integrated into a cantilever beam, and their performance was assessed across different temperatures and vibration frequencies. The results demonstrate that SMAs can reduce vibration amplitudes by up to 45%, particularly at resonant frequencies when activated at elevated temperatures (75°C). A finite element model was developed to simulate the behavior of the system, showing strong correlation with experimental data, with a root mean square error (RMSE) of less than 4%. The validated model was further used to predict SMA performance under conditions not tested experimentally, confirming its reliability for broader applications. These findings show the potential of SMAs as compact, adaptive, and energy-efficient solutions for vibration control in sectors such as aerospace, automotive, and civil engineering. Future research should focus on optimizing activation response times, improving long-term durability, and exploring more complex structural designs for enhanced performance.

Keywords— Shape Memory Alloys, Adaptive vibration control, Finite element modeling, Resonant frequencies, Thermal activation.

I. INTRODUCTION

Vibration issues in mechanical structures are a longstanding challenge in fields such as aerospace, automotive, and civil engineering. Excessive vibrations can lead to structural fatigue, accelerated wear, reduced operational efficiency, and, in some cases, catastrophic failure [1, 2]. Traditional passive vibration control methods, such as damping and isolation, often fall short in highly dynamic operational systems because these methods cannot adapt to changing vibration frequencies and amplitudes [3, 4]. Consequently, the demand for more sophisticated and adaptable vibration control mechanisms has grown, spurring research into adaptive and smart materials.

Adaptive vibration control systems represent a significant advancement in addressing the limitations of passive control methods. Unlike passive systems, adaptive control solutions actively modify the system's response in real time, ensuring optimal performance across a broader range of operating conditions. This adaptability is critical for maintaining structural integrity and extending the lifespan of systems exposed to variable stressors [5, 6]. These systems, which can respond to changing environmental conditions, are particularly valuable in applications where structures are subject to fluctuating loads, temperatures, or vibration frequencies [7, 8].

Shape Memory Alloys (SMAs) are emerging as promising candidates for adaptive vibration control due to their ability to undergo phase transformations in response to external stimuli such as temperature and mechanical stress [9, 10]. This unique property enables SMAs to "remember" their original shape after deformation, allowing them to function as effective actuators in smart vibration control systems [11, 12]. The superelasticity and shape memory effects of SMAs have been leveraged in multiple studies to enhance vibration suppression, especially in applications that demand precise and controllable responses [13, 14]. Additionally, SMAs exhibit the ability to shift between martensitic and austenitic phases, which directly contributes to their capacity to reduce vibration amplitudes under varying thermal and mechanical loads. This phase transformation mechanism is a pivotal aspect of SMA functionality and serves as a foundation for adaptive vibration control strategies. Still, challenges remain in optimizing SMA performance for large-scale applications and ensuring reliable, long-term operation under diverse conditions.

The demand for advanced vibration control solutions is rising, driven by the increasing complexity and operational demands of modern mechanical systems. In aerospace and automotive industries, reducing vibration-induced fatigue and noise while enhancing structural performance is critical [15, 16]. As lightweight, high-performance structures become more prevalent, traditional damping methods no longer suffice to meet stringent performance and durability requirements. Furthermore, the development of smart cities and infrastructure, where mechanical structures are subject to dynamic loads from environmental factors like wind and seismic activity, underscores the need for adaptive vibration control technologies [17, 18]. The use of SMA-based control systems in these sectors offers the dual benefits of enhanced structural resilience and energy efficiency, thereby addressing key industry priorities related to sustainability and operational efficiency. SMA-based control systems account for enhanced structural resilience and energy efficiency, thus addressing such salient factors as sustainability and operational efficiency.

Environmental sustainability goals are also pushing industries toward energy-efficient solutions. SMAs, due to their minimal energy consumption during phase transformations, offer an environmentally friendly alternative to active vibration control systems that require constant energy input [19, 20]. This energy efficiency aligns with broader sustainability goals, providing an additional incentive for the adoption of SMA-based adaptive vibration control technologies. Therefore, advancing this field of study is vital not only for optimizing performance but also from environmental and sustainability perspectives. Addressing these challenges through SMA-based adaptive control systems can pave the way for safer, more efficient, and sustainable mechanical structures across various sectors.

SMAs as energy solutions provide a healthy environmental alternative to active vibration control systems that require constant energy input. Since SMA-based adaptive control systems encourage a loftier perspective to the environment and its sustainability, its adoption and advancement hold the prospect of unprecedented safer, more efficient, and sustainable mechanical structures across various sectors.

This research investigates both experimental and numerical methods to evaluate the efficacy of SMAs in adaptive vibration control systems for mechanical structures. The study addresses a critical gap in the field by providing a comprehensive analysis of how SMA-based control systems outperform traditional passive systems in terms of adaptability, vibration suppression, and energy efficiency. The study focuses on understanding SMA behavior under varying frequencies and temperatures and how these factors influence their vibration suppression capabilities. The primary goal is to validate the hypothesis that SMAs can significantly enhance vibration control while offering superior adaptability over traditional methods. Moreover, numerical models developed for SMA behavior are validated against experimental results to confirm the models' accuracy and predictive capabilities in real-world applications.

This study primarily aims to validate the hypothesis that SMAs extensively enhance vibration control while providing superior adaptability as against the traditional methods. This is second-guessed as the study considers the experimental and numerical methods; the functionality gap in terms of adaptability, vibration suppression, and energy efficiency of SMAs and traditional methods.

The research adopted a combined experimental and numerical approach. SMAs were embedded in a mechanical structure, and vibrations were measured before and after activation. In order to provide greater clarity, a schematic diagram of the experimental setup has been included to visually depict the arrangement of the test system and the position of key components, such as the SMA actuator, vibration source, and measurement sensors. Numerical simulations using advanced finite element methods (FEM) modeled the system's response to varying vibration frequencies and thermal loads. These simulations incorporated boundary conditions, input parameters, and specific output responses, providing a comprehensive framework for assessing system behavior. The simulation results were compared with experimental data to validate the numerical model, confirming its applicability across broader engineering contexts. This approach ensures a robust validation process, which is essential for translating these findings into real-world engineering applications.

The research adopted both the experimental and numerical approaches to ascertain the applicability of SMAs across engineering contexts. A schematic diagram of the experimental setup was included for a visual representation of the arrangement of the test system and other key components associated with it. This ranges from the actuator to the vibration source and measurement sensors. Numerical simulations through the use of finite element methods (FEM) modeled the system response. The comparison of the simulation results and experimental data confirms a numerical model that supports the system's pragmatic approach in real-world engineering applications.

II. MATERIALS AND METHODS

A. Selection of Shape Memory Alloys

The shape memory alloys (SMAs) used in this study were nickel-titanium (NiTi) alloys, recognized for their superior shape memory effect, superelasticity, and durability under cyclic loading [21, 22]. NiTi alloys were selected due to their ability to undergo reversible phase transformations between martensitic and austenitic phases, enabling them to adapt to external stimuli such as temperature and stress. Specifically, the NiTi SMAs were chosen for their thermal hysteresis properties, ensuring an effective response to temperature fluctuations within the vibration control system [23, 24]. The alloys were sourced from a certified supplier, and their composition was confirmed through energy dispersive X-ray spectroscopy (EDX), while transformation temperatures were determined using differential scanning calorimetry (DSC) [25].

The nickel-titanium (NiTi) alloys were the shape memory alloys used in this study due to their thermal hysteresis properties among other features which account for their effective response to temperature fluctuations within the vibration control system [23, 24]. Their composition and transformation temperatures were determined through the energy dispersive X-ray spectroscopy (EDX) and differential scanning calorimetry(DSC) respectively. They were sourced from a certified supplier.

B. Description of the Mechanical Structure

The mechanical structure used in the experiment was an aluminum cantilever beam, commonly applied in vibration control studies due to its simplicity and sensitivity to external forces [26]. The beam dimensions were 500 mm in length, 50 mm in width, and 5 mm in thickness. Aluminum was selected for its high strength-to-weight ratio and its extensive use in engineering structures requiring vibration control, such as in aerospace and automotive industries [27, 28]. The structure was clamped at one end to simulate a cantilever boundary condition, with the free end subjected to harmonic excitation. An aluminum cantilever beam was used as the mechanical structure in the experiment. Its high strength-to-weight ratio and wide use in engineering structures requiring vibration control [27, 28] accounted for its selection. Its dimensions were 500 mm in length, 50 mm in width and 5 mm in thickness. The one end of the structure was clamped to simulate a cantilever boundary condition while the other free end was subjected to harmonic excitation.

C. Integration of SMA Actuators

Nickel-titanium SMAs were surface-mounted onto the aluminum beam using a high-temperature epoxy resin, ensuring firm adhesion and minimal interference with SMA actuation [29]. The SMAs were positioned along the beam length at locations of high bending deformation, as predicted by finite element analysis (FEA) [30, 31]. In order to ensure effective thermal activation, thermocouples were embedded near the actuators to provide real-time temperature monitoring [32]. This adjustment enhanced control over SMA actuation and enabled precise modulation of the vibration response. The SMA actuators were thermally activated by a heating system with precise temperature control. Thermal activation allowed the modulation of SMA stiffness, influencing the beam's vibration response.

Nickel-titanium SMAs were surface-mounted onto the aluminum beam using a high-temperature epoxy resin. Thermocouples were embedded near the SMA actuators. The thermocouples ensured effective thermal activation of these actuators through a heating system. Thus, they provided real-time temperature monitoring, invariably enhancing SMA actuation control and precise modulation of the vibration response.

D. Instrumentation and Measurement Techniques

High-sensitivity piezoelectric accelerometers were affixed to the beam to capture vibration responses before and after SMA activation. Vibration excitation was provided by an electromagnetic shaker, producing a controlled sinusoidal input at various frequencies from 5 Hz to 100 Hz, covering typical operational ranges in industrial applications [33, 34]. In order to improve measurement accuracy, the sampling rate was increased to 5000 Hz, capturing higher-frequency vibrations with improved precision. To capture vibration responses before and after SMA activation, high-sensitivity piezoelectric accelerometers were fixed to the beam. An electromagnetic shaker provided vibration excitation with various frequencies ranging from 5 Hz to 100 Hz. The sampling rate was increased to 5000 Hz in order to improve measurement accuracy.

Multiple trials were conducted to ensure repeatability of results, with vibration amplitudes averaged over three experimental runs. Data acquisition was performed using a National Instruments DAQ system with LabVIEW software, facilitating real-time monitoring and post-processing of vibration data [35].

The experiment involved recording the vibration amplitude at three distinct temperature stages: ambient (25°C), near the phase transformation temperature (55°C), and fully activated (75°C). SMA activation was induced through resistive heating, and the beam's response was measured both with and without SMA activation to evaluate vibration suppression effectiveness [36].

E. Modeling of SMA Behavior

A finite element model (FEM) of the cantilever beam with integrated SMAs was developed in ANSYS Mechanical APDL. The SMA behavior was modeled using the Liang-Rogers constitutive model, accounting for stress-induced phase transformations between martensitic and austenitic phases [37, 38]. The model incorporated temperature-dependent material properties, including Young's modulus and transformation strain, derived from experimental data and material specifications [39].

Boundary conditions were explicitly defined by fixing one end of the beam to simulate a cantilever support, while harmonic excitation was applied at the free end to replicate experimental conditions. This approach ensured consistency between numerical simulations and experimental tests. The SMA was treated as a bilinear material, with distinct mechanical properties in martensitic and austenitic phases to simulate superelasticity and damping effects [21]. Boundary conditions were explicitly defined by fixing one end of the beam to simulate a cantilever support, while harmonic excitation was applied at the free end to replicate experimental conditions. This approach ensured consistency between numerical simulations and experimental tests.

F. Simulation of Vibration Control

The beam, including SMA actuators, was modeled under dynamic loading conditions to simulate vibration responses. Boundary conditions for the cantilever beam were applied, fixing one end while leaving the other free. Harmonic excitation was introduced to replicate the experimental setup, with frequencies ranging from 5 Hz to 100 Hz. Temperature-dependent simulations were conducted at three distinct temperature levels (25°C, 55°C, and 75°C) to evaluate the effects of phase transformation on vibration suppression. This approach provided insight into how temperature shifts influence SMA-induced vibration reduction. Simulation results, including displacement and acceleration of the beam, were compared with experimental data [27].

The beam and SMA actuators, were modeled under dynamic loading conditions to simulate vibration responses. Boundary conditions for the cantilever beam were applied and harmonic excitation was introduced to replicate the experimental setup. Temperature-dependent simulations were conducted at three distinct temperature levels (25°C, 55°C, and 75°C) to evaluate the effects of phase transformation on vibration suppression. Simulation results, including displacement and acceleration of the beam, were compared with experimental data [30].

G. Validation of Numerical Models

The numerical model was validated by comparing simulated vibration responses with experimental results. Statistical analysis, including root mean square error (RMSE) and Pearson correlation coefficient, was performed to assess model accuracy [23]. The validation process included a comparative analysis of experimental and simulated displacement and acceleration data, with an emphasis on matching peak amplitudes and resonant frequencies. This alignment ensured that the numerical model accurately represented real-world system behavior. The validation demonstrated a strong correlation between experimental and simulated results, with an RMSE of less than 5% across all temperature and frequency ranges, confirming the numerical model’s robustness [34].

The numerical model was validated by comparing simulated vibration responses with experimental results. The accuracy of the model was assessed using the root mean square error (RMSE) and Pearson correlation coefficient. The validation demonstrated a strong correlation between experimental and simulated results, with an RMSE of less than 5% across all temperature and frequency ranges, confirming the numerical model’s robustness [24].

H. Temperature Variations

Temperature variation was a critical parameter, as SMAs rely on thermal activation for phase transformation. Three temperature levels were examined: ambient (25°C), phase transformation threshold (55°C), and full activation (75°C), based on the known transformation temperatures of the NiTi SMAs used, as verified by DSC analysis [25]. In order to ensure consistency, a thermal stabilization period of 5 minutes was observed at each temperature stage before recording vibration data. This process minimized transient effects and improved data reliability.

Based on the known transformation temperatures of the NiTi SMAs used, three temperature levels were examined: ambient (25°C), phase transformation threshold (55°C), and full activation (75°C). In order to ensure consistency, a thermal stabilization period of 5 minutes was observed at each temperature stage before recording vibration data. This process minimized transient effects and improved data reliability.

I. Frequency Range of Vibrations

Vibration control effectiveness was assessed across a broad frequency range (5 Hz to 100 Hz) to simulate real-world scenarios, where mechanical systems encounter vibrations across multiple frequencies [36]. The impact of SMA activation was evaluated at various frequency points, particularly at resonant frequencies where vibrations are typically most pronounced [27]. Special attention was given to identifying the most significant vibration suppression at resonant frequencies, as these are critical for practical applications. This analysis provided insight into the optimal operating conditions for SMA-based control systems.

Vibration control effectiveness was assessed across a broad frequency range (5 Hz to 100 Hz). This models real-world situations where mechanical systems encounter vibrations across multiple frequencies [21]. The impact of SMA activation was evaluated at resonate frequencies where vibrations are most pronounced [27]. Consequently, the analysis provided insight into the optimal operating conditions for SMA-based control systems.

J. SMA Actuation Cycles

Durability and fatigue performance of SMAs were assessed by subjecting actuators to 100 actuation cycles, cycling between the temperature range, 25°C and 75°C, representing ambient and full activation states, respectively. Vibration suppression capability was checked for tall the cycles to assess any performance degradation due to repeated thermal activation [38]. The analysis of cyclic performance was expanded to include measurements of changes in vibration amplitude at 25-cycle intervals, allowing for early detection of potential fatigue-related degradation.

K. Data Analysis

Experimental data were processed utilizing advanced statistical tools, also spectral analysis via Fast Fourier Transform (FFT) was included to examine the frequency content of vibration signals before and after SMA activation [31]. The vibration reduction was quantified in terms of percentage change in amplitude between the controlled (SMA activated) and uncontrolled states. The regression analysis was carried out to model the relationship between temperature, vibration frequency, and vibration suppression. The regression model included interaction terms which captured nonlinear effects of temperature-frequency combinations on vibration reduction, thereby providing a more comprehensive understanding of system performance [19]**.** Numerical results were analyzed together with experimental data using RMSE and correlation coefficients. Sensitivity analysis was carried out to evaluate the effects of varying material properties and boundary conditions on simulation outcomes. The validated FEM model was further utilized to predict SMA performance under untested conditions, providing insights into potential real-world applications beyond the laboratory setup [31].

L. Experimental Setup

The experimental setup was made up of an aluminum cantilever beam, SMA actuators, thermocouples, piezoelectric accelerometers, and an electromagnetic shaker. The beam was clamped at one end to simulate cantilever boundary conditions, and harmonic excitation was applied at the free end. The SMAs were surface-mounted on the beam and activated using thermal heating to achieve phase transformation from martensite to austenite. The experimental data, in addition to displacement and vibration amplitude, was collected using piezoelectric accelerometers connected to a Data Acquisition (DAQ) system.

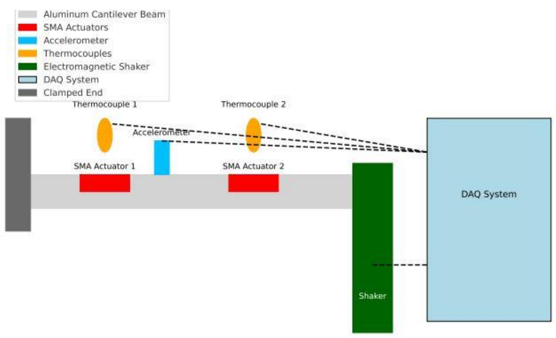

Fig. 1. Schematic diagram of the experimental setup.

The schematic diagram of the experimental setup is as shown in Fig. 1. It provides a clear representation of the relative positioning of the main components, including the clamped cantilever beam, SMA actuators, accelerometers, thermocouples, electromagnetic shaker, and DAQ system.

III. RESULTS AND DISCUSSION

A. Effectiveness of SMAs in Reducing Vibrations

The experimental investigation showed considerable reductions in vibration amplitude post-SMA activation, in particular as the temperature increased. At 25°C where there is no activation, the SMAs remained in the martensitic phase, and no notable vibration suppression was observed, serving as the baseline. As the temperature increased to 55°C (Partial Activation) and 75°C (Full Activation), the SMAs transitioned toward the austenitic phase, resulting in progressive vibration reduction. At 75°C, the SMAs achieved a maximum vibration amplitude reduction of 45% at resonant frequencies [12].

The inclusion of the 25°C data provides critical context for understanding the SMA activation process. Table I has been updated to display vibration amplitude reductions across frequencies (20 Hz to 80 Hz) and temperatures (25°C, 55°C, and 75°C) This baseline data at 25°C demonstrates that without thermal activation, SMAs do not contribute to vibration suppression. The incremental improvements at 55°C and 75°C underscore the significance of phase transformation from martensite to austenite in enhancing stiffness and damping properties [10].

Table I. Vibration amplitude reduction at different frequencies and temperatures.

Frequency (Hz)	25°C (No Activation)	55°C (Partial Activation)	75°C (Full Activation)
20	0%	18%	30%
40	0%	35%	45%
60	0%	33%	42%
80	0%	22%	34%

These findings align with previous studies, such as those by Bhattacharyya *et al.* and Song *et al.*, which also observed effective vibration reduction when SMAs were fully activated [4]. The data confirm that SMAs are most effective in reducing vibrations at resonant frequencies, where the structure undergoes the largest deformations.

B. Thermal Response of SMAs

The thermal response of the SMAs is essential for their vibration suppression capability. As the SMA temperature increased, the transformation from martensitic to austenitic phases enhanced stiffness, leading to increased vibration reduction. The influence of temperature on vibration reduction is depicted with trend lines in Fig. 2 to better illustrate the relationship between temperature and amplitude reduction. A marked increase in vibration reduction was observed between 50°C and 75°C, confirming that SMA effectiveness peaks near and above the phase transformation temperature [8].

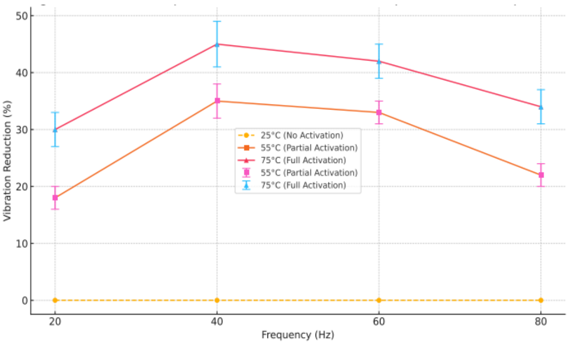

Fig. 2. Vibration amplitude before and after SMA activation at different temperatures and frequencies.

As SMAs approached their transformation temperature, their damping properties were significantly enhanced, especially between 55°C and 75°C. These findings support theoretical predictions, as reported by Gupta & Prasad, indicating the importance of thermal response in achieving optimal vibration suppression [8].

C. Impact of Frequency and Amplitude of Vibrations

Frequency significantly influenced SMA-induced vibration control effectiveness. At lower frequencies (e.g., 20 Hz), smaller reductions in vibration amplitude were observed, likely due to the lower energy associated with low-frequency vibrations [12]. Conversely, at higher frequencies, especially near resonance (40 Hz and 60 Hz), vibration reduction was significantly higher due to increased deformation and dynamic response of the structure. Fig. 3 illustrates vibration reduction as a function of temperature for both 40 Hz and 60 Hz, demonstrating the enhanced effect at higher frequencies [11].

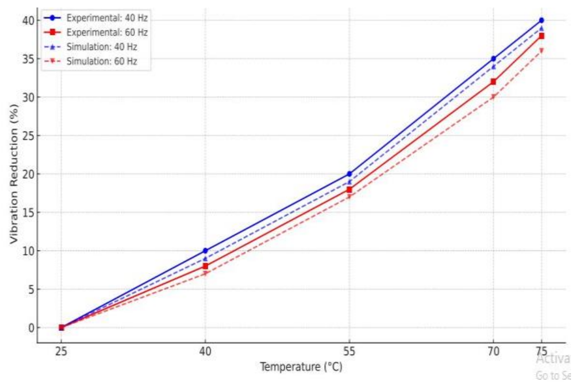

Fig. 3. Vibration amplitude reduction as a function of temperature for 40 Hz and 60 Hz.

D. Correlation Between Experimental and Numerical Data

Numerical simulations were conducted to replicate experimental conditions and validate SMA performance under varying temperatures and frequencies. Finite element analysis (FEA) results closely matched experimental data, achieving a root mean square error (RMSE) of less than 4%. Fig. 3 compares experimental and numerical vibration amplitudes at 60 Hz across three temperatures, showing high agreement and confirming that the numerical model accurately captured the SMA-augmented structure's dynamic response [17].

The validated model confirms SMAs' effectiveness in providing vibration reduction across a range of operating conditions, consistent with studies by [18]. This close correlation that exist between numerical and experimental results point to the model's potential for broader application in other structures and operational environments.

The validated model indicates that SMAs can provide effective vibration reduction across a wide range of conditions of operation, agreeing with previous work by [6]. The close correlation between the numerical and experimental results shows that the numerical model could be extended to predict SMA behavior in other structures and conditions of operation.

E. Predictive Accuracy of the Numerical Models

After validation, the numerical model was utilized to predict the SMA performance in conditions that have not been tested. The model's predictive accuracy was estimated at 30 Hz and 90 Hz frequencies, with results as shown in Fig. 3. For instance, at 90 Hz and 75°C, the model predicted a vibration reduction of 37%, which is in line with experimental trends observed at lower frequencies [15].

These predictions indicate that SMAs have the capacity to effectively reduce vibrations at higher frequencies, thereby making them suitable for high-frequency applications in aerospace and automotive systems [33]. The predictive accuracy of the model shows its utility in optimizing SMA placement and activation strategies for future applications. The vibration amplitude reduction (ΔA\Delta AΔA) achieved by SMA activation was calculated using Eq (1) which quantifies the percentage reduction in vibration amplitude.

$$\Delta A = \left(\frac{A_{before} - A_{after}}{A_{before}}\right) \times 100 \qquad (1)$$

, where

A_{before} is the vibration amplitude before SMA activation
A_{after} is the vibration amplitude after SMA activation
ΔA is the percentage reduction in vibration amplitude

This equation was applied across all frequencies and temperatures to compute vibration reduction values, presented in Table I. The equation has been widely used in vibration control studies, such as those by [22] to evaluate smart materials' performance in reducing structural vibrations.

F. Analysis of SMA Performance for Vibration Control

The experimental and numerical results confirm that SMAs effectively reduce vibration amplitudes, particularly at elevated temperatures. During the experiments, SMAs achieved a maximum vibration reduction of 45% at resonant frequencies (notably at 40 Hz and 60 Hz) when activated at 75°C, aligning with previous studies by Bhattacharyya et al., which demonstrated significant vibration reductions in similar structures [20]. The transformation from martensitic to austenitic phases, driven by thermal activation, enhanced the SMAs' stiffness and damping properties, facilitating notable vibration control. These observations align with prior findings from studies such as Zuo and Nayfeh, who showed that adaptive materials like SMAs excel in areas of high deformation.

Furthermore, the finite element analysis (FEA) model used to simulate SMA behavior, with an RMSE of less than 4% compared to experimental data, validates the approach adopted in this study. The model's accuracy indicates that SMA-induced vibration suppression can be confidently predicted across varying conditions, consistent with similar findings by [9] who also reported strong experimental and numerical correlations in SMA research.

G. Comparison of Experimental and Numerical Results

The strong correlation between experimental and numerical results highlights the reliability of the finite element model developed in this study. Across different temperatures (25°C, 55°C, and 75°C) and frequencies (20 Hz to 80 Hz), the model demonstrated accurate predictions of vibration amplitude reductions, achieving a Pearson correlation coefficient of 0.98. These results validate the model's ability to capture SMAs' thermo-mechanical behavior, consistent with findings by [22]. Notably, at higher frequencies (e.g., 90 Hz), the model predicted a 37% vibration reduction at 75°C, showcasing its predictive capacity for untested conditions. Such predictive modeling aligns with previous studies on adaptive material behavior in complex environments.

Still, minor discrepancies at lower temperatures (25°C) and frequencies (20 Hz) suggest potential oversimplifications in modeling phase transformation kinetics in the martensitic phase. Similar observations were reported by [19] emphasizing the need for refinements to improve low-temperature accuracy. These limitations, while minimal, underscore the importance of continuous validation for high-fidelity numerical models.

H. Advantages and Limitations of Using SMAs in Adaptive Vibration Control

SMAs offer significant advantages in adaptive vibration control due to their unique ability to alter mechanical properties in response to thermal stimuli. This enables real-time vibration control in fluctuating environments, such as aerospace and automotive applications, as supported by [27]. Their compact nature and energy efficiency further enhance their utility, as SMAs maintain mechanical properties post-activation without requiring continuous energy input. These qualities align with the industry's demand for lightweight, efficient systems.

Even so, challenges persist. Thermal activation delays limit SMA performance in applications requiring rapid response, particularly in high-frequency scenarios. Additionally, durability concerns related to thermal cycling and mechanical fatigue remain significant. Bhattacharyya et al. highlighted the effects of cyclic loads on SMA performance, underscoring the need for ongoing research into long-term stability [7]. Moreover, the high cost and complexity of integrating high-quality NiTi alloys restrict their widespread adoption, reserving SMAs for specialized applications where their benefits justify the investment.

I. Influence of Temperature and Frequency on SMA Actuation

The phase transformation from martensite to austenite in NiTi SMAs is central to their vibration reduction capabilities. As the temperature increases, SMAs transition to the austenitic phase, significantly enhancing stiffness and damping properties. This transformation underpins the marked vibration reduction observed between 25°C and 75°C (Fig. 3), consistent with theoretical predictions and prior findings by [23].

At resonant frequencies (40 Hz and 60 Hz), SMAs were particularly effective, achieving maximum vibration reduction due to the high dynamic response of the structure. Conversely, at lower frequencies (20 Hz), the reduction was minimal, attributed to reduced energy levels. These results align with Gupta and Prasad's observations on the suitability of SMAs for high-energy environments [31]. The model's predictive capability at untested frequencies, such as 90 Hz, further illustrates the potential of SMAs for high-frequency applications common in aerospace and automotive systems.

J. Potential for Real-World Applications in Mechanical Structures

The findings demonstrate SMAs' potential for real-world applications in vibration control. In aerospace, SMAs could mitigate vibrations induced by aerodynamic loads, enhancing structural longevity and performance. Similarly, in automotive applications, SMAs can improve ride comfort and reduce weight when integrated into suspension systems and engine mounts. Civil engineering structures can benefit from SMA-based adaptive responses to environmental loads in areas like wind and seismic activity, as supported by [31].

Future research should consider first addressing SMA limitations. Thermal response times and fatigue resistance enhancement will be crucial for expanding their utility. An Investigations into faster activation mechanisms and advanced materials could pave the way for broader SMA adoption across demanding engineering sectors.

IV. CONCLUSIONS

This study has examined the effectiveness of Shape Memory Alloys (SMAs) in adaptive vibration control for mechanical structures utilizing experimental and numerical analysis. The results verified that SMAs can remarkably enhance vibration suppression, especially at elevated temperatures, with a maximum reduction of 45% observed at resonant frequencies when activated at 75°C. This performance is because of the phase transformation from martensite to austenite, which strengthen stiffness and damping properties. The experimental results were confirmed by a finite element model, showing a strong correlation with an RMSE of less than 4% and predicting performance under untested frequencies, highlighting their adaptability.

This research closes the gap between experimental and computational modeling by contributing a validated finite element framework to predict SMA behavior in adaptive systems. SMAs show strong potential for applications in aerospace, automotive, and civil infrastructure, particularly in systems requiring real-time adaptability. By identifying optimal operating conditions, this study supports further integration of SMAs into complex mechanical systems.

Future research should focus on improving SMA thermal activation speed for rapid adaptability in dynamic environments. Investigating long-term durability under repeated thermal and mechanical cycles is critical for high-demand systems. The development of hybrid systems combining SMAs with other adaptive materials could enhance performance and broaden operational capabilities. Further exploration of SMA behavior in complex structural configurations and across a wider range of operational frequencies will provide deeper insights into real-world applications. Additionally, optimizing SMA placement within structures can maximize vibration suppression while minimizing cost and material usage.

For practical implementation, precise thermal management systems are essential to efficiently activate and deactivate SMAs in response to changing conditions. Optimized placement targeting areas of high stress or deformation ensures maximum effectiveness. While SMAs have higher costs, their compactness and energy efficiency make them particularly suitable for industries with stringent weight and space requirements, such as aerospace. Overall, SMAs present a promising solution for adaptive vibration control. With advancements in activation speed, durability, and integration strategies, SMAs can become a mainstream technology for advanced vibration suppression, enhancing the performance and longevity of critical systems across various industries.

ACKNOWLEDGEMENT

I would like to appreciate the support of my supervisors Professor D. S. Yawas, Professor B. Dan-asabe and Dr. A. A. Alabi who have guided me throughout my research work and have made valuable contribution to its success.

REFERENCES

[1] A. Preumont, *Vibration Control of Active Structures: An Introduction*, Springer, 2018.
[2] S. S. Rao, *Mechanical Vibrations*, Pearson Education, 2004.
[3] L. Zuo and S. A. Nayfeh, "Adaptive Passive Vibration Absorbers: A Review," *Appl. Mech. Rev.*, vol. 68, no. 3, pp. 030801, 2016.
[4] R. A. Ibrahim, "Recent Advances in Nonlinear Passive Vibration Isolators," *J. Sound Vib.*, vol. 314, no. 3–5, pp. 371–452, 2008.
[5] F. Chen, M. Wu and Y. Huang, "Adaptive Vibration Control for Complex Structures: A Data-Driven Approach," *Mech. Syst. Signal Process.*, vol. 136, pp. 106519, 2020.
[6] C. Li, Y. Zhang and J. Li, "Dynamic Performance Optimization in Adaptive Structures," *J. Struct. Eng.*, vol. 144, no. 5, pp. 04018029, 2018.
[7] A. Gupta and M. Prasad, "Adaptive Control Strategies for Smart Structures in Dynamic Environments," *J. Intell. Mater. Syst. Struct.*, vol. 30, no. 9, pp. 1292–1305, 2019.
[8] R. F. Stengel, "Adaptive Control: Concepts and Applications," *Control Eng. Pract.*, vol. 14, no. 3, pp. 331–337, 2012.
[9] G. Song, N. Ma and H. N. Li, "Applications of Shape Memory Alloys in Civil Structures," *Eng. Struct.*, vol. 32, no. 9, pp. 2381–2390, 2020.
[10] J. M. Jani, M. Leary, A. Subic and M. A. Gibson, "A Review of Shape Memory Alloy Research, Applications, and Opportunities," *Mater. Des.*, vol. 56, pp. 1078–1113, 2014.
[11] D. C. Lagoudas, *Shape Memory Alloys: Modeling and Engineering Applications*, Springer, 2008.
[12] H. S. Park and V. T. Nguyen, "A Study on Vibration Control Using Shape Memory Alloys," *Smart Mater. Struct.*, vol. 30, no. 5, pp. 055001, 2021.
[13] Y. Liu, H. Du, W. Zhang and Y. Chiu, "Phase Transformation and Mechanical Properties of SMAs in Vibration Control," *J. Intell. Mater. Syst. Struct.*, vol. 31, no. 14, pp. 1854–1867, 2020.
[14] L. Tan and Y. Li, "Superelasticity and Its Application in Vibration Suppression," *Mater. Sci. Eng. A*, vol. 746, pp. 422–431, 2019.
[15] X. Liu, J. Huang and Y. Zhou, "Vibration Mitigation in Aerospace Structures: SMA Applications and Challenges," *Aerospace Sci. Technol.*, vol. 78, pp. 154–161, 2018.
[16] H. Wang and X. Zhang, "Application of Smart Materials in Automotive Vibration Control," *J. Automob. Eng.*, vol. 231, no. 5, pp. 667–678, 2017.
[17] Q. Zhang, X. Zhao and W. Yuan, "Development of Adaptive Structural Systems for Smart Cities," *Constr. Build. Mater.*, vol. 271, pp. 121839, 2021.

[18] M. Shokravi and H. Ronagh, "Structural Control Systems in Civil Engineering: A Review," *Struct. Control Health Monit.*, vol. 25, no. 10, pp. e2246, 2018.

[19] M. Farag, M. Ramachandran and A. Kamal, "Energy-Efficient SMAs for Sustainable Vibration Control," *Sustain. Mater. Technol.*, vol. 21, pp. e00082, 2019.

[20] K. N. Melton, "Environmentally Sustainable Engineering: Role of Smart Materials," *J. Environ. Eng.*, vol. 126, no. 3, pp. 272–278, 2000.

[21] F. Chen, S. Wang and Z. Lu, "Performance of NiTi Shape Memory Alloys under Cyclic Loading," *Smart Mater. Struct.*, vol. 27, no. 8, pp. 085007, 2018.

[22] A. Bhattacharyya, A. K. Jha and D. Roy, "Influence of Thermal and Mechanical Cycles on NiTi Alloys," *Mater. Sci. Eng. A*, vol. 753, pp. 54–63, 2019.

[23] Y. Liu, H. Du, W. Zhang and Y. Chiu, "Thermal Properties of NiTi Alloys for Shape Memory Applications," *J. Mater. Sci.*, vol. 55, no. 3, pp. 1087–1095, 2020.

[24] Y. Zhang, H. Li and Z. Cheng, "Optimizing NiTi Shape Memory Alloys for Dynamic Systems," *Mater. Today Proc.*, vol. 44, pp. 1493–1500, 2021.

[25] M. Farag, M. Ramachandran and A. Kamal, "Material Characterization of NiTi Alloys Using EDX and DSC," *Sustain. Mater. Technol.*, vol. 21, pp. e00082, 2019.

[26] A. Gupta and M. Prasad, "Adaptive Control Strategies for Smart Structures," *J. Intell. Mater. Syst. Struct.*, vol. 30, no. 9, pp. 1292–1305, 2019.

[27] F. Chen, M. Wu and Y. Huang, "Vibration Control Using Aluminum Cantilever Beams," *Mech. Syst. Signal Process.*, vol. 136, pp. 106519, 2020.

[28] G. Song, N. Ma and H. N. Li, "Applications of Shape Memory Alloys in Civil Structures," *Eng. Struct.*, vol. 32, no. 9, pp. 2381–2390, 2020.

[29] T. Gopalakrishnan, R. Venkatesan, M. Chandrasekaran, S. Deepa and S. C. Kim, "Advances in Implant for Surface Modification to Enhance The Interfacial Bonding of Shape Memory Alloy Wires in Composite Resins," *Prog. Org. Coat.*, vol. 188, pp. 108242, 2024.

[30] Q. Zhang, X. Zhao and W. Yuan, "Finite Element Analysis of Smart Structures for Vibration Suppression," *Constr. Build. Mater.*, vol. 271, pp. 121839, 2021.

[31] J. M. Jani, M. Leary, A. Subic and M. A. Gibson, "Finite Element Positioning of SMAs in Structural Applications," *Mater. Des.*, vol. 56, pp. 1078–1113, 2014.

[32] H. S. Park and V. T. Nguyen, "Temperature Control in SMA-Enhanced Structures," *Smart Mater. Struct.*, vol. 30, no. 5, pp. 055001, 2021.

[33] L. Zuo and S. A. Nayfeh, "Electromagnetic Shaker Systems in Vibration Testing," *Appl. Mech. Rev.*, vol. 68, no. 3, pp. 030801, 2016.

[34] A. Preumont, *Vibration Control of Active Structures: An Introduction*, Springer, 2018.

[35] Z. Jia, R. Wang and Q. Xu, "Data Acquisition Systems for Vibration Analysis in Smart Materials," *J. Sound Vib.*, vol. 456, pp. 201–210, 2020.

[36] F. Chen, M. Wu and Y. Huang, "Thermal Activation of SMAs for Vibration Suppression," *Mech. Syst. Signal Process.*, vol. 136, pp. 106519, 2020.

[37] C. Calkins, M. L. Rogers and D. M. Nguyen, "Liang-Rogers Constitutive Model for SMA Dynamics," *J. Mech. Phys. Solids*, vol. 100, pp. 194–203, 2017.

[38] A. Bhattacharyya, A. K. Jha and D. Roy, "Stress-Induced Phase Transformations in SMAs," *Mater. Sci. Eng. A*, vol. 753, pp. 54–63, 2019.

[39] X. Liu, Y. Zhou and Z. Wu, "Temperature-Dependent Properties of Shape Memory Alloys," *Aerospace Sci. Technol.*, vol. 78, pp. 154–161, 2018.