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DAMPING OPTIMIZATION IN LOCALLY RESONANT METASTRUCTURES VIA HYBRID GA-PSO ALGORITHMS AND MODAL ANALYSIS

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ABSTRACT

This study explores the optimization of bandgap characteristics in locally resonant metastructures through advanced artificial intelligence (AI) and optimization algorithms, focusing on the accurate estimation of resonator damping ratios. By developing a novel mathematical framework for metastructure analysis, this research diverges from traditional methods, offering a more nuanced approach to bandgap manipulation. This research significantly improves metastructure modeling accuracy by precisely estimating resonator and structural damping ratios, enhancing model fidelity crucial for analysis, control strategies, and design optimization. Through a combination of model simulations and experimental validation, the efficacy of the Hybrid Genetic Algorithm-Particle Swarm Optimization (GA-PSO) algorithm is demonstrated, highlighting its potential for practical applications in engineering metastructures. This paper not only provides a robust method for estimating damping ratios but also opens new avenues for future research, including the application of machine learning techniques and the development of intelligent materials. The findings of this study contribute to the foundational understanding necessary for the advancement of mathematical modeling metamaterials, with broad implications for industries where precise vibration control is crucial.

Keywords: Bandgap Optimization, Modal Expansion Method, Experimental Damping Estimation

1. INTRODUCTION

The burgeoning field of metamaterials has revolutionized engineering and material science by offering properties not found in nature, particularly in controlling wave phenomena. These engineered materials are notable for their bandgaps-specific frequency ranges where wave propagation is hindered. These bandgaps are critical in applications aimed at reducing vibration and noise. However, the inherent damping in metamaterials, originating from their structural components and embedded resonators, poses a challenge. The resonator's damping ratio, denoted as ζ_r, is a key determinant of bandgap efficacy and thus a focus for enhancing the vibration suppression capabilities of these materials.

The exploration of metamaterials has advanced significantly in recent years, with a particular focus on their unique wave manipulation capabilities. Research by Valipour et al. [1] and Dalela et al. [2] has demonstrated how metamaterials can be designed to exhibit bandgaps, effectively blocking specific frequency ranges. These bandgaps are pivotal in applications requiring vibration suppression and noise control.

The role of AI in material science has grown exponentially, with studies like Diao et al. [3] showcasing how machine learning algorithms can predict and optimize material properties. The application of AI in metamaterials, as explored by Song et al. [4], is an emerging field that promises to revolutionize the design and functionality of these materials.

The complexity of metamaterials, especially those exhibiting bandgaps, necessitates sophisticated optimization techniques. The works of Zagaglia et al. [5] and Meng et al. [6] have highlighted the efficacy of algorithms like Genetic Algorithms, Particle Swarm Optimization, and others in fine-tuning the properties of dynamic systems for optimal performance.

The integration of AI with optimization algorithms in the context of metamaterials is a relatively new concept. Recent studies, such as those by Xiong et al. [7], and Salsa et al [8] have begun to explore this integration, showing promising results in the dynamic manipulation of bandgaps and enhancing the functionality of metamaterials.

This work breaks new ground by developing a fresh mathematical formulation for the analysis of metastructures, moving beyond conventional Bloch and dispersion curve methodologies. This innovative framework allows for a more nuanced AI and optimization algorithm-based analysis of bandgap phenomena.

The importance of this research lies in its capacity to significantly enhance the accuracy of mathematical models for metas-

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tructures through precise estimation of both resonator and structural damping ratios. This improvement in model fidelity is vital for in-depth analysis, robust control strategies, and efficient design optimization of metastructures.

The current approaches to metastructure analysis are limited in their ability to adapt to variable damping scenarios, presenting a challenge in the real-world application of bandgaps. This research proposes a solution to this limitation by enabling precise damping ratio adjustments within the bandgap optimization process.

The effectiveness of this new framework is demonstrated through a combination of model predictions and real-world experiments. This validation supports the claim that AI-driven optimization can more effectively tailor bandgap properties for practical use, providing a clear path to bridge the gap between theoretical and applied metamaterials research.

The article is structured as follows: Section 2 discusses the research methods, incorporating modal expansion and optimization algorithms to model the metamaterial and identify critical parameters influencing its bandgap properties. Section 3 analyzes the results from these optimization algorithms, assesses their effectiveness in capturing the dynamics of the metastructure, and examines their implications for vibration suppression. Section 4 offers conclusions and suggests directions for future work.

2. ANALYTICAL AND EXPERIMENTAL APPROACHES FOR METASTRUCTURE OPTIMIZATION

This study refines the analysis of metastructures using a distributed parameter model, focusing on modal dynamics and system transfer functions. It simulates real-world conditions by integrating noise into theoretical models and employs optimization algorithms like the Hybrid GA-PSO for parameter estimation. This approach balances traditional modal analysis with modern computational techniques, enhancing our grasp of metastructural dynamics for more effective design and vibration suppression strategies. The incorporation of actual experimental data further validates the optimization methods, ensuring their practical applicability in complex system analysis.

2.1 Modal Transfer Function Dynamics of Structure

The study employs modal analysis within a distributed parameter model to explore the dynamic characteristics of a metastructure, consisting of an aluminum rectangular beam with integrated local resonators. This analytical approach facilitates the identification of natural frequencies and mode shapes, which are used for the control of the structure's bandgap properties.

Equations (1) and (2) elucidate the interaction between the beam's displacement and the resonators' movement, as well as the influence of external excitations. These equations are derived from a comprehensive modal decomposition approach, leveraging the system's orthogonality conditions to simplify the complex dynamics.

$$\begin{aligned} &\ddot{z}_m(t) + 2\zeta_m\omega_m\dot{z}_m(t) + \omega_m^2 z_m(t) \\ &- \sum_{r=1}^{N_r} m_r\omega_r\left(\omega_r z_r(t) + 2\zeta_r\dot{z}_r(t)\right)\phi_m(x_r) \\ &= \mathbb{Q}_{b_m}(x,t), \quad m = 1,2,\ldots,N_m \end{aligned} \tag{1}$$

Equation (1) captures the modal dynamics of the beam, incorporating the effects of damping and resonator interaction. It presents a detailed account of how the resonators' characteristics and positioning influence the beam's response to dynamic loads.

$$\begin{aligned} &\ddot{z}_r(t) + 2\xi_r\omega_r\dot{z}_r(t) + \omega_r^2 z_r(t) + \\ &\sum_{m=1}^{N_m}\ddot{z}_m(t)\phi_m(x_r) = \mathbb{Q}_{b_r}(t), \quad r = 1,2,\ldots,N_r \end{aligned} \tag{2}$$

Conversely, Equation (2) details the resonators' dynamics, highlighting the interaction between resonator movements and the structural modes. The approach discussed more in [9] to identify natural frequencies and mode shapes within a metastructure. The analysis involves developing partial differential equations through a distributed parameter model to describe the system's dynamics. These equations are then discretized and solved numerically to gain a better understanding of the metastructure's modal characteristics, enabling the precise manipulation of bandgaps within the structure.

In reaching the stage of formulating the transfer function, the analysis first considers the resonator masses (m_r), which are proportionally determined by the structure's mass distribution at the resonators' attachment points. This relationship is quantified by a mass ratio (μ), reflecting the resonators' total mass relative to the base structure's mass, as represented by the formula $m_r = \mu m(x_r)\,dx_r$. This ensures that the resonator masses directly correspond to the structural mass distribution, thereby aligning resonator behavior with the overall dynamics of the structure. For systems incorporating numerous resonators, an approximation is employed, equating the summation over discrete resonators to a continuous integral over the structure's length. Taking the Laplace transform of equations (1) and (2), followed by mathematical manipulation, leads to the derivation of a transfer function. This function elucidates the relationship between the displacement of the structure's m-th mode and the corresponding excitation force as [9]:

$$\frac{Z_m(s)}{Q_{b_m}(s)} = \frac{1}{s^2\left(1 + \frac{\mu(2\zeta_r\omega_r s + \omega_r^2)}{s^2 + 2\zeta_r\omega_r s + \omega_r^2}\right) + 2\zeta_m\omega_m s + \omega_m^2}, \quad m = 1,2,\ldots,N_m \tag{3}$$

In this context, $Z_m(s)$ represents the Laplace-transformed displacement of the structure's m-th mode, $Q_{b_m}(s)$ symbolizes the Laplace-transformed external force, ζ_m and ζ_r are damping ratio of structure's m-th mode and resonator, respectively. ω_m and ω_r are the natural frequencies of the structure's m-th mode and the resonators, respectively.

2.2 Estimation of Damping Ratio in Metastructures

In the study of metastructures, estimating the damping ratio ζ_r from experimental data is pivotal for the effective modeling of vibration suppression and dynamic response tuning. Various methods can be employed for this estimation, each with its specific advantages and requirements. These include Frequency Response Analysis, System Identification Techniques, Energy Decay Method, Optimization Algorithms, and Bayesian Inference.

To estimate the damping ratio, optimization algorithms are utilized due to their ability to navigate complex, multidimensional parameter spaces. These algorithms are particularly effective in situations where the objective function is non-linear or nonsmooth, as often encountered in real-world data from metastructures. An objective function is defined to quantify the error between the experimental data and theoretical model predictions. Several algorithms are considered for algorithm Selection and configuration:

Nelder-Mead Simplex Algorithm: A heuristic search method ideal for non-smooth functions, enabling robust initial parameter estimation without derivatives. Genetic Algorithm (GA): This algorithm excels in finding global solutions in complex problems characterized by multiple local minima.

Particle Swarm Optimization (PSO): It simulates a social process, effectively honing in on global optima, especially in continuous optimization scenarios.

Artificial Bee Colony (ABC) Algorithm: Inspired by the foraging behavior of bees, it balances local and global search effectively, useful for complex parameter estimation tasks.

Hybrid GA-PSO: Combining GA's exploration and PSO's exploitation efficiency, this approach aims to quickly and reliably find global optima in multi-modal data landscapes.

For implementation, each algorithm is configured with appropriate parameters such as learning rate, population size, mutation rates, and particle velocities. The choice and configuration of the algorithm depend on the specific requirements of the problem and the nature of the experimental data. The selected algorithm is run to optimize the ζ_r, using the objective function to guide the search. This process is iterative, involving continuous evaluation and refinement based on performance metrics.

2.3 Integration in Metastructure Damping Estimation

These algorithms are particularly suited for metastructure analysis due to their ability to handle non-linearities and discontinuities in the objective function, which commonly arise from complex modal interactions within the structure. To estimate ζ_r, the mentioned algorithms can be configured to:

- Define an initial range of possible damping values based on physical constraints and preliminary data.
- Evaluate the fitness of each candidate solution by integrating the damping values into the metastructure model and comparing the resulting dynamic response with experimental measurements.
- Iteratively refine the population of algorithms based on the fitness evaluations, converging on a solution that best fits the experimental data.

The Sum of Squared Errors (SSE) is a statistical measure commonly used to quantify the difference between predicted values and observed data, especially useful in optimizing damping ratios in metastructures. SSE is calculated by summing the squares of the differences between observed experimental responses (y_i) and model predictions ($\hat{y}_i$) across n data points at various excitation frequencies. This formula provides a scalar value indicating the magnitude of error across all frequencies.

In the context of damping ratio estimation for metastructures, minimizing SSE helps in fine-tuning the parameters of optimization algorithms. The process includes simulating the metastructure model across a range of frequencies, comparing the predicted responses to the actual observed responses, and using SSE as the objective function to guide optimization.

Given a dataset consisting of n observed experimental data points y_i at different excitation frequencies, and corresponding model predictions $\hat{y}_i$, the SSE is calculated as follows:

$$\mathrm{SSE} = \sum_{i=1}^{n} (y_i - \hat{y}_i)^2$$

Where y_i is the observed experimental response of the metastructure at the i-th excitation frequency. $\hat{y}_i$ is the predicted response from the metastructure model using the estimated damping ratios at the same frequency. n is the total number of data points, encompassing various excitation frequencies used during the experimental testing and simulations.

By minimizing the SSE, the optimization algorithms adjust the damping ratios ζ_r and ζ_m to achieve a closer match between the model predictions and the experimental results.

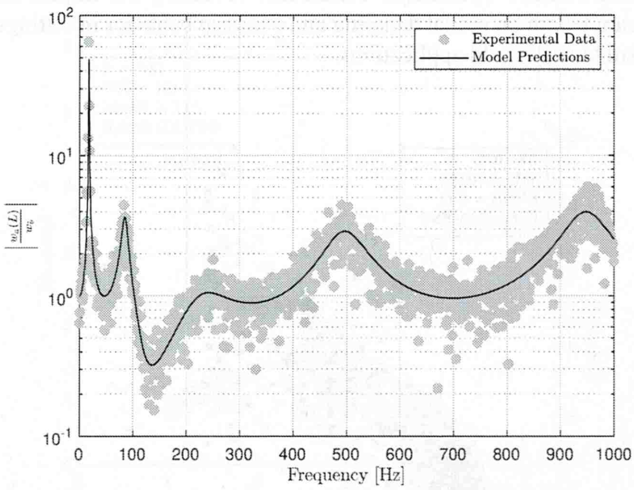

FIGURE 1: Comparison of the beam's transmittance: noisy signal versus model predictions, highlighting the algorithm's effectiveness in identifying transmittance characteristics within the bandgap frequency range. Parameters are as listed in Table 1 with initial simulations for noisy signal evaluation, using parameters L_{m_0}, m_{r_0} and k_{r_0}.

3. RESULTS AND DISCUSSION

In this section, the analysis extends to incorporating noise within theoretical models to closely mimic real-world scenarios, aiming to estimate the damping ratio ζ_r in systems characterized by a locally resonant bandgap. This study further delves into the utilization of actual experimental data, segmented into two distinct parts: a simple beam and a metastructure. Each segment is examined to determine the structural modal damping ratio ζ_m, demonstrating the efficacy and adaptability of the Hybrid

TABLE 1: Geometric and material properties of the studied rectangular aluminum beam

Parameter	Value	Parameter	Value
L_{m_0}	0.3 m	m_{r_0}	17 g
L_m	0.91 m	k_{r_0}	9kN
w_m	40 mm	m_r	10 g
h_m	3 mm	k_r	1.65 kN/m
ρ_m	2700 kg/m^3	N_r	8
E_m	69.5 GPa	N_m	8

GA-PSO algorithm across diverse experimental contexts. The outcomes of this investigation affirm the model's capability to accurately predict dynamic behavior, emphasizing its relevance and potential in enhancing vibration suppression techniques in metastructures.

The use of different beam lengths in our study—0.3 meters for preliminary tests to assess basic dynamic responses and modal analysis under controlled conditions, and 0.9 meters for comprehensive experimental validation—allows us to explore metastructure behavior across various scenarios. The shorter beam facilitates detailed observation of higher frequency dynamics for initial model validations, while the longer beam helps simulate more realistic operational conditions, revealing the impact of beam length on modal damping and bandgap behavior in settings akin to real-world applications.

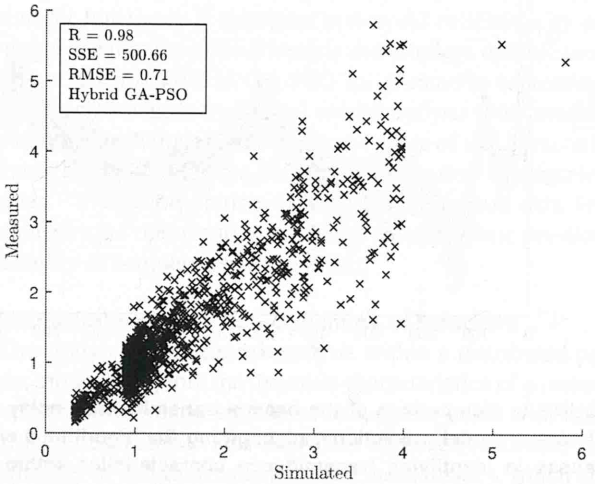

FIGURE 2: Scatter plot demonstrating the correlation between measured and simulated data via the Hybrid GA-PSO algorithm, evidencing high model accuracy with a correlation coefficient (R) of 0.98.

The algorithm's performance in calculating ζ_r is illustrated in Figure 1. The nominal ζ_r is 0.2 as an initial guess, and the results are contextualized within the parameters outlined in Table 1, which details the geometric and material properties of the rectangular aluminum beam under investigation. The findings indicate the algorithm's robustness in parameter estimation amidst experimental uncertainties. Figure 2 presents a scatter plot comparing measured data against values simulated by the Hybrid GA-PSO algorithm. The horizontal axis (Simulated) represents the predicted values of the dynamic response of the metastructure, normalized to the same scale as the experimental measurements, which are depicted on the vertical axis (Measured). Each data point corresponds to a specific excitation frequency used during the simulations and experimental testing, ranging from 0 to 5 arbitrary units reflecting normalized response magnitudes. The tight clustering of data points around the line of unity and the high correlation coefficient (R = 0.98) suggest a strong agreement between the model's predictions and the measured data. The scatter plot highlights the algorithm's precision in estimating the damping parameter ζ_r, as evidenced by the low root mean square error (RMSE = 0.71) and the sum of squared errors (SSE = 500.66), which quantify the model's predictive accuracy. This figure substantiates the Hybrid GA-PSO's efficacy in capturing the underlying dynamics of the metastructure under study.

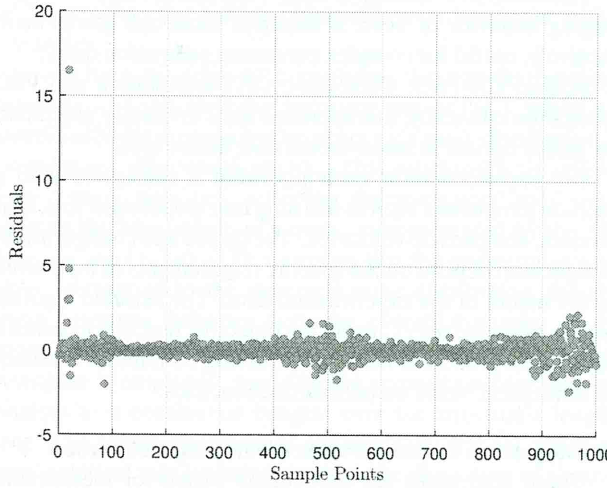

FIGURE 3: Residual plot from the Hybrid GA-PSO model prediction demonstrating the residuals' distribution against sample points, underscoring the model's accuracy with a high coefficient of determination (R^2).

Figure 3 reveals the model's residual distribution, crucial for evaluating the Hybrid GA-PSO algorithm's accuracy in estimating ζ_r. The residuals, mostly centered around zero, suggest a strong model fit, corroborated by a high R^2 value (0.91). Outliers at the start may signal deviations due to experimental anomalies or noise, warranting further investigation to enhance the algorithm's reliability.

3.1 Empirical Analysis of a Basic Beam Structure

To substantiate the theoretical model and optimization approaches proposed in this study, an experimental validation was conducted using a cantilever beam setup. This setup is depicted in Figure 4. The experiment involved a cantilever beam composed of aluminum, with 3 mm in thickness, 4 cm in width, and 0.91 m in length. This beam, representative of a standard metamaterial structure, was devoid of any locally resonant subsystems.

The experimental rig included a 100N TIRA 51110 Shaker, which provided base motion to excite the beam. The response

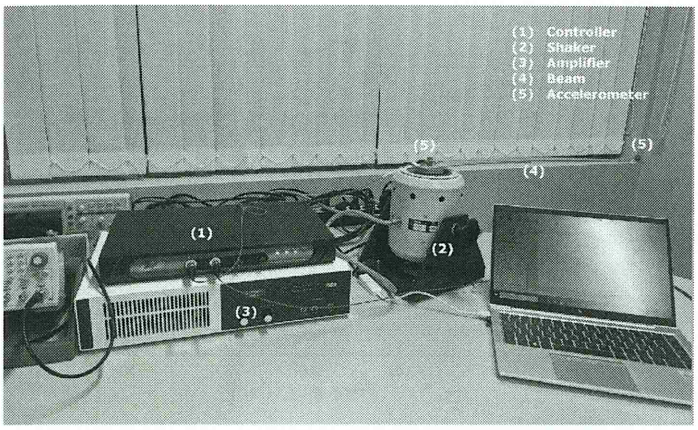

FIGURE 4: Experimental setup showcasing the simple cantilever beam attached to the Shaker, with the Dytran Accelerometers positioned at the base and tip, and connected to the Power Amplifier and Controller.

of the beam was meticulously measured using a Dytran Accelerometer 3055D21, a single-axis TEDS accelerometer capable of 100mV/g. This accelerometer, weighing 10 grams, was employed to capture the tip acceleration, while a second accelerometer of the same model was used at the base for control purposes. The Power Amplifier BAA 120 was utilized to amplify the input signals to the Shaker. The Vibration Controller VR9500, was employed to regulate, control the base, and monitor the vibrational inputs and responses. It is worth noting that the addition of hardware, specifically the low-noise accelerometer wire, introduced additional mass to the system. This added mass, assumed to be approximately 1% of the accelerometer's mass, was factored into the experimental analysis to ensure accurate representation of the beam's response.

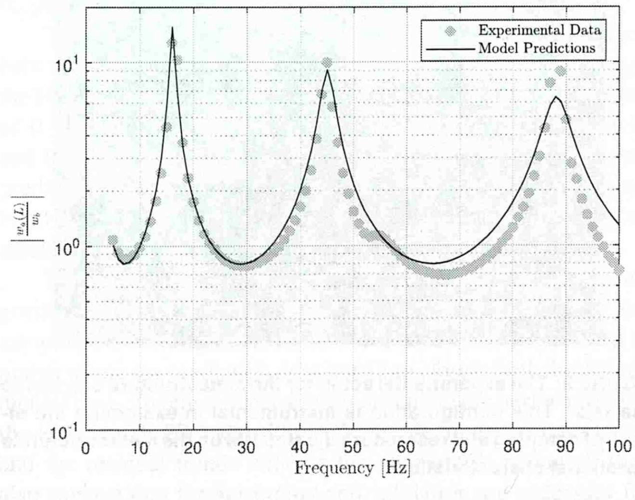

FIGURE 5: Transmittance response of a cantilever beam with Hybrid GA-PSO algorithm estimations, highlighting the model's alignment with experimental data for structural modal damping ratio (ζ_m) estimation.

The response of the cantilever beam under base excitation generates data on the dynamic behavior of metamaterials. The data obtained from this experimental setup will be further analyzed and compared with model predictions.

Since the resonators are not incorporated into the system for the first part of the experiment, the focus shifts to estimating the modal damping ratio (ζ_m) of the main structure. Drawing on conclusions from the previous sections, the Hybrid GA-PSO algorithm emerged as a strong candidate for such estimations. In this phase of the research, this algorithm is employed to determine ζ_m, leveraging its demonstrated proficiency in parameter estimation within complex dynamic systems.

Figure 5 presents the transmittance response, comparing the experimental data with theoretical model prediction. The plot illustrates the algorithm's effectiveness in estimating ζ_m, crucial for accurate dynamic modeling of the cantilever beam. The close alignment of the model predictions with the experimental data across the frequency spectrum validates the accuracy of all algorithms including Hybrid GA-PSO algorithm. This successful estimation of ζ_m underscores the potential of hybrid optimization techniques in flexible structures, where accurate damping characterization is essential for designing and controlling dynamic systems.

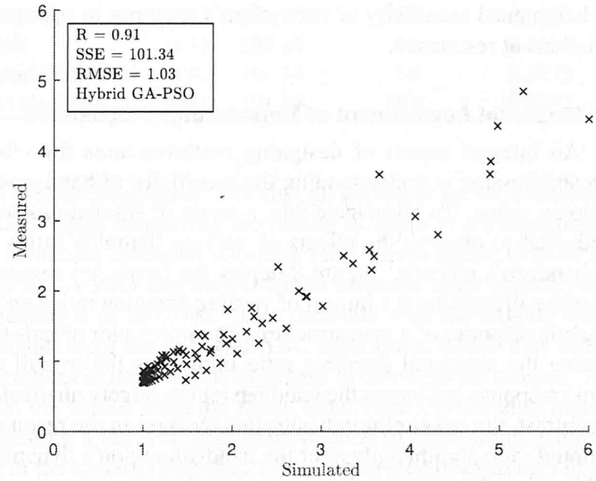

FIGURE 6: Scatter plot comparing measured data to Hybrid GA-PSO simulated estimations, demonstrating the algorithm's efficacy in predicting the structural modal damping ratio (ζ_m) with a correlation coefficient (R) of 0.91.

The scatter plot in Figure 6 illustrates the correlation between the measured and simulated data points using the Hybrid GA-PSO algorithm for estimating the modal damping ratio. The correlation coefficient (R) of 0.91 indicates a strong positive relationship, suggesting that the algorithm can predict the system's behavior with a high degree of accuracy. The SSE and RMSE provide further insight into the model's precision, with lower values indicating a closer fit to the experimental data. In this case, an RMSE of 1.03 reflects a reasonably accurate model, although there is room for improvement in minimizing the prediction error.

The residuals plot in Figure 7 predominantly indicates a sat-

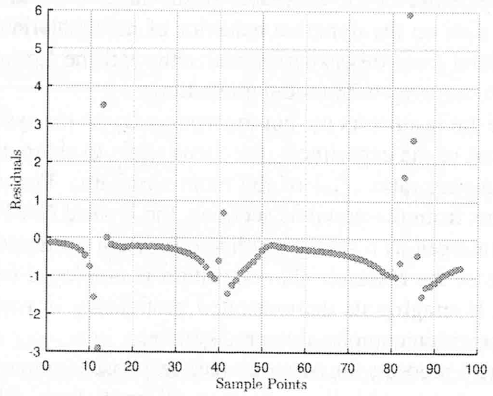

FIGURE 7: Residual analysis of the Hybrid GA-PSO model predictions showcasing the estimation accuracy across the experimental data set, with a focus on identifying outlier discrepancies for further model refinement.

isfactory model fit, as evidenced by the majority of residuals clustering near the zero line. However, the presence of outliers with higher residuals at the structure's modal resonant frequencies suggests that the model's predictions diverge from the experimental data at these critical points. This could be due to the heightened sensitivity of the system's response to parameter variations at resonance.

3.2 Empirical Assessment of Metastructural Dynamics

An integral aspect of designing metastructures for vibration suppression is understanding the sensitivity of bandgaps to damping ratios. To investigate this, a series of simulations were conducted to observe the effects of varying damping ratios on the bandgap's efficacy. Figure 8 depics the frequency response functions illustrating the impact of varying damping ratios on the dynamic response of a metastructure. The upper plot reveals that altering the structural damping ratio influences the overall dynamic response but leaves the bandgap region largely unaffected. In contrast, the lower plot indicates that changes in the resonator damping ratio significantly alter the bandgap region's dynamics, highlighting the critical role of resonator damping in tuning the metastructure's vibration suppression capabilities.

Building upon the simulation insights, an experimental analysis was conducted on an actual metastructure to validate the theoretical findings and assess the practicality of bandgap manipulation through damping variations. This experiment aims to corroborate the simulation results with real-world data, establishing the reliability of the proposed models and the feasibility of achieving targeted vibration suppression through bandgap engineering. The experimental setup is captured in Figure 9, illustrating the prototype of metastructure real-world application. The resonators, integral to the metastructure, were crafted from pure aluminum, featuring a thickness of 2 mm, a width of 20 mm, and a length of 11.3 mm. A set of nuts and bolts served as adjustable tip masses, enabling the fine-tuning of the natural frequency to the target 64 Hz, as determined by Finite Element Method (FEM) analysis.

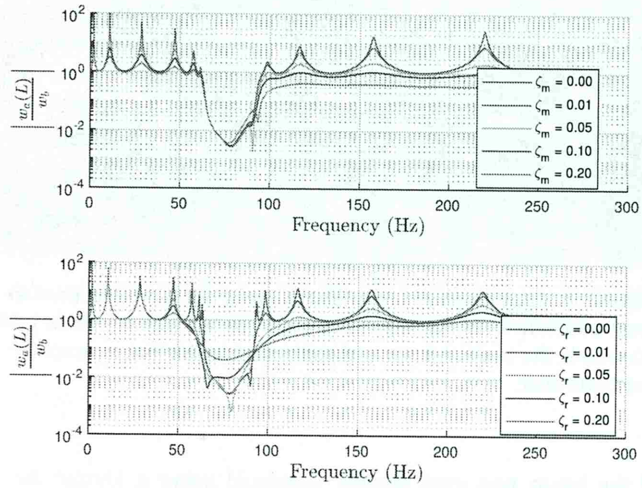

FIGURE 8: Transmittance highlighting the effects of damping ratio variations on a metastructure's dynamic response, with a focus on bandgap region alterations.

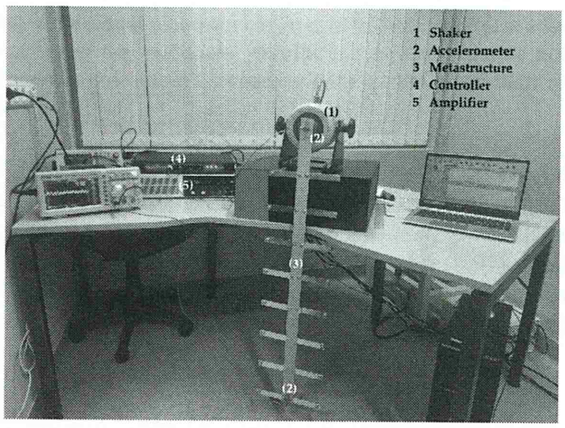

FIGURE 9: The experimental setup for the metastructure's dynamic analysis. This configuration is instrumental in examining the effects of damping and resonator adjustments on the metastructure's vibrational characteristics.

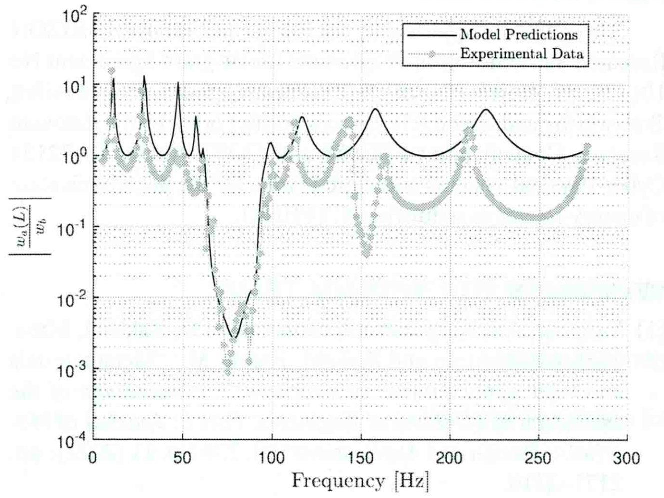

FIGURE 10: Comparison of experimental data with theoretical model employing estimated damping ratio

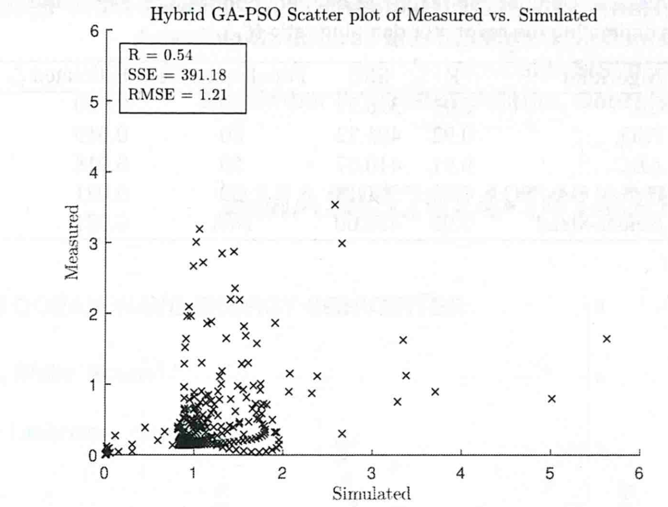

FIGURE 11: Hybrid GA-PSO Scatter plot of Metastructure's Measured vs. Simulated data in predicting the resonator damping (ζ_r).

This experimental arrangement was utilized to invoke the bandgap phenomenon and study its sensitivity to the damping ratios in a controlled environment. By systematically altering the tip mass, the resonant frequency of the metastructure could be adjusted, thereby shifting the bandgap. The data illustrated in Figure 10 compares experimental data with model predictions that estimate ζ_r using the GA-PSO algorithm. The observed transmittance peaks and troughs align well with the predicted values, particularly in the lower frequency range up to 150 Hz, which includes the designed bandgap region. Beyond this, while the model continues to follow the general trend of the experimental data, some deviations become apparent, suggesting areas for further refinement of the model. Notably, the bandgap's expected impact is clear, with a marked reduction in transmittance indicating effective vibration suppression within the targeted frequency range.

The data depicted in Figure 11 is indicative of the correlation between the measured and simulated values, obtained through the Hybrid GA-PSO algorithm. The scatter plot, with an R-value of 0.54, suggests a moderate correlation. The SSE of 391.18 and RMSE of 1.21 reflect the discrepancies between the model predictions and the experimental observations. These metrics highlight areas where the model could be further calibrated to enhance its predictive accuracy.

Figure 12 presents the residual plot resulting from the algorithm's predictions. The distribution of residuals along the sample points illustrates the model's areas of strength, as well as points where the prediction does not align closely with the experimental data. Together, these figures articulate the performance of the Hybrid GA-PSO algorithm. While the moderate correlation and the residual trends indicate the algorithm's potential, they also suggest that further tuning and validation are necessary for the model to reliably predict dynamic behavior in metastructures.

As compiled in Tables 2 and 3, the different optimization algorithms, while varying slightly in the correlation coefficient (R) and the sum of squared errors (SSE), consistently identified the damping ratios with enough precision for the theoretical model. Upon comparing the results in Table 3, it's evident that the estimated resonator damping ratio values obtained from the Hybrid GA-PSO and Nelder-Mead methods align closely, both indicating a ζ_r of 0.021. This contrasts with the slightly lower estimates from the PSO and ABC algorithms, which may reflect differences in their search strategies or convergence criteria. Notably, the values from the initial table were significantly higher, suggesting a refinement of experimental or algorithmic parameters in the updated analysis. The convergence of estimates in the updated table, particularly for ζ_r, reinforces the robustness of the optimization methods and supports their reliability for accurate metastructure analysis.

TABLE 2: Comparison results of different optimization algorithms in estimating the structural modal damping ratio (ζ_m)

Algorithm	R	SSE	Population size	Estimated ζ_m
GA	0.92	104.57	80	0.0273
PSO	0.92	102.40	80	0.0271
ABC	0.92	103.35	50	0.0268
Hybrid GA-PSO	0.92	101.34	50	0.0273
Nelder-Mead	0.91	101.34	N/A	0.0272

The consensus on ζ_m and ζ_r values highlights the algorithms' success in capturing the metastructure's key dynamics. Validation by experimental data emphasizes their potential in designing and optimizing metastructures for enhanced vibration suppression.

4. CONCLUSION

This research represents the design and optimization of locally resonant metastructures for vibration suppression. Through the integration of advanced AI and optimization algorithms, a new methodology for estimating damping ratios has been established, shedding light on the sensitivity of bandgap characteristics to these critical parameters. The key contributions of this paper are summarized as follows:

TABLE 3: Comparison results of different optimization algorithms in estimating the resonator damping ratio (ζ_r)

Algorithm	R	SSE	Population size	Estimated ζ_r
GA	0.93	398.29	80	0.020
PSO	0.92	405.22	80	0.019
ABC	0.91	410.67	50	0.018
Hybrid GA-PSO	0.94	391.18	50	0.021
Nelder-Mead	0.90	420.00	N/A	0.021

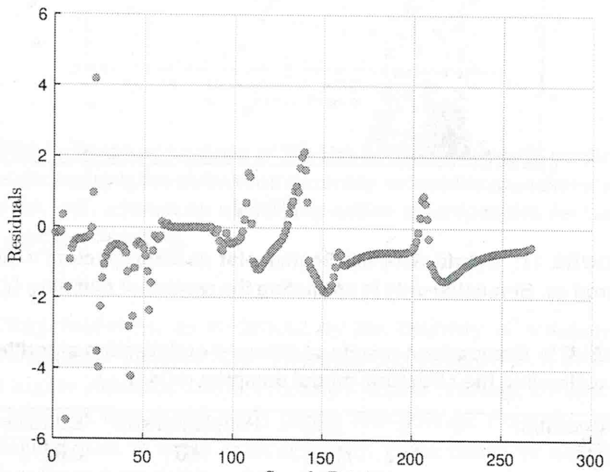

FIGURE 12: Distribution of residuals from the Hybrid GA-PSO algorithm's predictions.

- A novel mathematical formulation for the analysis of metastructures is utilized to enhance the precision of bandgap optimization;
- The study demonstrated the significance of accurately estimated damping ratios in the manipulation of bandgap properties for effective vibration suppression;
- A reliable framework was established to address the gap in current methodologies regarding variable damping scenarios within metastructures;
- The efficacy of the Hybrid GA-PSO algorithm was validated against experimental data, reinforcing its potential for real-world applications in the engineering of metastructures.

The insights from this study suggest promising avenues for future research, such as developing adaptive control mechanisms that dynamically adjust damping ratios based on varying conditions and exploring the scalability of these methodologies for larger and more complex metastructures. Future efforts may focus on refining these algorithms for greater precision, testing more complex metastructural configurations, and integrating broader experimental data to enhance the robustness and real-world applicability of the models. This research moves the field of metastructure optimization forward by effectively integrating AI and optimization techniques, although it also highlights the need for careful interpretation of results due to the limitations of the current methodologies.

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