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DEVELOPMENT OF A DEVICE FOR MATERIAL DENSITY CHARACTERIZATION USING FREQUENCY RESPONSE FUNCTION (FRF) ANALYSIS

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Abstract—**This paper presents the design and fabrication of a device for characterizing materials through Frequency Response Function (FRF) analysis by using their dynamic vibrational response. The device integrates a vibration motor, accelerometer, and National Instruments (NI) data acquisition system, controlled via LabVIEW and processed using MATLAB, to measure frequency responses of cantilever beam samples—stainless steel, mild steel, FR4 composite. Preliminary tests demonstrate distinct vibrational signatures, suggesting a potential correlation between density and modal parameters. This work provides a foundation for developing a simple and efficient material-characterization tool for applications in materials science and engineering.**

Keywords— **Material density, frequency response function (FRF), vibration analysis, device development, non-destructive testing.**

Abbreviations: FRF (Frequency Response Function), NI (National Instruments), DAQ (Data Acquisition), DC (Direct Current), kHz (Kilohertz), MATLAB (Matrix Laboratory), LabVIEW (Laboratory Virtual Instrument Engineering Workbench), and IDDATA (Identification Data Object)

I. INTRODUCTION

Material density, a critical mechanical property, governs a material's behaviour under dynamic loading, influencing applications in structural design, aerospace, and manufacturing. Traditional density measurement techniques, such as gravimetric analysis or helium pycnometry, are precise but often labour-intensive, requiring specialized equipment or posing limitations in material compatibility [1][2][3][4][5]. This research introduces an innovative alternative: a device that employs Frequency Response Function (FRF) analysis to characterize density based on vibrational response [7][8][9][10].

II. MATERIALS AND METHODS

II. a Material Selection and Sample Preparation -
Materials with different known densities, such as stainless steel, FR4 composite, and mild steel, wereselected for experimentation. Samples were prepared with controlled density variations to assess their impact on FRF [1][4][5][6].

II. b Experimental Setup- A vibration motor was used to induce vibrations, and accelerometers measured the response across a range of frequencies. The data acquisition system included NI DAQ modules, connected to LabVIEW for signal processing [7][8][9][11].

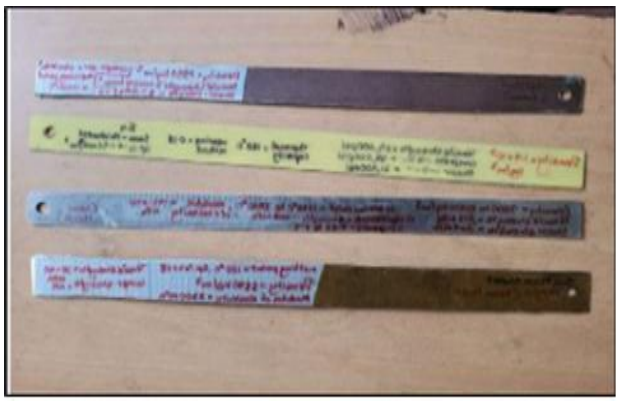


Fig. 1.Material samples used in the experiment

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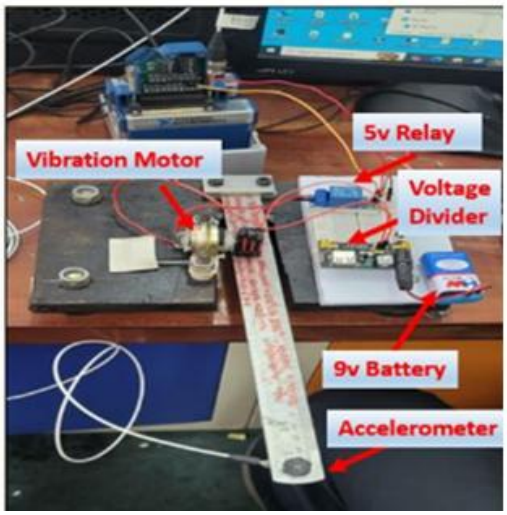


Fig. 2.testing setup

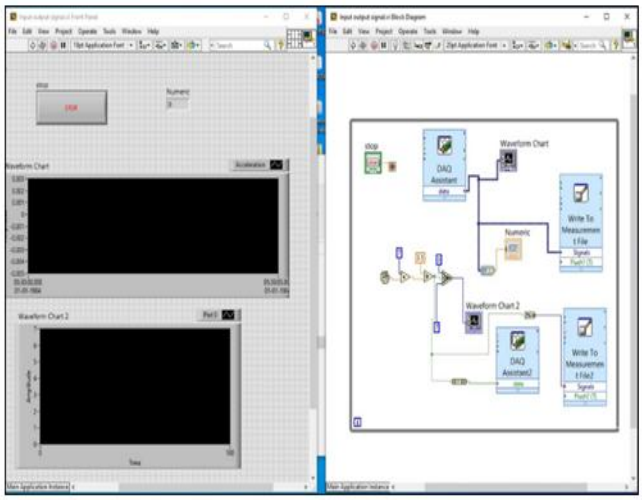


Fig. 3. LabVIEW interface and block diagram for input-output data acquisition.

II. c Construction of Experimental Setup-The experimental setup consisted of a rigid base frame to minimize external interference, onto which the material samples were securely mounted. The vibration motor was affixed to the setup, ensuring consistent excitation. Accelerometers were strategically placed at key locations on the samples to capture vibrational responses effectively. The entire setup was housed in a controlled environment to mitigate external noise and unwanted vibrations.

The main components used in the experimental setup are listed below:

1.Vibration Motor (DC): Induces controlled vibrations in the cantilever beam via eccentric weight; powered by 9V battery, controlled by relay.

2.Accelerometer: Captures beam's dynamic response for FRF analysis.

3.NI DAQ 9401: Controls motor via relay, generating varied input signals (0-7 V).

4.NI DAQ 9234: Logs high-resolution vibration data (1 kHz) from accelerometer.

5.LabVIEW: Controls DAQ, logs and visualizes data, saves for MATLAB analysis.

6.(5 V) Relay: Switches motor on/off via NI DAQ 9401 signals.

7.Voltage Divider: Adjusts 9V to motor's 5V requirement.

8.(9 V) Battery: Powers motor and relay.

The accuracy of FRF measurement can be affected by the excitation method, accelerometer position, sensor mass, mounting condition, sampling frequency and external vibration [7][9][11].

II. d Data Processing and Analysis- The acquired data was processed using MATLAB to extract Bode plots and determine key modal parameters. The influence of density variation on natural frequencies and damping ratios was analyzed. The acquired data were processed using MATLAB to generate frequency-response and Bode plots. Frequency-domain analysis was performed to identify resonance peaks and compare the dynamic responses of the tested materials. [7]–[9], [15]

Additional statistical techniques, such as regression analysis, were applied to quantify the relationship between density and vibrational response.

This LabVIEW setup allows for real-time data acquisition and processing of acceleration data from the vibrating samples. It not only visualizes the data but also logs both raw and processed data, enabling comprehensive analysis of the material's dynamic behavior [6][7].

III. RESULTS AND DISCUSSION

III. a Observed Frequency Response Data-

Initial analysis of the acquired FRF data showed distinct frequency shifts corresponding to different material densities. The results indicate a strong correlation between density changes and modal parameter variations [9][10][12][13][14].

1. Stainless Steel - Input and Output Frequencies: The initial stainless-steel data indicated a consistent vibrational response, enabling a preliminary assessment of its resonance characteristics [9][13].

Preliminary Observations: Stainless steel exhibited stability in response across a range of frequencies, suggesting it has a higher resistance to vibrational changes, which aligns with its known high density and rigidity.

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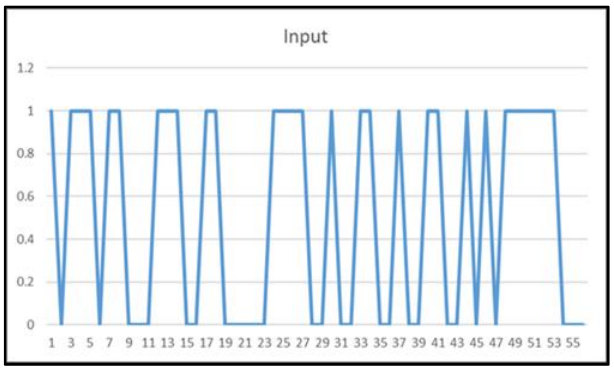


Fig. 4. Stainless steel input data (voltage vs time)

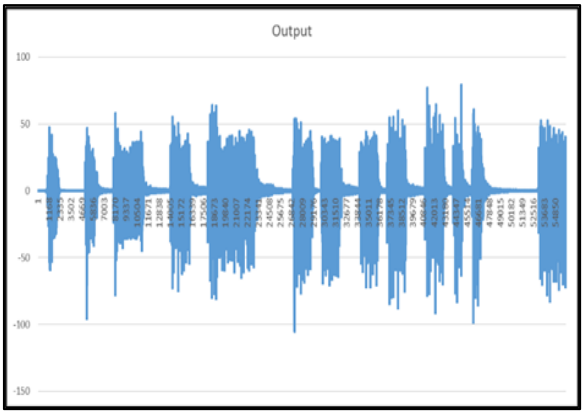


Fig. 5. Stainless steel output data (Acceleration vs time)

2. FR4 (Fiberglass Reinforced Epoxy): The initial FR4 data exhibited a vibrational response distinct from that of the metallic samples, indicating differences in stiffness and damping characteristics [10][14].
Preliminary Observations: FR4 displayed signs of significant energy dissipation, consistent with materials used for vibration damping and electrical insulation, hinting at its suitability for applications where such properties are desired.

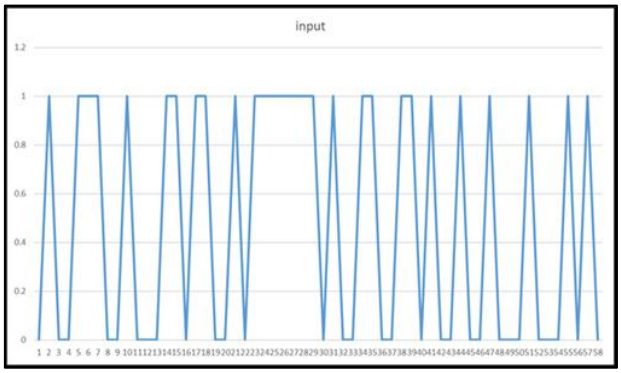


Fig. 6. FR4 input data (voltage vs time)

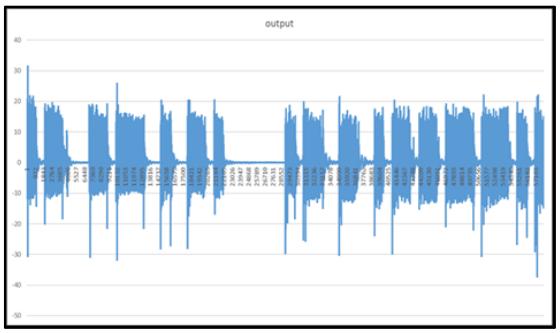


Fig. 7. FR4 output data (Acceleration vs time)

3. Mild Steel: The initial mild-steel data demonstrated a consistent vibrational response, enabling a preliminary assessment of its resonance characteristics [9][12][13].

Preliminary Observations: Mild steel's response suggests it has intermediate vibrational characteristics, positioned between stainless steel and FR4 in terms of rigidity and damping.

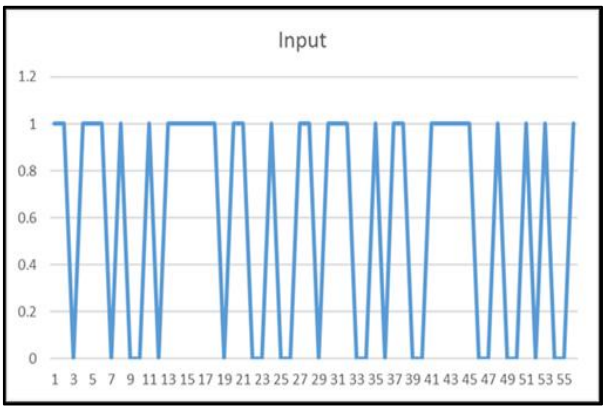


Fig. 8. Mild-steel input data (voltage vs time)

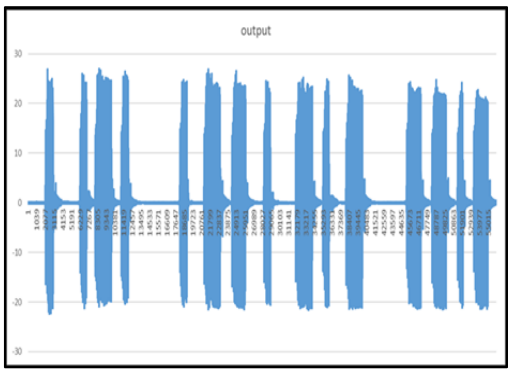


Fig. 9. Mild-steel output data (Acceleration vs time)

III. bMATLAB Code for Data Processing and Visualization

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This MATLAB code analyzes time-series data from an Excel file to examine the relationship between input and output signals. It reads the data; computes mean for unique time points and creates a uniform time vector. After interpolating the input and output, it plots these signals in the time domain. The code then performs Fourier transforms to generate frequency spectra, calculates the transfer function spectrum with smoothing, and estimates a transfer function model using an [iddata] object. Finally, it visualizes the frequency response with a Bode plot, focusing on the dynamic [7][8][9][15].

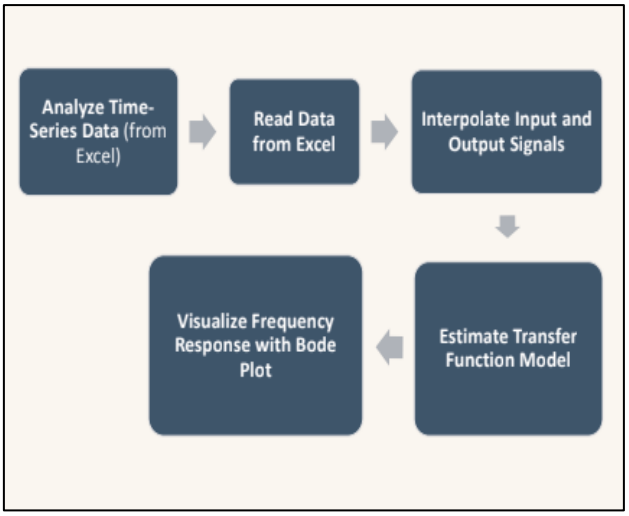


Fig. 10. MATLAB-based FRF data-processing workflow

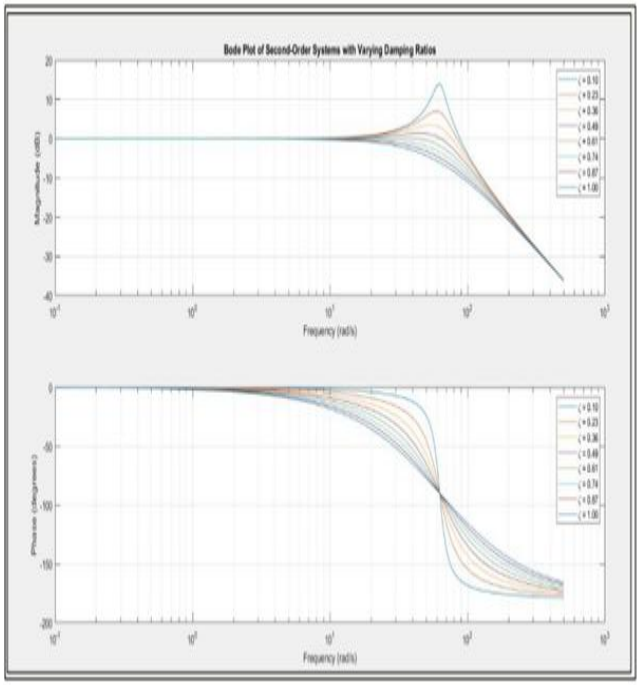


Fig. 11. Stainless Steel FRF

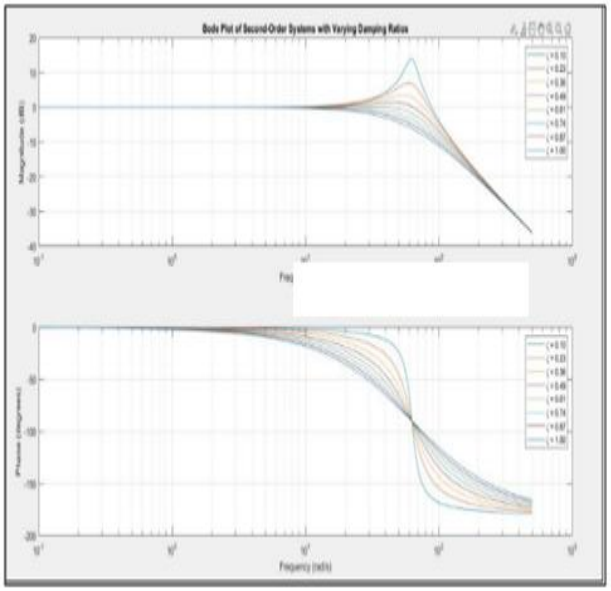


Fig. 12. Mild Steel FRF

III. c Plotting FRF Using MATLAB

The FRF (Frequency Response Function) plots generated from MATLAB effectively illustrate the frequency-dependent behavior of each material under study. These plots provide a comprehensive understanding of how material density influences key vibration characteristics such as resonance frequencies, damping properties, and amplitude responses. By analyzing the shifts in natural frequencies, we can observe how changes in material density alter the structural dynamics, affecting the stiffness and mass distribution of the material [7][8][9][15].

Furthermore, the damping effects captured in these plots highlight how different densities impact energy dissipation within the material, which is critical for applications requiring vibration control [12][13]. The variations in amplitude responses also serve as indicators of how efficiently a material can absorb or transmit vibrational energy, making these plots valuable for optimizing material selection in engineering applications [9][10][13].

Complementing the FRF analysis, the Bode plots provide additional insights by illustrating both phase and magnitude responses over the entire frequency spectrum. The magnitude plot reveals how the material's response varies in intensity across different frequencies, while the phase plot indicates the time delay between input excitation and output response. These visualizations collectively reinforce the observed density-FRF relationship, offering a robust validation framework for studying material behavior under dynamic conditions.

Ultimately, the combined analysis of FRF and Bode plots enables a deeper understanding of the intricate relationship between material density and vibrational characteristics,

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aiding in material optimization for applications such as structural damping, noise reduction, and mechanical design.

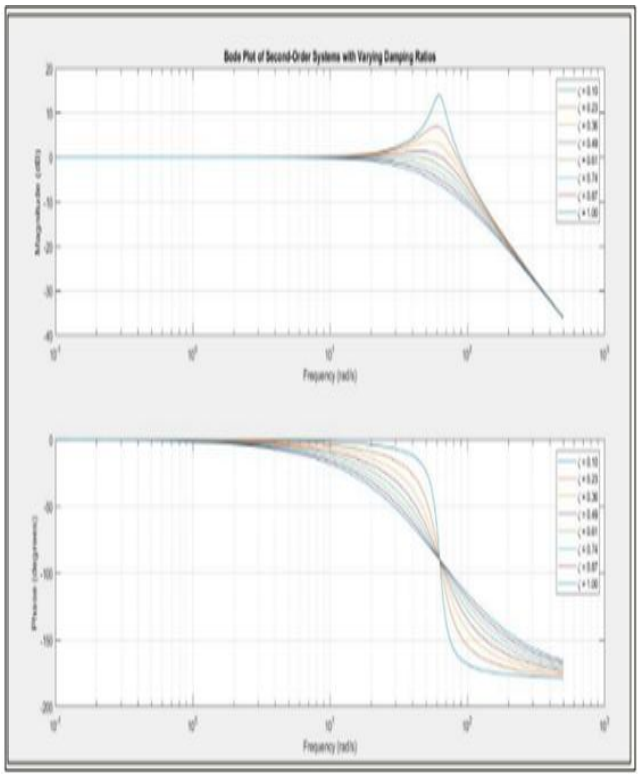


Fig. 13.FR4 FRF

III. d Interpretation of Findings:

As shown in Figs. 11-13, the tested materials exhibited different frequency-response characteristics. For specimens with comparable geometry and boundary conditions, the measured natural frequencies varied with the combined effects of density, mass distribution, and elastic stiffness. The preliminary results indicate that FRF parameters may support material characterization; however, additional controlled testing is required to isolate the influence of density [7][9][10][13].

III. e Limitations: While the study demonstrates the feasibility of FRF-based density characterization, challenges such as experimental uncertainties and environmental factors remain. Noise interference and minor imperfections in sample preparation may have introduced variability in results [7][8][9][11].

IV. CONCLUSION

This study investigates the feasibility of utilizing Frequency Response Function (FRF) analysis for material density **Conflict of Interest:** The authors declare that they have no conflict of interest related to the content or publication of this research paper.

characterization, demonstrating a direct correlation between density variations and vibrational response characteristics. Experimental results from stainless steel, FR4 composite, and mild steel samples indicate that natural frequencies increase as density decreases, consistent with theoretical predictions. Furthermore, damping ratios and FRF magnitude responses exhibit material-dependent variations, influenced by microstructural properties and internal energy dissipation mechanisms.

The methodology employed, including controlled excitation using a vibration motor, data acquisition via accelerometers, and frequency-domain analysis in MATLAB, confirms FRF as a computationally efficient approach for density characterization. The findings suggest that FRF-based techniques could complement or potentially replace conventional density measurement methods, particularly in applications requiring rapid, in-situ material assessment [9][10][12][13].

Future research should focus on broadening the scope of tested materials, exploring the impact of environmental factors such as temperature and humidity, and integrating machine learning models for automated density prediction. Additionally, the development of portable FRF-based measurement devices could enhance real-world applicability in structural health monitoring and quality control industries.

Overall, this study establishes FRF analysis as a promising tool for material density characterization, providing a foundation for further advancements in vibration-based evaluation techniques.

V. FUTURE SCOPE

The current work lays the foundation for advanced material characterization tools that can be further developed into compact, automated systems for industrial use. Future efforts can focus on integrating wireless data transmission for remote monitoring, expanding the range of tested materials to include polymers and composites with complex internal structures, and implementing real-time analysis using embedded microcontrollers. Additionally, combining this vibrational analysis with machine learning algorithms could enable predictive insights into material behavior, opening possibilities for adaptive material selection in dynamic environments such as aerospace, automotive, and structural health monitoring systems.

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