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MANYETİK LEVİTASYON ALTINDA BİR KONSOL KİRİŞİN DENEYSEL TİTREŞİM ANALİZİ

EXPERIMENTAL VIBRATION ANALYSIS OF A CANTILEVER BEAM UNDER MAGNETIC LEVITATION

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Özet

Bu çalışmada, manyetik levitasyon (maglev) sistemi kullanılarak elektromanyetik kuvvet etkisi altındaki bir konsol kirişin deneysel olarak modellenmesi ve titreşim davranışının incelenmesi amaçlanmıştır. Deneysel düzenekte, bir ucundan ankastre olarak sabitlenmiş alüminyum bir kirişin serbest ucu ferromanyetik bir malzeme ile kaplanmış ve elektromıknatıslar tarafından oluşturulan manyetik alana maruz bırakılmıştır. Bu sayede sistem içerisinde kontaksız (temassız) bir sönümleme mekanizması elde edilmiştir.

Kurulan deney düzeneğinde, farklı frekanslarda uygulanan tahrikler altında kirişin dinamik tepkileri ölçülmüş ve frekans tepki fonksiyonları elde edilmiştir. Bu veriler kullanılarak sistemin doğal frekansı ve sönümleme karakteristikleri belirlenmiş, ardından optimizasyon yöntemleri ile ikinci derece transfer fonksiyonu kullanılarak deneysel modelleme gerçekleştirilmiştir.

Ayrıca, elektromanyetik kuvvetin büyüklüğü değiştirilerek sistemin sönüm oranı üzerindeki etkisi incelenmiş ve manyetik kuvvetin artırılmasının titreşim genliğini önemli ölçüde azalttığı gözlemlenmiştir. Literatürdeki benzer çalışmalarla uyumlu olarak, kontaksız elektromanyetik sönümleme yönteminin, geleneksel mekanik sönümleyicilere kıyasla sistem dinamiklerini değiştirmeden etkili titreşim bastırma sağladığı doğrulanmıştır.

Elde edilen sonuçlar, maglev tabanlı elektromanyetik sistemlerin esnek yapıların deneysel modellenmesinde ve aktif titreşim kontrolünde yüksek doğruluk ve uygulanabilirlik sunduğunu göstermektedir. Bu çalışma, kontaksız sönümleme yaklaşımı kullanılarak kiriş sistemlerinin modellenmesine ilişkin literatüre deneysel bir katkı sağlamaktadır.

Anahtar Kelimeler: Manyetik levitasyon, Elektromanyetik sönümleme, Kiriş modelleme, Deneysel analiz

Abstract

In this study, it is aimed to experimentally model a cantilever beam under the effect of electromagnetic force using a magnetic levitation (maglev) system and to investigate its vibration behavior. In the experimental setup, the free end of an aluminum beam fixed at one end is coated with a ferromagnetic material and exposed to the magnetic field generated by electromagnets. In this way, a contactless damping mechanism is achieved within the system.

In the established experimental setup, the dynamic responses of the beam were measured under excitations applied at different frequencies, and frequency response functions were obtained. Using these data, the natural frequency and damping characteristics of the system were determined, and subsequently, experimental modeling was carried out using a second-order transfer function through optimization methods.

Additionally, by varying the magnitude of the electromagnetic force, its effect on the damping ratio of the system was examined, and it was observed that increasing the magnetic force significantly reduces the vibration amplitude. Consistent with similar studies in the literature, it has been confirmed that the contactless electromagnetic damping method provides effective vibration suppression without altering the system dynamics compared to conventional mechanical dampers.

The obtained results demonstrate that maglev-based electromagnetic systems offer high accuracy and applicability in the experimental modeling of flexible structures and active vibration control. This study provides an experimental contribution to the literature on the modeling of beam systems using a contactless damping approach.

Keywords: Magnetic levitation, Electromagnetic damping, Beam modeling, Experimental analysis

1. Introduction

In modern engineering applications, flexible beam-type structures (such as robotic arms, space structures, energy harvesting devices, and vibration sensors) exhibit sensitive dynamic behavior in response to external excitations. Accurate determination of the natural frequencies, mode shapes, and damping ratios of these structures plays a critical role in vibration control, structural health monitoring, and parameter identification. In particular, systems actuated by magnetic forces overcome the limitations of conventional mechanical excitation by enabling contactless actuation.

The dynamic behavior of flexible beam structures has long been studied in engineering systems for applications such as vibration control, structural health monitoring, and energy harvesting. Analytical models based on Euler–Bernoulli beam theory are commonly used as fundamental tools for predicting natural frequencies and mode shapes; however, experimental validation is essential due to material heterogeneity, boundary conditions, and additional components present in real systems (Abbas, et al. 2025).

Many studies have investigated the modal parameters of cantilever (fixed-free) beams with an attached tip mass. The additional mass significantly reduces the natural frequencies, alters the mode shapes, and affects the damping characteristics of the system. This effect is widely utilized in areas such as energy harvesting devices, parametric resonance, and structural parameter identification. Experimental and numerical studies have demonstrated the systematic influence of the added mass on frequency response functions (FRFs) (Meesela, 2018).

In recent years, beam systems actuated by magnetic forces that provide contactless excitation have attracted increasing attention. Studies involving ferromagnetic tip coatings or magnetic actuators have enabled the acquisition of cleaner and more repeatable FRF data compared to traditional mechanical excitations. This approach has proven effective in applications such as active vibration control, electromagnetic damping, and magnetically coupled energy harvesting (Jiang, et al. 2021).

Guo, et al. (2023) conducted a theoretical, simulation-based, and experimental study on the effects of added mass in weight-sensing structures, systematically revealing the different impacts of mass distribution, center of gravity, and stiffness distribution on natural frequencies. The results showed that added mass parameters significantly alter the frequencies, providing an important basis for the design of high-precision measurement systems.

Beam systems actuated by magnetic forces or incorporating magnetic coupling have become prominent due to their contactless excitation advantages. Feng, et al. (2025) designed and experimentally investigated a broadband vibration energy harvester based on orthogonally magnetically coupled dual cantilever beams. By adjusting the magnetic angle and spacing, they optimized the coupling between two piezoelectric oscillators to widen the frequency bandwidth. Experimental results demonstrated that the proposed magnetic coupling configuration significantly improved energy harvesting efficiency and broadened the operating frequency range.

Electromagnetic actuation and damping techniques have also been effectively applied to ferromagnetic beams. Siddiqui, et al. (2015) implemented electromagnetic damping on a flexible cantilever beam made of ferromagnetic material and experimentally compared vibration reduction under different electromagnetic force levels. Using a constant DC power supply, they proposed a new method and showed that increasing electromagnetic force significantly improves the damping ratio. Similarly, Gospodarič, et al. (2007) developed an active electromagnetic damping system for a laterally vibrating ferromagnetic cantilever beam. Using a switching current amplifier and a pair of electromagnets, they aimed to actively control vibrations. Experimental results confirmed that the proposed system effectively reduces lateral vibrations.

Studies investigating the effect of added mass under different environmental conditions are also available in the literature. Sedlar, et al. (2011) performed experimental modal analysis on a cantilever beam partially submerged in water, comparing modal parameters in air and water environments and quantitatively determining the “added (virtual) mass” effect. Using modal added mass calculations along with model updating and reduction techniques, they showed that the frequency decrease in water is largely due to the added mass effect.

In the literature, processing experimentally obtained FRF data in MATLAB to develop parametric models is a common approach. However, studies systematically investigating variable added mass configurations combined with ferromagnetic tip coatings and performing FRF-based modeling under magnetic excitation are limited. The present study aims to fill this gap by coating the free end of a cantilever aluminum beam with ferromagnetic material to make it sensitive to magnetic forces, altering system dynamics with different added masses, and analyzing experimentally obtained FRFs for each configuration using MATLAB to develop a mathematical model. This approach provides a practical experimental framework for modal analysis and parameter identification of magnetically actuated flexible structures.

In this context, an aluminum beam fixed at one end and free at the other was designed, and its free end was coated with ferromagnetic material to make it responsive to magnetic forces. Different magnitudes of added masses were integrated into the system to gradually modify its dynamic characteristics, and experimental frequency response functions were obtained for each configuration. The acquired data were analyzed using MATLAB to develop the mathematical model of the system. This study aims to experimentally demonstrate the effect of the combination of magnetic actuation and variable mass on the modal analysis of flexible beams and to contribute a practical modeling approach to the literature.

2. Conceptual Framework

In this study, an aluminum beam fixed at one end and free at the other was first designed. The free end of the beam was coated with a ferromagnetic material to enable observation of the effect of magnetic forces on the beam motion. Then, different magnitudes of added masses were placed on the beam to alter the modal characteristics of the system. After each mass addition, the experimentally obtained frequency response functions were recorded in detail and analyzed in MATLAB, and the parametric modeling of the system was successfully completed.

3. Methods

The beam, made of Al 6063 material, was fixed at one end, while its free end was coated with ferromagnetic material and positioned inside the maglev device to be influenced by magnetic forces.

The dimensions of the aluminum beam used are (360 × 40 × 0.7) mm. The chemical composition of the material is given in Table 1, and its mechanical properties are presented in Table 2.

Table 1. Chemical Composition of Al 6063 Material

Fe	Si	Cu	Mn	Mg	Zn	Cr	Zi	Other
0.35	0.2-0.6	0.1	0.1	0.45-0.9	0.1	0.1	0.15	0.15

Source: The Aluminum Association, (2024)

Table 2. Mechanical Properties of Al 6063 Material

Temper	Yield Strength (MPa) min-max	Tensile Strength (MPa) min-max	Elongation (%50) min-max	Hardness (Brinell) min-max
0	50	100	26	25
T1	90	150	24	45
T4	90	160	21	50
T5	110-175	150-215	12	60
T6	170-210	205-245	12	75
T8	240	260	9	80

Source: The Aluminum Association, (2024)

3.1. Magnetic Levitation System

In the experimental setup, a maglev device (Magnetic levitation system 33 – 210) was used to generate a magnetic field and determine the amplitude of vibrations in the cantilever beam (Figure 1). The maglev unit consists of a connection interface panel with a mechanical unit on which a coil is mounted. An infrared sensor is connected to the mechanical unit. Figure 2 shows the control panel of the maglev device.

Figure 1. Magnetic levitation system

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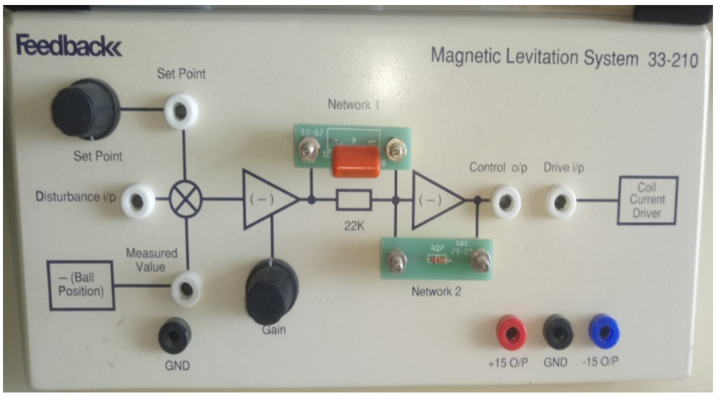

Figure 2. Control panel of the maglev device

Source: Created by the author.

The Maglev system measures 370 mm x 250 mm x 260 mm and weighs approximately 10 kg. The system has an internal power supply and can operate independently in analog mode without any computer control software.

3.2. Data Card

PCI 1711U data card was used in the experimental setup. The technical specifications of the 1711U DAQ card are given in Table 3. Here, the data card reads analog and digital inputs from all input lines.

Table 3. Specifications of the PCI-1711U DAQ Card

16-channel single-ended analog input
12-bit A/D converter with sampling rates up to 100 kHz.
Programmable gain
Automatic channel/gain display
FIFO panel memory (1,024 samples)
2 x 12-bit output channels
16-channel digital input and 16-channel digital output
Programmable calculator on the panel

Source: Created by the author.

To allow the free end of the fixed aluminum beam to be affected by the magnetic force coming from the coil, a low-carbon steel piece (35 x 40 x 1.7 mm) was glued to it with a special adhesive. The reason for gluing the low-carbon steel to the end of the aluminum beam is that the greatest vibration occurs in this region. The experimental system was set up by positioning the free end of the aluminum beam so that it was aligned with the coil and position sensors in the magnetic levitation device (Figure 3).

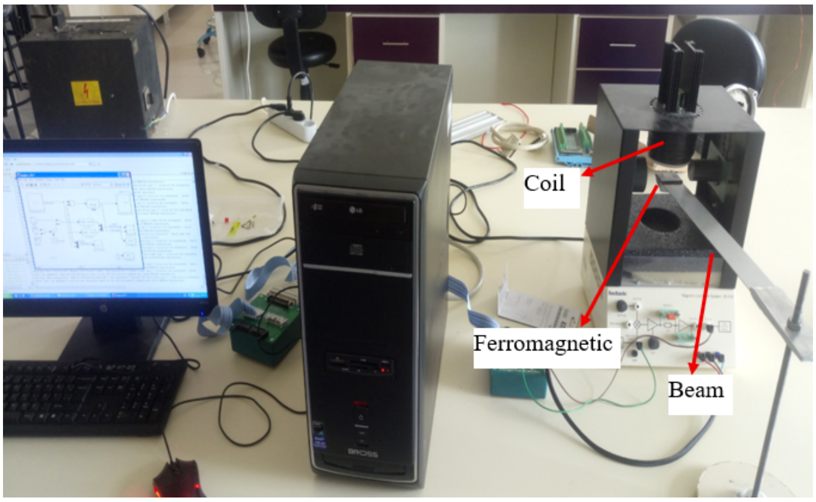

Figure 3. Experimental setup

Source: Created by the author.

The aim is to dampen the vibrations generated in the aluminum beam under magnetic forces. Subsequently, the system was modeled by integrating different mass values into the beam, and the experimentally determined frequency response functions were analyzed in the Matlab program.

4. Results and Discussion

In digital mode, the maglev system operates using MATLAB®/Simulink software. Feedback software for Simulink is provided for implementing control algorithms and the interface between the PC and the maglev system hardware. It runs in a MATLAB® environment that enables the determination of system parameters and modeling of the system. Figure 4 shows the MATLAB®/Simulink block diagram of the system. Real-time experiments were digitally configured and performed using this block diagram.

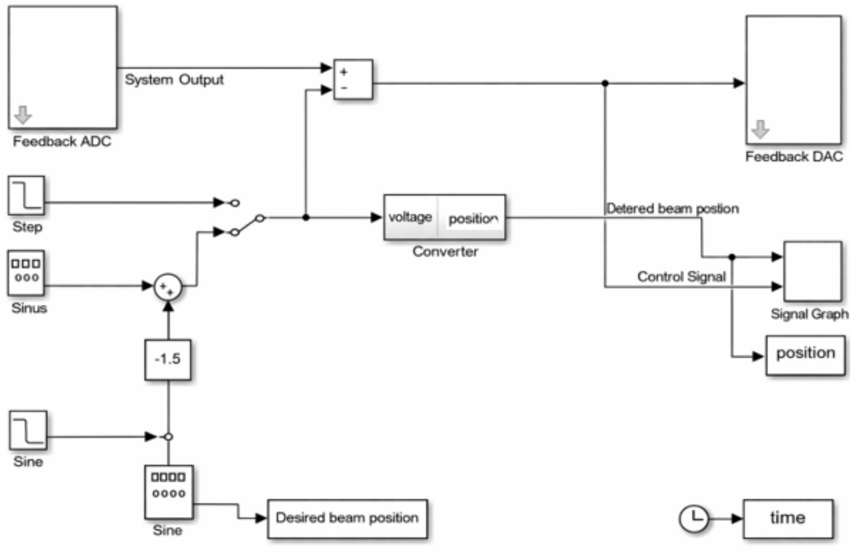

Figure 4. MATLAB® / Simulink model of the maglev system

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In this study, the natural frequency of the beam was first determined by sending signals with a constant amplitude of 0.2 mm at different frequencies in the range of 2-10 Hz with a sinusoidal input to the system. The graphs below show the steady-state responses obtained in response to the sinusoidal inputs sent to the system (Figures 5-8). The response with the highest amplitude shows us that the resonance frequency of the system is the frequency given for the input. Therefore, knowing that the resonance frequency is also the natural frequency of the system, it is revealed that the natural frequency is 5.96 Hz (Figure 6(a)).

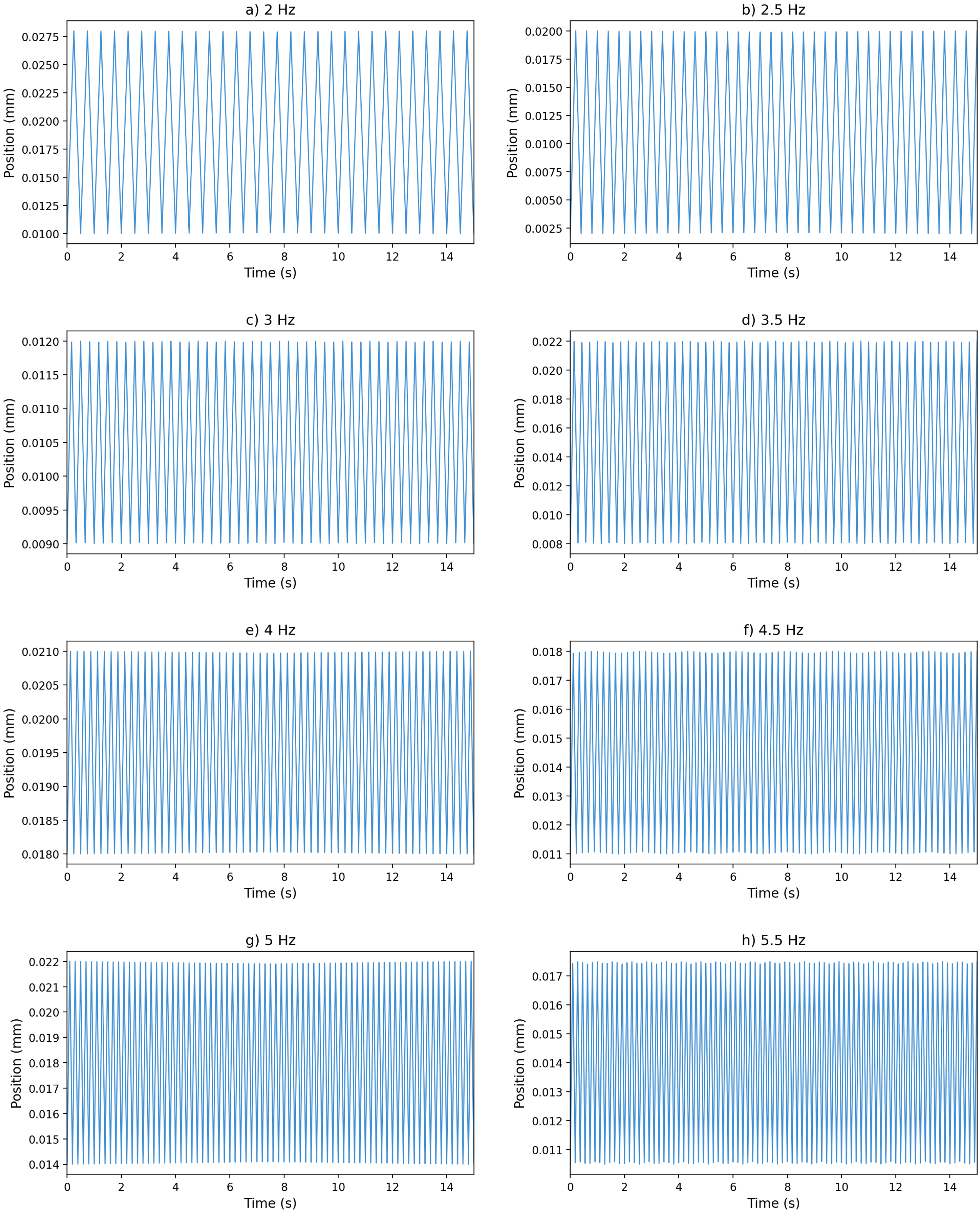

Figure 5. Responses obtained to sinusoidal inputs of different frequencies.

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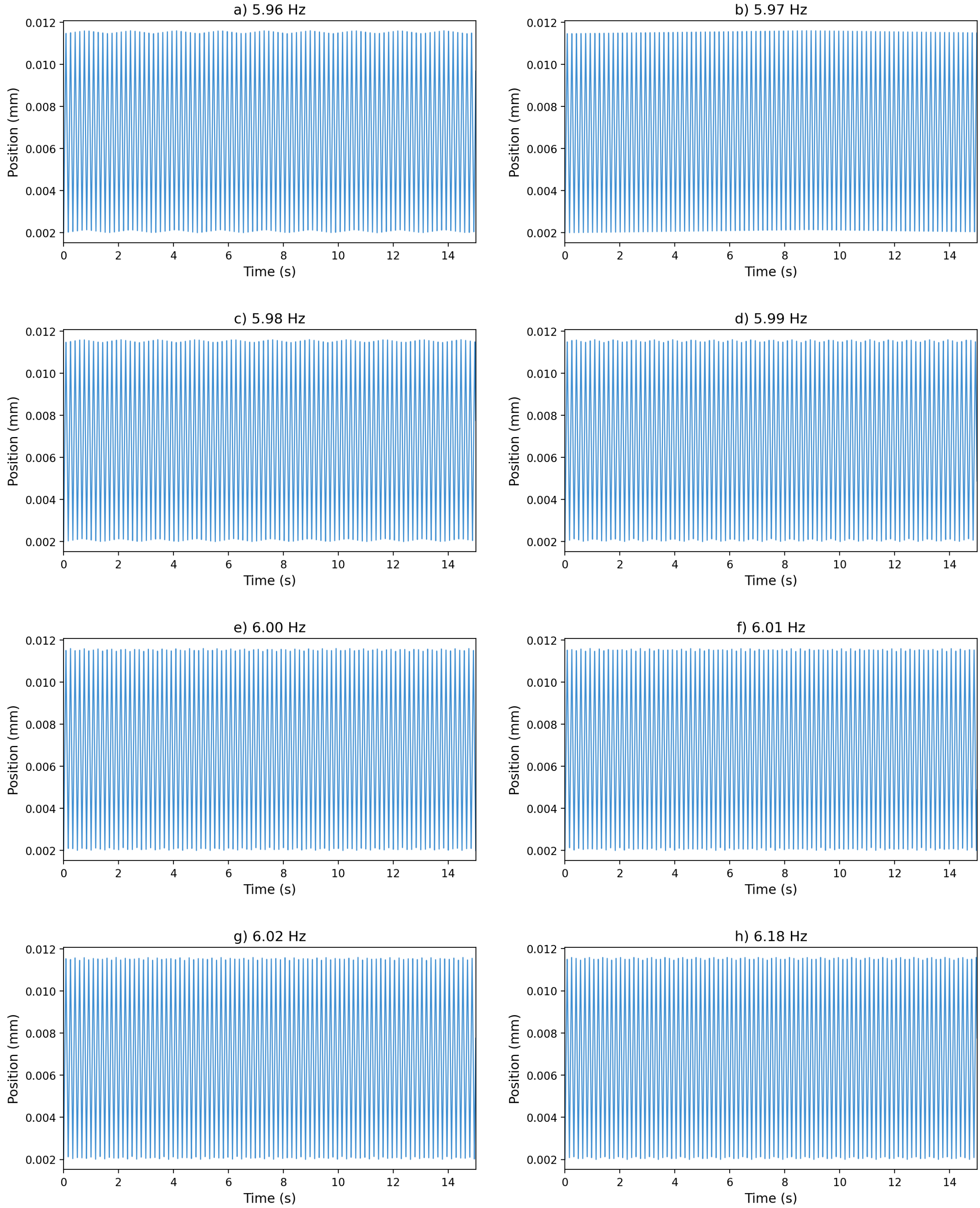

Figure 6. Responses obtained to sinusoidal inputs of different frequencies.

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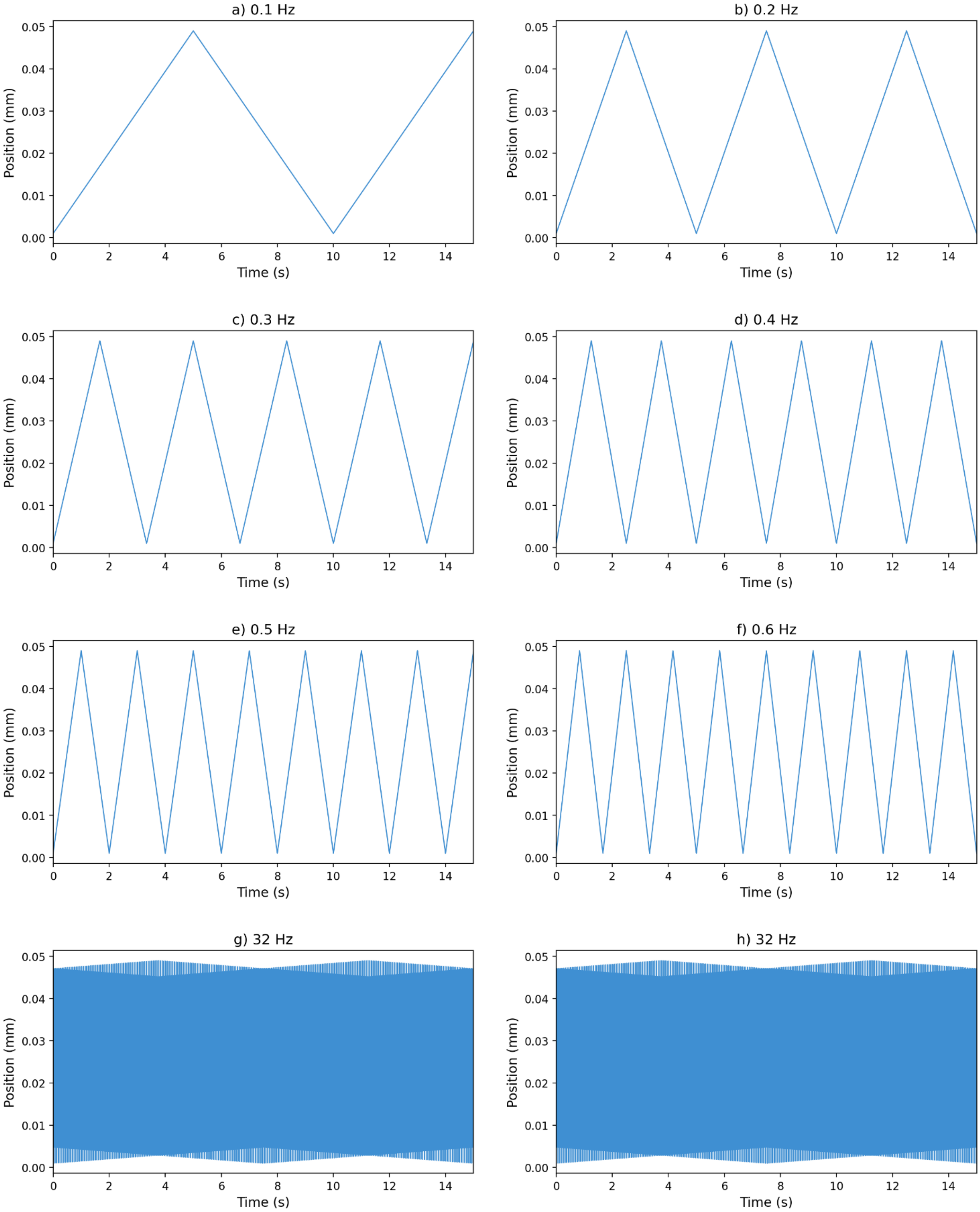

Figure 7. Responses obtained to sinusoidal inputs of different frequencies.

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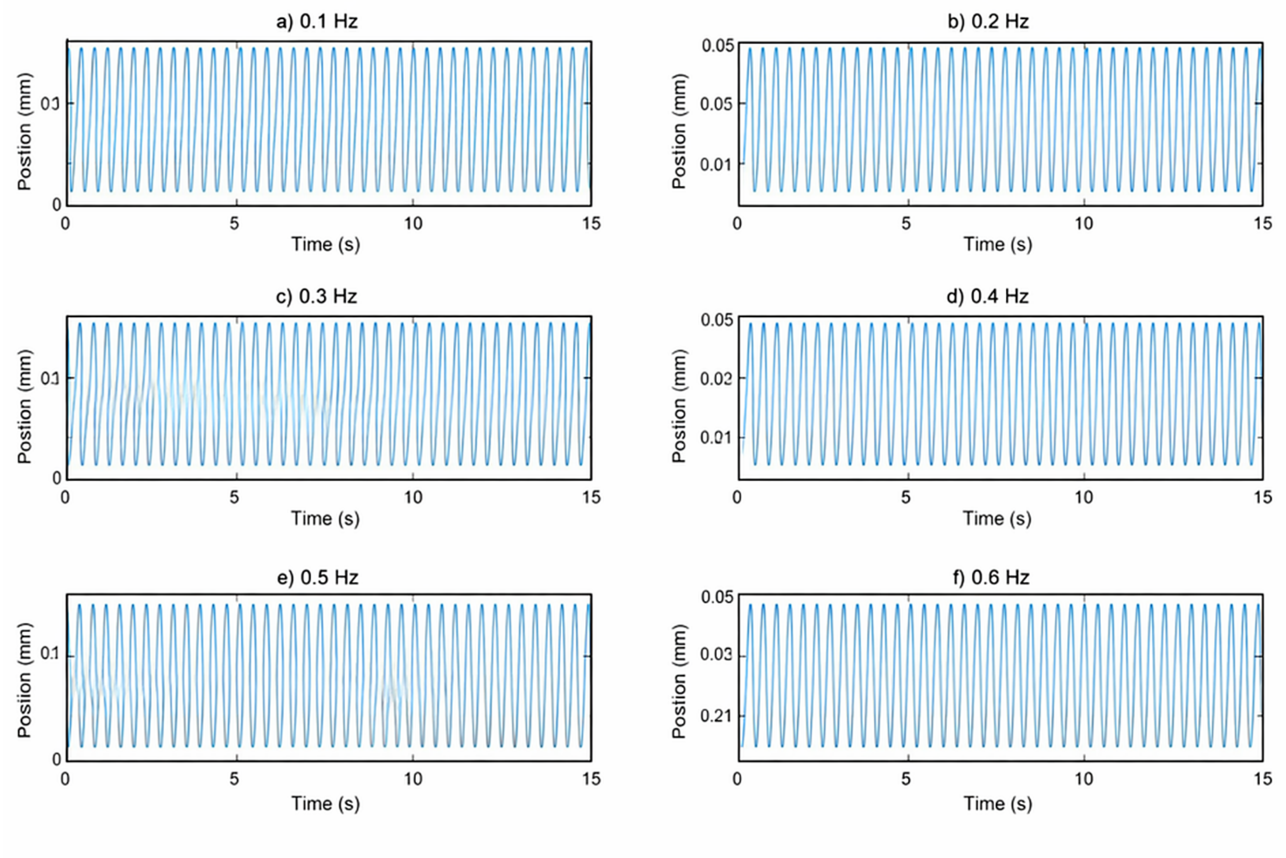

Figure 8. Responses obtained to sinusoidal inputs of different frequencies.

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Amplitude values were calculated in dB based on the steady-state responses obtained for different frequency (Hz) inputs, and Figure 3.9 was obtained corresponding to the input frequencies. Here, the frequency values were also converted to rad/s. The peak point in the graph is the natural frequency of the system and was calculated as 37.45 rad/s.

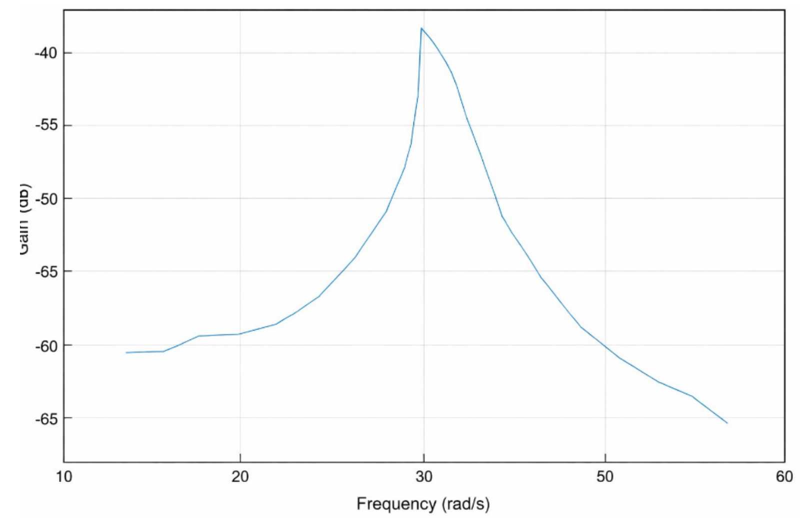

Figure 9. Amplitude-frequency graph obtained from experimental data.

Source: Created by the author.

The characteristic equation was then used to obtain the system's transfer function (Equation 1).

$$G(s) = \frac{k}{s^2 + 2\xi w_n s + {w_n}^2} \tag{1}$$

Here, the natural frequency was experimentally determined as $w_n = 37.44$ rad/s. k and ξ represent the gain and damping ratios, respectively.

The data obtained in the Matlab program were plotted on the Bode diagram (Figure 10), and the specified gain and damping ratio values were optimized using the fmincon command to obtain the closest gain and damping ratio values, thus obtaining the system's transfer function. The optimization results showed an error rate of 4.741% and a correlation coefficient of $R^2 = 0.9562$. Therefore, it can be said that the system's transfer function was successfully obtained through optimization (Figure 11).

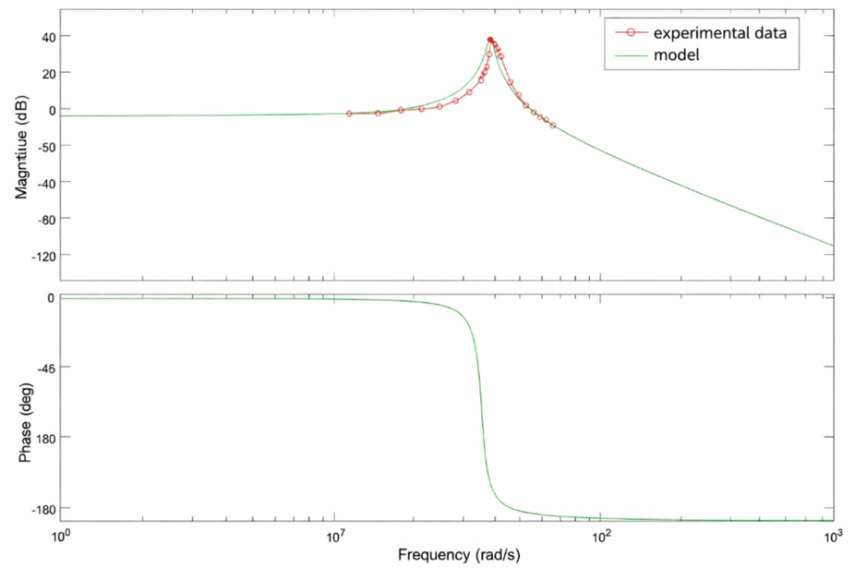

Figure 10. Experimental data and the plotting of the bode graph.

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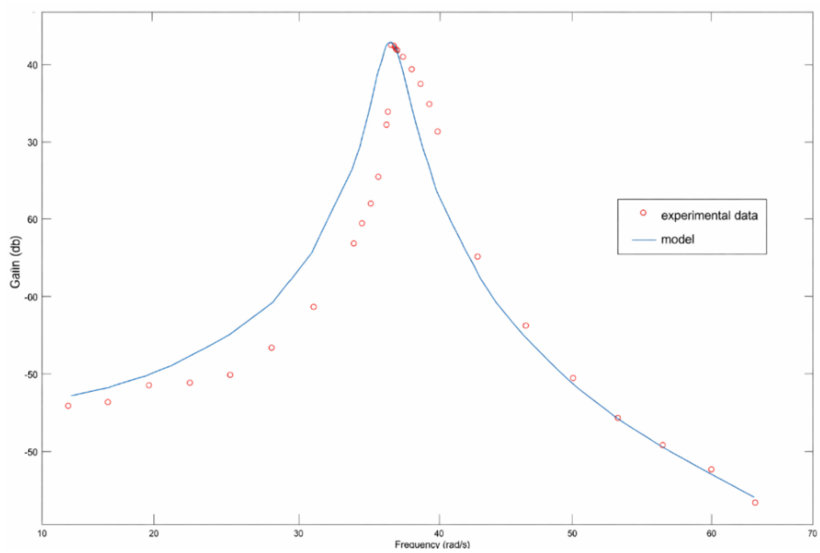

Figure 11. The graph obtained as a result of optimization.

Source: Created by the author.

Figure 11 was obtained to provide a more detailed view of Figure 10. Through the optimization performed, k=1.0913 and ξ=0.0304 were found. Therefore, the transfer function of the system was obtained as follows (Equation 2).

$$G(s) = \frac{1.0913}{s^2+2.276s+1402.34} \tag{2}$$

Finally, the phase angles of the obtained continuous response curves were calculated and plotted on the Bode diagram, resulting in Figure 12.

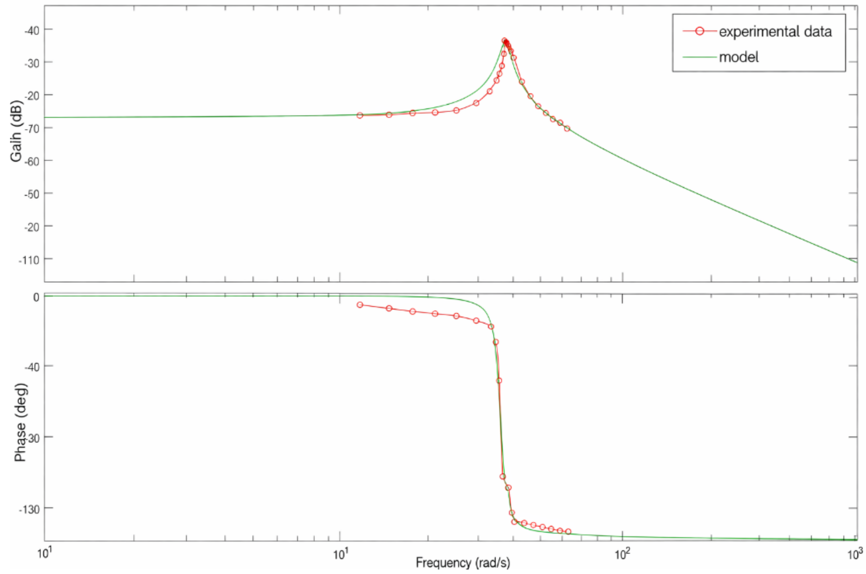

Figure 12. Experimental data and bode plot plot (Phase angle)

Source: Created by the author.

5. Conclusion and Suggestions

In this study, the dynamic behavior of a fixed-free aluminum beam under the influence of electromagnetic force was experimentally investigated using a magnetic levitation-based system, and the mathematical model of the system was successfully obtained. By coating the free end of the beam with ferromagnetic material, a contactless excitation and damping mechanism was created, thereby minimizing classical mechanical contact-related errors. As a result of the experimental analyses, the natural frequency of the system was consistently determined using both time-domain and frequency-domain data. Findings obtained from the frequency response functions showed that the system has a natural frequency of approximately 5.96 Hz (37.45 rad/s). This value is consistent with experimental observations and clearly reveals the resonant behavior of the system. The second-order transfer function of the system was obtained with high accuracy through optimization studies performed in MATLAB. The agreement of the obtained model with the experimental data was confirmed with an error rate of 4.741% and a correlation coefficient of $R^2 = 0.9562$. These results show that the proposed modeling approach reliably represents the system dynamics. Furthermore, when the effect of electromagnetic force on the system was examined, it was observed that as the magnetic effect increased, the vibration amplitude decreased and effective damping was achieved in the system. This shows that the electromagnetic damping method offers high efficiency along with the advantage of contactless control.

In conclusion, it has been shown that magnetic levitation-assisted electromagnetic systems are an effective, precise, and applicable method for experimental modeling of flexible structures and vibration control. This study provides an experimental contribution to the frequency response function-based modeling approach, especially in magnetically driven systems, and creates an important infrastructure for future studies in fields such as active vibration control, smart structures, and energy harvesting systems.

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DECLARATIONS

SECTION	STATEMENT / DISCLOSURE
Author Contributions	**A.M:** Conceptualization, Methodology, Investigation, Writing - original draft. **E.K:** Formal analysis, Data curation, Writing - review & editing. Author have read and agreed to the published version of the manuscript.
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