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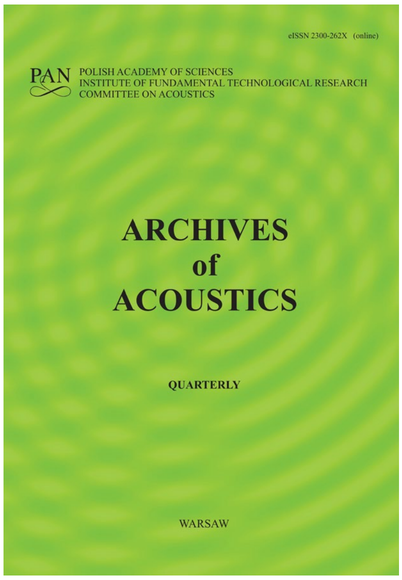

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Active Vibration Suppression of a Thin Circular Pipe

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Abstract

The article presents an active vibration damping system for a thin-walled cylindrical tube, which is a simplified model of a lightweight robot arm (LWR – Lightweight Robot). The proposed solution integrates control algorithms, piezoelectric materials and a hardware and software environment enabling real-time control. Macro Fiber Composite (MFC) elements were used for active vibration reduction, acting simultaneously as sensors and actuators. The object on which the research was conducted was a tube with an external diameter of 40 mm, this element was rigidly mounted at a distance of 1 meter from the free end, simulating cantilever conditions. The stimulation of the object to vibration was carried out using the MFC actuator, while the system response was recorded in the xPC Target environment. Based on the measurement data, the mathematical model of the object was identified in the discrete domain using the ARX method. The obtained model was used to design a controller based on the pole location method, which was implemented on a real test stand. The experimental results showed the effectiveness of the designed control system in reducing the amplitude of natural vibrations of the structure. The use of MFC elements as sensor elements and actuators enabled effective vibration damping in real time, confirming the usefulness of the proposed solution in the context of improving the precision of robotic systems.

Keywords: active vibration control; lightweight robot arm; Macro Fiber Composite; PID controller; system identification; piezoelectric actuators.

Acronyms

ARX – AutoRegressive with eXogenous inputs,
ARMAX – AutoRegressive Moving Average with eXogenous inputs,

LWR – Lightweight Robot (Arm),
MFC – Macro Fiber Composite,
PID – Proportional–Integral–Derivative (controller),
xPC – Real-time MATLAB/Simulink execution environment (xPC Target),
RMS – Root Mean Square,
FEM – Finite Element Method,
PZT – Lead Zirconate Titanate (classical piezoelectric ceramic),
DoF – Degrees of Freedom.

1 Introduction

Modern robotics, particularly in the context of lightweight robotic arm structures, demands increasingly higher precision in positioning, faster response times, and adaptability to dynamic environments. One of the central challenges in the design of robotic systems is the effective suppression of structural vibrations. These disturbances necessitate slower operational speeds and longer cycle times, ultimately leading to increased production and maintenance costs (**Iskandar 2020**). Despite ongoing advancements in articulated robotic arms, which are widely used in manufacturing and material handling, these systems remain vulnerable to undesirable dynamic behaviour, particularly vibrations. The prevailing design trend of reducing structural mass to lower energy consumption further exacerbates the susceptibility of LWRs to vibration-induced instability **(Zhong et al. 2019)**. Vibrations reduce operational precision and cause unintentional deviations in the end-effector trajectory. In dynamic and unpredictable environments, external disturbances can compromise both accuracy and repeatability—two critical parameters in automated and precision-driven applications. This issue is particularly pronounced in lightweight robot arms (LWRs), where mass reduction is typically achieved at the expense of structural stiffness, increasing the system's susceptibility to adverse dynamic effects. The study on the control of a flexible arm manipulators started as a part of the space robots research because due to LWRs light weight, ease of maneuverability and less power consumption these kind of manipulators are very useful for space applications (**Sobieszczanski-Sobieski et al. 1997**; **Cannon and Schmitz**; **1984**). Flexible manipulators are used also for surgical and micro-surgical operation, describes research in active instruments for enhanced accuracy in micro-surgery (**Leniowska and Leniowski 2012**; **Riviere at al. 2003**). Nowadays, in science and engineering, the pursuit of lightweight design represents both a well-established and continually evolving area of research. In contemporary applications, lightweight solutions are expected to meet not only technical and economic criteria but also align with principles of sustainability.

Designing a control law for a flexible robotic system involves reconciling conflicting requirements. On one hand, the system is expected to exhibit rapid dynamic responses. When the structure and parameters of the robot's model are accurately known, control strategies based on control theory can be applied to achieve high-speed performance. In practice, however, the model and its parameters are often only approximately known, which complicates the synthesis of such control laws. Precise dynamic modelling plays a fundamental role in model-based control, which remains one of the most widely used approaches for industrial robotic systems. The mathematical models of flexible robots have been considered by many researchers. Typically, obtaining an accurate dynamic model involves two main stages:

1. Formulating dynamic equations using established methods such as the principle of virtual work, the Newton–Euler formalism, Kane's method (**Book1984**; **DeLuca1989**; **DeLuca1991**), or a finite element method (**Bayo1987**; **Chedmail1989**).

2. Estimation of dynamic parameters through identification techniques that rely on the linear parameterisation of the dynamic model **(Ljung**; **1999; SODERSTROM 1983)**. This approach refers to the methodology of determining a mathematical representation of a system by fitting model parameters to observed input–output data. The central idea is to capture the intrinsic dynamics of the system within a chosen model structure, such as transfer functions or state–space formulations.

Over the past several decades, identification techniques has received considerable attention, as it provides a systematic way to translate experimental measurements into relative reliable models. Such models not only offer insight into the underlying physical or engineering processes but also serve as essential tools for simulation, control design, and optimization. For these reasons there has been a strong trend towards extending or even replacing classical model-based approaches with modern data-driven and hybrid methods. These techniques enable the design of controllers directly from experimental input–output data, thereby reducing the dependency on precise analytical models, which are often difficult to obtain for lightweight flexible structures with distributed parameters and nonlinearities. A comprehensive review by Yang, Li, and Luo (**Yang 2024**) summarizes the rapid development of data-driven vibration control (DDVC), highlighting subfields such as iterative learning control, reinforcement learning, and model-free adaptive control, all of which demonstrate strong potential for vibration suppression in robotic and aerospace applications. The authors emphasize that data-driven methods provide advantages in adaptability to uncertainties, reduced modelling effort, and robustness against disturbances, which are particularly valuable for thin-walled, lightweight manipulators. Similar directions are also explored in the context of pipelines and fluid-conveying structures, where system identification combined with adaptive feedback improves damping performance under variable operating conditions (**Ding 2023**). This experimental-based technique has been also used by the authors in active vibration suppression (**Leniowska and Kos**; **2009**; **Leniowska and Mazan 2015**; **Leniowska at al. 2022**; **Pater et al. 2024**) and it will be applied herein.

An important stream of recent research focuses on advanced robust control strategies. For example, Qin et al. (**Qin 2023**) proposed a data-driven H_∞ control method that ensures stability and performance guarantees without requiring an exact plant model, achieving effective vibration attenuation in flexible beam-like structures. These approaches stand in contrast to classical ARX/ARMAX-based identification, positioning themselves as scalable solutions for real-time industrial implementations. Complementary work by Zhang et al. (2025) has shown that combining data-driven design with hybrid piezoelectric actuators leads to significant improvements in damping efficiency, which suggests new pathways for integrating simple controllers with advanced materials in practice.

Parallel to algorithmic progress, actuator and sensor technologies have undergone significant advances. While traditional lead zirconate titanate (PZT) ceramics remain widely studied, modern Macro Fiber Composites (MFC) and adaptive hybrid actuators offer improved flexibility, reduced fragility, and higher strain energy density, making them well suited for lightweight robotics applications (**Masaid et al. 2023**). Recent studies also highlight the importance of distributed sensor–actuator networks, where piezoelectric patches are optimally placed to target dominant modes and increase control authority. In addition, semi-active strategies such as piezoelectric shunt damping circuits have been extensively reviewed by Marakakis et al. (**Marakakis et al. 2019**), who underline that shunted PZT elements—when combined with active feedback—enable hybrid approaches balancing energy efficiency with wideband damping performance. This trend towards multi-modal, hybrid suppression strategies positions classical active control within a broader landscape of contemporary solutions.

Within this broader context of active vibration and noise suppression, adaptive feedforward control methods based on least-mean-square (LMS) algorithms have been extensively investigated (**Pawelczyk 2004**; **Bismor 2014 a**; **Bismor 2014 b**). The limitations of the hybrid active feedforward noise control (ANC) configuration were analyzed, demonstrating that its practical performance depends heavily on careful consideration of secondary path dynamics and adaptive mechanisms. These results are particularly relevant for lightweight, distributed-parameter structures, where computational resources are constrained, and thus motivate the search for control strategies that remain effective under similar practical limitations in vibro-acoustic systems.

Taken together, these developments indicate that the state of the art in vibration suppression is moving towards integration: data-driven algorithms coupled with advanced actuators and hybrid control architectures. For lightweight robotic arms, this means that even relatively simple controllers such as PID, when embedded in modern mechatronic setups and supported by efficient identification procedures, can remain competitive. Our study, therefore, complements these advances by demonstrating how a classical control law can be effectively combined with MFC-based actuation in a real-time environment, providing a practical and experimentally validated benchmark against which more complex, data-driven strategies may be assessed.

This paper proposes the usefulness solution in the context of improving the precision of robotic systems based on the use of Macro Fiber Composite (MFC) piezoelectric elements, which serve both as sensors and actuators. The key innovation lies in the integration of experimentally derived dynamic models with a real-time digital PID controller, enabling effective damping of vibrations under realistic operating conditions. Despite the development of more advanced control methodologies in recent years, PID controllers continue to be widely applied across various industrial domains owing to their effectiveness and robustness as well as in feedback control of a flexible robot manipulators (**Ho and Tu 2005**; **Ang et al. 2005**; **Akyuz et al. 2011**). The developed control system was validated through both simulation and physical experiments. Potential applications include lightweight robotic systems and high-precision devices where vibration minimization is critical to performance and operational safety. This paper is structured as follows: In Chapter 2 the considered object, the aluminium tube which serve as prototype LWR robotic arm is described and technical specifications of the MFC elements are given. In chapter 3 a method of dynamic parameters estimation through identification techniques to develop mathematical model is provided. Chapter 4 provides brief notes on the PID conroler used. Chapter 5 gives an overview on the implemented program code. View on the complete system which represents a digital PID controller with supporting hardware is given in Chapter 6. Finally, Chapter 7 provides the testing results and conclusions.

2 Materials and Methods

In the context of research on active vibration damping in lightweight robotic structures of the LWR (Lightweight Robot) type, a thin-walled tube made of aluminum alloy Al99.5 was selected as a representative model of a robotic arm. This component, characterized by appropriately selected geometric dimensions (detailed in Table 1), was rigidly clamped at one end, simulating cantilever boundary conditions. On its surface, Macro Fiber Composite (MFC) piezoelectric elements were mounted, serving a dual role as sensors detecting vibrations and actuators for excitation and compensation of vibrations. The locations of the MFC elements distributed along the object are presented in Table 2. One of the transducers was configured as an exciter, generating a chirp signal ranging from 1 Hz to 1 kHz over a period of 30 seconds.

Table 1: Geometric parameters of the structural element

Parameter	Value [mm]
Outer diameter	40
Inner diameter	38
Wall thickness	2
Total length	2000
Clamping length	1000

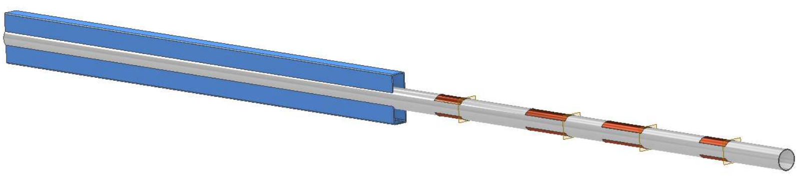

Figure 1: Schematic representation of the tested structure: a thin-walled aluminum tube equipped with MFC piezoelectric transducers for active vibration control

Table 2: Arrangement of MFC elements relative to the mounting point ($x = 0$ at the center of the object)

Element	x_{left} [mm]	x_{middle} [mm]	x_{right} [mm]	Width [mm]
MFC 1	109.0	142.5	176.0	67.0
MFC 2	343.0	394.5	446.0	103.0
MFC 3	540.0	591.5	643.0	103.0
MFC 4	792.5	826.0	859.5	67.0

The experimental placement of the MFC elements was based on modal analysis with a Polytec laser vibrometer. Sensors were positioned away from the modal nodes to maximize strain sensitivity, and the locations of the elements are listed in Table. 2. Four transducer pairs were mounted on the upper and lower surfaces of the tube to capture the structural response and provide actuation authority for vibration suppression. Real-time experiments were conducted using the xPC Target platform. A linear parametric model of the tube was identified directly from the input–output data and subsequently used for controller design. This approach enabled a realistic representation of the system's dynamic behavior and facilitated the development of an effective vibration control algorithm.

Macro-Fiber-Composite (MFC) transducers consist of parallel piezoelectric fibres embedded in a polymer matrix, which provides flexibility and mechanical robustness. Constructed from parallel-aligned piezoelectric fibers embedded in a polymer composite matrix, MFC transducers exhibit suitability for operation under dynamic conditions and can be mounted on surfaces with irregular geometries.They can be bonded to curved or irregular surfaces.

In this study, MFC transducers were applied to actively suppress vibrations in a thin-walled aluminum tube which serves as a lightweight robot arm. Sensors and actuators locations were selected from the modal analysis to avoid nodes. The transducers were mounted using a two-component adhesive, ensuring a durable bond with minimal influence on the mass and stiffness of the structure.

Compared to traditional PZT piezoceramics, MFCs exhibit several distinct advantages, primarily due to their flexibility, resistance to mechanical deformation, and high effectiveness in vibration damping. Moreover, each element is capable of both sensing strain and generating actuation forces. The best performance was obtained with elements of 35 mm × 103 mm; smaller transducers were less effective.The parameters of the elements used are provided in Table. 3

Described above the thin-walled aluminium tube was used as a test model, selected due to its geometric and material properties, which make it highly susceptible to vibrations. The aim of this study was to develop an effective active vibration reduction algorithm for the aluminium tube which serve as prototype LWR robotic arm. The foundation of the research involved the use of piezoelectric materials in the form of MFC (Macro Fiber Composite) elements, which act both as sensors and actuators responsible for active vibration suppression. To achieve the research objectives, a dedicated laboratory test stand had to be designed and constructed (**Pater et al. 2024**). It was developed to enable vibration measurements, identification of the

Table 3: Technical specifications of the MFC element

Parameter	Value	Unit
Model	06L18-044D	–
Width	34	mm
Length	103	mm
Thickness	0.3	mm
Polarization voltage	+1500 / -500	V
Piezoelectric coefficient d_{31}	-2.1E+02	pm/V
Piezoelectric coefficient d_{33}	4.6E+02	pm/V

dynamic properties of the structure, and their active suppression using appropriately selected controllers.

3 Mathematical model

Effective vibration suppression requires a thorough understanding of the robot's dynamic characteristics. Dynamic identification of mechatronic systems is a process aimed at developing a mathematical model of the investigated object based on experimental measurement data. This method is particularly useful in cases where constructing an accurate theoretical model is challenging due to complex system geometry, numerous physical parameters, or the presence of nonlinearities. Estimation of dynamic parameters through identification techniques involves analyzing the system's response to known excitation inputs and constructing mathematical models that accurately reflect its behavior. One such approach is the use of MFC elements for sensing, combined with ARMAX-based system identification (**Isermann**; **2013**) to model dynamic properties. These experimentally developed models are crucial for the design of active feedback-based vibration control systems and also preserve the essential features of the object dynamics within the considered vibration band. The key components of the experimental approach include the appropriate selection of the excitation signal and precise measurement of the system's response. This allows for the extraction of essential information about the system's dynamic characteristics, such as resonance frequencies, damping properties, and transfer functions.

The integrated excitation and data-acquisition chain is shown in Fig. 2. A precomputed `.wav` signal is played by the laptop's built-in sound card; the line-out feeds a power amplifier that drives the MFC actuator. For synchronization, the same line-out is routed in parallel to the ADC (the measurement card integrated with the `xPC` target), which simultaneously samples it together with the MFC sensor output. The `xPC` target performs sampling and buffering and streams the data to `MATLAB` for recording and analysis. During identification experiments the sampling frequency was 10 kS/s for all channels, and the pre-processing consisted of removing the DC component (detrending by subtracting the sample mean) from each time series.

In the experiment, a chirp signal was used, which enables excitation of the tested system over

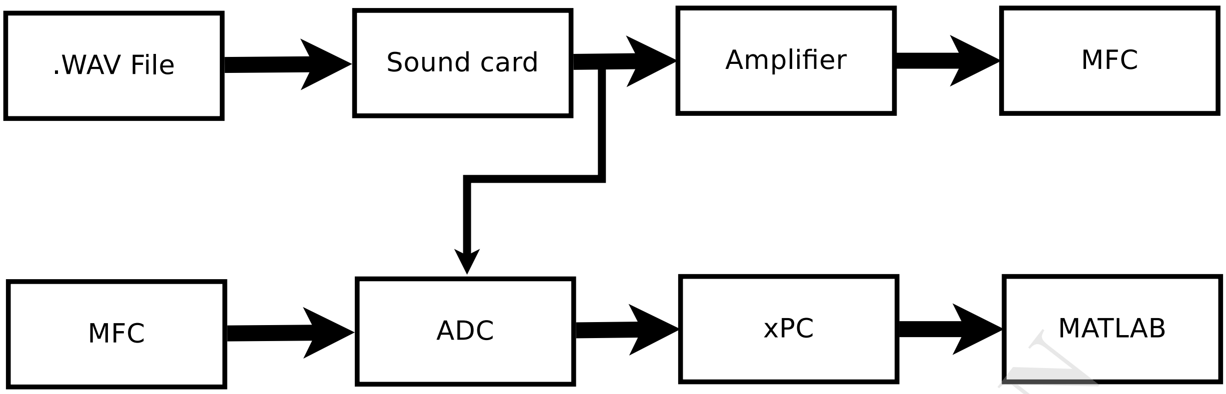

Figure 2: Integrated system for excitation generation and data acquisition. The sound-card line-out is split: one branch drives the amplifier–MFC actuator path, the other is sampled by the ADC (measurement card of the `xPC` target) for synchronization.

a wide frequency range within a single measurement run. This approach allows for obtaining the frequency response and identifying the system's resonant frequencies without the need to repeat the experiment for individual frequencies. Such a method is widely used in dynamic system analysis, as it allows for efficient and rapid acquisition of the system's frequency response.

The time-domain data collected during the experiment was imported into the MATLAB environment using the System Identification Toolbox. This module enables data analysis and the identification of mathematical models, both in the form of transfer functions and state-space models. With advanced algorithms, it is possible to accurately fit the model structure to the actual behaviour of the studied system. This requires proper selection of the sampling frequency to ensure sufficient time resolution, particularly when analysing higher-frequency components. The identification process involves matching the model structure including the number of poles and zeros to the recorded data. Through an iterative parameter-fitting procedure, a model was developed that accurately reflects the dynamic properties of the robot arm. Such a model can subsequently be used for control system design, simulation, and analysis of how different parameters affect the system's dynamics. An experimental approach based on real measurement data offers several advantages over purely theoretical methods. Models developed from experimental data can accurately capture nonlinearities, complex geometries, and unpredictable dynamic effects. Measurement technologies based on piezoelectric sensors and laser vibrometry enable detailed analysis even of complex mechatronic structures. The resulting mathematical models provide a solid foundation for the further design and optimization of dynamic systems. As part of the identification process, commonly used ARX (AutoRegressive with eXogenous inputs) and ARMAX (AutoRegressive Moving Average with eXogenous inputs) models were employed. These are fundamental tools for modelling linear systems. Both models use input and output data to create a difference equation that describes the system's dynamics. The key distinction between ARX and ARMAX lies in their treatment of noise—the ARMAX model includes an additional term that accounts for the dynamics of noise components (**Ljung**; **1999**).

$$y(t) + a_1 y(t-1) + \cdots + a_n y(t-n) = b_1 u(t-1) + \cdots + b_m u(t-m) + e(t) \tag{1}$$

In this model, $y(t)$ denotes the output signal, $u(t)$ represents the input signal, a_i and b_i are the model coefficients, and $e(t)$ denotes the noise term, which is assumed to be white noise. The model assumes that the disturbances are random in nature and affect only the output.

4 PID control

In the developed active vibration control system, the PID controller was implemented in a discrete-time form, consistent with the digital real-time architecture of the xPC Target platform. Instead of the continuous PID equation, the controller was realised using the following standard discrete transfer function:

$$G_{\mathrm{PID}}(z) = K_p \left(1 + \frac{T_s}{T_i}\frac{1}{1-z^{-1}} + \frac{T_d}{T_s}(1-z^{-1})\right) \tag{2}$$

where K_p is the proportional gain, T_i the integral time constant, T_d the derivative time constant, and T_s the sampling period. The integral part is implemented using the discrete accumulator $\frac{1}{1-z^{-1}}$, while the derivative part uses the backward difference $(1-z^{-1})$, ensuring numerical stability and robustness to measurement noise.

This discrete transfer-function formulation is well suited for real-time vibration suppression because it provides predictable phase characteristics and stable operation near high-Q resonances. In this study, the PID controller was tuned to increase the effective damping of the dominant vibration modes (214 Hz and 574 Hz) identified in Section 3. Combined with MFC sensor–actuator pairs, the discrete PID controller enabled effective attenuation of resonant oscillations under both harmonic and broadband excitations. The final values of the tuned parameters used during experiments are listed in Table 5.

5 Model identification

The objective of this study was to develop an effective algorithm for active vibration reduction in the LWR robotic arm. The research was based on an experimental mathematical model of the system, obtained using the ARX (AutoRegressive with eXogenous inputs) method. Data was recorded and subsequently used in the model identification process. The transfer function of the considered object takes the form:

$$G(z^{-1}) = \frac{b_0 + b_1 z^{-1} + b_2 z^{-2} + b_3 z^{-3} + b_4 z^{-4} + b_5 z^{-5}}{a_0 + a_1 z^{-1} + a_2 z^{-2} + a_3 z^{-3} + a_4 z^{-4} + a_5 z^{-5} + a_6 z^{-6}} \tag{3}$$

The obtained data for the discrete model are presented in Table 4

6 Vibrations suppression simulation and tests

In the next step, the PID controller was tuned in a simulation environment based on the identified models. The PID controller parameters used during the experiments are summarized

Table 4: The values of the A and B coefficients adopted in the object identification process

i	$A(z^{-i})$	$B(z^{-i})$
5	−4.473	0.0870
4	8.095	−0.3335
3	−7.392	0.4914
2	3.393	−0.3298
1	−0.6226	0.0851

in Table 5. These settings were selected based on the tuning procedure described in Section 4.6 and were applied to the physical object during testing. Providing these values ensures that the presented control performance can be independently verified.

Table 5: PID controller settings used in the experiment

Parameter	Value
Proportional (P)	5.5
Integral (I)	4.0
Derivative (D)	5.0

The response of both the system and the controller was recorded for a first vibration resonanse frequency of 214 Hz, Fig. 3.

Similar effectiveness was observed at the second resonance frequency of 574 Hz, where the vibration amplitude was considerably reduced when the controller was turn on. In subsequent stages of the research, the object was subjected to excitation composed of two harmonics (214 Hz and 574 Hz). Despite the increased signal complexity, the PID controller effectively reduced the amplitudes of both vibration components, demonstrating its capability to operate under more complex dynamic conditions (Fig. 4).

Additionally, when applying a chirp signal with a frequency sweep ranging from 1 Hz to 1 kHz, an increase in vibration amplitude was observed near the resonance frequencies. After activating the controller, vibrations were successfully suppressed, especially at critical points within the frequency band, confirming the versatility of the control system and its ability to perform under variable excitation conditions (Fig. 5)

The results of the experimental tests are presented below. Data were recorded in the same manner as in the previous cases.

During the conducted experiments with the real mechanical system subjected to active vibration reduction, the effectiveness of the PID controller was evaluated. Tests were performed for various types of excitations, including harmonic signals at resonance frequencies of 214 Hz and 574 Hz, their combination, and a chirp signal. In each case, the controller was activated after a predefined time interval, allowing comparison of the system's behavior before and after control activation. For the harmonic excitation at 214 Hz, the system without control exhibited

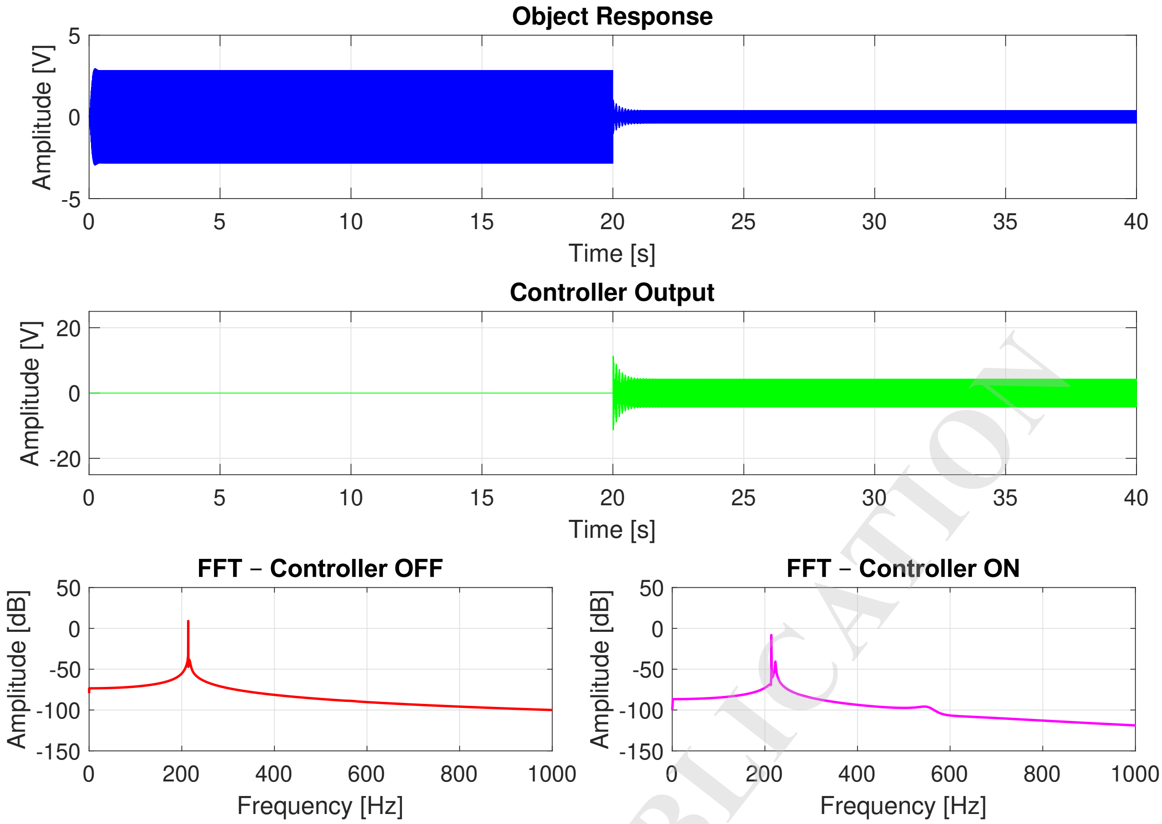

Figure 3: Simulation result – time course and corresponding frequency spectrum for 214 Hz; 0-20 seconds; the open loop control system, 20-40 seconds the close loop control system

large amplitude vibrations characteristic of resonance. After enabling the PID controller, a significant reduction in oscillation amplitude and gradual damping of vibrations were observed. The damping process was smooth and free of overshoot, indicating properly tuned controller settings and its effectiveness in improving system stability. Similar phenomena were observed for the resonance frequency of 574 Hz. Without the controller, the system showed sustained oscillations with considerable amplitude. Upon activation of the PID controller, a rapid and effective vibration reduction occurred, enhancing the quality of the dynamic response. This process was also stable and free from adverse effects, confirming the efficiency of the applied control system. When the object was subjected simultaneously to two harmonic excitations at 214 Hz and 574 Hz, the system exhibited particularly unfavorable dynamic behavior with large oscillation amplitudes in the uncontrolled state. Activation of the PID controller resulted in a significant reduction of vibration amplitude and gradual suppression of oscillations caused by the superposition of the two resonant components. The vibration reduction levels obtained in the simulations were highly favorable for the considered resonant frequencies (51.11% and 48.51%). However, the reductions achieved in the experimental tests were significantly lower; for the 214 Hz resonant frequency, a reduction of 21.53% was observed (Table 6). When the object is forced with a chirp signal, the results are slightly better. Detailed results are summarized in the Table.7. Nevertheless, the results confirm that the proposed solution enables effective vibration reduction despite of its simple structure.

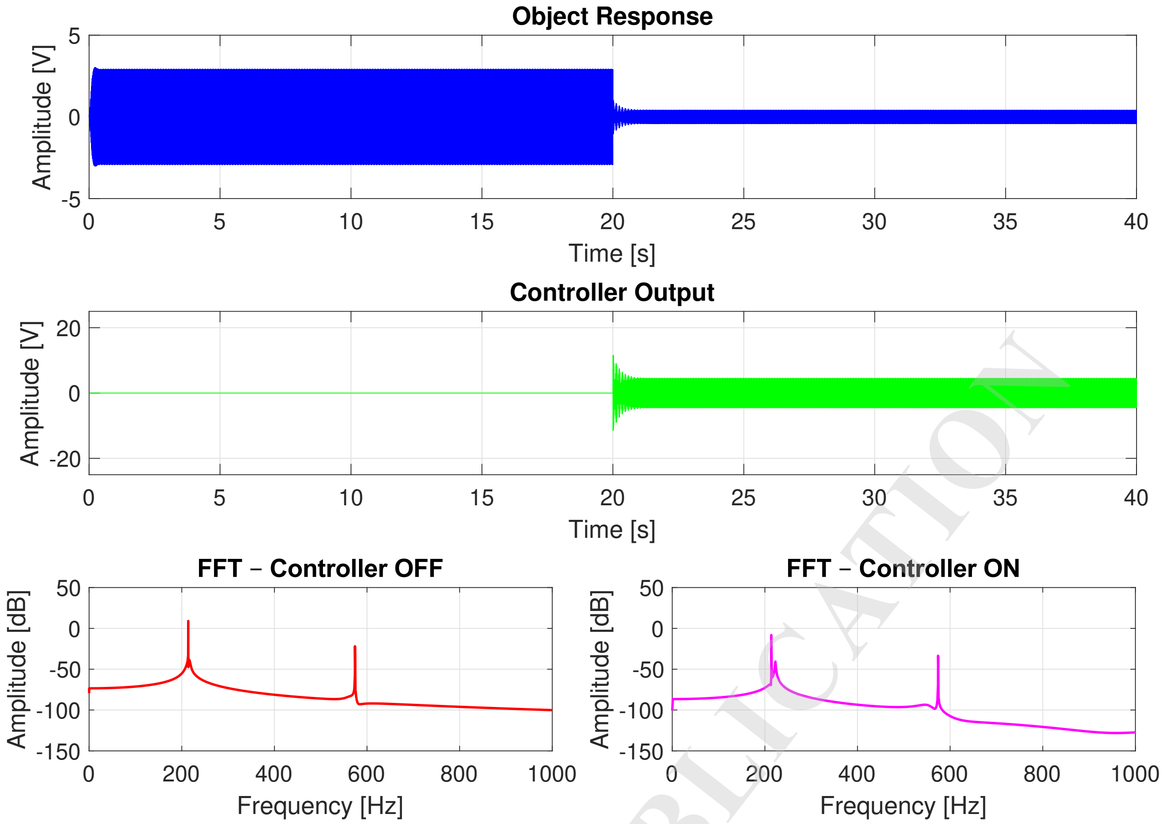

Figure 4: Simulation result – time course and corresponding frequency spectrum for the sum of frequencies 214 and 574 Hz; without a controller from 0 to 20 seconds, and with a controller from 20 to 40 seconds

Table 6: Vibration attenuation based on the object response

Excitation	**Average amplitude controler OFF [V]**	**Average amplitude controler ON [V]**	**Attenuation [%]**
214 Hz (simulation)	2.25	1.10	51.11
214+574 Hz (simulation)	2,35	1.21	48.51
214 Hz (experiment)	3,53	2.77	21.53

Table 7: Vibration attenuation based on the object response

Excitation	**Max amplitude controler OFF [V]**	**Max amplitude controler ON [V]**	**Attenuation [%]**
Chirp (simulation)	2,55	0,85	66.67
Chirp (experiment)	3.85	2.37	38.44

7 Conclusion

The conducted research confirmed the effectiveness of the developed active vibration reduction system utilizing a PID controller. The control system, designed based on an ARX-type mathematical model of the object, demonstrated high efficiency both in simulation environments and real-world conditions. The obtained results validate the correctness of the adopted assumptions as well as the suitability of the chosen modeling and control methods which is confirmed by the data in the Table.6 and Table.7. The use of Macro Fiber Composite (MFC)

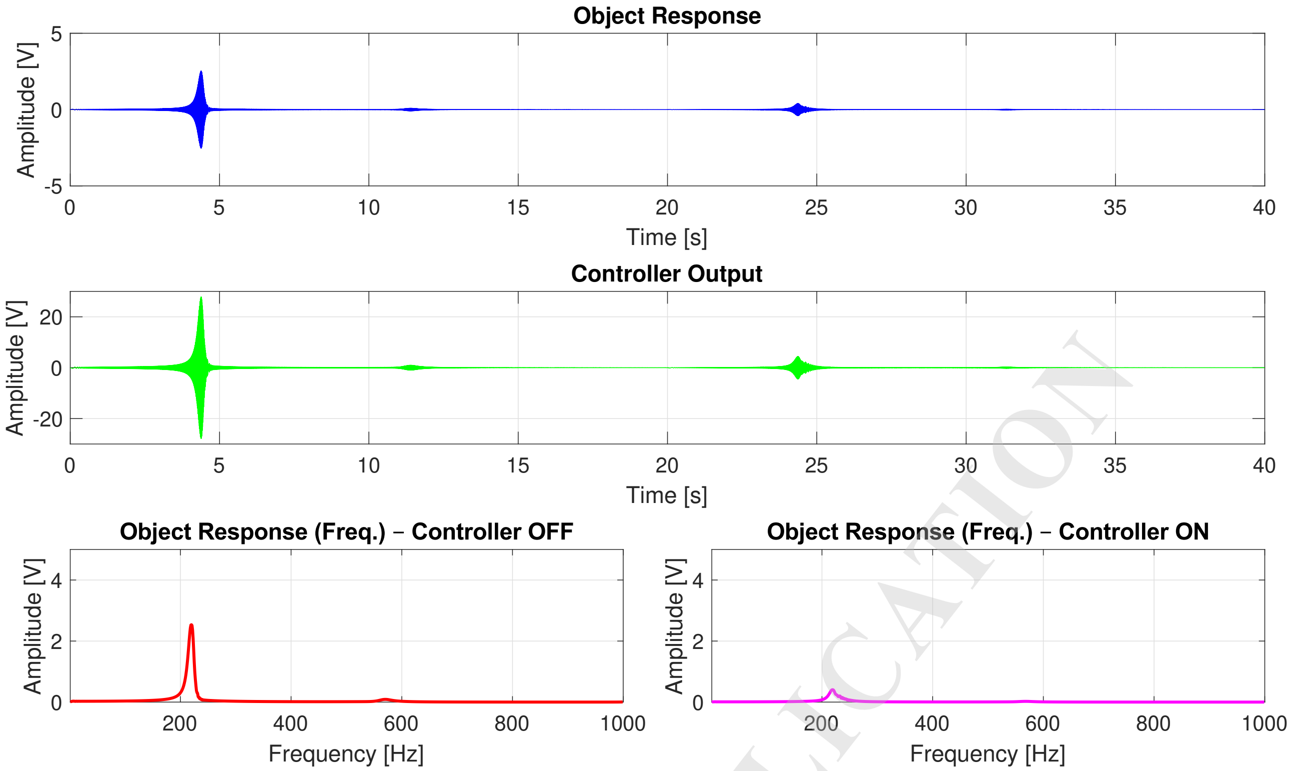

Figure 5: Simulation result – time course and corresponding frequency spectrum of chirp signal with frequency 1–1000 Hz, without controller from 0 to 20 seconds and with controller from 20 to 40 seconds

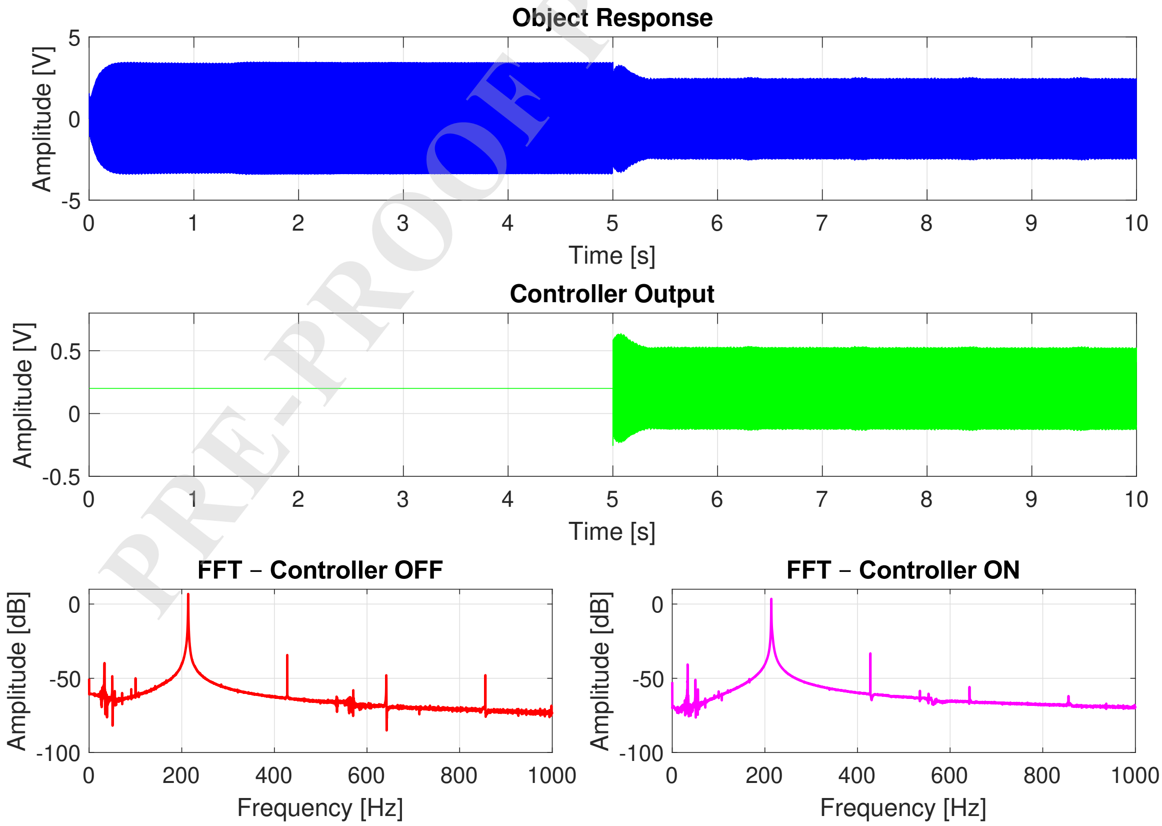

Figure 6: Experimental results – the time response for the frequency of 214 Hz excitation; 0-5 seconds the open loop control system, 5-10 seconds the close loop control system

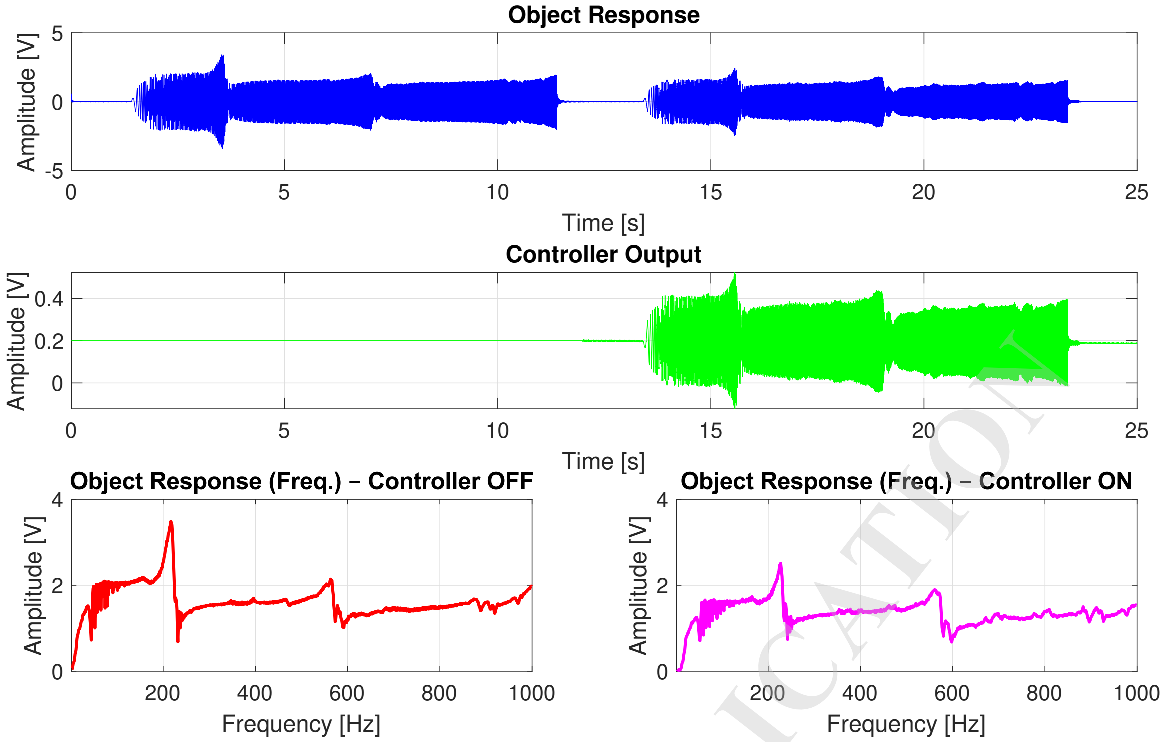

Figure 7: Experimental results – the time response for chirp signal (from 1 Hz to 1000 Hz) excitation; 0-5 seconds the open loop control system, 5-10 seconds the close loop control system

piezoelectric materials as sensors and actuators proved to be an effective and practical solution. The high sensitivity of these elements, combined with their capability for active vibration damping, enabled precise monitoring and elimination of vibrations in lightweight structures such as thin-walled tubes modeling robot arms. The developed control system demonstrated its versatility by effectively suppressing vibrations induced by both simple harmonic excitations and more complex input signals. This indicates its potential applicability across a wide range of engineering applications, particularly in robotics and mechatronics. A key factor in the overall process was the accurate modeling of the object, facilitated by tools such as the xPC Target system within the MATLAB environment. Precise identification of the dynamic properties of the structure directly contributed to the effectiveness of the developed control algorithm. The obtained results provide a solid foundation for further research and development. The presented solution can be adapted to more complex structures and integrated with advanced control strategies, such as adaptive or predictive control. This system opens new perspectives for active stabilization of lightweight robotic structures, contributing to improvements in their precision and operational reliability.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors' contribution

Author MP and LL conceptualized the study and wrote the original draft. Author MP and MG performed the measurements, analysis and contributed to data interpretation. All authors reviewed and approved the final manuscript.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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