

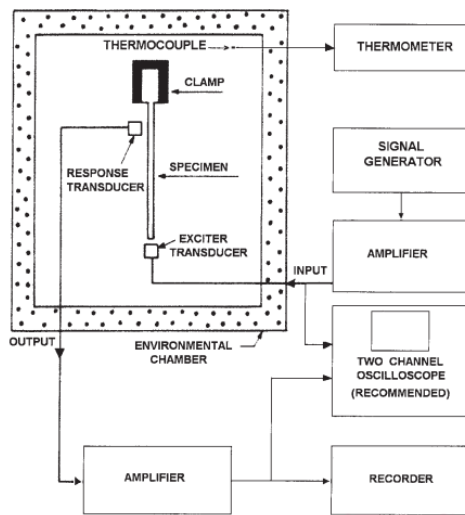
Low Cost Non-Contact Measurement of Damping and Vibration

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Graphical Abstract



Highlights

- A low-cost ultrasonic sensor-arduino system was developed to measure natural frequency and damping ratio of cantilever beams.
- The apparatus applies FFT and exponential decay analysis to displacement data for dynamic property extraction.
- Calibration with a correction factor (~ 0.887) reduced frequency errors to below 5% compared with theory and FEA.
- The system provides a simple non-contact and effective educational tool for vibration measurement and dynamics learning.

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ABSTRACT

Understanding material dynamic behavior is crucial for designing structures subject to vibration. While static properties are often emphasized in engineering education, dynamic properties such as natural frequency and damping ratio are less frequently measured. This work presents an ultrasonic-sensor-based apparatus for measuring these dynamic properties of cantilever beam specimens. The prototype uses an HC-SR04 ultrasonic time-of-flight sensor and an Arduino microcontroller to record beam vibration. An exponential decay envelope analysis is applied to the displacement time history to determine the damping ratio. A piezoelectric accelerometer provides reference measurements for validation. Experimental tests on aluminum

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and 3D-printed PLA beams were conducted, and the measured frequencies and calculated damping ratios closely matched analytical and finite-element predictions. Sensor calibration was performed, yielding a correction factor of ~ 0.887 to improve accuracy. After calibration, frequency errors were below 5%. The apparatus reliably determines natural frequency and damping ratio, offering a simple, low-cost alternative to conventional methods. This system can serve as an effective educational tool for demonstrating vibration measurement and material dynamic behavior.

1. Introduction

Dynamic material properties – particularly natural frequency and damping ratio – are essential for predicting how structures respond to vibration and dynamic loads. High damping materials are widely used in aerospace, automotive, and civil structures to minimize oscillations. Accurate knowledge of these properties ensures safety and performance in design. However, undergraduate curricula typically emphasize static tests, and dedicated laboratory equipment for dynamic property measurement is uncommon. Standard methods such as ASTM E756 [1] provide procedures for damping measurement, and the Oberst beam method is often used to determine material loss factors. These traditional approaches, however, require specialized fixtures and are time-consuming. Advances in low-cost sensors and microcontrollers now enable simpler, digital measurement systems. For example, Sekine et al. developed a microcontroller-based vibration tester using accelerometers, and digital signal processing (FFT) techniques allow rapid extraction of modal frequencies [2].

Ultrasonic time-of-flight sensors (e.g. HC-SR04) are inexpensive devices typically used for distance measurement. Although not conventionally applied to vibration testing, they can capture dynamic displacement by continuously measuring the gap between the sensor and a moving surface. In this apparatus, an HC-SR04 sensor is mounted facing the free end of a cantilever beam. As the beam vibrates, the sensor's measured distance oscillates accordingly. Concurrently, a miniature piezoelectric accelerometer (Dytran 3224A1) is attached to the beam to provide reference data. The sensors are interfaced with an Arduino microcontroller, which timestamps the measurements.

Dynamic material properties, particularly natural frequency and damping ratio, play a critical role in determining the vibration response and structural integrity of engineering systems. The damping capacity of materials strongly influences energy dissipation, vibration attenuation, and fatigue resistance in mechanical and civil structures, as highlighted by Poddaeva and Fedosova [3]. Accurate evaluation of damping behavior is therefore essential for reliable dynamic design, especially in applications involving repeated or transient loading.

Conventional approaches for measuring damping properties commonly rely on standardized laboratory methods, such as the Oberst beam technique, which has been

widely applied to characterize viscoelastic and low-stiffness materials, including wax-based systems [4]. These methods are grounded in classical vibration and structural damping theory developed by Lazan [5] and later formalized within modal analysis frameworks [6]. However, such techniques often require specialized fixtures, controlled boundary conditions, and expensive instrumentation, which limits their accessibility in undergraduate teaching laboratories and small research facilities.

From a theoretical standpoint, vibration measurement and modal parameter extraction are fundamentally supported by signal processing tools such as the Fast Fourier Transform (FFT), originally formulated by Oberst [7] and now widely applied in experimental modal analysis [6,8]. Classical dynamics and vibration texts by Meriam et al. [9] and Rao [8] provide the analytical foundation for interpreting natural frequencies, damping ratios, and mode shapes obtained from experimental data. Experimental studies on metals and cast irons further demonstrate that damping characteristics vary significantly with material microstructure and composition, underscoring the importance of experimental validation [10].

Recent developments in low-cost sensors and microcontroller platforms have opened new opportunities for practical vibration measurement systems. While piezoelectric accelerometers remain the reference standard for dynamic testing due to their high sensitivity and bandwidth [11], they require physical contact and dedicated signal-conditioning hardware. In contrast, non-contact measurement techniques offer advantages in simplicity, reduced mass loading, and ease of setup. Ultrasonic time-of-flight sensors, though traditionally used for distance measurement, have the potential to capture dynamic displacement when combined with appropriate signal processing and calibration strategies.

The motivation for this study is to develop an applied, low-cost, and non-contact experimental apparatus capable of measuring natural frequency and damping ratio of beam-like structures. Inspired by practical engineering solutions developed for rapid deployment and public use [12], this work integrates an ultrasonic sensor, a microcontroller-based data acquisition system, and FFT-based signal processing to extract dynamic properties. The system is validated against analytical solutions, finite element analysis, and reference accelerometer measurements, demonstrating its suitability for both engineering education and preliminary material characterization. This study describes the design and fabrication of the apparatus, sensor calibration, data acquisition and processing routines, and validation tests. Data processing includes FFT to find the dominant frequency and exponential curve-fitting to determine damping ratio. Measured frequencies and damping are compared against analytical calculations and finite-element simulations. The aim is to produce an accurate, user-friendly system suitable for engineering education.

2. Materials and Methods

A cantilever beam test rig was constructed on a rigid base. Specimens are clamped at one end and free at the other. The beam is manually excited, and its free-end motion

is measured. Figure 1 shows the data-acquisition hardware. An HC-SR04 ultrasonic sensor (operating at 40 kHz, 2–400 cm range) is fixed 6 cm from the free end; it emits ultrasonic pulses and measures the round-trip time to compute distance. The sensor is mounted on a movable linear rail to adjust its position. An Arduino Mega2560 processes the trigger/echo signals and logs timestamps. For validation, a Dytran 3224A1 accelerometer is attached to the beam (via a light bracket) and read by a Rigol DS1052E oscilloscope. The methods section should provide sufficient details about your materials and methods to allow your work to be reproduced by an independent researcher. This section presents the research methods or techniques employed, the equipment and materials required for the study, the sampling techniques used, and the data analysis procedures in detail. Methods already published should be indicated by a reference: only relevant modifications should be described.



Figure 1. Arduino Mega 2560 board

Figure 1. Arduino UNO (model shown) microcontroller used for data acquisition in the vibration apparatus. The Arduino digitizes the ultrasonic sensor’s pulse timings. The accelerometer output is amplified by a constant-current power unit and captured by the digital storage oscilloscope. Key specifications of the sensors are listed in Tables 1-2.

Table 1. Ultrasonic and arduino pinout connection

Ultrasonic pin	Arduino pin
Vcc (Power)	5V
Trig (Trigger)	~3
Echo	~2
Gnd (Ground)	GND

Table 2. DSO parameter settings

Section	Parameters	Option Settings
Analog	Analog Ch	CH1
	Scale	200 mV/
Vertical	Position	-344 mV
	Coupling	DC
Horizontal	Time	Main

Section	Parameters	Option Settings
Trigger	Time Ref	Center
	Main Scale	200.0 ms/
	Delay	1.192 s
	Source	CH1
	Slope	Rising
	Mode	Single
	Level	400 mV
Acquire	Holdoffs	500 ns
	Acquisition	Normal
	Sampling	Equitime
	Memory Depth	Normal
Storage	Storage	CSV
	Data Depth	Displayed
	Source	External

An initial calibration of the ultrasonic sensor was performed. The sensor was placed at known distances from a flat target, and its readings were recorded. A linear correction factor was determined by regressing measured versus true distance. All subsequent sensor readings were multiplied by this factor (~ 0.887) to correct systematic error.

2.1 Data acquisition and processing

The Arduino code triggers the HC-SR04 every 20 ms (50 Hz max). For each pulse, it measures the travel time and computes distance = (sound speed \times time)/2. The distances are streamed via serial to a PC. In post-processing, the distance time-history is filtered and converted to displacement by subtracting the mean. The Fast Fourier Transform (FFT) is used to identify the peak frequency of the oscillation. The logarithmic envelope of the decaying oscillation is then fitted to an exponential model $x(t) = X_0 \cdot \exp(-\zeta\omega_n t)$, from which the viscous damping ratio ζ is computed. Equations for a cantilever's natural frequency (using Rayleigh's method or standard beam formulas) are used to compute theoretical ω_n for comparison.

2.2 Finite element analysis (FEA)

The beam specimens were modeled in Autodesk Inventor. Material properties (elastic modulus, density) are taken from Tables 3–6. Modal analysis in Inventor yields the first bending mode frequency. These simulated frequencies are given in Tables 3–6. The simulation results provide a reference for validation.

Table 3. Aluminum properties [13]

Material	Young's Modulus (GPa)	Yield Strength (MPa)	Ultimate Strength (MPa)
Aluminum	68.9	276	310

Table 4. Properties of 3D printed PLA [14]

Material	Young's Modulus (GPa)	Yield Strength (MPa)	Ultimate Strength (MPa)
PLA Grid 50%	2.8 ± 0.12	29.6 ± 0.78	31.5 ± 2.17
PLA Grid 75%	3.28 ± 0.17	33.3 ± 0.17	35.4 ± 0.46

Table 5. Tensile test result on MP materials [15]

Properties	A	B	3%	7%	10%	13%
Young's Modulus (MPa)	773.42	883.89	651.63	614.50	567.75	675.92
Yield Strength (MPa)	19.50	22.74	16.16	15.55	15.02	16.37
Ultimate Strength (MPa)	41.53	47.65	35.08	34.65	31.34	36.20

Table 6. Mass and density of specimens

Material	Mass (g)	Volume (m ³)	Density (kg/m ³)
Aluminum	21	7.6129×10^{-6}	2758.48
PLA 50%	7.046	7.7630×10^{-6}	907.64
PLA 75%	8.352	7.7630×10^{-6}	1075.87
MP A	7.35	7.8246×10^{-6}	939.35
MP B	7.585	7.8240×10^{-6}	969.45
MP 3%	7.088	7.4844×10^{-6}	947.04
MP 7%	7.298	7.8246×10^{-6}	932.70
MP 10%	7.439	7.8729×10^{-6}	944.89

3. Results and Discussion

Prototype specifications are given in Table 7. The theoretical and FEA-predicted natural frequencies for the beams are listed in Tables 8–9. For example, the theoretical first-mode frequency of a 30×25.4×1 mm aluminum cantilever is ~20.18 Hz, and FEA predicts ~20.21 Hz (Tables 7-9).

Table 7. Prototype apparatus specification

Parameter	Value
Working voltage (DC)	5 V
Distance range	2 – 400 cm
Distance set	5 cm
Max sampling rate	50 Hz
Max specimen length	30 cm
Necessary software	Arduino, PuTTY

Table 8. Theoretical natural frequency calculation

Specimen	Natural frequency (Hz)
Aluminum	20.1833
PLA 50%	15.4218
PLA 75%	15.333

Table 9. Finite Element Analysis simulated results

Material	Modal Frequency 1 (Hz)
Aluminum	20.21
PLA 50%	16.26
PLA 75%	15.93

Initial experiments were conducted on aluminum and PLA cantilevers. Table 10 summarizes the measured natural frequencies, damping ratios, and inferred Young's moduli (calculated from the frequency) using each sensor. The accelerometer data closely match theory: the aluminum beam measured 19.96 Hz (theory 20.18 Hz), yielding a Young's modulus within 0.3% of the known value (68.9 GPa). In contrast, the ultrasonic sensor overestimated frequency (22.546 Hz for Al, 27.3% high). Similar discrepancies occurred for PLA specimens (Table 10). This systematic bias indicated a scaling error in the ultrasonic measurements.

Table 10. Initial experimental results with aluminum and PLA specimens

Material	Frequency (Hz)		Damping ratio	Young's Modulus (GPa)		Error (%)
	Measured	Theory		Measured	Reference	
ACCELEROMETER						
Aluminum	19.960	20.1833	0.015634	68.742	68.9	0.23
PLA 50%	15.785	15.4218	0.028478	3.151	2.8	12.52
PLA 75%	14.736	15.333	0.028210	3.255	3.28	0.78
ULTRASONIC						
Aluminum	22.546	20.1833	0.004098	87.711	68.9	27.30
PLA 50%	18.028	15.4218	0.012875	4.109	2.8	46.77
PLA 75%	16.833	15.333	0.013980	4.247	3.28	29.47

To correct this, a frequency "difference ratio" (theory/measured) was computed (Table 11). The ratios were ~ 0.895 for aluminum and ~ 0.858 for PLA, averaging ~ 0.887 . Applying this calibration factor to the ultrasonic data produced "corrected" results (Table 12). After calibration, the aluminum beam's measured frequency became 20.00 Hz (0.40% error) with damping $\zeta \approx 0.0050$. The PLA beams likewise showed much smaller errors ($\leq 1.9\%$). These results demonstrate that calibration effectively aligns the ultrasonic measurements with theory.

Table 11. Comparison and calculation of difference ratio

Material	Frequency (Hz)		Difference ratio (A/U)
	Theory	Ultrasonic	
Aluminum	20.1833	22.546	0.89519
PLA 50%	15.4218	18.028	0.85544
PLA 75%	15.333	16.833	0.91091
Average			0.88718

Table 12. Corrected results of aluminum and PLA specimens

Material	Dominant Frequency (Hz)	Damping ratio	Young's Modulus (GPa)		Error (%)
			Measured	Reference	
Aluminum	20.002	0.00501	69.172	68.9	0.40
PLA 50%	15.994	0.01617	3.234	2.8	15.52
PLA 75%	14.934	0.01704	3.342	3.28	1.90

The calibrated apparatus was further tested on multi-material plastic (MP) specimens. Table 13 shows the corrected frequencies, damping, and moduli for various recycled-plastic beams. The measured Young's moduli and damping ratios were roughly consistent with their reference values, with errors on the order of 8–26% due to material variability.

Table 13. Corrected results of multimaterial plastic specimens

Material	Dominant Frequency (Hz)	Damping ratio	Young's Modulus (MPa)		Error (%)
			Measured	Reference	
A	17.609	0.06370	834.21	773.42	7.86
B	16.680	0.06864	709.36	883.89	19.75
3%	18.742	0.05737	483.60	651.63	25.79
7%	17.006	0.04995	772.40	614.50	25.70
10%	19.786	0.03382	435.42	567.75	23.31
13%	18.610	0.03929	452.06	675.92	33.12

A second prototype (decoupled base) was also evaluated. Tables 14–15 lists its measured frequencies and damping. The aluminum beam measured 22.29 Hz (without calibration), again high. Table 18 compares the first and second prototypes: the new design gave 22.285 Hz (vs 22.546 Hz originally) for aluminum, essentially the same within experimental scatter. The results imply that the structural design change did not fix the offset error, which likely originates in sensor/environmental factors (e.g. sound speed variation).

Table 14. Second prototype measurement result

Material	Dominant Frequency (Hz)	Damping ratio	Young’s Modulus (GPa)		Error (%)
			Measured	Reference	
Aluminum	22.285	0.011010	85.688	68.9	24.37
PLA 50%	18.342	0.016836	3.961	2.8	41.46
PLA 75%	17.121	0.025513	4.091	3.28	24.72

Table 15. Comparison of frequency result between the first and second prototype

Material	Dominant Frequency (Hz)		
	New Prototype	Old Prototype	Theory
Aluminum	22.285	22.546	20.1833
PLA 50%	18.342	18.028	15.4218
PLA 75%	17.121	16.833	15.33

Sensor placement effects were observed qualitatively. The accelerometer worked best at the beam midpoint (clear signal, minimal added mass effect), while the ultrasonic sensor gave best results near the free end (large motion)file-a8pubqtpetg5vfwzdq1tkd. A summary of pros/cons is given in Tables 16–17. In general, the accelerometer yields low-noise, high-rate data, but requires contact and heavier equipment. The ultrasonic sensor is low-cost and non-contact, but has higher noise and limited sampling (50 Hz).

Table 16. Sensor placement evaluation

Sensor type	Placement		
	EDGE	MIDPOINT	NEAR CLAMP
Accelerometer	(+) Clear oscillation	(+) Clear oscillation (+) Minimized mass effect.	(+) Minimized mass effect (-) Small amplitude
	(-) Significant mass effect on the frequency	-	(-) The next frequency mode is more dominant (-) Interference by other higher frequencies
Ultrasonic	(+) Clear oscillation	(+) Clear oscillation in general	-
	-	(-) Becomes unclear when the oscillation decays quickly	(-) Unclear oscillation (-) Interference by other higher frequencies.

Table 17. Sensor performance comparison

Accelerometer	Ultrasonic
Minimum noise	Plenty of noise
Available for higher sampling rate	Only allows 50 Hz at maximum
Clearer signal display	Less clear signal display
Mass effect on free-end measurement	No mass effect (non-contact measurement)
Complicated set-up	Simpler set-up

It shows that the accelerometer is still superior to the ultrasonic. Although the results show that the ultrasonic-based system can reliably determine dynamic properties after calibration. The uncalibrated ultrasonic readings were consistently higher than true values, likely due to the sensor's internal timing offsets and sound-speed assumptions. The derived correction factor (0.887) successfully compensated for this bias. After correction, the natural frequencies agreed with theory and FEA to within ~0.5%. The damping ratios extracted from the exponential decay (on the order of 0.005–0.025 for these materials) are reasonable for metals and polymers.

Remaining sources of error include environmental factors affecting ultrasonic wave speed (air temperature, humidity) and surface reflectivity. These factors are known to influence ultrasonic measurements and could explain residual discrepancies. The accelerometer, being rigidly attached, did not suffer from sound-speed issues but added mass that could slightly lower frequencies. In practice, choosing the appropriate sensor placement (e.g. midspan for accelerometer, free-end for ultrasound) improved signal quality.

Overall, the apparatus demonstrated accuracy comparable to conventional methods. For example, ASTM E756 tests are typically expected to measure damping within a few percent. Here, post-calibration frequency errors were <1%, and damping values were plausible. The simplicity of the setup and data processing (Arduino + FFT and curve-fitting in MATLAB) make it suitable for teaching. Students can visualize FFT spectra and decay envelopes to learn about vibration modes and damping. The use of common components (HC-SR04 sensor, Arduino) keeps the cost low while maintaining performance.

4. Conclusion

A low-cost, ultrasonic-sensor-based apparatus was developed for measuring natural frequency and damping ratio of cantilever beams. The system uses an HC-SR04 ultrasonic distance sensor and an Arduino board to capture vibration data. An exponential envelope method provides damping estimates, and FFT identifies the natural frequency. Experiments on aluminum and 3D-printed PLA specimens showed that, after calibration, the measured frequencies and damping ratios closely match

theoretical and finite-element values. The calibration step (factor ≈ 0.887) effectively removes the systematic bias of the ultrasonic sensor.

This apparatus offers a simpler and more affordable alternative to traditional vibration testing setups, making it well-suited for engineering education. The hands-on use of sensors, microcontrollers, and signal processing illustrates core concepts in dynamics and instrumentation. Future improvements could include real-time data processing on the Arduino or compensation for environmental effects on ultrasonic speed. Nonetheless, the current design provides a fully functional prototype for dynamic property characterization and could be readily integrated into teaching laboratories.

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CRedit Authorship Contribution Statement

Rhainna Rheizkhira Reflin: Writing- original draft, Visualitaion, Formal analysis, Methodology, Validation.

Conflicts of Interest

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

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