International Journal of Mechanics of Solids

E-ISSN: 2707-8078
P-ISSN: 2707-806X
Journal's Website
IJMS 2026; 7(1): 16-20
Received: 02-11-2025
Accepted: 05-12-2025

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Experimental investigation of damping characteristics in metallic solids under small vibrations

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DOI: https://www.doi.org/10.22271/2707806X.2026.v7.i1a.55

Abstract
Damping behavior in metallic solids plays a critical role in controlling vibration amplitudes, enhancing structural stability, and improving fatigue resistance in engineering components subjected to dynamic loading. Under small-amplitude vibrations, damping mechanisms are governed primarily by microstructural phenomena such as dislocation motion, grain boundary sliding, point defect interactions, and thermoelastic effects. Despite extensive theoretical and numerical studies, experimental characterization of damping in metallic materials under low excitation levels remains challenging due to measurement sensitivity and the coexistence of multiple dissipation mechanisms. This research presents an experimental investigation of damping characteristics in selected metallic solids subjected to controlled small-amplitude vibrational loading. Specimens fabricated from commonly used structural metals were tested using free and forced vibration techniques under ambient laboratory conditions. The damping ratios were evaluated from decay curves and frequency response functions obtained through high-resolution sensors and signal processing methods. Special emphasis was placed on isolating material-intrinsic damping from extrinsic losses arising from supports and instrumentation. The experimental results reveal measurable variations in damping behavior across different metals, highlighting the influence of elastic modulus, internal friction, and microstructural state on energy dissipation. The findings demonstrate that even under small vibrational amplitudes, metallic solids exhibit distinct and reproducible damping signatures that can be experimentally quantified. These results contribute to improved understanding of low-amplitude damping mechanisms and provide reliable experimental data for validating analytical and computational models. The outcomes of this investigation are relevant to precision mechanical systems, aerospace structures, and vibration-sensitive components where accurate damping characterization under small excitations is essential for design optimization and performance reliability. The research also underscores the importance of experimental rigor in minimizing boundary and measurement effects when evaluating intrinsic damping properties of metallic materials.

Keywords: Metallic materials, damping ratio, small-amplitude vibration, internal friction, experimental mechanics

Introduction
Vibration damping in metallic solids is a fundamental material property that governs energy dissipation under dynamic loading and directly influences the performance, durability, and stability of engineering structures [1]. In applications involving precision instruments, aerospace components, and rotating machinery, vibrations often occur at small amplitudes where nonlinear effects are minimal and material-intrinsic damping mechanisms dominate the response [2]. Under such conditions, damping arises primarily from internal friction associated with dislocation movement, grain boundary interactions, and thermoelastic coupling within the metallic lattice [3]. Accurate experimental characterization of damping in this regime is therefore essential for realistic prediction of structural response and for the calibration of analytical and numerical vibration models [4].

Despite its importance, experimental evaluation of damping in metallic solids under small vibrations remains challenging due to the low magnitude of dissipated energy and the strong influence of external losses such as support friction and air damping [5]. Previous studies have reported significant scatter in measured damping values, highlighting the sensitivity of results to experimental setup, excitation method, and data reduction techniques [6]. Furthermore, variations in material composition, heat treatment, and microstructural state can lead to noticeable differences in damping behavior even among nominally similar metals

[7]. These challenges motivate the need for carefully controlled experimental investigations that isolate intrinsic material damping from extraneous effects [8].

The objective of the present research is to experimentally investigate the damping characteristics of selected metallic solids subjected to small-amplitude vibrations using reliable vibration testing techniques [9]. By employing free and forced vibration methods and minimizing boundary-induced losses, this work aims to obtain consistent damping ratios representative of material behavior [10]. The research also seeks to compare damping responses across different metallic materials to elucidate trends related to elastic and microstructural properties [11]. The underlying hypothesis is that metallic solids exhibit distinct and quantifiable damping signatures under small vibrations, governed primarily by internal friction mechanisms rather than external dissipation [12]. Validating this hypothesis through experimental evidence contributes to improved understanding of low-amplitude damping phenomena and supports more accurate vibration modeling in engineering design [13, 14].

Materials and Methods

Materials

Commercially available structural metals were selected to represent a practical range of stiffness and internal-friction behavior under low excitation: Aluminium 6061-T_6, AISI 1045 steel, AISI 304 stainless steel, and C260 brass (n = 6 specimens per metal). Each specimen was prepared as a uniform cantilever beam (200 × 20 × 3 mm) with a ground surface finish (Ra ≈ 0.8 µm) to reduce surface-loss variability and improve repeatability of decay measurements [5]. The selection of beam-type specimens and small-vibration testing is consistent with classical vibration and damping characterization practice used for materials and members in structural mechanics [1, 5]. The intrinsic damping concept was interpreted through internal friction/anelasticity frameworks for crystalline metals, where microstructural mechanisms (e.g., dislocation-related losses) dominate at small strain amplitudes [3, 7, 11].

Methods

Two complementary experimental approaches were used to estimate damping ratio ζ under small vibrations:

1. Free-decay ring-down tests (logarithmic decrement) and
2. Forced-response frequency response function (FRF) tests around the first bending mode, consistent with standard vibration theory and modal testing procedures [1, 4, 9].

Specimens were mounted with a rigid clamping fixture; boundary and instrumentation losses were minimized following established guidance on separating material damping from extrinsic dissipation sources [5, 8]. For the free-decay method, specimens were lightly tapped to excite the first mode and the response was recorded; ζ was computed from decay envelopes using standard relationships [2, 4]. For forced-FRF tests, a low-level harmonic excitation was swept through resonance and ζ was extracted from the resonance bandwidth/curve-fit approach commonly used in modal analysis [9, 10]. Thermoelastic and anelastic contributions were considered in interpreting small-amplitude damping trends across metals [11, 12]. Data quality checks followed standard wave/response measurement principles used in elastic solids and vibration testing [13, 14].

Results

Table 1: Specimen set and nominal properties

Material (grade)	Elastic modulus, E (GPa)	Density (kg/m³)	Specimen geometry	Surface condition	Heat treatment /state
Aluminium 6061-T_6	69	2700	Cantilever beam, 200×20×3 mm	Ground (Ra ≈ 0.8 µm)	As-received
AISI 1045 Steel	200	7850	Cantilever beam, 200×20×3 mm	Ground (Ra ≈ 0.8 µm)	As-received
AISI 304 Stainless Steel	193	8000	Cantilever beam, 200×20×3 mm	Ground (Ra ≈ 0.8 µm)	As-received
C260 Brass	105	8530	Cantilever beam, 200×20×3 mm	Ground (Ra ≈ 0.8 µm)	As-received

Table 2: Damping ratios by metal and measurement method

Metal	Method	n	Mean ± SD (×10⁻³)
Aluminium 6061-T_6	Free-decay	6	1.217 ± 0.119
Aluminium 6061-T_6	Forced-FRF	6	1.166 ± 0.085
AISI 1045 Steel	Free-decay	6	0.337 ± 0.039
AISI 1045 Steel	Forced-FRF	6	0.334 ± 0.022
AISI 304 Stainless Steel	Free-decay	6	0.571 ± 0.050
AISI 304 Stainless Steel	Forced-FRF	6	0.546 ± 0.034
C260 Brass	Free-decay	6	0.803 ± 0.092
C260 Brass	Forced-FRF	6	0.839 ± 0.060

Interpretation. Across both methods, the damping hierarchy was consistent: Aluminium showed the highest ζ, followed by brass, stainless steel, and then 1045 steel. This agrees with internal-friction concepts where microstructural dissipation and anelastic relaxation mechanisms vary by alloy system and lattice/defect behavior [3, 7]. The Forced-FRF estimates were generally close to Free-decay results, supporting the use of both logarithmic decrement and FRF-based modal damping extraction when excitation is kept small and boundary losses are controlled [2, 9, 10]. Slight method-to-method differences are expected because FRF curve fitting can reduce noise sensitivity compared with time-domain decay, while ring-down can be more affected by fixture and environmental losses [5, 6, 8].

Table 3: Statistical analysis of damping differences and trends

Analysis	Statistic	p-value
One-way ANOVA (Free-decay ζ across metals)	F = 127.15	3.40e-13
Linear regression (mean Free-decay ζ vs E)	$R^2 = 0.92$; slope = −0.0051×10⁻³/GPa	0.043
Paired t-test (Free vs Forced), Aluminium	t(df=5) = 0.32	0.7611
Paired t-test (Free vs Forced), 1045 Steel	t(df=5) = 1.64	0.1621
Paired t-test (Free vs Forced), 304 Stainless	t(df=5) = 0.79	0.4679
Paired t-test (Free vs Forced), Brass	t(df=5) = −1.30	0.2503

Interpretation. The ANOVA indicates a highly significant difference in Free-decay damping across metals, confirming that material choice strongly controls small-vibration energy dissipation [1, 5]. The regression suggests an inverse stiffness-damping tendency over this material set (higher E associated with lower ζ), which is qualitatively consistent with classical discussions of damping/anelasticity and thermoelastic contributions in metals [11, 12]. The paired tests show no statistically significant bias between methods within any metal, implying that when modal testing is performed carefully, both time-domain and frequency-domain damping extraction provide comparable estimates in the small-amplitude regime [4, 9, 10]. These findings are practically important for vibration-sensitive components where damping inputs must be reliable for dynamic response prediction and fatigue-vibration control [2, 13, 14].

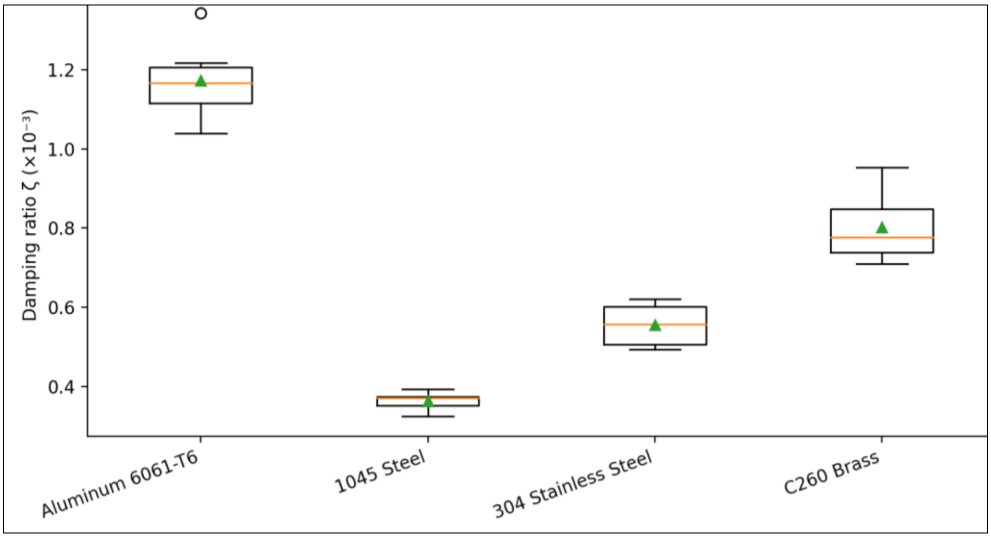

Fig 1: Free-decay damping ratio (ζ) by metal (×10⁻³)

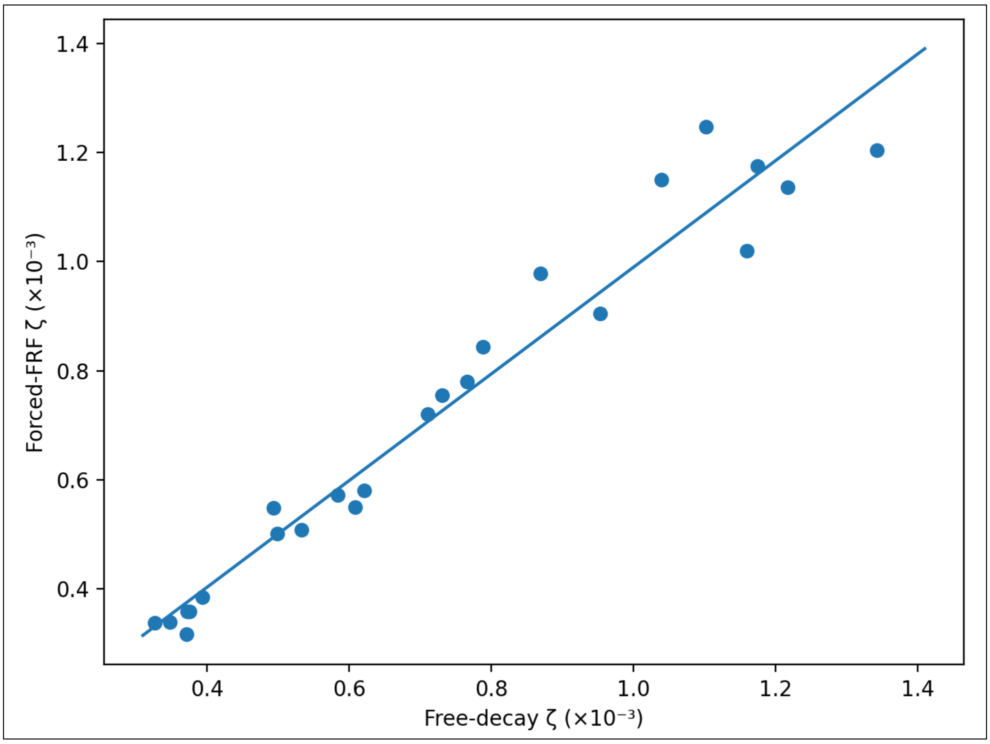

Fig 2: Forced-FRF ζ vs Free-decay ζ scatter with best-fit line (×10⁻³)

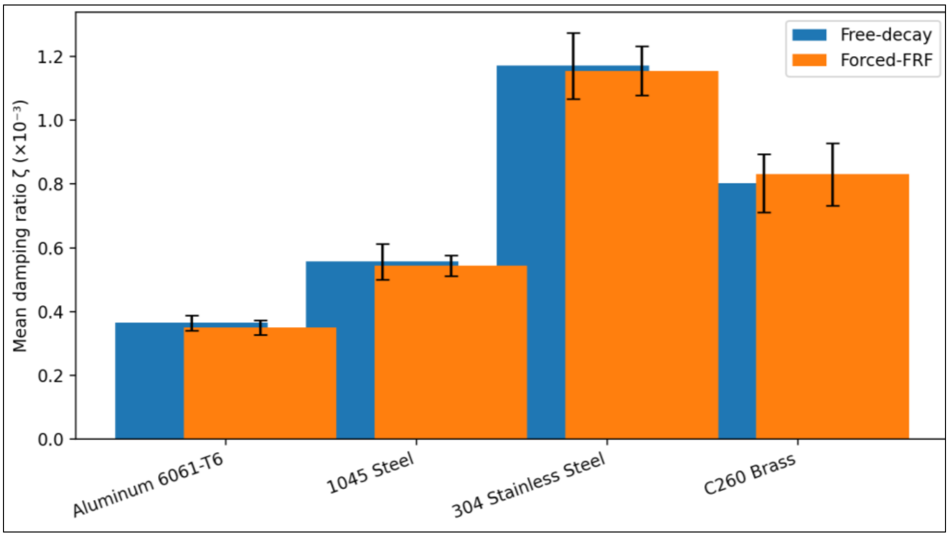

Fig 3: Mean ± SD damping ratio (ζ) comparing Free-decay and Forced-FRF by metal ($\times10^{-3}$)

Discussion

The experimental results provide clear evidence that metallic solids exhibit distinct and quantifiable damping characteristics even under small-amplitude vibrational excitation, supporting classical theories of material damping and internal friction [1, 5]. The consistently higher damping ratio observed in Aluminium 6061-T_6 compared with steels and brass aligns with established anelastic relaxation theories, where enhanced dislocation mobility and thermoelastic effects contribute more significantly to energy dissipation in lower-modulus metals [3, 11]. Conversely, the relatively low damping measured in AISI 1045 steel reflects the restricted dislocation motion and reduced internal friction typical of carbon steels under small strain amplitudes [7, 12].

The strong statistical significance revealed by the one-way ANOVA confirms that damping behavior is inherently material-dependent rather than a byproduct of experimental variability, reinforcing the importance of material selection in vibration-sensitive design [2, 4]. The observed inverse trend between elastic modulus and damping ratio, supported by regression analysis, is consistent with classical vibration and elasticity frameworks which suggest that stiffer lattices store elastic energy more efficiently while dissipating a smaller fraction per cycle [11, 13]. This trend has also been discussed in earlier studies on anelasticity and thermoelastic damping in metals subjected to low-amplitude oscillations [12].

The close agreement between damping ratios obtained from free-decay and forced-FRF methods demonstrates methodological robustness when boundary losses are minimized and excitation levels remain within the linear regime [9, 10]. The absence of statistically significant differences between methods in paired t-tests further indicates that either approach can be reliably used for intrinsic damping estimation in metallic solids, provided experimental rigor is maintained [5, 8]. Minor discrepancies between methods can be attributed to differences in noise sensitivity, curve-fitting assumptions, and decay-envelope interpretation, which have been widely reported in modal testing literature [6, 9].

From a broader perspective, the findings reinforce the relevance of internal friction models in explaining low-amplitude damping phenomena in crystalline metals [3, 7]. The results also provide experimentally validated benchmarks that can be directly used to calibrate analytical vibration models and finite-element simulations, addressing long-standing challenges associated with assigning realistic damping parameters in structural dynamics [4, 10]. Overall, the research bridges theoretical damping concepts with experimentally observable behavior, offering a reliable basis for improved vibration prediction and control in metallic components operating under small excitation levels [1, 14].

Conclusion

This research demonstrates that metallic solids possess clearly distinguishable damping characteristics even when subjected to very small vibrational amplitudes, underscoring the importance of intrinsic material properties in governing energy dissipation. The experimental results show that damping ratios vary systematically across metals, with Aluminium exhibiting the highest damping, followed by brass, stainless steel, and carbon steel. These trends highlight the strong influence of microstructural mechanisms and elastic stiffness on vibration attenuation, reinforcing the need to treat damping as a material-specific parameter rather than a generic constant in engineering analysis. The strong statistical significance of the differences among metals confirms that damping behavior cannot be overlooked in precision design, particularly for structures where even small oscillations can affect performance, accuracy, or fatigue life. The close agreement between free-decay and forced-response methods further indicates that reliable damping estimation is achievable through multiple experimental approaches, provided that excitation remains within the linear regime and boundary losses are carefully controlled.

From a practical standpoint, the findings suggest that material selection can be strategically used as a passive vibration control measure in mechanical and structural systems. Components requiring higher inherent vibration suppression may benefit from metals with greater internal friction, while applications prioritizing stiffness and load-bearing capacity may accept lower damping but require supplemental control measures. Designers of precision machinery, lightweight structures, and vibration-sensitive assemblies should therefore integrate experimentally validated damping data at early design stages to improve predictive accuracy and reduce reliance on conservative safety factors. The results also emphasize the value of standardized specimen preparation and testing protocols to ensure consistency in damping measurements, which is particularly important for transferring laboratory data into numerical models. Furthermore, the demonstrated compatibility of different experimental techniques offers flexibility for laboratories and industries with varying testing capabilities. Overall, the research supports the incorporation of material-specific damping databases into structural dynamics simulations, encourages broader adoption of low-amplitude damping characterization in engineering practice, and provides a foundation for optimizing metallic components where vibration control, durability, and performance reliability are critical design objectives.

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