Impact of Particle Packing Density on the Frequency Response of an Additively Manufactured Particle Damper

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This paper explores the influence of particle packing density on the frequency response characteristics of particle dampers fabricated using Laser Powder Bed Fusion (LPBF). This study experimentally validates that packing density can be used as a post-printing technique to target specific modal resonances in a system. Central to this investigation is the development of a model that describes the behavior of a particle damper under sinusoidal excitation. It effectively captures the complex interactions between the particles and the damper's housing as they respond to various vibrational stimuli. The model utilizes a continuous transfer function approach using an input-output relationship. The paper highlights the potential advantages of using LPBF-manufactured particle dampers over conventional damping systems. These include enhanced flexibility in material integration, the ability to manufacture complex geometries, acoustic emission mitigation, and lower maintenance needs.

I. Introduction

Addressing the vibration effects on dynamic systems is essential in maintaining the safety and longevity of components. Ranging from aerospace structures to industrial mechanisms, vibrations, if left unaddressed, can lead to accelerated wear, compromising the integrity and performance of mechanical systems. Damping systems emerge as a crucial solution to mitigate these detrimental effects. Damping involves converting the kinetic energy associated with vibrations to other forms of energy, thereby reducing their amplitude and duration.

Passive damping techniques offer several advantages. They are well-established and easy to implement, contributing to their wide use in industrial applications. Moreover, passive dampers are known for their durability and robustness. They can withstand a wide range of operating conditions without significant degradation in performance. This reliability is particularly important in critical systems where failure or malfunction could have severe consequences. However, traditional passive damping techniques have limitations, such as fixed damping characteristics and lack of adaptability, making them less suited to dealing with dynamic changes in vibration conditions. Despite these limitations, the advantages of passive damping techniques make them valuable for various engineering applications where simplicity and reliability are crucial.

Passive dampers can be strategically placed throughout a structure or system to provide localized damping at specific points of interest [1]. This decentralized damping approach allows for targeted vibration control and can effectively reduce resonant vibrations by identifying prominent mode shapes and placing dampers where the antinodes reside. By doing so, structural stresses are minimized. However, traditional passive damping techniques also have some limitations. For instance, passive dampers are typically made of multiple materials and parts, which can introduce complexities and potential points of failure.

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To overcome some of these limitations and provide improved damping performance, emerging technologies such as Laser Powder Bed Fusion (LPBF) particle dampers are being explored. LPBF is an additive manufacturing technique that uses a high-energy laser to melt and fuse metallic powders [2], allowing the creation of complex geometries with high precision, less weight, and desirable mechanical properties [3]. In LPBF particle dampers, unfused particles encapsulated in pockets within the manufactured component can be optimized to dampen out certain mode shapes. This integrated solution improves the dynamic performance of printed components without significantly altering their design.

Although particle dampers' effectiveness in targeted vibration suppression and reducing acoustic emissions is acknowledged, a research gap that necessitates further investigation of the particles' behavior within the damper pocket is identified [4–6].

Research indicates efforts being made to study the damping characteristics using analytical approaches where a mathematical model of the damping behavior of a cantilever hollow member with perforations is developed and validated using an experimental approach [7]. The study indicates that using a hollow pocket embedded in the component increases its damping. The analytical model of the damping ratio is obtained as a function of the base excitation amplitude, perforation dependent stress functions, and the number of perforations along with the damping coefficients.

A study by Liao et al. [8] on the energy dissipation of particle dampers was conducted by using a novel energy method. The authors set out to explore the highly nonlinear behavior of particle dampers using energy-dissipation as the main performance metric. A two-way coupled model of the discrete element method and multi-body dynamics are two approaches adopted in this work to analyze the complex interactions between particles. This study theorizes that the damping effects of a particle damper are caused by contact forces generated when the particles impact the hollow chamber. The interaction between the loose particles and the chamber's wall produces negative work, dissipating energy, in turn reducing the overall displacement of the particle damper.

Investigations into particle dampers applications and methods by which they are modeled and tested are presented by Gagnon et al. [9]. It is noted that particle dampers demonstrate appealing properties in mitigating shock and vibration in high-rate dynamic environments however the highly nonlinear interactions between particles within the pocket remain ambiguous. The literature proposes further studies to be made on the use of implicit numerical particle solvers to take into consideration the effects of gravity, centrifugal, and parasitic vibration forces on particle behavior.

The work presented by Ye et al. [6] takes into consideration particle dampers in the context of seismic event damping. This research examines the dependency that damping magnitude and effective bandwidth have on parameters such as auxiliary mass ratio, gap clearance, mass ratio of particles to the total auxiliary mass, frequency characteristics, and input excitation. This literature also proposes a simplified approach where an equivalent single-particle damper is adopted for an approximated analytical solution to provide corresponding system parameters. This approach greatly simplifies the computational requirements needed to solve the analytical solution making high-rate predictions of particle damper behavior more feasible.

In previous work, the authors have investigated the LPBF-manufactured cantilever beam in mitigating shock. Using a solid beam for reference, a particle damper with varying packing densities is compared. An inverse relationship is found between the packing factor of the particles within the pocket and the damping ratio [10]. In this work, the authors set to examine the phase and magnitude responses of the particle damper under base excitation. More specifically, the feasibility of targeted damping of a particular resonant mode of an LPBF-manufactured beam. Through an input-output

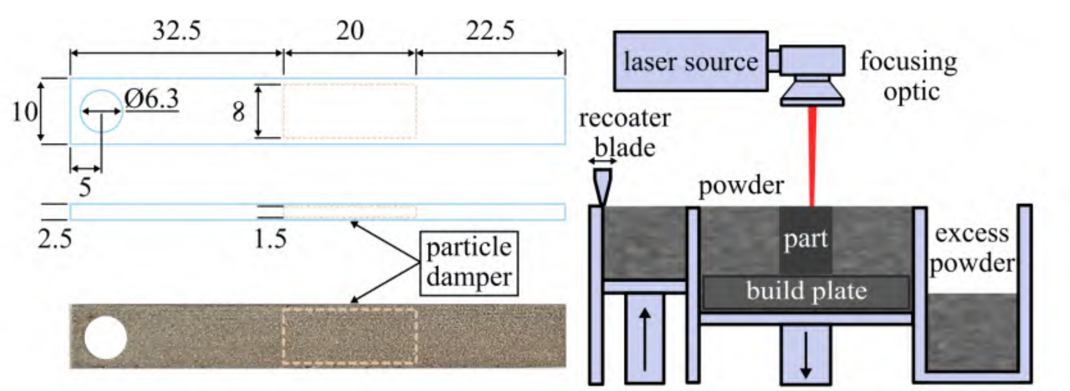

Fig. 1 Particle damper test sample manufactured using LPBF with key components of the system annotated and dimensions reported in mm.

relationship deduced from experimentation, a transfer function model is developed to model the frequency response of the particle damper where the desired mode resides.

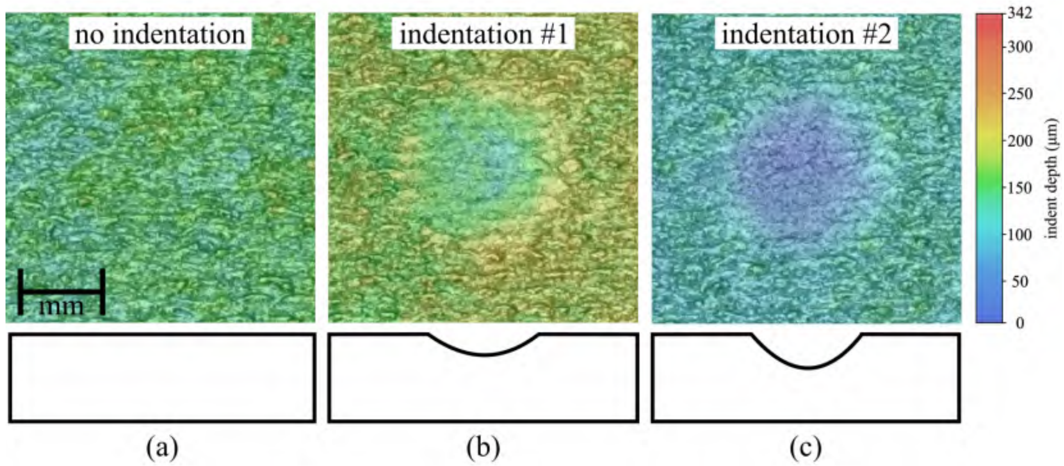

Fig. 2 Digital microscope scan of the particle damper surface with (a) no indentation, (b) indentation #1, and (c) indentation #2.

II. Particle Damper Fabrication

In this research, a cantilever beam was manufactured using 316L stainless steel powder by an AcontyMIDI printer. The dimensions are shown in Figure 1. Notable printing parameters, including power, speed, laser spot, and hatch distance, were set at 200 W, 800 mm/s, 100 µm, and 100 µm respectively. Additionally, a solid beam with identical dimensions and printing parameters was manufactured as a reference. To vary the packing factor of the particle damper, a press is used to indent the surface of the beam where the pocket is located, reducing the volume in which the particles of the damper reside. Three cases of damping factors were investigated in this work as presented in Figure 2. A digital microscope is utilized to capture topography images of the beam before and after the indentation. For the indentation cases depicted in Figure 2, the indentation area is selected as the region of interest for volume measurement. The concave volumes obtained from the 3D profile measurements are 0.26 mm^3 and 0.36 mm^3, for indentation #1 and indentation #2 respectively. With the original volume of the pocket being 240 mm^3, the particle damper volume for the other two cases is calculated to be 239.74 for indentation #1 and 239.64 mm^3 for indentation #2.

III. Experimentation

To study the frequency response of the particle damper under continuous excitation, this section presents the testing apparatus, shown in Figure 3, along with the experimental procedure undertaken to develop a particle damper model. The goal of the experimental phase is to investigate the effects of the packing factor (the volume fraction of particles within the solid material) on the frequency response of a part manufactured using LPBF. Previous work conducted by the authors has indicated a 33% reduction in the quality factor of a particle damper exposed to high-energy shock [10]. This study will further examine the particle damper's performance under continuous excitation. The experiment was conducted by fixing the LPBF-manufactured beam onto an electromagnetic shaker. Using accelerometers mounted on the electromagnetic shaker and the particle damper's pocket, the frequency response of the particle damper is studied in the bandwidth of 1-8 kHz.

Preliminary investigation indicates that the location of the flexural mode targeted with the damper resides within this bandwidth. The second resonant mode of the cantilever beam was chosen for this work due to its relative low dependency on the fixity. This aided in the repeatability of the experiment without significantly altering the dynamics of the system. As preliminary results, shown in Figure 4 (a) and (b), a trend can be observed, where the modal resonance of the beam is effectively reduced by the particle dampers. It is also noted that the samples exhibited less damping as the packing factor increased. Additionally, an increase in the resonance frequency is observed in the particle damper cases as the infused particles in the damper's pocket decrease the overall density of the part making it resonate at a

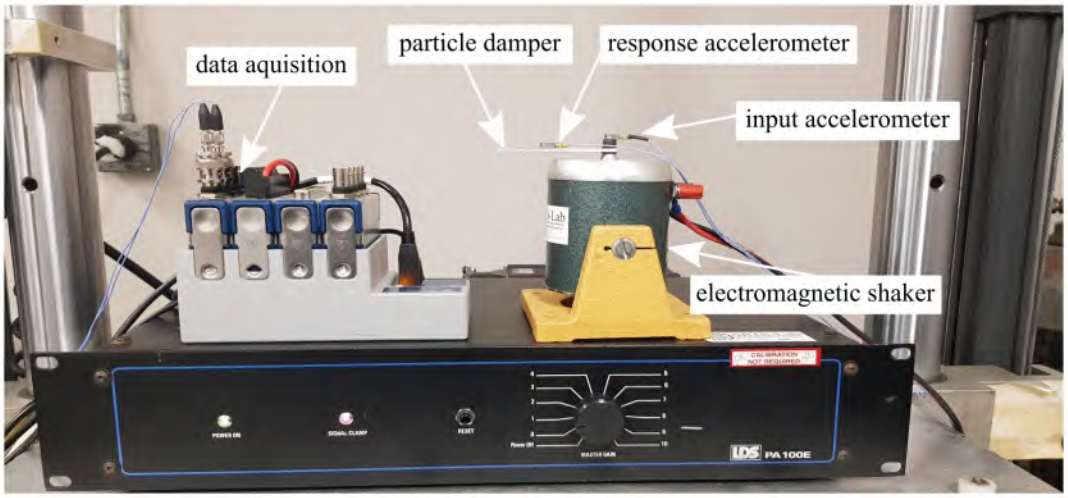

Fig. 3 Frequency response experimental setup with key components annotated.

slightly higher frequency. This also confirms the claim that particle dampers also aid in manufacturing higher-damping components without any additional weight to the component.

IV. Model Training Results

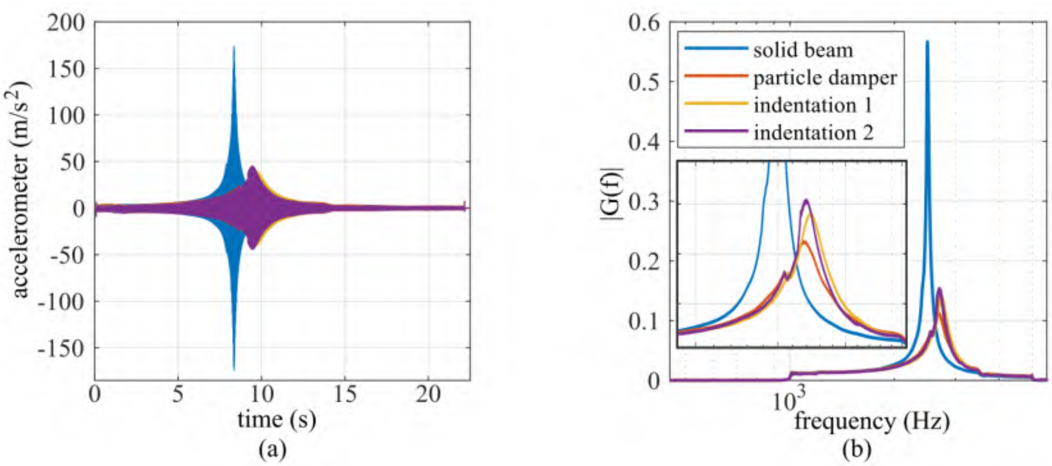

Fig. 4 Frequency response experiment with (a) time domain, and (b) frequency domain responses of the solid beam and particle damper with three cases of packing factors.

Utilizing data from the experimental phase an input-output relationship is modeled for no indentation case shown in Figure 2. Using a continuous modeling technique, an s-domain transfer function was chosen as the backbone of the model due to the simplicity of the sample and boundary conditions adopted in this work. During the modeling process, a grid search was conducted to scan for the optimal order of the transfer function model while avoiding overfitting. This was conducted by using different iterations of the experiment for model training and validation. Training parameters such as iteration and tolerance are set to 100 and 0.001 respectively. The highest correlation model was found to be 6 poles and 5 zeros transfer function with an 88.79% fit. Equation 1 shows the s-domain transfer function model representing case (a) of the particle damper beam. Figure 5 shows the bode plot associated with the transfer function model.

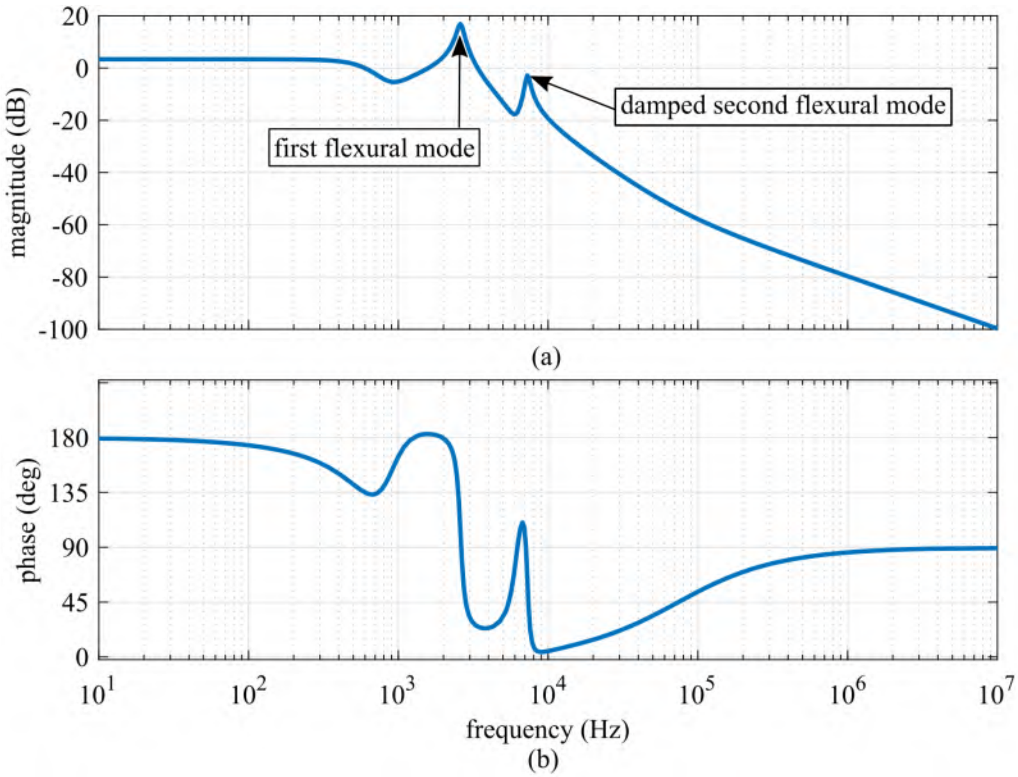

Fig. 5 Bode plot with (a) magnitude and (b) phase curves of the transfer function model $G(s)$ with the second flexural mode of the cantilever beam annotated.

$$G(s) = \frac{-648.5s^5 - 3.071e08s^4 - 4.595e12s^3 - 4.736e17s^2 - 1.563e21s - 1.436e25}{s^6 + 9929s^5 + 2.397e09s^4 + 1.577e13s^3 + 6.18e17s^2 + 2.737e21s + 9.733e24} \tag{1}$$

This transfer function model describes the frequency response properties of the second flexural mode of an LPBF-manufactured cantilever beam with targeted damping using an embedded particle damper. Using this modeling approach along with the experimental procedure, complex components with multiple modes can be studied where the order of the transfer function is increased to be able to describe the complexities associated with nonuniform mode shapes and their resonance properties.

V. Conclusion

LPBF-manufactured particle dampers present a promising alternative to traditional damping systems. Their homogeneous material composition and potential for complex part integration offer advantages such as improved damping characteristics, acoustic emission mitigation, reduced weight, and lower maintenance requirements. While challenges exist in manufacturing complex parts, ongoing advancements in additive manufacturing techniques are expected to address these limitations. This work aims to further clarify the relationship between the packing factor of particle dampers and their damping properties under continuous vibration. This work also validates the feasibility of targeting specific modal resonance using the proposed manufacturing technique. A crucial aspect of the study was the development of a transfer function modeling process. This model provides insight into the magnitude and phase responses under various vibration conditions. Through this approach, this investigation not only validates the feasibility of using LPBF in damping applications but also opens new avenues for further research and development in the field of advanced manufacturing and vibration control technologies.

Acknowledgments

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