Modeling Post-Process Indenting Using the Discrete Element Method for Particle Density Control in Additively Manufactured Dampers

Samuel Roberts[a], Yanzhou Fu[a], Joud N. Satme[a], Daniel Kiracofe[b], Austin R.J. Downey[a,c], and Lang Yuan[a]

[a]Department of Mechanical Engineering, University of South Carolina, Columbia, USA
[b]Beehive Industries, West Chester, OH , USA
[c]Department of Civil and Environmental Engineering, University of South Carolina, Columbia, USA

ABSTRACT

Laser powder bed fusion (LPBF), a technology within additive manufacturing, has demonstrated a remarkable ability to fabricate uniquely complex parts. One unique ability of LPBF is the integration of particle dampers by leaving areas of a part unfused during the manufacturing process. Particle dampers made in this way are fully integrated into the component and require no extra weight or materials. These attributes make them both cost- and production-effective. Previous work has indicated that changing the packing density of these particles by indenting the damper space can alter the qualities of the particle dampers, allowing for specific frequencies to be targeted. In this study, we propose using the discrete element method to model the effects of changing particle packing density in a particle damper created using LPBF. The discrete element method model can study the particles within the damper in greater detail and potentially gain more information than an experimental analysis. In this work, we model a 0.2×0.8×0.15 mm pocket containing approximately 1,300 particles. To simulate an indent compacting the particles, a sphere is created outside the pocket and moved partially into the pocket, reducing the available space for the particles. To validate the effectiveness of the models, we conduct multiple simulations with varying particle packing densities by altering the size and depth of the indent in the simulated pocket space. We then compare the pocket displacement over time across models under the vibrations and compare these results to experimentally obtained damping quality factors. Our findings suggest that the discrete element method model can demonstrate the effects of changing particle packing density in a particle damper by creating an indent in the damper space.

Keywords: Laser Powder Bed Fusion, Additive Manufacturing, Particle Dampers, Discrete Element Method, Particle Packing Density, Kinetic Energy, Vibration Damping, Energy Dissipation Rates

1. INTRODUCTION

Vibrations are a leading cause of degradation over time in dynamic mechanical systems. There are multiple damping solutions to alleviate these issues, and they can be divided into two categories: active and passive. Active dampers utilize a combination of sensors and actuators to analyze vibrations and generate forces to counteract them. They are ideal for scenarios that require adaptability over a wide range of frequencies.[1] However, active dampers can be cost-intensive and require power to operate. Passive vibration dampers have no such restrictions, but their effective frequency range is smaller than that of an active damper.[2]

Further author information: (Send correspondence to Austin R.J. Downey)
Austin R.J. Downey: Email: austindowney@sc.edu

One such passive damper is the particle damper. Particle dampers are relatively simple, comprised of a pocket in which particles are free to move about. As the damper vibrates, the particles dissipate energy through non-conservative forces such as friction.[3] The system's simplicity makes for a reliable particle-damping solution in potentially extreme use cases, such as extreme temperatures.[4] Creating particle dampers in a mechanical part, however, may create extra failure points. A solution to this issue is laser powder bed fusion (LPBF) additive manufacturing. LPBF refers to a method of additive manufacturing where metallic powder is spread over a build plate to be fused together at high temperatures in a specified pattern by a laser, as seen in Figure 1. This method creates high-quality, low-tolerance, and complex parts.[5] It is ideal for parts that are impossible to create through traditional manufacturing approaches or in cases where it would be too expensive through said approaches.

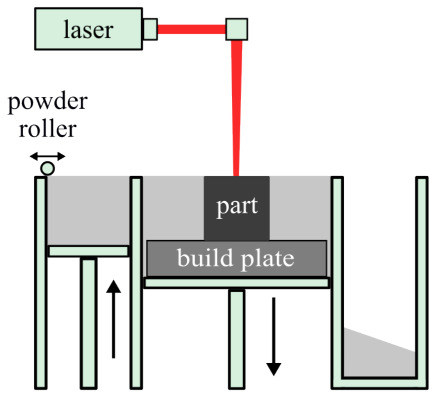

Figure 1. Simplified diagram of LPBF additive manufacturing.

Parts manufactured using LPBF have a unique opportunity to feature fully integrated particle dampers created during manufacturing.[6] Particles are present throughout the process, so one can simply leave a section of particles unfused within the part. This allows particle dampers to be placed in numerous configurations without requiring extra materials, extra weight, or an alteration of the part's design. A diagram of the beam and measurements used for our simulations can be seen in Figure 2.

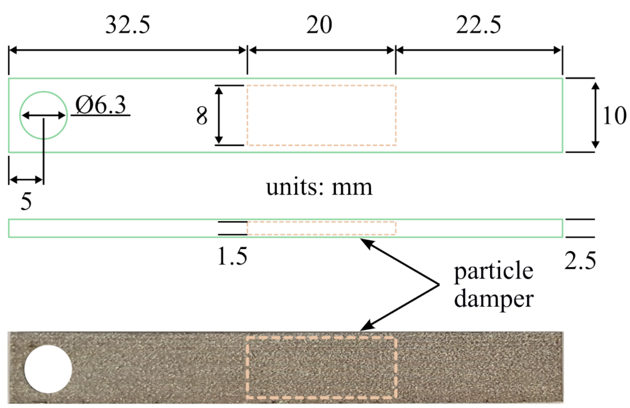

Figure 2. Beam with particle damper manufactured using LPBF.

Previous work has indicated that the damping qualities of an LPBF particle damper can be influenced by altering the packing density of the particles within the damper. This is done by indenting the damper to force particles closer together. In doing so, an inverse relationship between particle packing density and damping can be observed.[7,8] This research attempts to replicate the trends in these findings using a software approach and the discrete element method (DEM).

The DEM is a method of computing the properties of large quantities of particles interacting with one another, and it is gaining popularity for its ability to simulate particle dampers.[9] One primary issue with LPBF particle dampers is they can not be tested without access to an LPBF printer. Acquiring one and using it can be extremely costly, making free and open source DEM software especially alluring as a cheap alternative to experimental testing. Additionally, DEM software allows us to make observations we could not make with experimental testing, such as observations about the interior of the damper or even the particles themselves.[10] We are using YADE as our free and open source DEM software, as it uses a Python front-end, making it easy to work with while fulfilling our needs.

In this work, we simulate three pockets representing portions of a particle damper: one without an indent and two with varying indent sizes. We compare the displacements of each simulation. Numerical results obtained in this study align with prior experimental studies,[7,8] where indentations in the pocket cause a reduction in the damping capabilities of the particle damper, demonstrating the potential for the DEM to be a reliable tool for optimizing particle damper design in additive manufacturing. The key contribution in this work is the development of a DEM-based simulation using YADE to model how altering particle packing density—by introducing an indent in the damper space—affects the damping behavior in LPBF-integrated particle dampers. Simulation code and data for this paper is made available through a public repository.[11]

2. METHODOLOGY

Before running simulations, we input dimension and location information for the simulated pocket, the beam, and the damper. The beam itself is not simulated, but it is used to calculate properties of the simulated pocket, such as its displacement as if it were in a beam. Other properties, such as the material properties of the beam and particles, are also needed. All material properties and parameters aside from pocket indent volume were kept consistent between simulations.

The simulations in YADE are broken into two distinct steps: particle settlement and pocket agitation. In the particle settlement step, particles with varying sizes are generated within bounds set in an input parameter file. The particles are generated randomly within the boundary with sizes chosen according to a normal distribution centered around a particle diameter of 25 μm. When generating the particles, YADE does not check for overlap between particles before placing them. Once the simulation begins, overlapping particles are forced away from each other at high velocity, creating a tendency for them to escape the pocket where the walls are thin such as the corners where walls connect (see Figure 3). To prevent particles from escaping, the walls of the pocket are temporarily extended so that particles can't escape at the intersections between walls; this also ensures the particle count remains consistent between simulations. If the simulation is to be indented, a rigid sphere is generated outside the pocket and moved such that a spherical cap is present within the damper and is in contact with the particles. Then, in both indented and non-indented simulations, the particles are placed under the effects of gravity and left to settle until the total kinetic energy of the simulation reaches a set value (in this case, the value was 10^{-11} J). This is done to ensure that the initial energy within the system is consistent between damper agitation simulations.

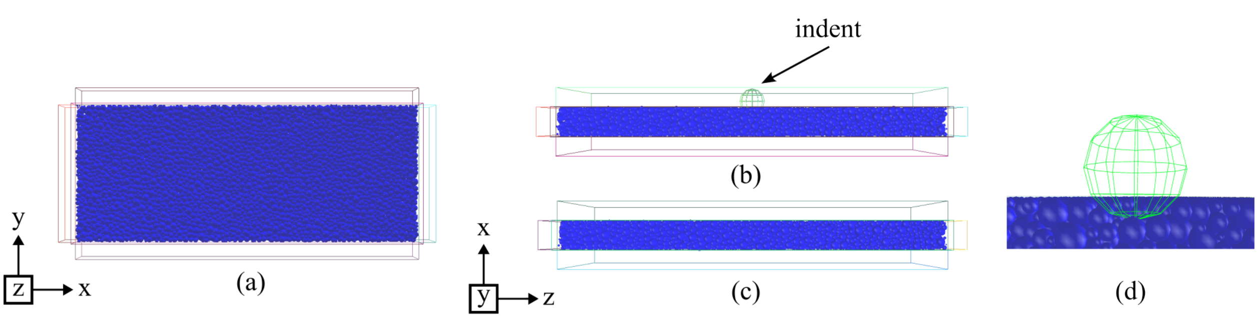

Figure 3. Simulation of a damper pocket, done in YADE, showing: (a) front view, (b) side view with simulated indent, (c) side view without indent; (d) cross-section of indent.

Once the particles have settled, relevant positional information of each particle, and indent if applicable, is stored for use in the pocket agitation simulation. To prevent the addition of the indent in the form of a sphere affecting calculations, the material of the sphere is altered to be of insignificant mass. An impulse force is applied to the pocket at the start of the simulation based on parameters in the input file. For our simulations, we used a 14 N impulse force. The pocket is then left to settle into a steady state over time. As the simulation runs, we collect positional, force, and kinetic energy data; this paper only focuses on the position of the pocket. The overall process can be seen in the flowchart presented in Figure 4

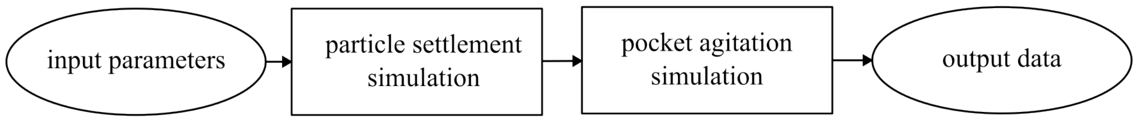

Figure 4. Flowchart of the simulation process.

Figure 3 shows pockets containing roughly 13000 particles. The simulations we ran, however, were scaled down to roughly 1300 particles. This was done to save time, as larger-scale simulations require significantly more computational power. Simulation time was cut by approximately 70%, allowing us to improve the code quickly and run multiple concurrent simulations. The volumes of the indents were chosen in increasing increments, as we are interested in the general trends based on indent size. However, care was taken to ensure the base diameter of the spherical cap (making up the indent) did not exceed 75% of the shortest length between the sides of the wall it was attached to. This was done to ensure the indent achieved its intended volume without exceeding the boundaries of the pocket.

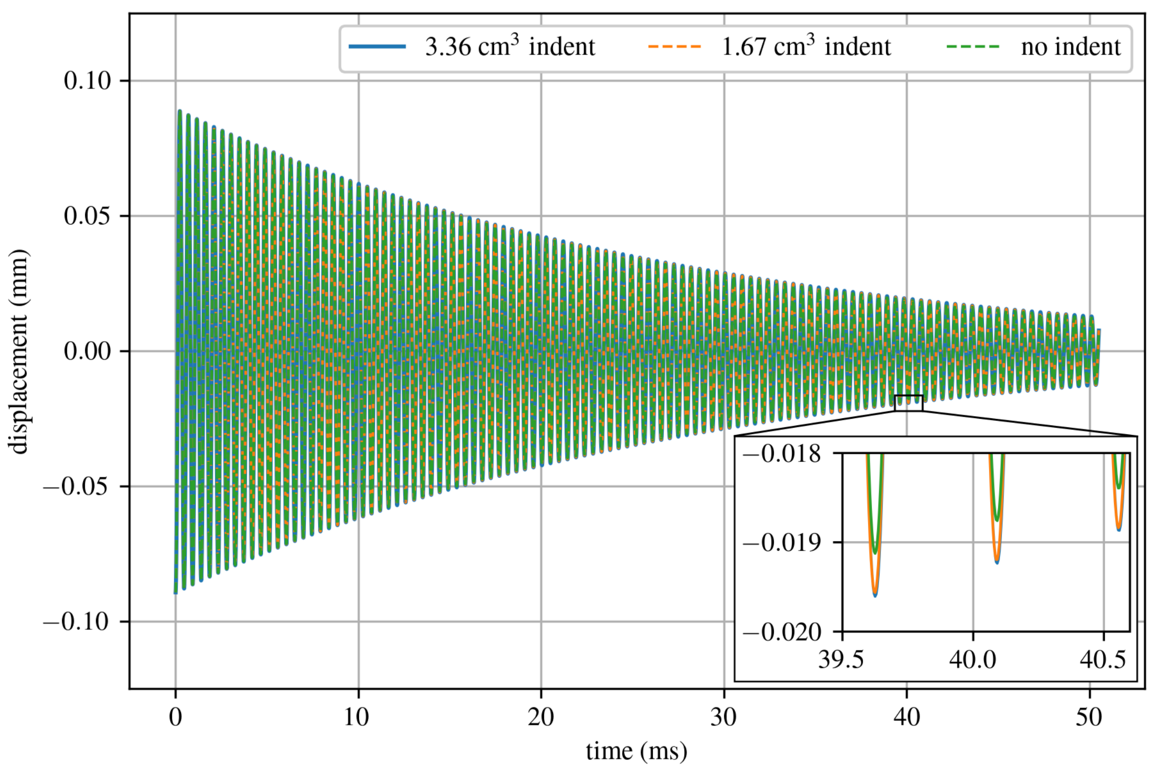

Figure 5. The displacement of the pocket, with the inset showing that increasing indent size causes an increase in overall displacement of the pocket.

Prior research done by Matthew Postell found that numerical damping in YADE reduced accuracy in real-world experiments.[12] We confirmed this independently by running multiple test simulations, finding the trends observed to be opposite of those observed in real-world experiments. As such, we disabled numerical damping in YADE for all forces except contact forces. Doing so aligned the simulation results closer to those of the experimental results previously obtained by the authors.[7,8]

3. RESULTS AND DISCUSSION

Figure 5 shows the pocket displacement data. Note that "displacement" represents the displacement of the imaginary beam where the pocket sits from its resting position. Differences in results between simulations are on the scale of nanometers and visible in the inset of Figure 5. This is likely a side-effect of the simulated pockets and associated indents being scaled down. We did not change the mean particle size when scaling down, but the indent sizes were limited by the size of the pocket, resulting in a lower increase in packing density compared to a larger pocket with a similar indent-to-pocket volume ratio. The ability to observe changes on such a small scale without expensive equipment demonstrates a key advantage DEM modeling has over experimental testing.

We found that as packing density increased via increasing indent volume, the amplitude of displacement increased. This is expected as the larger indentations increase the packing density of the particles, limiting their movement and the energy losses attributed to friction at the interface of the particles. Data gathered by Fu et al. shows a similar trend when using shock tests.[8]

A fast Fourier transform was applied to the displacement data to obtain Figure 6. We can observe an increase in the modal resonance of the pocket as the packing factor increases. This aligns with previous experiments using both shaker[7] and shock[8] testing. However, we did not replicate the increase in resonant frequency associated with an increased particle packing density. Thus, more refinement can be done to improve simulation accuracy.

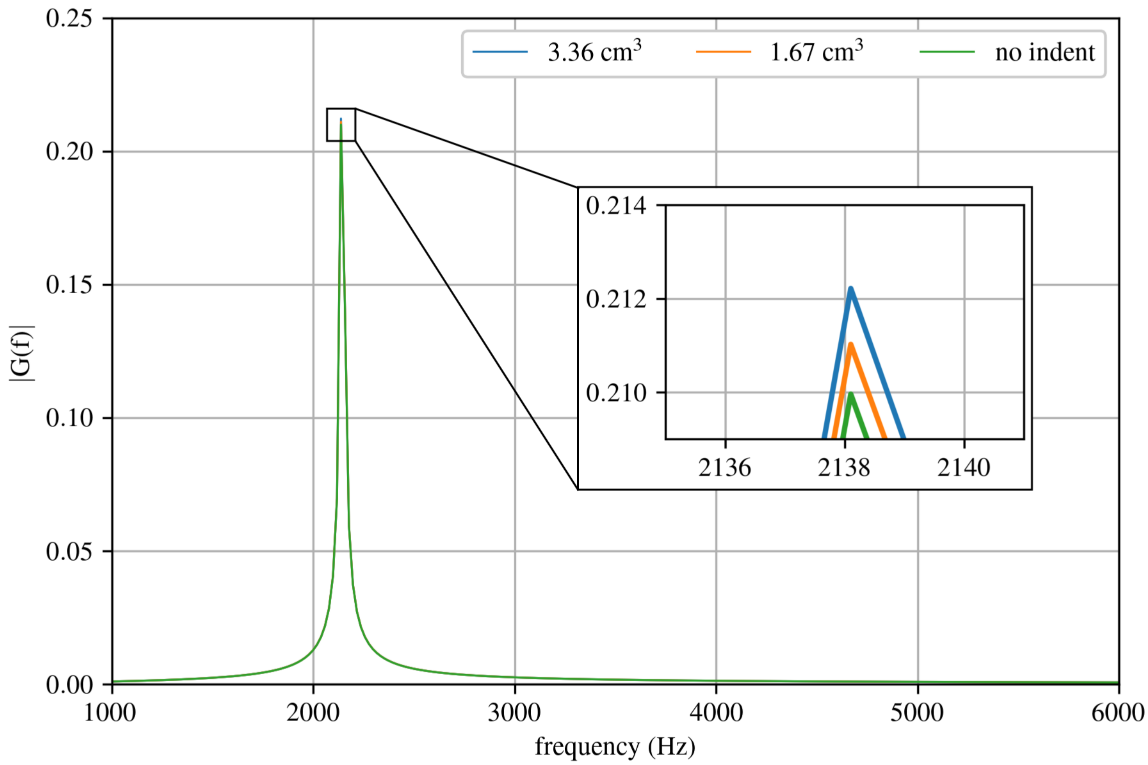

Figure 6. The frequency domain responses of the simulated dampers, with the inset showing that an indentation of the pocket causes a reduction in the damping ability of the particle damper.

4. CONCLUSION

In this paper, we proposed using discrete element modeling to observe changes in particle packing density of integrated particle dampers made using LPBF additive manufacturing. The DEM is already popular for simulating particle dampers, however little work has been done to investigate the ability of such simulations to observe changes in particle packing density in LPBF particle dampers. It was found that such simulations are able to predict trends observed in multiple real-world experiments. Specifically, the reduction in damping associated with increasing particle packing density. This suggests that using DEM computer modeling through free and open-source software could provide an efficient way to predict how parts using LPBF particle dampers with subtle variations will behave without having to manufacture numerous prototypes. While our work demonstrates the potential of using DEM software for such particle dampers, further research into accurately predicting properties of real-world dampers is needed.

ACKNOWLEDGMENTS

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