Integration of Particle Dampers with Additive Manufacturing for Sustainable Aviation

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Additive manufacturing, particularly laser powder bed fusion technology, can be utilized to strategically leave powder unfused in certain cavities of a printed structure. The particles in these cavities dissipate the kinetic energy through impact and friction leading enhanced dampening performance. Furthermore, particle dampers integrated with additive manufacturing contribute to sustainable aviation goals due to their lightweight, cost-effective construction, and minimal integrity risks. Although additively fabricated particle dampers are favorable, determining the optimal design parameters requires a deep understanding of the design process. For instance, the damping characteristic of particle dampers is extremely sensitive to the boundary conditions of the main body. Therefore, this study examines the effects of boundary conditions on the particle damping using experimental methods. To this end, six different test specimens with particle dampers and a full-fused solid beam made of In718 were employed and the dampening performance was determined by performing modal testing by impulse excitation under clamped-free and free-free boundary conditions. The results confirmed that the damping characteristic of the particle dampers were significantly influenced by the imposed boundary conditions. Besides, particle-filled cavities provide considerably better damping compared to the solid beam with limited shift in natural frequencies and significant mass reduction. These findings can be used to optimize particle damper designs for a variety of aviation applications in terms of sustainability.

1. Introduction

Metal additive manufacturing (AM) technologies has been extensively used in the aviation sector due to benefits including reduced lead times, inventive and lightweight designs, and allowing novel material development [1]. These benefits in the manufacturing process make it possible to reduce the cost of production while improving the structural performance of the fabricated components. In addition, the opportunities offered by AM help to reach the ultimate objective of sustainable aviation by lowering fuel consumption and carbon emissions from aircraft [2]. Therefore, from a sustainable aviation standpoint, AM technology is going to be necessity rather than just a technique to create components with higher structural performance or cost-effectively.

There is a strong correlation between lightweight design solutions and fuel consumption and thereby to emissions in the aviation industry [3]. In this sense, additive manufacturing technology has the potential to facilitate lightweight design since it gives engineers a considerably better degree of design freedom than traditional manufacturing processes, which have geometrical restrictions. In particular, AM makes it feasible to fabricate complicated geometries that have been topologically optimized, which are impossible to manufacture using traditional subtractive manufacturing methods. This helps to maximize material efficiency for a given design domain and structural performance of components which have positive impact on fuel consumption of aircrafts [4].

In addition to combining complex geometry and high-performance design solutions with relatively low mass, a further potential benefit of additive manufacturing from sustainability standpoint is the amount of material that is required for the component used in manufacturing [5]. This indicates that powder or molten material is laid down only where it is required. In this sense, AM drastically minimizes the amount of waste material generated during production compared to subtractive manufacturing methods and allows for the reuse of unfused materials. This is also represented by a ratio between the initial mass of material and the mass of material remaining in the manufactured component, named as buy-to-fly ratio. It was reported that buy-to-fly ratio varies between 12:1 to 25:1 for traditional manufacturing while it is approximately 1.5:1 for additively manufactured parts [6]. This confirms that AM reduces waste material through selective production, thus minimizing energy demand during the production process.

Another positive sustainability potential with AM technology is the possibility to combine multiple components into a single part for performance enhancement and risk management [1]. A notable example of such structures in this regard that also fully utilizes the aforementioned benefits of AM technology is additively integrated particle dampers which is an effective method for structural damping enhancement. Particle dampers reduce vibrations through non-elastic impact and friction between particles and walls, thereby exhibit remarkable advantages, such as effectively suppressing structural vibration, insensitivity to ambient temperature, high operating range, availability in a broadband, and low-cost design [7, 8]. In the additive manufacturing process, particularly laser powder bed fusion (LPBF), the powder is purposely left unfused in pre-defined cavities inside the structure, which enhance the damping performance of the manufactured structure.

The damping performance of particle dampers has been extensively studied analytically, numerically, and experimentally in the open literature [9]. There are, however, few studies that concentrated on the damping characterization of particle dampers manufactured through additive manufacturing. Forced-response tests were performed by Scott-Emuakpor et al. [10-13] to analyze the damping capacity of cantilevered In718 beams using an electrodynamic shaker and a laser vibrometer. In these studies, quantity and locations of the unfused powder pockets were defined as design parameters and their impact on the damping performance was reported comparatively. It was concluded from these studies that damping performance of the specimens with unfused powder are sensitive to both amount and positions of the unfused powder while there is no significant variation in natural frequencies among the fabricated specimens. Besides, it was demonstrated that specimens with 1–4% internal volume of unfused powder suppress vibrations beyond 90% compared to their fully-fused counterparts.

On the contrary to a forementioned studies, Ehlers et al. [8, 14] investigated the influence of different cavity sizes left unfused under free-free condition using an impulse hammer. It was highlighted in the study that analyzing specimens under free-free condition enables to evaluate component damping for the first beam bending mode which is not possible for clamped specimens. Besides, the impact of excitation force, excitation frequency, and cavity size on the damping performance for different materials was evaluated. The experimental results show that the cavity width and height have a stronger effect on damping in comparison to the cavity length. Furthermore, it was reported that vibration amplitudes can be significantly suppressed by particle damping and the damping performance for some particle-filled beams could be improved up to x20 compared to their fully-fused counterparts.

The fallowing study explores the impact of the boundary conditions on the damping performance of the particle-filled structures produced from In718 powder by LPBF. For this purpose, six different particle-filled specimens with varying unfused cavity height and number of cavities were printed and tested by means of the impulse hammer excitation under clamped-free and free-free boundary conditions. The natural frequencies and damping ratios were reported for the first bending mode and the damping values of the particle-filled specimens were compared to their fully-fused counterpart to identify the enhancement in the damping performance while reducing component mass.

2. Experimental methodology

This section describes the experimental methodology for identifying the effect of particle damping. The methodology includes developing a design of experiment (DOE) to determine how design parameters such as and boundary conditions affect the damping performance. By using additively printed particle-filled and fully-fused specimens for impulse hammer excitation, the relationship between modal parameters, natural frequency, damping ratios, and design parameters was established.

2.1 Design parameters

Beams with rectangular cross-section and varying number of cavities and cavity heights are fabricated to characterize the effect of particle-filling on the dampening performance. All beams were made of IN718 with external dimensions of 150×60×10 mm^3. The number of integrated particle-filled cavities are varied from one to three to identify the effect of total volume of unfused particles on the damping performance. To characterize the effect of the particle-filled cavity height, two different dimensions are used. The height of the thin and thick cavities are set to 4 mm and 6 mm respectively, and the width of the cavities are adjusted to keeping the volume of particle-filled cavities constant. For the specimens with an increasing number of cavities, the volume fraction between the particle-filled cavities and the total volume of the structures is 9.2%, 18.4%, and 27.6%, respectively. Figure 1 illustrates the schematics of the specimens and their dimensions. To assess the improvement in damping performance, a total of six different particle-filled specimens with different design parameters and a fully-fused specimen with the same dimensions are used. To examine the effects of the boundary conditions, the specimens are also tested under clamped-free and free-free conditions.

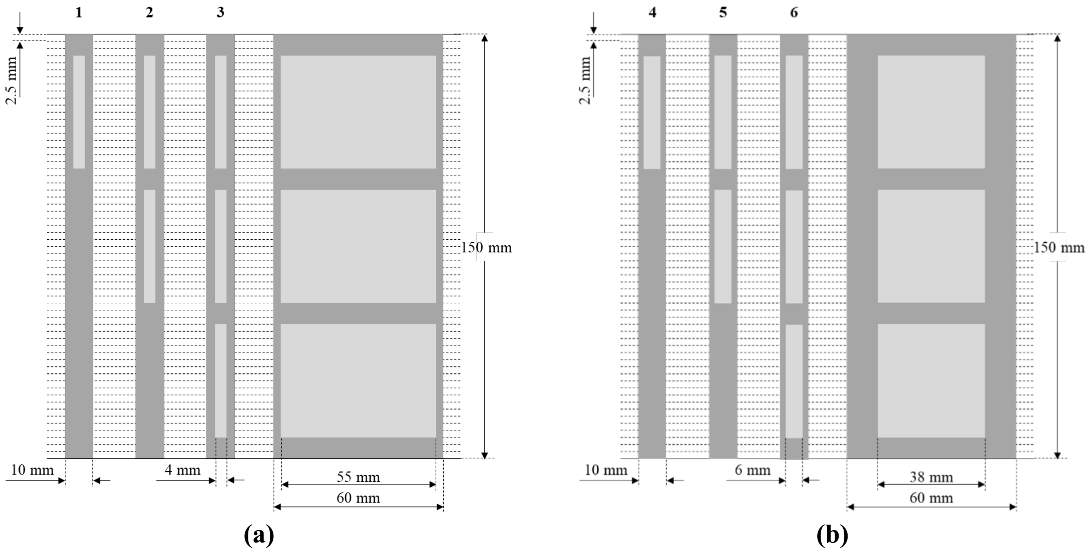
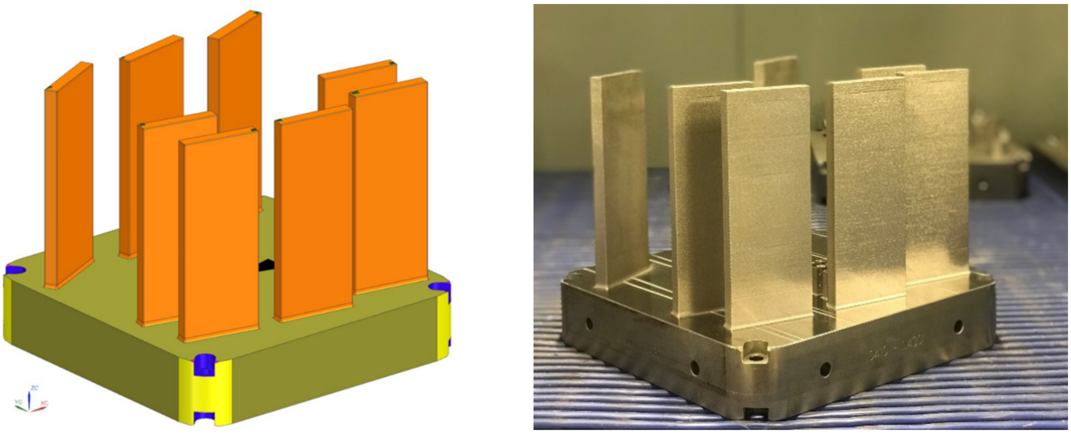


Figure 1. Specimens with a) thin unfused cavities and b) thick unfused cavities

2.2 Manufacturing

The specimens defined in the DoE are printed through LPBF based process to integrate particle dampers into specimens in one production step. This minimizes integrity risks and reduce material waste. In this process, particle-filled cavities are left unfused which saves production time and reduces energy demand in the production process. The proposed beam models were placed on a build plate in a CAD environment as given in Fig. 2a. It was then converted to machine readable format and this data is imported to Concept Laser M2 machine based on the powder-bed technology. The machine was loaded with Praxair In718 powder prior to the fabrication. After a powder evacuation process, the fabrication of the specimens was completed. The printed specimens are shown in Fig. 2b.

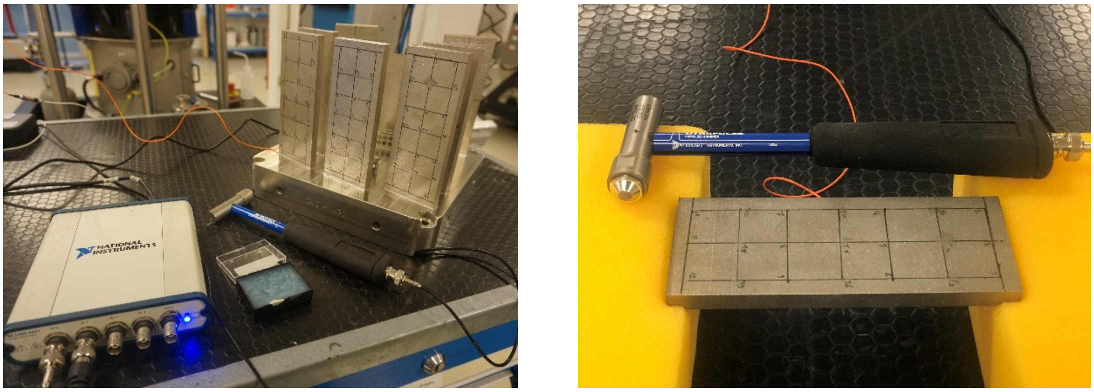


(a) **(b)**

Figure 2. a) Specimens placed on the build plate and **b)** Fabricated specimens

2.3 Modal testing

The printed specimens were tested under clamped-free and free-free boundary conditions. To simulate clamped-free boundary condition, the specimens were tested on the build plate before removal of the specimens from the build plate (see Fig. 3a). After clamped-free tests with an impulse hammer, the specimens were removed from the build plate using a wire electrical discharge machining (EDM) operation. The specimens were then placed on a foam base and tested to simulate free-free boundary conditions as shown in Fig. 3b.



(a) **(b)**

Figure 3. a) Clamped-free and **b)** free-free modal test setups

The specimens were excited from nine different locations as shown in Fig. 4 for averaging using a Dytran Dynapulse 5800B4 impact hammer. A Dytran 3225F1 accelerometer was placed on center of the back face of specimens to measure accelerations and National Instruments NI USB – 4431 was used for data acquisition and postprocessing. In this study, natural frequencies and damping ratios of all specimens for the first mode are reported to evaluate the effects of the particle damper. The rational fraction polynomial (RFP) method was used to obtain natural frequencies and damping ratios using frequency response function (FRF) curves. This method uses a complex function to fit a curve on FRF. This function can then be used to calculate the modal parameters [15].

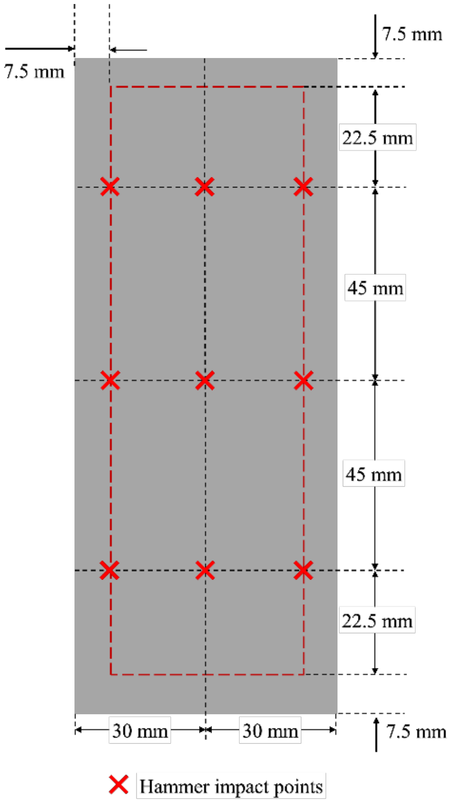


Figure 4. Excitation points on specimens

3. Results

We investigate the effect of the design parameters and boundary conditions on the damping performance in this section, where experimental results are provided comparatively. The natural frequencies, damping ratios for the first mode, and weight of the printed specimens are given in Table 1. Specimens were excited from 9 different places as indicated in Fig. 4, however, each damping ratio given in the Table 1 was averaged by these points to have a better interpretation. The total mass of the fabricated beams and volume fraction of the unfused cavity to total volume have a significant influence on the natural frequencies and damping performance. The mass of all beams was measured with a precision scale and given in the Table 1. Particle-filled beams are up to %13 lighter than their fully-fused counterpart. More specifically, each unfused cavity saves around 30 gr of material since the particles in the unfused cavities are less dense than those in fused material. Table 1 also shows that particle-filled cavities exhibit up to 12 times higher damping compared to the same component with fused powder while there is change in natural frequencies less then %3 for specimens both tested clamped-free and free-free. These results confirm that additively manufactured particle dampers improve the dampening performance with relatively low mass which has positive impact on fuel consumption of aircrafts. Besides, leaving particles unfused in the cavities reduces waste material through selective production, thus minimizing energy demand during the production process, which also contributes to sustainable aviation goals.

In the following, the effects of the predefined design parameters and boundary conditions on the damping performance are discussed in detailed.

Table 1. Dimensions, volume fraction, and mass of particle filled damper integrated specimens

Specimen	Boundary Condition	Natural Frequency (Hz)	Damping Ratio	Mass (gr)
Fully-Fused	Clamped	299.8	0.0059	736.5
	Free	1912	0.0010	
1	Clamped	313.9	0.0093	706.6
	Free	1915	0.0034	
2	Clamped	316.5	0.0112	677.1
	Free	1966.2	0.0086	
3	Clamped	303.7	0.0136	647.2
	Free	1956.7	0.0087	
4	Clamped	314.9	0.0143	707.6
	Free	1881	0.004	
5	Clamped	313.7	0.0271	676.5
	Free	1981.4	0.0111	
6	Clamped	300.9	0.0172	645.8
	Free	1912.8	0.0122	

3.1 Effects of variation in the number of cavities on the damping performance

A comparison of the damping performance of the specimens with a range of one to three unfused cavities is explored. Figure 5 shows attained damping ratio with respect to the number of cavities for the different cavity size and boundary conditions. Overall, the damping ratios enhance as the number of unfused cavities increase. The only case violating this trend is occurred for the thick specimen with three unfused cavities under clamped-free boundary condition. The specimen with three cavities exhibits a drop in damping performance after experiencing an anticipated enhancement with the increase in cavity number from one to two. The force response experiments for clamped-free beams conducted by Scott-Emuakpor et al. revealed a comparable trend [13]. They attributed this trend to the effects of large tip deflections, which increase the system's energy through the clamp. Therefore, it is suggested to discard 1st bending mode in damping assessments. Higher natural frequencies should be included, and the damping performance of the printed specimens should be correlated with the mode shapes to fully capture this behavior. These are dealt with in future works as they are outside the scope of the present study.

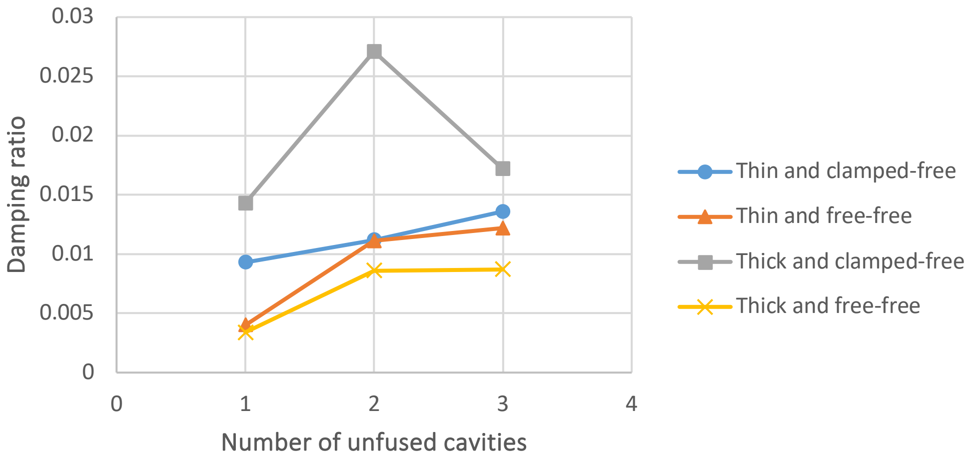


Figure 5. Effects of variation in the number of cavities on the damping ratio

3.2 Effects of variation in the cavity height on the damping performance

In this section, the influence of the cavity height on the effect of damping performance is examined. For this purpose, beams with two different cavity heights of 4 mm and 6 mm are fabricated to investigate the influence of the damping performance while keeping overall unfused particle volume constant. To achieve this, widths of the unfused powder cavities are adjusted. Figure 6 shows the damping ratios of the first mode of the beams with unfused cavities. It is apparent that the damping of the particle-filled beams increases with increasing cavity height for all specimens under both clamped-free and free-free boundary conditions. Ehlers et al. has also reported that the damping performance increases with increasing unfused cavity height [8]. Although the volume of the particle-filled cavities was not kept the same in their study, a similar trend was observed with the present study. The enhancement in the damping performance by increasing cavity height is related with the increasing cross-sectional area in the direction of vibration. This is not perfectly able to explain the behavior observed in the present study. Because, in the current study, the cross-sectional area was kept constant while increasing the height of the unfused cavity through reducing cavity width. According to the results, the variation in height in the direction of vibration has more impact than variation in the width on the damping performance.

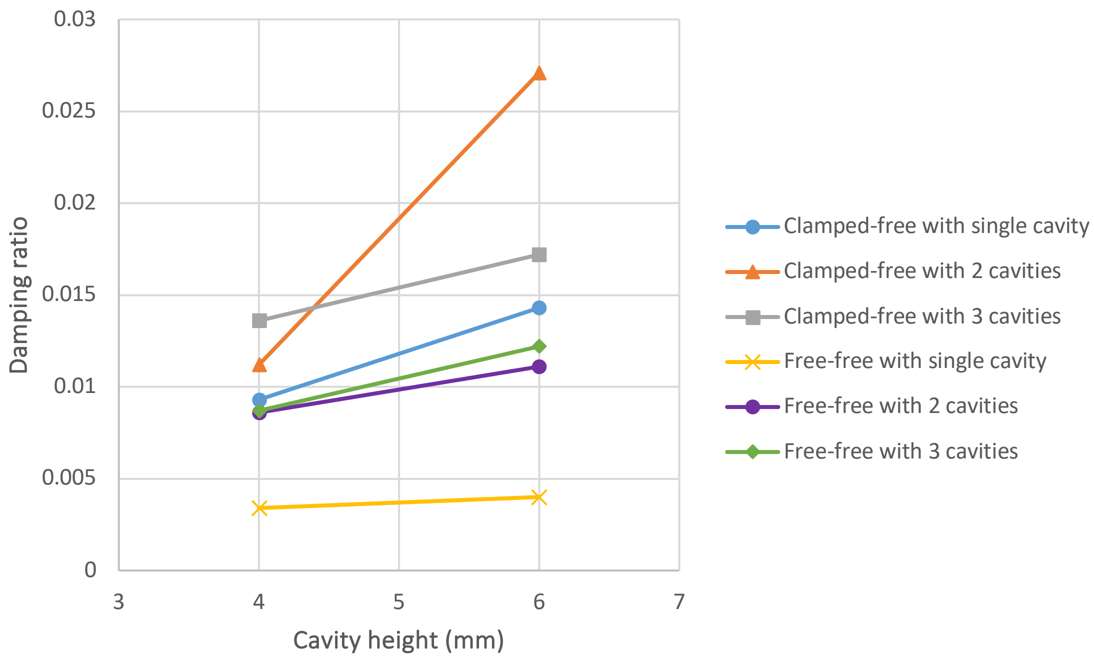


Figure 6. Effects of variation in the cavity height on the damping performance

3.3 Effects of boundary conditions on the damping performance

In this section, the focus of the evaluation is placed on the boundary conditions. The fabricated beams are tested under clamped-free and free-free to characterize the effect of the boundary conditions on the damping performance. The obtained damping ratios from impact hammer testing are compared in Fig. 7. It can be seen that damping values of the clamped-free specimens are higher compared to the specimens tested under free-free condition for the first bending mode. This can be explained by frequency and mode shape dependency of the damping performance. Ehlers et al. [8, 14] demonstrated the effect of the frequency dependency of the particle dampers on the damping performance through testing beams only free-free condition for higher bending modes. The results shows that damping decreases with increasing frequency. This confirms the findings of the present study. However, assessments should be repeated for the higher natural frequencies under different boundary conditions to have frequency dependent damping characterization and a better interpretation on the effects of boundary conditions on the damping performance.

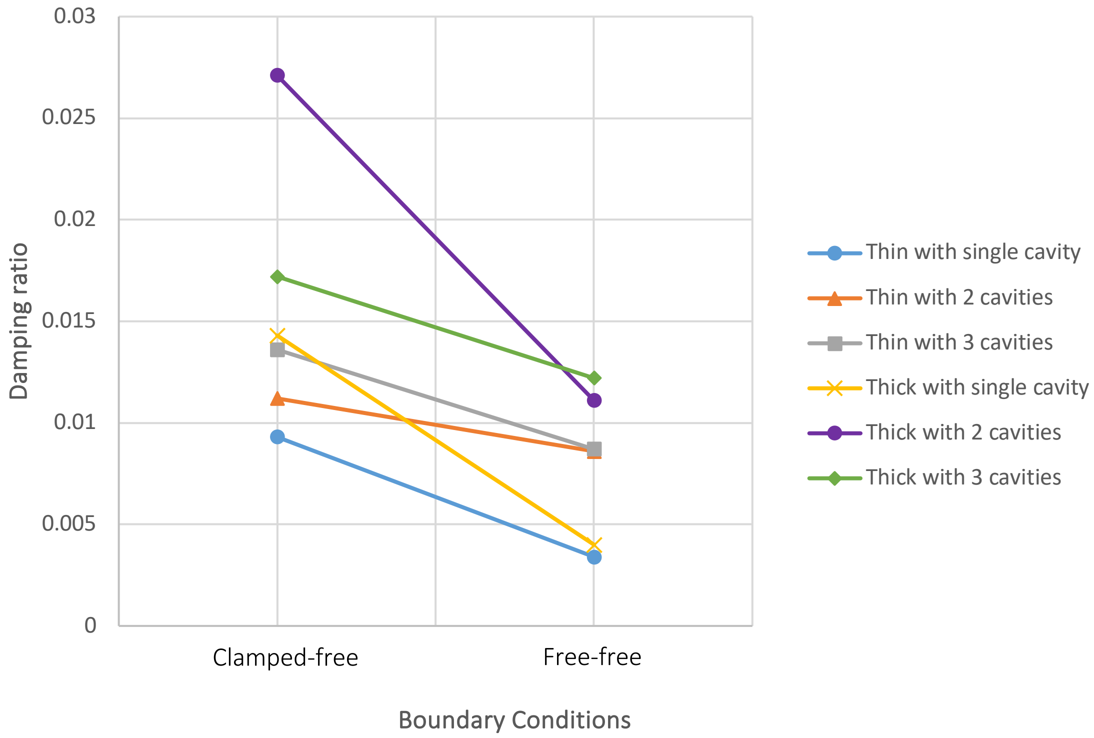


Figure 7. Effects of boundary conditions on the damping performance

4. Conclusion

In this study, the effect of particle damping was studied and integration of particle dampers into components though additive manufacturing were evaluated from sustainability standpoint. It was found that the particle-filled beams exhibit strongly better damping performance than their fully-fused counterpart. The damping ratios could be increased for all specimens for the first mode, while saving mass even up to %13. Furthermore, it was shown that increasing the particle-filled cavity height enhances the damping performance further and damping value is sensitive to the applied boundary conditions. Integration of particle dampers into components improves the structural performance and enables to lightweight design solutions which reduces fuel consumption and thereby to emissions in the aviation industry. Besides, particle-filled cavities are deliberately left unfused during the additive manufacturing process which minimizes energy demand and reduce the production time. In the light of these findings, completely novel application areas for achieving sustainable aviation goals may become available having a better understanding of particle damping.

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