Chapter 10
Experimental Investigation of the Damping Effect of Inherent Particle Damping Under Centrifugal Load

Mirco Jonkeren and Sebastian Tatzko

Abstract The passive damping mechanism of particle damping is capable of influencing the structural dynamic behavior of mechanical structures in terms of vibration mitigation. Especially additive manufacturing technologies offer a huge potential to integrate powder-filled cavities into structures and thus enable this inherent damping effect. The potential was already shown for additively manufactured beams but also for final products like gears. However, for rotating components such as gears, the centrifugal load may affect the damping mechanism adversely as relative motion of particles could be reduced. In this experimental study, we investigate particle damping in structural dynamics under rotation. For this purpose, we compare the damping behavior of additively manufactured gears with and without inherent particle damping under centrifugal load. For varying rotational speeds the vibration response is measured using a laser vibrometer that rotates synchronously with the gear. An automatic impulse hammer ensures identical excitation in each measurement while the applied force is also monitored. Gears with particle damping show a significant increase in damping. An essential dependency on centrifugal load is shown here, which increases the damping even further. Our findings contribute to the basic understanding of particle dynamics under centrifugal load and opens new paths to exploit particle damping in rotating structures.

Keywords Particle damping · LPBF · Centrifugal load · Gear · Rotational laser vibrometer

Introduction

Particle damping is a damping mechanism where cavities in a vibrating structure are filled with particles, either added or left as unmelted powder through additive manufacturing, such as laser powder bed fusion (LPBF). The energy dissipation of this mechanism is based on friction mechanisms and inelastic impacts, which serve to effectively reduce the vibrations [1]. While structures with conventionally added particles have been the subject of detailed investigation in the past, research into powder-based particle dampers has developed in connection with the field of additive manufacturing. The additive manufacturing process enables the inclusion of unmelted powder within the cavities of a structure, thereby expanding the potential for innovative construction solution [2, 3, 4, 5].

The effect of particle damping on mechanical structures, such as beams, has been the focus of previous studies, particularly in relation to non-rotating motion. Nevertheless, with regard to rotating systems, the available research is less extensive. A general study on the energy dissipation characteristics of granular materials sloshing in a rotating container is presented in [6]. In [7], investigations are carried out on a rotating beam on the effectiveness of particle dampers under centrifugal loads, whereby the particle damper oscillate in a direction perpendicular to the centrifugal load. A dependence between the ratio of the centrifugal acceleration to the maximum acceleration amplitude and the performance of the particle damper is shown. The application of particle dampers in gear systems is presented in [8, 9, 10], where holes are drilled in the gears and filled with particles. It is observed that the total energy dissipation of the damper also increases with an increase in rotational speed. The positive correlation between the damping effect and rotational speed is only given within a limited speed range. The combination of particle damping utilizing powder bed based additive manufacturing processes and its application in gears has been demonstrated in [11]. It is shown that the integration of powder-filled cavities resulted in a significant reduction in the vibration amplitude. Nevertheless, further research is required to gain a more comprehensive understanding of the behaviour of particle damping in additively manufactured gears under centrifugal load.

Mirco Jonkeren · Sebastian Tatzko
Institute of Dynamics and Vibration Research, Leibniz University Hannover, An der Universität 1, 30823 Garbsen, Germany
e-mail: jonkeren@ids.uni-hannover.de; tatzko@ids.uni-hannover.de

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Experimental Methodology and Analysis

A series of tests were carried out on a set of gears manufactured additively from X3NiCoMoTi 18-9-5, as presented in [11]. Laser powder bed fusion is the additive manufacturing process employed to achieve this. The characteristics of a fully fused gear are compared with those of two gears containing unmelted powder in integrated cavities in the teeth. The two gears differ in terms of their cavity sizes (G-02: small cavities and G-03: large cavities). The experimental setup with one of these gears is shown in Figure 1. The gears are mounted on a sleeve that is connected to a shaft. The sleeve has been designed with the objective of minimizing the contact area between the gear and the rotating shaft of the test rig, thus reducing the friction damping between them (see detail view in Figure 1, in which the sleeve is shown in black and the contact surfaces are marked in red). The excitation is applied as an impulse to the gear with an automatic impulse hammer (see Figure 1 right). The out-of-plane vibration response is measured using a scanning laser doppler vibrometer (SLDV) that rotates synchronously with the gear (see Figure 1 left). An optical derotator, manufactured by *Polytec*, is employed for this purpose. This enables the non-contact measurement of vibration on rotating objects, based on a rotating Dove prism that enables speed-controlled tracking of the laser beam. The speed information required for control is provided by an encoder signal from the drive motor. Subsequently, a Fourier transformation was performed and the calculated spectra of a total of ten individual measurements per rotational speed were averaged. The rotational speed was varied from 0 rpm to 400 rpm in steps of 20 rpm. Figure 2 shows an example of an averaged spectrum of the fully fused gear. The identified natural frequencies were then employed in the application of a filter for specific eigenmodes. The present study examines the vibration mode, which is also shown in Figure 2. For the fully fused gear without integrated particle damping, the corresponding natural frequency is 12385 Hz as illustrated by the red circle. Signal filtering is conducted using a digital bandpass FIR filter (finite impulse response filter) with a cutoff frequency of 50 Hz below and above the peak of the frequency of the examined vibration mode. These upper and lower cutoff frequencies are shown by the red transparent area in Figure 2. In accordance with [12, 13], it is crucial that the input data is processed in both the forward and reverse directions during the filtering process. The filtered time data is exemplarily shown in Figure 3 for the fully fused gear (left) and the gear G-03 (large cavities) with particle damping (right). It is noticeable that the vibration amplitudes of the examined mode decay at a slower rate for the fully fused gear than for the gear with powder-filled cavities. This filtered time data is used to identify the damping ratio of that single mode. For this, an exponentially decaying function is utilized to fit an envelope to the filtered time data of each measurement:

$$\dot{x}(t) = \hat{\dot{x}}_0 e^{-\delta t} \tag{1}$$

Here $\dot{x}$ represents the surface velocity, δ the exponential decay constant. $\hat{\dot{x}}_0$ is the initial value of the surface velocity at the specified time, which is defined at the time of the maximum value of the measured time data after excitation (see in Figure 3 near 0.05 s). For such an individual mode, the damping ratio D is defined as:

$$D = \frac{\delta}{\omega_0} \tag{2}$$

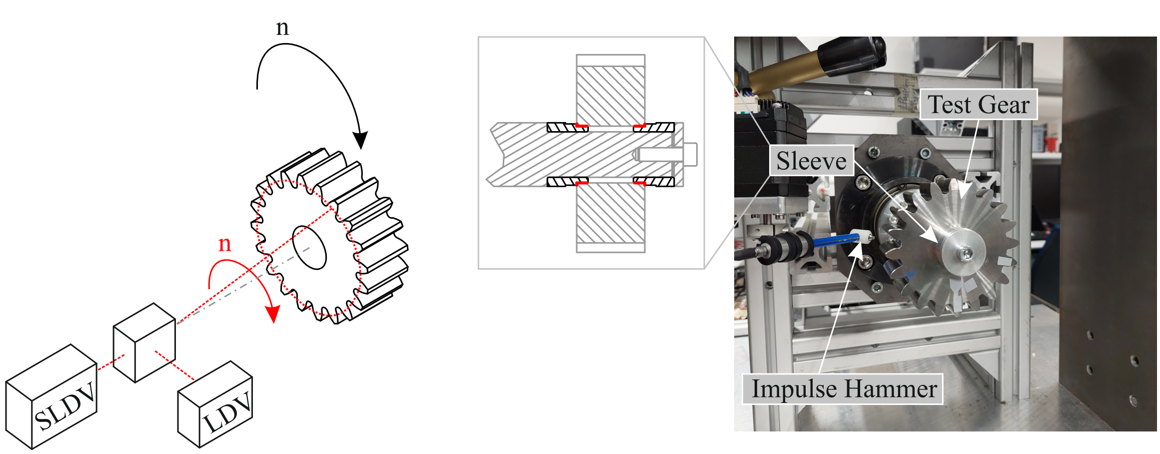

Fig. 1 Schematic illustration of the experimental test setup for measuring the system response of rotating gears out-of-plane (left). Experimental setup with mounted gear and the automatic impulse hammer used for excitation (right).

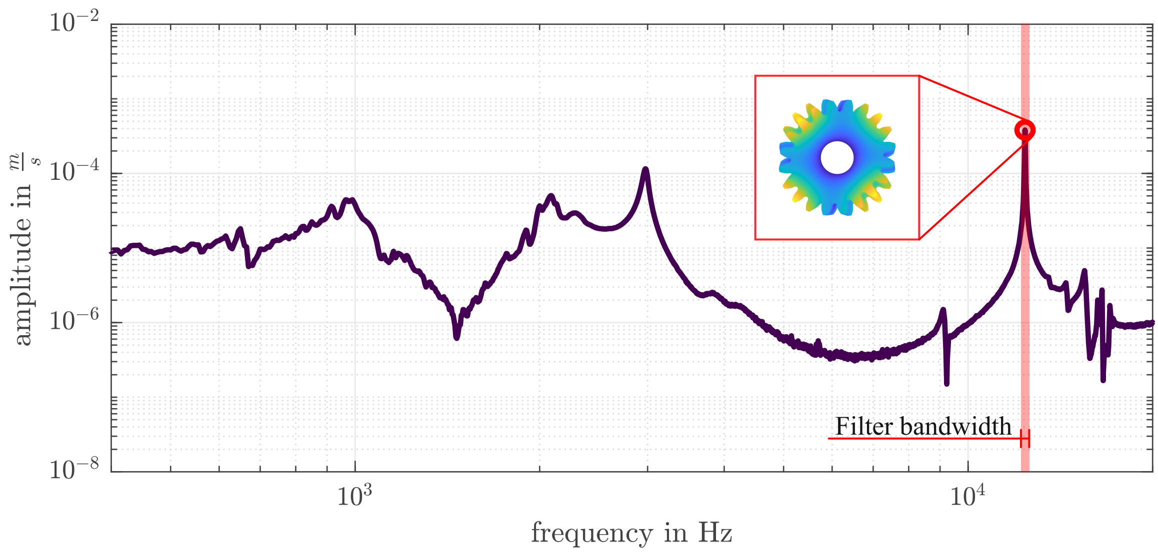

Fig. 2 Averaged frequency spectrum of the system response of the fully fused gear. The frequency range employed for signal filtering is indicated by a red transparent area above and below the analyzed resonance frequency (red circle). Corresponding vibration mode (detail view).

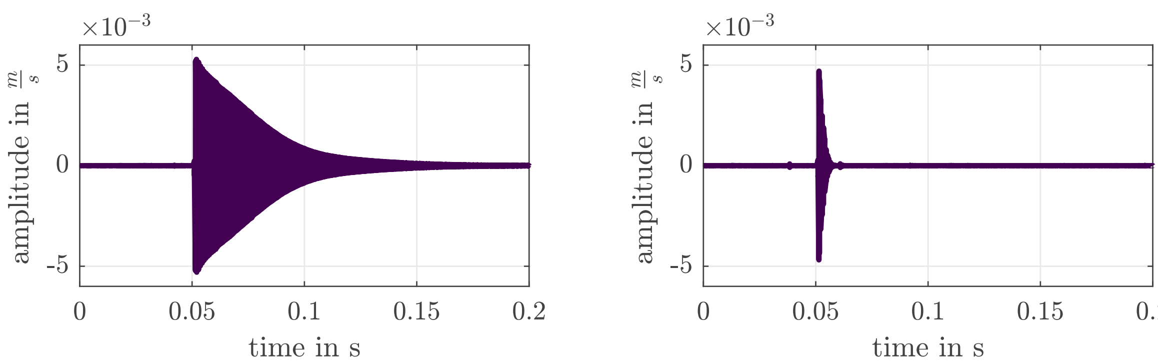

Fig. 3 Filtered time data at a rotational speed of $n = 300$ rpm. Free decay of the fully fused gear without integrated particle damping (left) and for the gear G-03 (large cavities) with integrated particle damping (right).

The natural frequency of the undamped system ω_0 is related to the damped natural frequency ω_d by:

$$\omega_0 = \frac{\omega_\mathrm{d}}{\sqrt{1 - D^2}} \tag{3}$$

This leads to the following equation for calculating the damping ratio:

$$D = \frac{\delta}{\omega_\mathrm{d}} \frac{1}{\sqrt{1 + \frac{\delta^2}{\omega_\mathrm{d}^2}}} \tag{4}$$

Figure 4 shows the damping performance of the fully fused gear in comparison to the two gears with powder-filled cavities in terms of the calculated damping ratio according to equation (4) for different rotational speeds. The mean value of the ten individual measurements for each rotational speed along with the standard deviation are presented. It can be observed that the damping ratio of the gears with integrated particle damping is higher in all speed ranges. The examination of the data reveals a greater range in damping values for the gears with integrated particle damping in comparison to the fully fused gear without. In particular, the data set exhibits a larger standard deviation at 220 rpm, 280 rpm and above from 360 rpm, which may be indicative of outliers.

A comparison of the gears reveals that the damping ratio remains nearly constant over the examined range of rotational speed for the fully fused gear. For the gear with the large integrated and powder-filled cavities it can be oberseved that the damping ratio increases with an increase of rotational speed. This trend is observable across the entire speed range. These results demonstrate a qualitative trend that is in accordance with the findings of [8]. This tendency is not as pronounced for the gear G-02 with the small cavities, but a slight increase can also be observed.

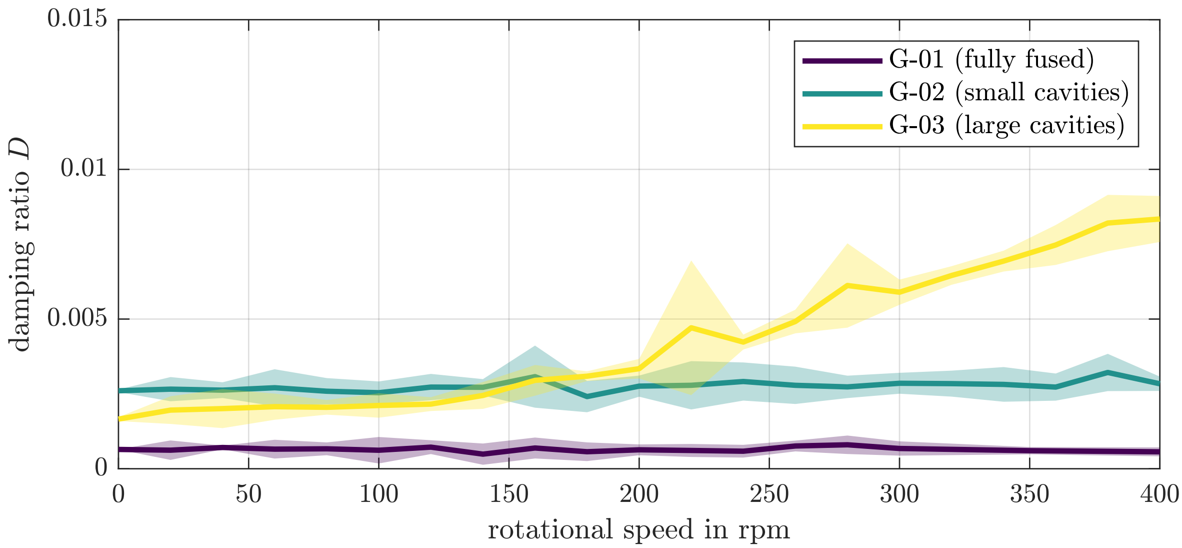

Fig. 4 Calculated damping ratios of the examined vibration mode for the fully fused gear and the two gears with integrated powder-filled cavities. The graphs show linear interpolation between calculated damping ratios at discrete rotational speeds. Corresponding standard deviations are indicated by transparent areas.

Conclusion

In conclusion, this experimental study investigates the dynamic response of three additively manufactured gears excited with a deterministic impulse excitation signal. The system response is measured using a laser vibrometer that rotates synchronously with the gear to capture the decaying time history at various rotational speeds. By conducting ten measurements at each rotational speed and analyzing the frequency spectrum of the system response, the decaying time data were filtered to isolate and examine one specific mode. The damping ratio for this vibration mode was calculated for each rotational speed. The results demonstrate that the damping increases with rotational speed for powder-filled gears, especially those with large cavities. Damping of the fully fused gear did not show any dependence on rotational speed. These findings contribute significantly to the understanding of the benefits of particle damping in gear systems.

In future, further investigations should aim to provide a detailed analysis of particle motions and interactions within the cavities under centrifugal load. It would be beneficial to analyze the trend in further studies at higher speeds in order to determine whether the damping ratio eventually reaches a plateau or whether it begins to decline at some point, as reported for example in [8]. A detailed analysis of the observed damping fluctuations at high speeds, in particular the outliers and speeds above 360 rpm, would be useful. It is important to determine whether these fluctuations are due to the system or are influenced by the test setup. This consideration is relevant as tangential forces can be induced during excitation by surface roughness and hammer tip, which may have a greater effect at higher speeds.

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