Applying a Viscoleastic Model to Multiple Unique Additively-Manufactured Trapped-Powder Dampers

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1 Introduction

Metal additive manufacturing processes facilitate the fabrication of geometrically complex metal structures. When used for part consolidation, additive manufacturing can result in decreased damping due to lost frictional interfaces. Other potential additively manufactured parts, such as turbine blades [1], are destined for high-vibration environments where increased damping is highly desirable. One proposed technique for increasing damping in additively manufactured parts, and therefore delaying high-cycle fatigue failure, involves strategically incorporating pockets of unfused metal powder into the structure [1]. This technique has demonstrated the potential to dramatically increase the inherent damping without significantly affecting the strength and stiffness of a structure or requiring additional assembly or post-processing steps. Nevertheless, reliably modeling this phenomenon is an active area of research due to complex effects of powder state, magnitude-dependent damping, and other factors. While some success has been had in modeling powder particles using discrete element codes [2], this approach is very computationally expensive, making it cumbersome for designer use.

Black et al. [3] recently proposed approximating trapped powders as linear viscoelastic materials (VEM), with the material properties adjusted to capture the powder at a set vibration amplitude. This method is computationally efficient and accessible via standard finite-element packages. This work reviews the degree to which Black's model was able to capture the measured damping of the samples that were used to derive the equivalent material properties for the powder. Those samples were all beams with powder pockets of differing dimensions. Those same viscoelastic material properties are then used to predict the damping of several tuning forks and the results are evaluated. In addition, the viscoelastic model is extended to include kinetic-energy-based damping, to see if this can address its deficiencies.

2 Methods

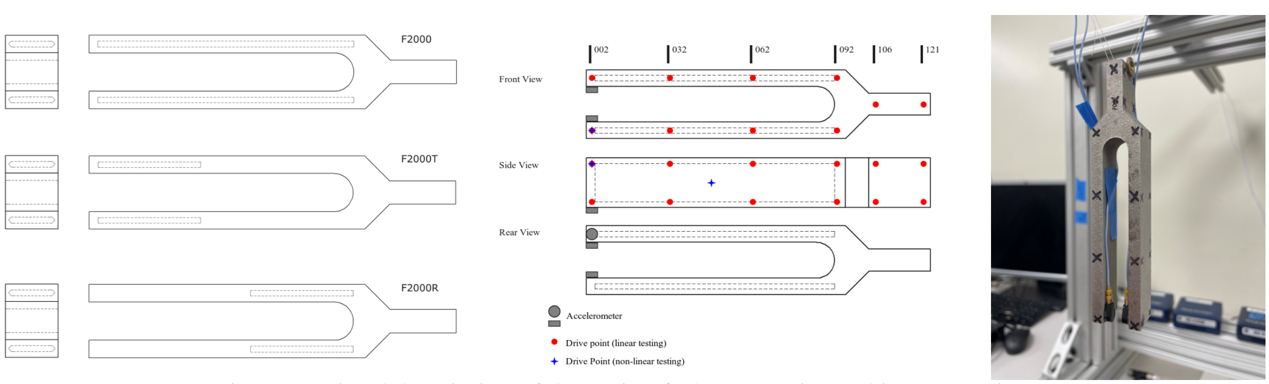


Figure 1: Visual description of the tuning fork geometries and impact testing set-up

The amplitude-dependent damping and frequency behavior of the tuning forks was found using impact modal testing. The test setup and geometries for the tuning forks are shown in Figure 1. Amplitude-dependent frequency and damping were extracted from accelerometer data using a Hilbert-based method. In contrast with the beams tested by Black [3], the tuning forks were hung such that the length of the tines was in the direction of gravity. This affects the way in which the powder settles and may have impacted the results.

Black's viscoelastic model utilizes the complex-stiffness method in ABAQUS finite element software [3]. Since both the beams and tuning forks were made of 316L Steel, the fused and powder material properties found by Black were directly applied to the tuning forks.

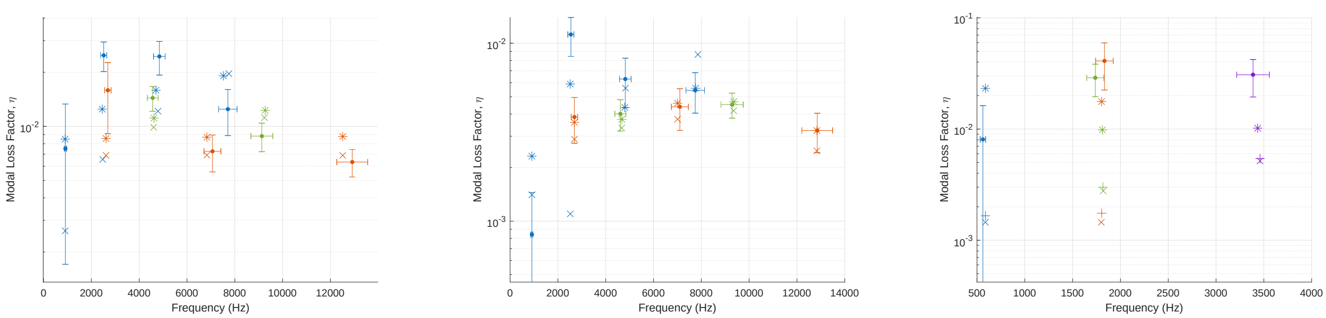
In addition to the original viscoelastic modeling, a modal strain and kinetic energy (MSKE) model [4] was used to predict the trapped powder behavior. This model linearizes the damping calculations and extends the model to include damping due to kinetic energy-based effects resulting in Eq. 1. In this equation, the first two terms represent the damping due to strain for both the fused and powder material while the third term represents kinetic-energy-based damping of the powder. In each term, η_i is a material property and $F_{i,mat}$ is the fraction of strain or kinetic energy within the given material. In these calculations, the $F_{i,mat}$ and frequency values are outputs of a real-valued modal analysis in ABAQUS. MSKE fused powder properties were chosen to match those used by the VEM model, assuming that $\eta_{s,powder}$ is roughly equivalent to the shear loss factor.

$$\eta_{tot} = \eta_{s,powder}F_{s,powder} + \eta_{s,fused}F_{s,fused} + \eta_{k,powder}F_{k,powder} \tag{1}$$

The MSKE parameters were optimized using a different approach than was used for the VEM model. The VEM parameters were optimized for the B1000 beam (1mm thick pocket throughout the beam) using the same properties for all modes [3]. The MSKE parameters were optimized for the two-pocket beam (which has two 20mm long, 1 mm thick pockets placed at the antinodes of the second bending mode). Furthermore, different MSKE pocket parameters were used for the soft direction modes and the other modes. This is consistent with the suggestion made in [5] that high aspect ratio pockets should be modeled as anisotropic. Interestingly, if VEM properties are optimized separately for soft and non-soft modes, little to no improvement is seen in our model. Meanwhile, the MSKE method benefits greatly from this separation, showing very different kinetic-energy damping behavior for soft and non-soft modes. However, this approach could not be directly applied to the tuning forks, because their modes tended to mix soft, stiff, and torsional movements, making them difficult to categorize. Therefore, both soft and non-soft MSKE parameters were applied to the tuning fork, and the results for each mode are reported separately.

3 Results and Discussion

A sample of the frequency and damping results for the beams and tuning forks is shown in Figure 2. The MSKE and VEM properties used are given in Table 1.



(a) B1000 beam (b) two-pocket beam (c) F2000T tuning fork

Figure 2: Damping and frequency results for three geometries. Color refers to mode or modetype. For the beams, blue refers to soft modes, orange to stiff modes, green to torsional modes. Error bars report one standard deviation of the experimental data. Marker types refer to the model, × for the VEM model, * for the MSKE model. For the tuning fork, * refers to the MSKE Soft model while + denotes the MSKE Stiff/Torsional model (see Table. 1)

VEM Parameter	VEM	MSKE Parameter	MSKE Soft	MSKE Stiff/Tors
Young's Modulus (MPa)	21624	Young's Modulus (MPa)	5274	21704
Poisson's Ratio	0.45	Poisson's Ratio	0.12	0.05
Shear loss factor	0.45	$\eta_{\text{s,powder}}$	0.12	0.51
Bulk loss factor	0.0	$\eta_{\text{k,powder}}$	0.15	0.0

Table 1: Table of optimized VEM and MSKE properties for high amplitude modal behavior

For the beam data, the VEM model appears to capture the stiff and torsional modes quite well, with most errors falling within one standard deviation. Notably, the optimized MSKE parameters for stiff and torsional modes closely parallel those used in the VEM model with similarly accurate results, despite being optimized on separate beams. The exception is Poisson's ratio, which the beams appear not to be sensitive to. This parallel, along with the model's accuracy, suggests that the strain-based loss behavior of the VEM model is sufficient to model the stiff and torsional modes of the beams.

At the same time, the VEM model struggles to capture the trend of the soft direction modes. The most drastic example is the two-pocket beam's second soft direction mode as seen in Figure 2b. Although the two-pocket beam was designed to damp the second soft-bending mode, the viscoelastic model predicts very low damping. The MSKE model aims to address this deficiency by including a kinetic energy damping mechanism. In this case, the kinetic energy factor is shown to drastically improve our estimates of this mode. Similarly, this kinetic energy factor also improves the soft direction estimates of B1000 in Figure 2a. Hence, by optimizing the soft and non-soft directions separately and including a kinetic energy factor, the MSKE model shows promise for capturing both soft and stiff direction behavior of the beams.

However, the kinetic energy factor negatively impacts our estimate of the two-pocket beam's first soft-direction mode, resulting in an absolute error of 175%. In contrast, the maximum absolute damping error for the viscoelastic model (soft mode 2) was only 90%. Nevertheless, the average absolute damping error for both models is similar despite this outlier, 31% and 35% for MSKE and VEM, respectively.

Generally, the tuning fork data in Figure 2c is not well predicted by any of the models, with average errors of roughly 90%. Notwithstanding, the tuning fork data reinforces several observations. As expected, the non-soft MSKE and the VEM models behave similarly. Again, the soft MSKE model, which utilizes the kinetic energy factor, drastically overpredicts the first mode, but improves our estimates of every other mode. Neglecting the first mode, the soft MSKE model reduces the average error by 27%, from 90 to 63%.

The failure to predict the tuning fork results is not surprising. The tuning fork pockets are 2mm thick, where the beam pockets are only 1mm thick. Larger pockets tend to have more unfilled space, significantly influencing damping characteristics [6]. Additionally, the tuning fork pockets have chamfered corners to improve manufacturability. Such changes in pocket geometry affect the particle-to-wall impact behavior that the kinetic energy factor aims to capture [1]. While not yet fully understood, part orientation with respect to gravity during testing also has the potential to affect damping performance. Furthermore, poor estimates of the first mode could be a sign of frequency-dependent behavior, which is common in analogous systems such as particle impact dampers [7].

In summary, trapped-powder dampers were modeled as viscoelastic materials, improving computational time and complexity as compared to discrete element models. Black's VEM model did a good job of capturing the stiff and torsional behavior of the beams for which it was optimized. The MSKE model was proposed and, to some extent, overcame the deficiencies of the VEM model for the beams' soft direction modes. However, neither model precisely predicted the measured damping of the modes of a tuning fork that also included pockets of trapped powder. The conference presentation will show results for the two other tuning forks in Fig. 1, as well as a set of gears with powder in the gear teeth and will discuss the benefits and limitations of each model in more detail.

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