# Development of Analytical Methods for Particle Damping

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## Abstract

Particle dampers are highly nonlinear auxiliary mass dampers whose energy dissipation, or damping, is derived from a combination of mechanisms including plastic deformations, external and internal friction, and momentum transfer. To complicate matters, the predominate energy dissipation mechanism may vary depending on parameters such as cavity fill ratio, vibration amplitude levels, etc. Research has indicated that particle dampers could be a viable option for extreme environment applications, such as at elevated temperatures and/or under centrifugal loading. However, to date, the lack of a robust design methodology has limited particle damper usage to "trial-and-error" applications. The objective of this effort is to develop the necessary design methodology to enable the successful design and application of particle dampers. Experimental and analytical efforts toward this goal are presented.

## Introduction

The drive for improved performance and reduced weight in extreme environment structures has led to highly stressed components susceptible to high cycle fatigue (HCF) failures. One method to reduce these failures is to incorporate passive damping into the design of these components.

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Due to the extreme temperatures and potentially high centrifugal loads, application of usual damping systems to extreme environment structures, such as turbine engine blades, has been extremely limited. Many typical damping systems are not suitable for such environments. For example, polymeric viscoelastic damping can only be used in a limited temperature range (generally below 500°F) since polymeric materials degrade at elevated temperatures. Vitreous enamel damping may work if survival and production issues can be resolved. Friction damping works for lower order modes, but wear and life issues exist. Powder lubricant damping offers potential, but this immature technology requires further development and may require complex implementation schemes.

Particle damping offers a damping mechanism that is rugged, reliable, and simple to implement. Particle damping, used to imply multiple auxiliary particles of small size in a cavity, was first used to limit undesirable oscillations more than fifty years ago. These dampers are highly nonlinear auxiliary mass dampers whose primary energy dissipation, or damping, is derived from a combination of mechanisms including plastic deformations, external and internal friction, and momentum transfer. The predominate energy dissipation mechanism may vary depending on numerous variables including structural response levels and centrifugal loading levels on the particles. Particle damping offers the possibility of being designed to be insensitive to extremely high temperatures. Numerous metallic, ceramic, or oxide materials could be used to provide high resistance to temperature, corrosion, and thermal aging affects.

Although studies of particle damping have been conducted over recent years, many questions remain to be answered to enable this potentially versatile and robust technology to be effectively applied to high temperature structures. This statement is especially true for the application of particle dampers to centrifugal environments of gas turbine airfoils. Currently a comprehensive design method does not exist that will allow particle damping technology to be implemented without extensive trial and error testing. The following paragraphs discuss analytical and experimental efforts toward the development of a such a method.

## Analytical Modeling

Ideally, the analytical design method would include a first-order model which can be used for preliminary design purposes and design studies, along with a finite element model implementation for more sophisticated design and analysis, and final design validation. The first-order model would be analogous to $4^{th}$ and $6^{th}$ order beam theory typically used for preliminary design of viscoelastic damping systems. Initial first-order modeling has focused on a single degree-of-freedom (SDOF) system with a single particle impact damper as shown in Figure 1.

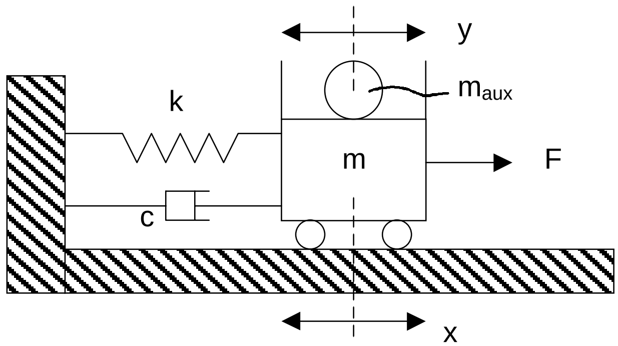


Figure 1. SDOF System with Single Particle Impact Damper

For this system, the primary and auxiliary mass (i.e. the particle damper mass) are free to move independently, with periodic collisions between the auxiliary mass and the cavity walls which are attached to the primary mass. Between collisions the equations of motion for the primary and auxiliary masses can be written as:

$$m\ddot{x} + c\dot{x} + kx = F - \mu g m_{aux}\,\mathrm{sgn}(\dot{x} - \dot{y})$$
$$m_{aux}\ddot{y} = \mu g m_{aux}\,\mathrm{sgn}(\dot{x} - \dot{y})$$

In the above equations, external friction (i.e., friction between the primary and auxiliary masses) is included, with $\mu$ equal to the coefficient of friction and $g$ representing the gravity (acting downward in Figure 1) or potential centrifugal load on the particle. The $\mathrm{sgn}(\dot{x} - \dot{y})$ term ensures that the friction forces act in the opposite direction of the relative motion between the masses. When collisions occur, it is necessary to consider the momentum transfer between the primary and auxiliary masses. The momentum transfer can be accounted for by using the momentum equation,

$$m\dot{x}_b + m_{aux}\dot{y}_b = m\dot{x}_a + m_{aux}\dot{y}_a$$

along with the following definition for the coefficient of restitution:

$$e = \frac{\dot{x}_a - \dot{y}_a}{\dot{y}_b - \dot{x}_b}$$

where $e$ is the coefficient of restitution for impacts between the auxiliary mass and cavity walls; and the *a* and *b* subscripts refer to the velocities after and before the impact, respectively.

To track the motions of the primary and auxiliary masses, it is necessary to numerically integrate the equations of motion. To perform the numerical integration, a FORTRAN program has been written which numerically integrates the equations using a $4^{th}$ order Runge-Kutta algorithm. Papalou[1] and Moore, et al[2] examined a similar SDOF system using a $4^{th}$ order Runge-Kutta algorithm with satisfactory results. Unlike previous analytical efforts, however, this first-order model includes friction between the primary and auxiliary masses and the response of the system under random excitation is being examined.

Figure 2 shows the predicted undamped and damped response of the second fundamental bending mode of the experimental test beam depicted in Figure 3. For the damped cases, tungsten carbide (WC) particles with auxiliary to primary mass ratios of 9.4% and 34.3% were examined. Damped responses with and without external friction are shown. These results indicate that, at least for the case examined, the effects of momentum transfer are much more significant than the effects of external friction. Considerable damping is possible with each of these configurations with greater damping at the higher mass ratio.

## Experimental Testing

To gain a better understanding of the damping effects of various particle damper parameters, experimental testing is being performed. Results from the experimental testing will be used to validate and refine the analytical models. The experimental test specimen is a 6061-T6 aluminum beam measuring 11.75 inches in length, 2.0 inches in width, and 0.125 inch in thickness, as shown in Figure 3. A clamp covers 2.0 inches of the beam's length at one end, leaving a free length of 9.75 inches length to vibrate in a fixed-free (cantilever) condition. A particle damper cavity is mounted 1.125 inches from the beam's free end and constitutes a "lumped mass" added to the beam at that location. The first fundamental bending mode of the beam-damper system is at approximately 36 Hz with an empty mass loaded damper cavity. For the experimental testing reported herein, the system has been excited with band-limited random noise spanning a frequency range of 0 to 500 Hz.

The beam is excited using a shaker attached to the beam through a stinger positioned 1.0 inch from the beam's clamped end. The experimental beam test configuration is shown in Figure 4.

Results from the experimental testing demonstrate that momentum transfer can result in significant damping. Figures 5 and 6 compare the second fundamental bending mode (undamped peak at approximately 195 Hz) response of the undamped but mass loaded baseline beam to the response of a beam damped with –20+30 mesh WC pellets at three different excitation levels. For the damped response shown in Figure 5, an approximate auxiliary to primary mass ratio of 9.4% was used, while a ratio of 34.3% was used for the results in Figure 6. With a mass ratio of 9.4% and specified cavity size, the damping effectiveness decreases as excitation increases. However, for a mass ratio of 34.3% with the same cavity size, the damping effectiveness increases. These results indicate that there exists an optimum excitation level for a given mass and clearance combination. In this sense, the particle damper is similar to a tuned damper in that it can be "tuned" for optimum attenuation of a given mode/excitation level combination.

Experimental testing also indicates that internal friction (i.e., friction between the various auxiliary masses) can have a significant effect on the damping. Figure 7 compares the response of the undamped beam to the response of a beam damped with 60 grit silicon carbide (SiC) particles. For the damped response shown in Figure 7, an approximate auxiliary to primary mass ratio of 8.0% was used. The SiC particles completely filled the cavity and prevented significant particle motion and any resulting losses due to momentum transfer. Thus, any resulting losses are due to the internal friction as particles shift and settle. Experimental testing also indicates that damping increases as the particle size decreases due to the increased surface contact. Irregular-shaped particles, which do not "pack" as well as spherical or semi-spherical particles, result in increased damping. These results are particularly important from the standpoint of damping under centrifugal loads. Under centrifugal loads the particles will "pack" against the outboard wall of the cavity. The vibratory accelerations may not be sufficient to overcome the external friction loads and create losses due to momentum transfer. However, it is anticipated that the particles will still be able to shift and settle relative to one another resulting in internal friction losses.

## Analytical/Experimental Results Comparison

Experimental testing has demonstrated that significant damping is possible due to both momentum transfer and internal friction. The first-order analytical model reasonably predicts the losses due to momentum transfer. However, modifications are required to include internal friction in the first-order analytical model. Inclusion of internal friction in the simple first-order model may involve modeling single particles on two layers and using fill ratio or packing density to determine the amount of time particles are in contact with each other. Once the first-order model has been modified and correlated with experimental testing, the model will be integrated into finite element analysis for sophisticated design and analysis and final design validation.

## Conclusions and Recommendations

Based on the analytical and experimental efforts to date, the following conclusions and recommendations are made:

- Particle dampers dissipate energy via various mechanisms including momentum transfer and internal friction. Experimental testing has demonstrated that significant damping is achievable with each of these mechanisms.
- The first-order analytical model reasonably predicts the losses due to momentum transfer. Modifications are required to account for internal friction. In addition, further experimental and analytical efforts are required to fully understand the effects of the various dissipation mechanisms.
- For centrifugally loaded and/or high temperature structural systems, particle damping offers a damping technique which is rugged, reliable, and simple to implement. Development of a comprehensive design method will allow particle damping technology to be implemented without extensive trial and error testing.

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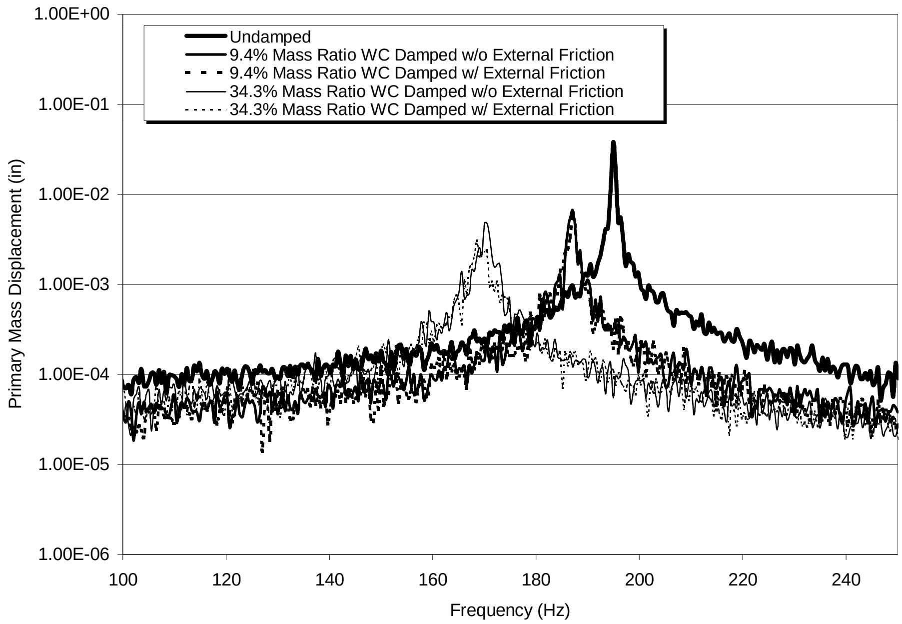


Figure 2. Predicted Response of Undamped and WC Damped Beams with Mass Ratios of 9.4% and 34.3%

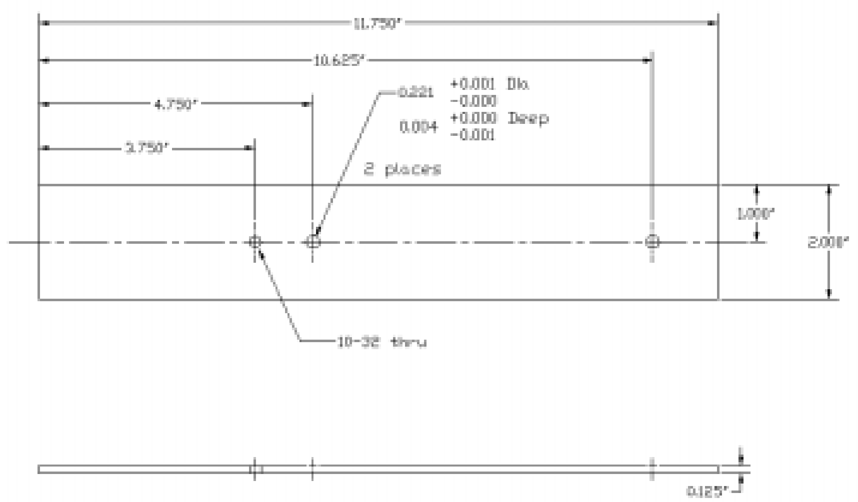


Figure 3.  Experimental Beam Test Specimen

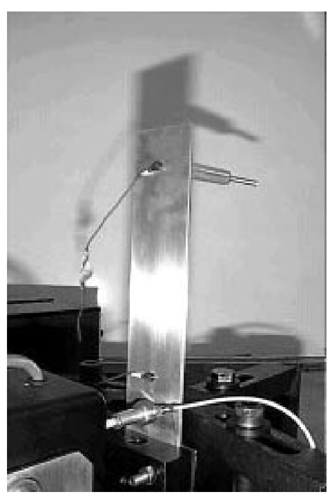

Figure 4.  Experimental Beam Test Configuration

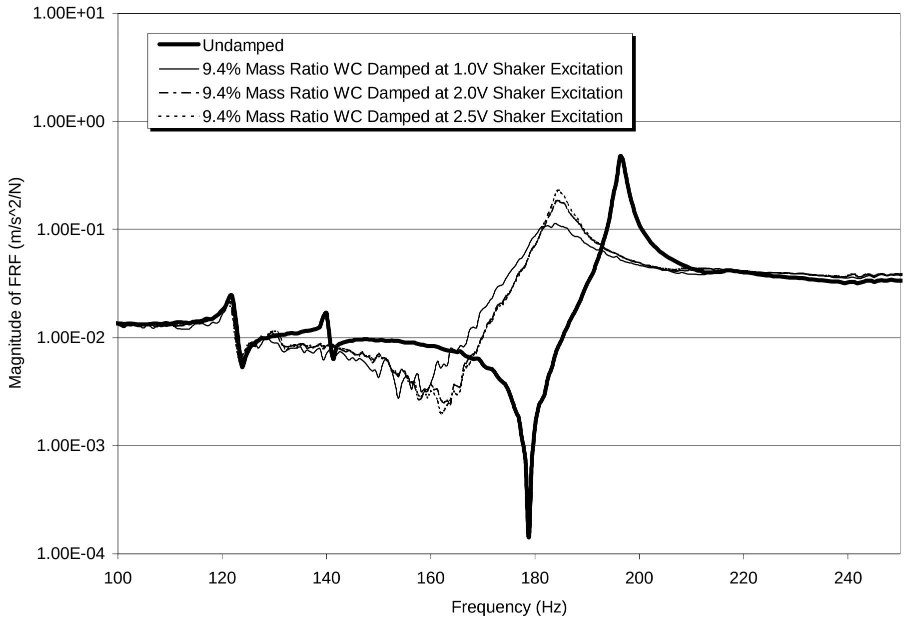


Figure 5. Measured Response of Undamped and WC Damped Beams
Mass Ratio of 9.4%

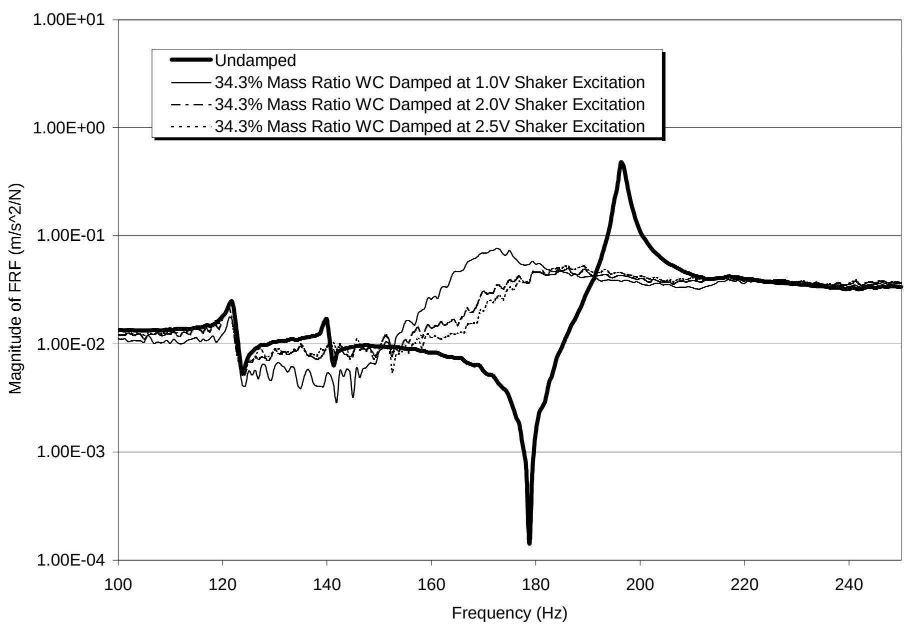


Figure 6. Measured Response of Undamped and WC Damped Beams
Mass Ratio of 34.3%

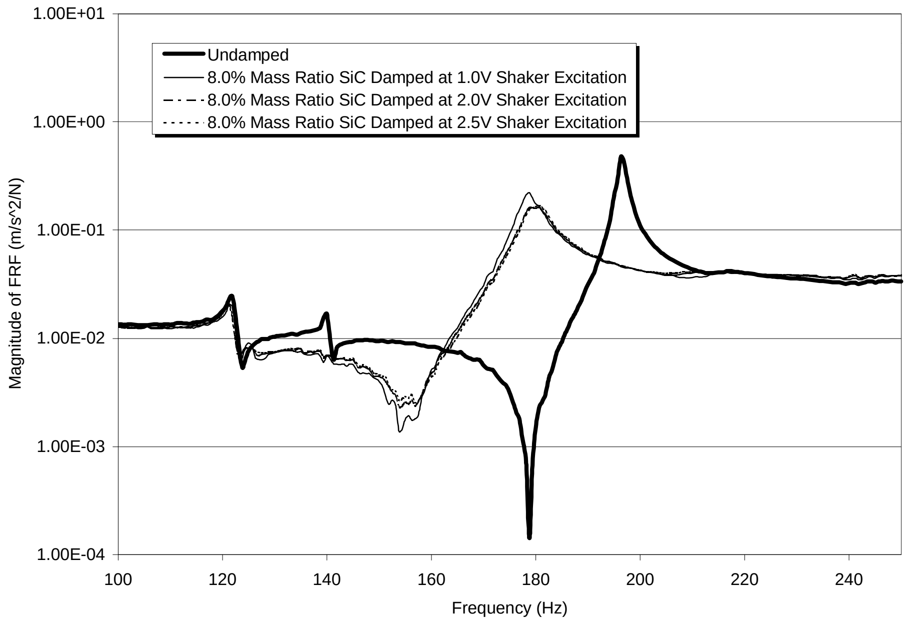


Figure 7. Measured Response of Undamped and SiC Damped Beams
Mass Ratio of 8.0%