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An experimental model for the analysis of energy dissipation in particle dampers

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Particle damping is a very promising passive damping technique, however, it is still rarely used in technical applications due to its complex dimensioning. An experimental model is developed in order to investigate the energy dissipation of the dampers regardless of the underlying structure. The testbed consists of a particle box with a free-free boundary condition which is excited by an acceleration controlled shaker. The loss factor and the energy dissipation are obtained via the complex power. The particle damper can be analyzed over a wide frequency and acceleration range. Different particle numbers are used showing the high potential of particle dampers for different excitation ranges.

1 Introduction

One very promising passive damping technique are particle dampers being a derivative of impact dampers. Instead of using only one impact object, dozens or even millions of particles are used. The structural vibrations are transmitted via the particle container onto the particles. Interactions between particles and between particles and the container walls cause an energy dissipation by impacts and frictional phenomena. Particle dampers show several advantages when compared to other existing passive damping techniques. They may be insensitive to temperature and environmental conditions, do not degrade in time and they are at least as effective as other damping techniques [3], [4].
Despite the efficiency of particle dampers that was demonstrated experimentally, they have been used only in a few different engineering applications so far, mostly designed for a very specific system. This might be due to the fact, that the processes in the particle dampers are highly nonlinear and depend on a variety of different influence parameters like the filling ratio, excitation frequency, and vibration amplitude [2].
In this paper, an experimental setup is introduced and investigations are performed concerning the energy dissipation of particle dampers alone. Excluding the underlying vibrating structure and concentrating on the particle damper, enables to make general statements about the energy dissipation effects. Thus, the testbed consists only of the particle box with a free-free boundary condition and is excited by an acceleration controlled shaker. A large frequency and acceleration range is analyzed. The complex power is calculated by the measured acceleration and input force, whereas the energy dissipation and the loss factor are evaluated via the complex power. The loss factor is the ratio of the dissipated energy to the total energy in the system.

2 Testbed

A systematic representation and a picture of the developed testbed are shown in Fig. 1. The testbed consists of an aluminum, cubical particle box with an inner edge length of 4 cm supported by two ropes, i.e. a free-free boundary condition. The control and measurement systems are from Brüel & Kjaer. While the box is excited by the LDS V455 shaker, its acceleration is controlled via the LDS Comet system. The data acquisition is accomplished by the Output Generator Module - Type 3160 with a sampling frequency of 32.8 kHz. Due to the impacting particles on the box walls, the acceleration signal is very noisy. In order to use this acceleration signal in the control of the excitation two accelerometers are used. The accelerometer for controlling the shaker is additionally equipped with a mechanical low-pass filter. It consists of a plastic with a Young's modulus of $86\,\mathrm{N/mm^2}$. This filter is designed in a way that its eigenfrequency ω is at 2.5 kHz. Hence, the particle impacts on the box walls are filtered efficiently. Simultaneously, frequencies up to the measurement range of 1 kHz are only little influenced. The accelerometer and the force sensor for the data acquisition and calculation of the complex power are not equipped with a filter. The feasible measurement range of the system is between 40 Hz till 1 kHz and between $10\,\mathrm{m/s^2}$ till $400\,\mathrm{m/s^2}$. The measurement range is divided into a logarithmic grid of 108 points. Nine frequencies and twelve accelerations are used and each point is measured for 2.5 s, as limitations in the controller and the data acquisition system prohibit the use of frequency dependent measurement times.

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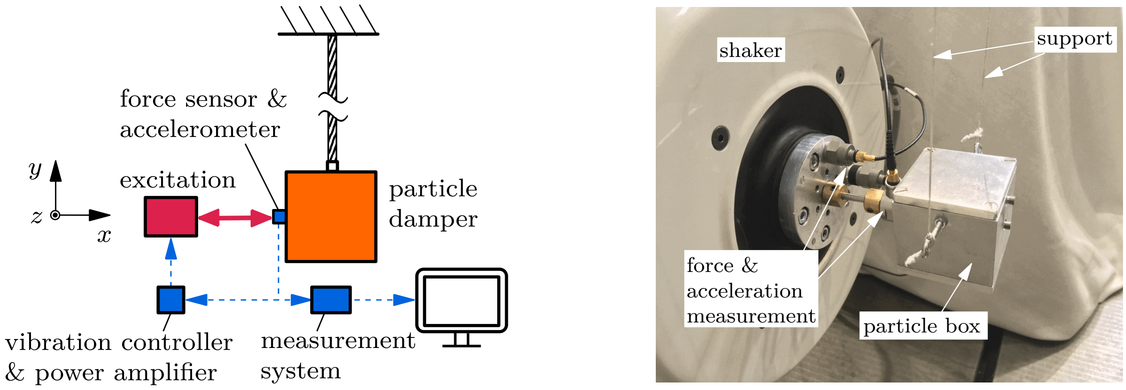

Fig. 1: Systematic representation (left) and picture (right) of the testbed.

For the determination of the dissipated energy and the loss factor, the complex power P

$$P = \frac{1}{2} F V^*, \tag{1}$$

introduced by Yang [5], is used. Hereby, F denotes the Fourier transform of the measured force and V^* the conjugate Fourier transform of the velocity. As the acceleration is measured, the velocity is calculated by the complex acceleration A and the excitation frequency Ω via

$$V = \frac{A}{i\Omega}. \tag{2}$$

The loss factor η is defined as the ratio of the dissipated power P_{diss} to the maximum power stored in a cycle $P_{\max}$ as

$$\eta = \frac{P_{\mathrm{diss}}}{P_{\max}} = \frac{\mathrm{Real}(P)}{\mathrm{Imag}(P)}. \tag{3}$$

The dissipated energy per radiant E_{diss} is obtained by

$$E_{\mathrm{diss}} = \frac{P_{\mathrm{diss}}}{\Omega}. \tag{4}$$

3 Energy dissipation of particle dampers

In a first step, the energy dissipation and the loss factor of the empty box is analyzed, as this is the reference for the other measurements. The results are shown in Fig. 2. As expected, the energy dissipation of the empty box is very small, as it only comes from frictional effects of the box itself and the boundary condition. This can also be seen at the loss factor. Its mean value is about 0.02. In the next step, particles are filled in the box. Unhardened, steel balls which are used in the hardened form for ball bearings are utilized. These have a high degree of roundness

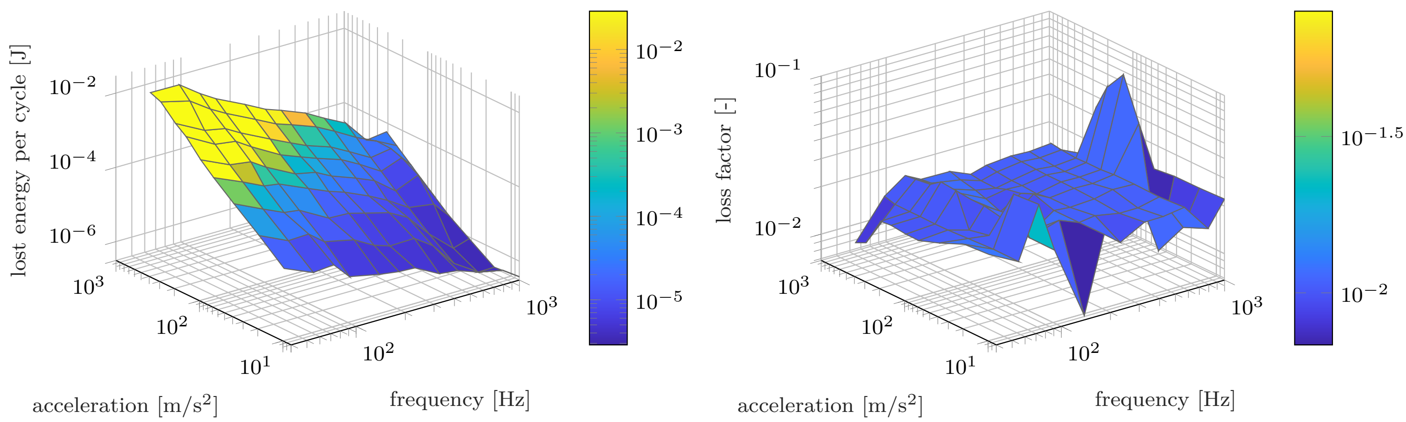

Fig. 2: Lost energy per cycle (left) and loss factor (right) of the empty box.

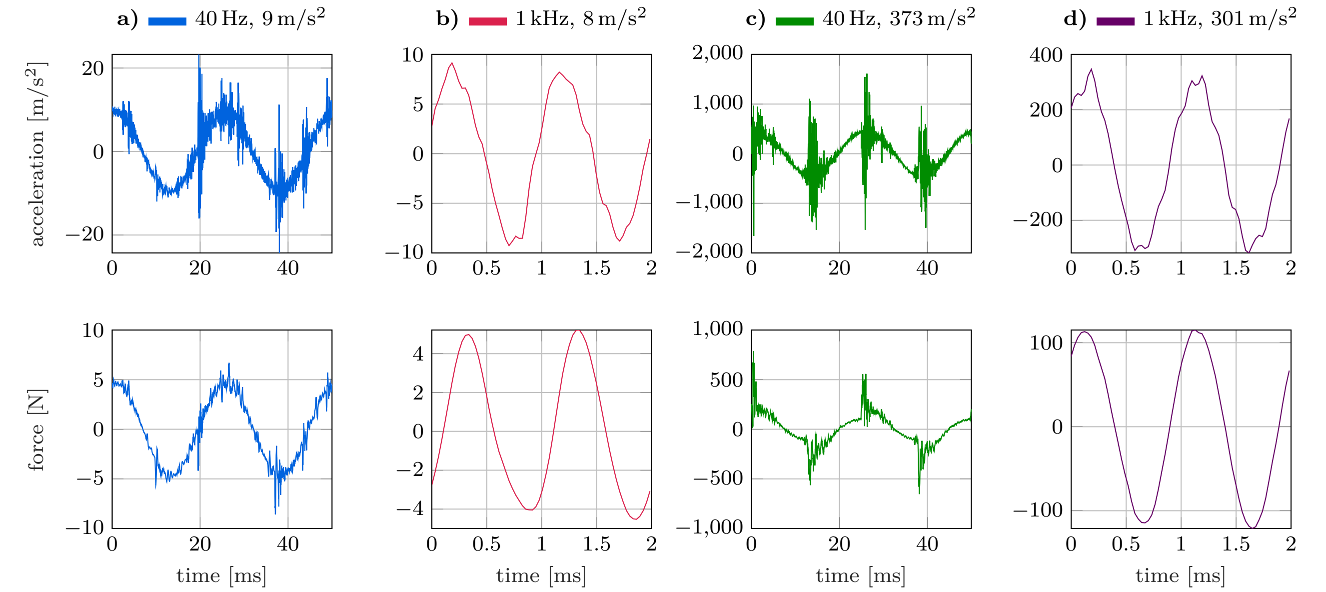

Fig. 3: Measured acceleration and force of two vibration periods at desired 40 Hz and 1 kHz and 10 m/s² and 400 m/s².

and accurate material parameters are available for later simulation purposes. For the first setup, 58 of 62 maximum possible particles with a radius of 5 mm are used. The total weight of the particles is 241 g. In Fig. 3, the measured acceleration and force of two vibration periods for the four edge points of the measurement range, i.e. the desired values are at 40 Hz and 1000 Hz and at 10 m/s² and 400 m/s², are shown. All the plots differ in their characteristics due to the chaotic behavior of the particles. One can observe that the impacts on the box walls are getting more intense for lower frequencies and higher accelerations. Especially in Fig. 3 c) very high impacts are observed. These high impacts are the reason for the use of the mechanical low-pass filter for the controller, as otherwise the controller would abort. Another phenomenon is that the resulting acceleration of the box is smaller than the desired one for higher frequencies. The difference in Fig. 3 b) is 1.25, whereas it is 1.33 for Fig. 3 d). This behavior is due to the transfer function of the filter. Neglecting the material damping, the transmissibility G of the acceleration sensor at 1 kHz is

$$G = \frac{1}{1-\left(\frac{\Omega}{\omega}\right)^2} = \frac{1}{1-\left(\frac{1000\,\mathrm{Hz}}{2500\,\mathrm{Hz}}\right)^2} = 1.19, \tag{5}$$

and thus very close to the difference of the signals.

The energy dissipation and loss factor for this setting are shown in Fig. 4. A high increase in the energy dissipation on a big area of the measurement range can be observed. Only at high frequencies and high accelerations the dissipation is comparatively small. The mean loss factor is 0.18. The factor is especially high at medium frequencies and medium accelerations. Also at high frequencies and low accelerations the loss factor is high. Indeed, in real applications this area is often not of interest. At the lower border of the frequency and acceleration range the loss factor starts to drop showing that here the ineffective area of the particle damper starts.

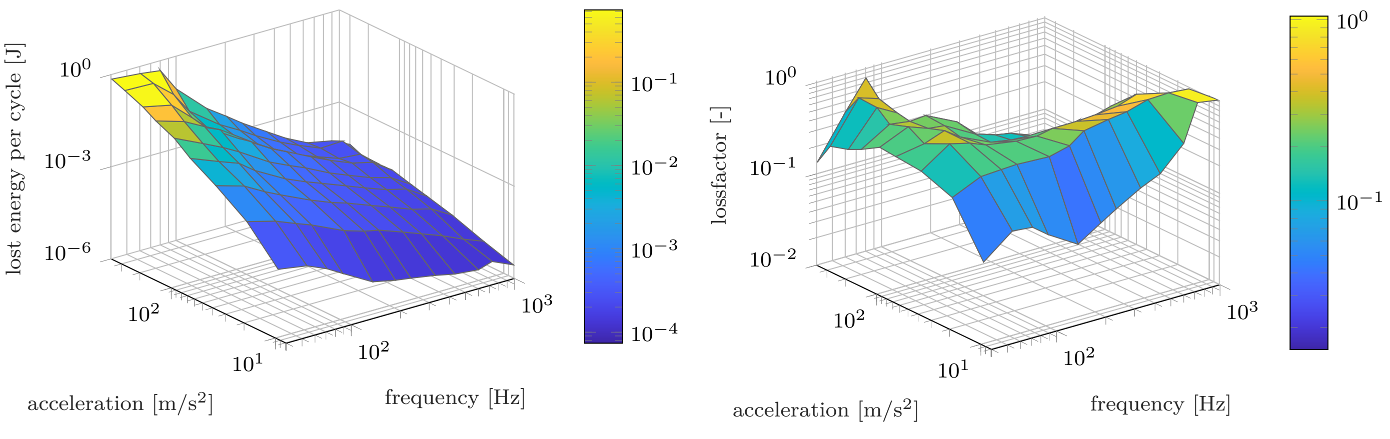

Fig. 4: Lost energy per cycle (left) and loss factor (right) of box with 58 particle of 5 mm radius.

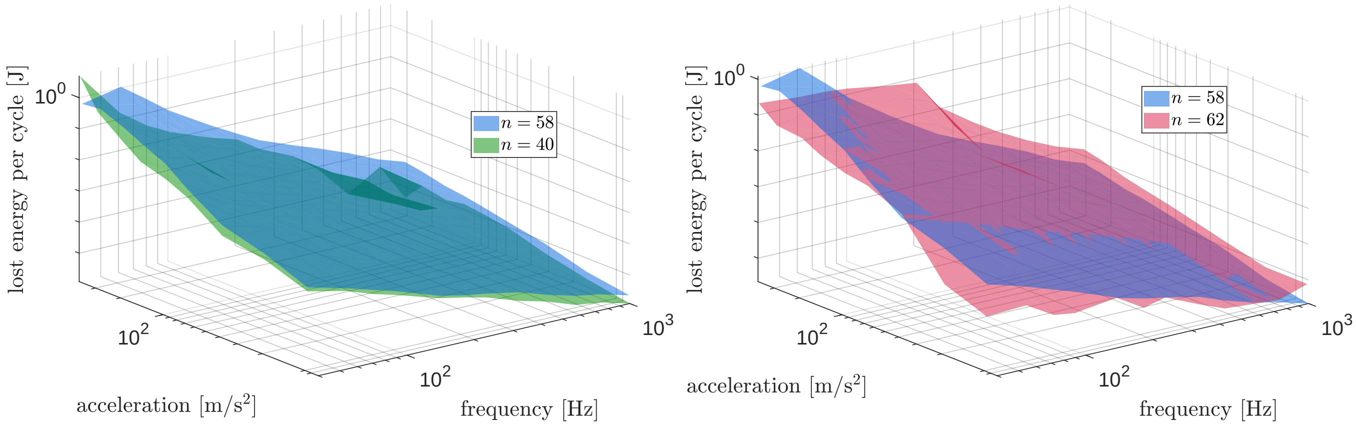

Fig. 5: Energy dissipation per cycle for 40 vs. 58 particles (left) and 58 vs. 62 particles (right).

In the next step, different filling ratios are compared. Therefore, 40, 58, and 62 particles are used. The results for the lost energy are shown in Fig. 5. Comparing, 40 with 58 particles in Fig. 5 (left), one can see that the 58 particles perform better on almost the complete measurement range. Only at low frequencies and high accelerations the 40 particles start to perform better. A different behavior is seen in Fig. 5 (right). For low accelerations, the 58 particles perform better as the 62 particles, in turn performing worse for high accelerations. Only at high accelerations and low frequencies this observation is not valid. The different particle behavior can be explained by the different particle activities [1]. The higher the particle activity is, the higher is the energy dissipation. As the activity is a nonlinear function depending on the frequency, acceleration and filling ratio of the particle box no general statements can be made.

4 Conclusion

An experimental setup for the determination of the energy dissipation and the loss factor of particle dampers is presented. Thereby the frequency range from 40 Hz to 1 kHz and an acceleration range from 10 m/s^2 till 400 m/s^2 is analyzed. A significant energy dissipation is determined with loss factors close to one for specific excitations showing the high potential of particle dampers. Also the filling ratio of the particle box showing a big influence on the dissipation energy, as for different frequency areas different filling ratios are better suited. With this parameter, a particle damper can be tuned for a specific excitation, thus maximizing the damping of the underlying structure.

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