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PARTICLE DAMPER NUMERICAL-EXPERIMENTAL CORRELATION

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ABSTRACT

The experimental and numerical characterization of a cylindrical particle damper making use of spherical steel particles and mounted onto a slender beam is presented. The simulation of the system is performed by coupling a discrete particle code running on a consumer GPU card with a multibody MBDyn model; the actual experiment is carried out by forcing the beam by means of a shaker. Specific numerical procedures are required to reduce as much as possible the run time required for a correct identification of the structure's transfer function.

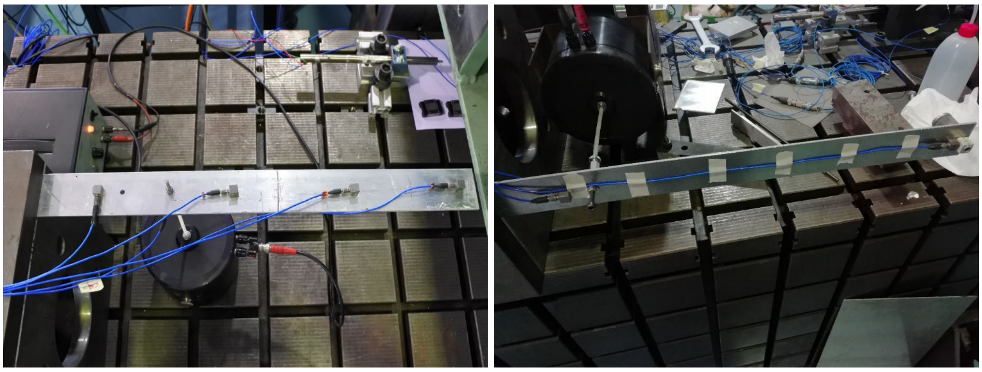
Keywords: particle damper, multibody, discrete element method, experimental

1 INTRODUCTION

Particle dampers provide a mean to introduce structural damping by means of a passive approach. Their main advantages lie in their relative simplicity, ease of installation, insensitivity to temperature and to hostile environments [6]. However, their effectiveness do depend on the actual frequency and magnitude of the vibrations they need to damp [10], and they stay inert below a certain threshold of acceleration in presence of gravity [5]. Analytical methods for particle dampers are limited to specific cases, and are difficult to calibrate without experimental data; therefore, particle dampers analyses are generally based on implementations of the discrete element method (DEM).

Furthermore, the behaviour of these devices is strongly influenced by the complex interactions between the relative direction of the vibration-induced velocity and the gravity acceleration field [1]; the shape of the cavity is an important factor as well. The amount of dissipation and damping provided by particle dampers is also correlated with the inner motion regimes of the enclosed particles, as shown for vertical oscillations by Zhang [13], and for horizontal oscillations by Meyer [9].

Many applications of these devices to the aerospace field have been considered in the literature, including aircraft components, turbine vanes and blades, spacecraft components and helicopter blades [6]. Contrary to civil applications, aerospace components are subjected to average acceleration loads whose intensity and orientation is not constant; nevertheless, the authors couldn't find references specifically addressing the issue of discrete element simulations of particle dampers in conditions of disalignment of gravity, motion and cavity's orientation.



(a) vertical oscillation (b) horizontal oscillation

Figure 1: Different arrangements of the experimental setup of the beam with accelerometers

In this paper, experiments of particle dampers arranged in different orientations with reference to both gravity and motion are reported; the experiments consisted in a slender cantilever beam with a particle damper near the free end, excited with a shaker at controlled acceleration amplitudes.

The experiments were numerically reproduced using a GPU-based particle damper discrete element solver, called PMB [2], coupled to the general-purpose multibody solver MBDyn [8]. Specific numerical procedures were developed to apply a numerical amplitude control to dynamic systems with strong non-linearities, such as particle damped multibody systems. Furthermore, since the particles' contact parameters were not measured before the experiments, some simulations were repeated using different sets of parameters to find a better correlation with the experimental results.

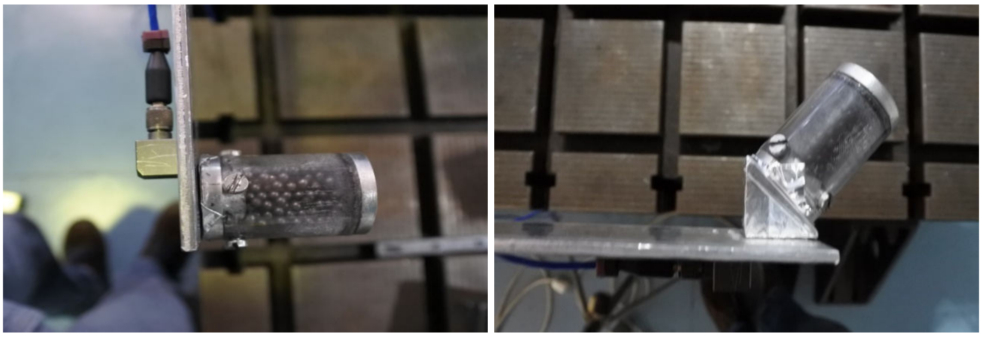
2 PARTICLE DAMPER EXPERIMENTS

The experiment consisted in measuring the transfer function of a deformable system coupled with a particle damper, which is excited with stepped sines around its first modal frequency. The amplitudes of the input sines are controlled to impose the level of the acceleration's RMS amplitude of the aforementioned particle damper. The scope of the experiment was to compute the damping coefficient around the first modal frequency of the deformable system for many levels of imposed acceleration amplitude, and obtain a relation between imposed acceleration and damping.

The setup is a rectangular-section cantilever beam with a cylindrical particle damper near the free end. The cylinder's axis was parallel to the shorter side of the section; the cantilever beam's axis was horizontal. A shaker excited the beam in the direction of the smaller cross-section bending stiffness. The base and the tip of the particle damper enclosure were in aluminium; the cylinder's lateral surface was made of 3 mm thick transparent PMMA; steel particles were enclosed by the damper. The experiment was repeated multiple times, arranging the beam to oscillate in the horizontal or in the vertical directions, as shown in figure 1, and orienting the particle damper's axis parallel, at 45 degrees, or at 90 degrees with respect to the motion direction, using an additional part, as shown in figure 2.

A reference run was carried without particles to identify the cantilever beam characteristics, such as its elastic modulus or its intrinsic damping. Table 1 shows the experimental setup geometric and identified characteristics.

The experimental RMS amplitude control on the particle damper was achieved by employing the acceleration measured near the particle damper as test signal; the control variable is the amplitude of the signal passed to the shaker. The outcome of the experiments, for controlled accelerations ranging from 0.5 g to 5.0 g, includes the response of the system at different input frequencies of the stepped sine signal around the first modal frequency (hence the transfer functions of the system), the time histories of the accelerometers and of the load cell, and high speed camera video shootings.



(a) Axis parallel to motion (b) Axis at 45 degrees to motion

Figure 2: Different orientations of the particle damper near the beam's free end

3 NUMERICAL SIMULATIONS SETUP

3.1 Discrete element solver

As the work for this study started, plenty of DEM solvers existed and were available to the authors; however, these solvers were found to execute simulations slower than expected. Therefore, to have full control on the used methods and calculations, and to have a fast solver to be used as a design tool, the decision to develop an ad-hoc DEM solver tailored to particle dampers was taken.

The developed code, called PMB, is a GPU based penalty-based discrete element solver for particle dampers with monodisperse spheres. Thanks to its simplicity, PMB was found to perform significantly faster than other discrete element solvers, while providing matching results with experiments from the literature and analyses with other solvers [2].

Amongs its characteristics, PMB employs a semi-explicit Euler's method for integration, a loose uniform grid broadphase, and a simple friction model without internal states. The latter is a directional friction model that neglects static friction and it is widely used in particle damping's literature [11]; this model was employed because it is less computationally expensive than models with internal states such as the Mindlin-Deresiewicz model, and because in highly dynamic systems it is often legitimate to ignore static friction between the colliding bodies [4].

To analyse the application of particle dampers on any structure or multibody system, PMB was coupled with MBDyn. The implemented co-simulation scheme was a loose coupling scheme, in which MBDyn sends position, velocity, rotation and angular velocity of the particle dampers node to PMB, and then receives the total force and moment resultants obtained from the collisions of the particles with the enclosure walls. Alternatively, tight coupling schemes are possible, see [14].

3.2 Numerical amplitude control technique

An iterative procedure to find the input amplitude needed to get a certain RMS response amplitude of a particle damper - multibody coupled system, excited with a sinusoidal external force with a certain frequency, is described. The response of the system considered by this procedure can be the displacement, velocity or acceleration of the particle damper or of any other point of the multibody system.

The procedure consists in running the simulation for a guess value of input amplitude of the shaker's force until the amplitude of the response converges. Convergence is achieved only when the amplitude of the response does not vary significantly for a certain number of periods. Depending on the converged value, the input amplitude is adjusted in order to obtain a response acceleration closer to the targeted value. MBDyn's module HFelem was modified to include this procedure and to measure the RMS of a test variable in each period and adjust the amplitude of the input.

It has to be remarked that, since particle damping is a highly non linear phenomenon, the considered response's amplitude must be the RMS amplitude. Indeed, the spectrum of the response of a

Description	Value		Description	Value	
cantiler beam length	0.543	m	beam section longer side	0.05	m
beam section shorter side	0.003	m	beam density	2695	kg/m^3
beam Young's modulus	72	GPa	beam shear modulus	27	GPa
reference first mode damping	0.5	%	shaker distance from root	160	mm
accelerometer #1 distance from root	75	mm	accelerometer #2 distance from root	241	mm
accelerometer #3 distance from root	382	mm	accelerometer #4 distance from root	519	mm
load cell mass	30	g	mass of an accelerometer	5	g
damper axis distance from root	533	mm	empty particle damper mass	23.8	g
enclosure inner diameter	19	mm	enclosure inner height	25	mm
enclosure bottom plate thickness	10	mm	number of particles	120	
particles diameter	3	mm	particles density	7800	kg/m^3
additional 45 deg block mass	31	g	additional 45 deg block cathetus	20	mm

Table 1: Geometric and identified characteristics of the experimental setup

structure coupled to a particle damper shows frequency content also at frequencies not related to that of the input, as shown by Sanchez [12]. In the same work, Sanchez also showed that dynamical systems with particle dampers may exhibit limit cycles or chaotic response; the developed convergence procedure wouldn't always work in these circumstances, but care was taken to deal with it as better as possible.

Since the procedure is very time consuming, some tricks were adopted to ease the convergence:

- Use a large tolerance on the convergence values. A particle damper is a device that consists of distinct impacting bodies that may impact slightly differently from one cycle to the next, and alter the response;
- Save time by adjusting the input before the response amplitude converged if the response is too low or too high without any reasonable doubt;
- Change the strategy used to compute the next guess of the input amplitude during the analysis; Two strategies are used to compute the next guess input amplitude:
  - employment of a "loosen" gradient descent method, in which the gradient is computed accounting for the large tolerance on the convergence;
  - multiplication of the previous input amplitude by the ratio between the values of the target RMS response and the converged RMS response.
- Recognize two-periods limit cycles;
- In case of failure of the previous strategies, the result that gave the closer converged value to the target value is assumed. In these circumstances, more complex limit cycles or chaotic responses are likely.

3.3 Numerical modelling and correlation with the experiment

The cantilever beam was modeled using geometrically exact finite volume beam elements with 3 nodes, non-linear geometry and intrinsically free from shear locking, already implemented in MBDyn [7].

The contact stiffness between the particles, and between the particles and the enclosure's walls was selected to obtain a limited overlap between particles, as the literature shows that good results can be achieved with low contact stiffnesses as long as the overlap between the particles does not exceed a certain amount [3]. This consideration is important for penalty-based DEM analyses with explicit integration methods, as a lower contact stiffness implies higher timesteps and hence shorter execution times. A reliable procedure was created to obtain the correct normal contact stiffness to contain the maximum overlap between particles.

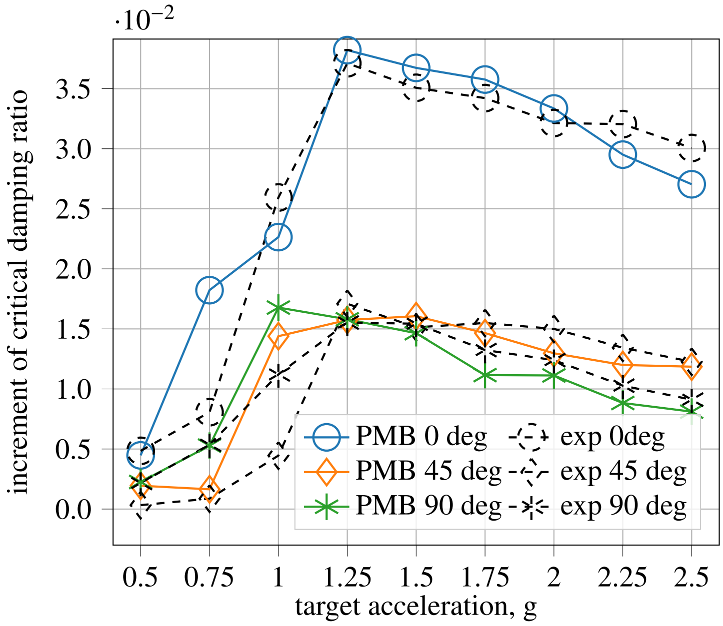


Figure 3: Comparison between experimental and simulation computed damping ratios, for the beam set to oscillate in the horizontal direction and different angles between the particle damper axis and the oscillation direction

The values of sliding friction coefficient and restitution coefficient found in the literature for the colliding materials used in the experiments are not uniquely defined: the friction coefficient relative to steel on steel sliding varies between 0.4 and 0.6, while the restitution coefficient is also dependent on the impact velocity; data from surveys from the literature show that it can be considered equal to 0.9 for the considered ranges of velocities.

Therefore, the selection of the sliding friction coefficient required a calibration by reproducing some of the experimental results for different values of the contact parameters. Since the rolling friction coefficient wasn't known a priori, as it also depends on the geometric imperfections of spherical particles, the calibration of its value also had to be included in this procedure.

The resulting contact parameters obtained with the correlation procedure were:

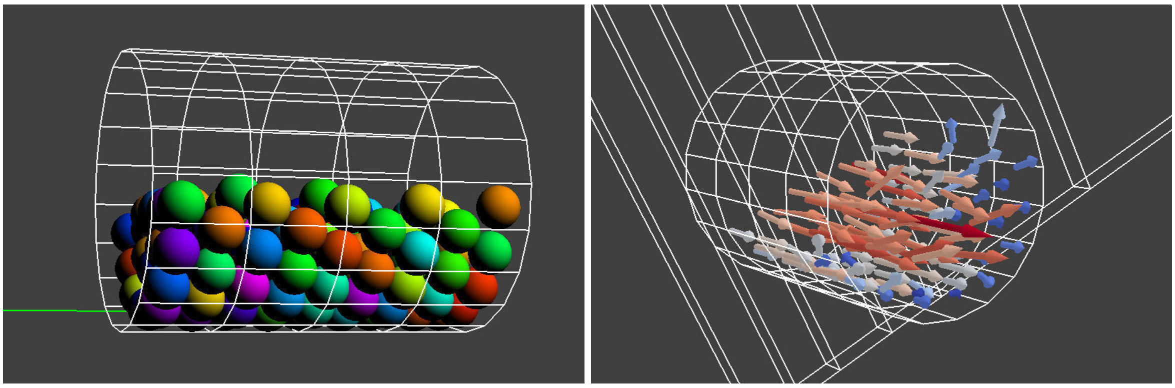
- sliding friction coefficient: 0.6
- rolling friction coefficient: 0.01

4 RESULT VALIDATION

All the experiments were reproduced using PMB in cosimulation with MBDyn using the contact parameters obtained from the correlation procedure.

Figure 3 shows the comparison between experimental and simulation computed damping ratios, for the beam set to oscillate in the horizontal direction; the damping ratios were computed using the half power method. The damping curves do correspond well for accelerations greater than 1.0 g. This correspondence was obtained also in the transfer functions, which are almost overlapping in most of the simulated cases.

However, for an imposed acceleration equal to 0.75 g for the particle damper aligned with the oscillation direction, and equal to 1.0 g for the particle damper not aligned with the oscillation direction, quite different damping ratios were obtained. In these situations, the particles in the simulation experienced an higher mobility than that of the experiments; the experimental video shootings show that few particles are moving, while the simulations' replay videos show that the upper layers of the particle bed



(a) Particles positions (b) Particles velocities

Figure 4: Frames of the simulation at imposed acceleration amplitude 0.75 g at frequency 6.3 Hz of the simulation of the experiment horizontally oscillating, with the damper's axis parallel to the oscillation's direction

already transitioned to a partial fluidization, which is a motion regime also found by Meyer in a different experiment [9].

Figure 4 shows a frame of the simulation at 0.75 g for the case of horizontal oscillation and particle damper's axis aligned to the oscillation's direction. As shown by the instant velocity of the particles, the particles closer to the axis of the damper have higher velocity than those closer to the enclosure lateral surface, creating more energetic impacts and increasing dissipation.

The authors believe that this inconsistency happened because the employed friction model was suboptimal and/or because many particles in the simulation arranged themselves in a hexagonal lattice near the lateral surface, leaving less particles near the center of the cavity.

5 CONCLUDING REMARKS

In this paper, particle damping experiments at different orientations of the cavity, gravity and motion directions were numerically reproduced and correlated. Despite some inconsistencies found in the simulation results with the beam oscillating in the horizontal direction for target acceleration values close to those of the transition to partial fluidization, good correspondence with the experimental results was found in both the transfer functions and the comparison with videos, regardless of the relative angle between the gravity, motion and particle damper's axis direction. No specific reason was demonstrated for the difference between the experimental and numerical results in those conditions, but the authors believe the the reason can be found in the simplified friction model or in the incidental arrangement of the particles during the simulations.

The correspondence between the experimental and numerical results was also obtained thanks to the employed correlation procedure, which identified those contact parameters that gives the best results, among physical admissible values.

The simulations benefited from the implementation of specific numerical amplitude control techniques, created to obtain the response of highly nonlinear dynamic systems, such as particle dampers attached to multibody systems or flexible structures; not only such techniques managed to speed up the convergence of the response, but they also made it possible to successfully compute the response in many cases where traditional convergence methods would fail.

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