

Discrete element method approach to modelling VPP dampers

Pawel Chodkiewicz^{1,}, Jakub Lengiewicz², Robert Zalewski¹*

¹Warsaw University of Technology, Institute of Machine Design Fundamentals, Narbutta 84, 02-524 Warsaw, Poland

² Institute of Fundamental Technological Research of the Polish Academy of Sciences, Pawińskiego 5B, 02-106 Warsaw, Poland

Abstract. In this paper, we present a novel approach to modeling and analysis of Vacuum Packed Particle dampers (VPP dampers) with the use of Discrete Element Method (DEM). VPP dampers are composed of loose granular medium encapsulated in a hermetic envelope, with controlled pressure inside the envelope. By changing the level of underpressure inside the envelope, one can control mechanical properties of the system. The main novelty of the DEM model proposed in this paper is the method to treat special (pressure) boundary conditions at the envelope. The model has been implemented within the open-source Yade DEM software. Preliminary results are presented and discussed in the paper. The qualitative agreement with experimental results has been achieved.

Keywords: VPP, discrete element method, Yade DEM, modelling, smart structures, smart materials

1 Introduction

In the paper, we analyse dampers based on Vacuum Packed Particles (VPP). They are composed of loose granular medium encapsulated in a hermetic envelope, with controlled pressure inside the envelope, see Fig. 1. When no pressure difference is applied (atmospheric pressure inside) then the system behaves more like classical loose granular media. When the internal pressure is reduced then the system is getting stiffer and, even more important, is also gaining the ability to dissipate a significant amount of mechanical energy under the cyclic excitation [1, 2].

* Corresponding author: pawel@chodkiewicz.com.pl

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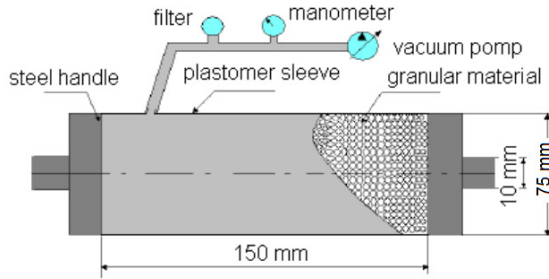


Fig. 1. VPP testing specimen

VPPs are quite novel smart structures, and are gaining increasing interest of the engineers around the world. One of the most advantageous features of VPP systems is the ability to easily change their shape when no underpressure is applied. In such an inactive state, the system can be suitably adjusted to a desired shape, and then the underpressure can be applied to “solidify” the system. This feature is exploited, e.g., to design robotic grippers that can carry objects of different geometries, [3, 4]. It can also be found in the medical field. Special mattresses, filled with the granular material, serve to safely transport injured patients, immobilizing their whole bodies [5]. Another medical application is the endoscope that can change its rigidity thanks to VPP [6]. VPP can also be used as dampers. For example, by properly adjusting the grain structure inside the VPP, one can filter out only selected sound frequencies [7, 8].

However, probably the most promising use of the Vacuum Packed Particles is to damp mechanical vibrations. The possibility to actively and quickly control the mechanical properties of VPP dampers makes it possible to adjust their design to various specific applications, e.g., cf. dampers with VPP core and springs [9, 10], or the engineering problem to damp beam vibrations [1, 2, 11, 12]. Vacuum Packed Particles were also used to damp vibrations in automobile industries. In [13], the authors use a damper with VPP core to eliminate vibrations of the car body. In general, dampers made of VPP can be viewed as a good replacement for magnetorheological (MR) or electrorheological (ER) devices, because VPP are more economical in production and more eco-friendly than MR and ER [14].

The VPP structures are also investigated by developing suitable mathematical models that would capture the complex mechanical response of VPP. In our earlier work [15], we tried to adapt phenomenological Gubanov model, successfully used in the past to analyze the complex properties of magnetorheological or electrorheological fluids. However, when applied to VPP, only part of mechanical response could be successfully represented by the model.

In this work, we present the approach to modelling the Vacuum Packed Particles by using Discrete Element Method (DEM). In the past, DEM has been successfully used to analyze various types of granular media, therefore, quite naturally and straightforwardly it can be adapted to modelling VPP systems. Also, such a direct approach to modelling will possibly give a tool to analyze the nature of dissipative response in VPP dampers at the microscopic (particle) level.

In Section 2, we describe the method to treat special boundary conditions at VPP envelope. In Section 3, DEM simulation details are provided and preliminary results are presented. Short conclusions are presented in Section 4.

2 Discrete element model of pressure-tight envelope

The discrete element model has been developed within the open source Yade DEM framework [16]. There are two components of Vacuum Packed Particles to be considered: the pressure-tight envelope made of foil and the granular material inside. As for the granular material, we adopted the standard frictional model for spherical particles, which is provided by Yade DEM. The DEM model of pressure-tight envelope is not standard, and its development is presented further in this Section. Additionally, special plugin for Yade DEM has been implemented to collect postprocessing data, necessary to further analyze the VPP time-dependent mechanical properties.

The pressure-tight envelope in VPP is made of foil that is subjected to pressure loading. Its discrete element model should capture the basic elastic mechanical response of the thin foil and should enable to properly apply the necessary pressure boundary conditions. What we propose is the special deposition of the discrete element particles building the envelope and appropriate algorithm to compute the external forces acting on the foil.

As for the geometry of the envelope, each building block is made of five spheres - one in the center (blue) and four neighbors (white), see Figs. 2 and 3. We assume further in this work that the discretization of the foil envelope is fine, i.e., the diameter of the foil particles are not larger than the thickness of the foil,

$$t_f \geq 2 \cdot r_{kf} \quad (1)$$

where t_f is the foil thickness and r_{kf} is the radius of spheres that create the envelope. This is schematically shown in the Figs. 3a-b, see also the discussion in the Remark at the end of this Section.

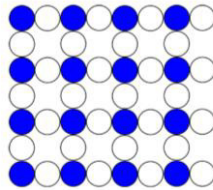


Fig. 2. Schematics of a foil envelope structure built of spheres

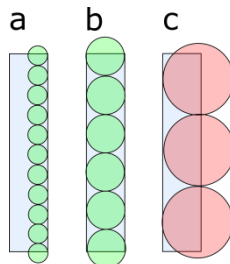


Fig. 3. Discrete element representation of a foil (through-thickness cross-section). Particle diameter can be (a) smaller than, (b) equal to and (c) larger than the thickness of the foil

If the diameters of the particles are different than the thickness of the foil, special treatment is necessary to properly represent the properties of the foil in the discrete element

setting. Instead of directly applying the Young modulus of foil E_f , the effective Young modulus of the particles E_{kf} must be used to reflect the difference in the thicknesses (and also to compensate the effect of the vacancies in the discrete structure, see Fig. 2),

$$E_{kf} = 2 \cdot E_f \cdot \frac{t_f}{2 \cdot r_{kf}} \quad (2)$$

The pressure boundary conditions at the envelope, in discrete element setting, are specified by appropriate forces applied to the envelope particles. (We only apply the forces to the blue particles, which has proved to give more stable behaviour during the simulation.) The force for a given particle is computed by integrating the pressures over the actual tributary area. This must be done at every iteration because the geometry of the envelope is constantly changing. The concept of tributary area is presented in Fig. 4.

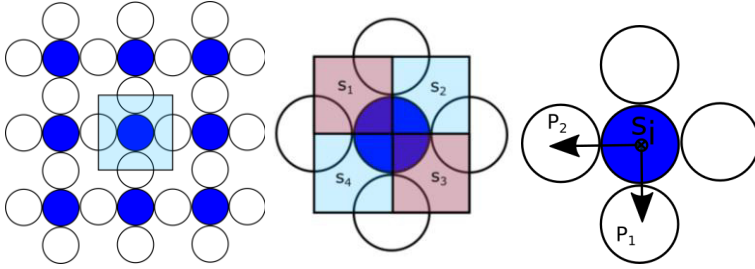


Fig. 4. The tributary area over which the pressures are integrated

The algorithm to compute the vector of external forces is the following. We compute four parts of the tributary area, s_1, s_2, s_3, s_4 , as the outer product of the appropriate differences between the *current* positions of the particles,

$$\mathbf{s}_i = (\mathbf{P}_i - \mathbf{S}_j) \times (\mathbf{P}_{1+(i\%4)} - \mathbf{S}_j), \quad (3)$$

where $i = \{0, 1, 2, 3\}$ is the index of the neighbour and j is the index of the middle (blue) particle. The tributary area vector is simply the sum of the four parts

$$\mathbf{A}_j = \mathbf{s}_1 + \mathbf{s}_2 + \mathbf{s}_3 + \mathbf{s}_4 \quad (4)$$

and the vector of the pressure force $\bar{\mathbf{F}}_j$ is the constant pressure of the intensity p integrated over the tributary area, i.e.,

$$\bar{\mathbf{F}}_j = \mathbf{A}_j \cdot p. \quad (5)$$

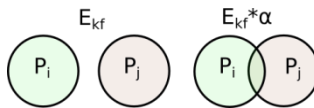


Fig. 5. The assumption of the Young modulus

Remark. In the present model, the diameter of the particles that build the foil is considered much smaller than the thickness of foil, see Fig. 3a, which assures necessary discretization quality. For example, with this assumption the expected buckling effects can be quite

straightforwardly captured. Conversely, if the diameters of the particles are larger than the foil thickness then special treatment is necessary to artificially increase the compliance of the foil for in-plane compression cases. One of the simplest possible treatments is to re-scale the Young modulus of the foil for compressive part of the deformation, see Fig. 5, i.e.,

$$E_{kf} \rightarrow \begin{cases} E_{kf} \cdot \alpha & \text{for } \|\mathbf{P}_i - \mathbf{P}_j\| < 2 \cdot r_{kf}, \\ E_{kf} & \text{otherwise} \end{cases}, \quad (6)$$

where $\alpha \leq 1$ is a properly adjusted scaling parameter.

3 DEM simulation and results

The simulation for the VPP damper has been performed in Yade DEM environment. The simulation consists of several stages, see Fig. 6. In the first two stages, the foil envelope is built and the loose granules are placed inside and above the envelope. Next, the simulation waits until the falling granules fill out the envelope (a special membrane is applied at the top boundary of the damper to only allow the downward passage of the particles). Then, the pressure BC is imposed at the envelope and the sinusoidal kinematic excitation is applied to the top part of the setup (i.e., the upper rings of the envelope and the top boundary).

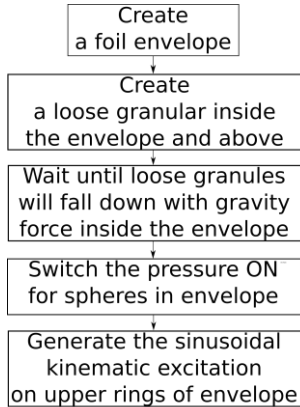


Fig. 6. The stages of the simulation

The simulation parameters are presented in Table 1, where r_{kf} is the radius of envelope particles, r_{kg} is the radius of spherical granules, s_r and s_h are the radius and the height of the damper, respectively, E_f is the Young modulus of the foil envelope, E_k is the Young modulus of the granules, ν_f is the Poisson ratio for the foil envelope and ν_k is the Poisson ratio for the granules.

Table 1. The values of the simulation parameters

Simulation parameters	r_{kf}	r_{kg}	s_r	s_h	E_f	E_k	ν_f	ν_k
Value	0.00025 [m]	0.001 [m]	0.01 [m]	0.05 [m]	100 [MPa]	1.0 [GPa]	0.25	0.25

The geometry of the envelope, see Fig. 7, has been simply built according to the following Python code,

```

for k in range(  $n_{kfr}$  ):
    for j in range(2,  $n_{kfh}$  ):
        if(k%2 == 0 and j%2 ==0):
            continue
        else:
            x =  $s_{rm} * \cos(k * \varphi)$ 
            y =  $s_{rm} * \sin(k * \varphi)$ 
            z =  $j * 2 * r_{kf}$ 

```

where s_{rm} is the radius at which the envelope particles are placed,

$$s_{rm} = \frac{r_{kf}}{\sin(\pi / n_{kfc})} , \quad (7)$$

where n_{kfc} is a number of spheres along the circumference of the envelope,

$$n_{kfc} = \text{floor}\left(\frac{2 \cdot \pi \cdot s_r}{2 \cdot r_{kf}}\right) , \quad (8)$$

and φ is the angular distance between the centres of the neighbouring envelope spheres along the circle,

$$\varphi = \frac{2 \cdot \pi}{n_{kfc}} \quad (9)$$

The number of spheres along the height of the damper, n_{kfh} , reads

$$n_{kfh} = \text{floor}\left(\frac{s_h}{2 \cdot r_{kf}}\right) \quad (10)$$

The top three rings (white colour in Fig. 7) and one bottom ring of the envelope are fixed in order to apply appropriate displacement boundary conditions.

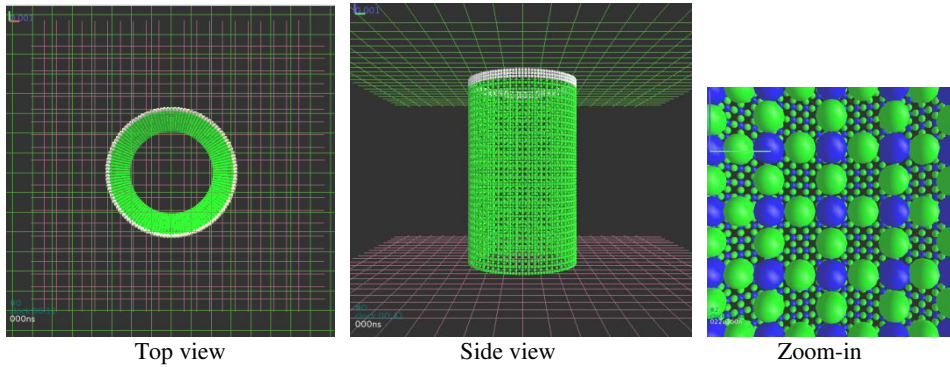


Fig. 7. Exemplary geometry of the envelope in Yade DEM.

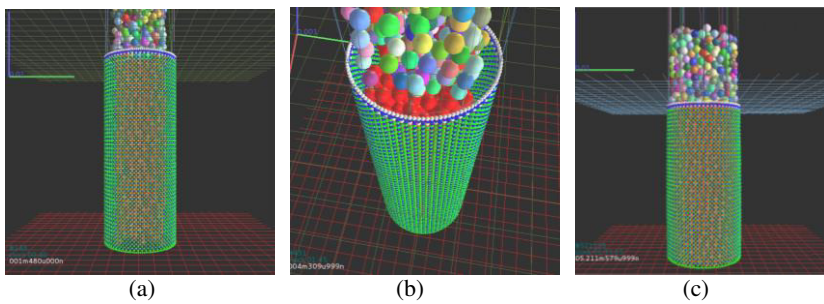


Fig. 8. The third stage of the simulation. Initially disposed granules (a) are filling out the envelope (b) until no more particles can be added (c).

For the geometry presented in Fig. 8, the whole simulation takes about 40 minutes to complete. It consists of initial four stages of the simulation, followed by 15 oscillations in the last stage. The comparison between the DEM simulation results and the earlier experimental results of [14], see Fig. 9, shows the satisfactory qualitative agreement of the force-displacement hysteresis loops.

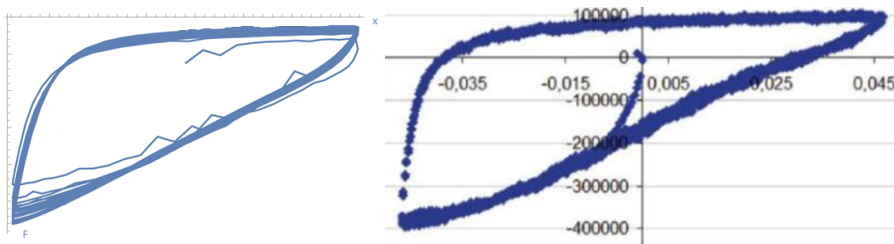


Fig. 9. Hysteresis loops. DEM simulation results (left) and the experimental results (right)

Conclusions

The preliminary results shown in this paper suggest that the DEM modelling is a promising tool to analyse VPP systems. The qualitative agreement of the hysteresis curves has been achieved between the DEM simulations and the earlier experimental results. The advantage of the DEM approach is that one can directly track the evolution of the granules, thus can

possibly observe and analyse the microstructural dissipative mechanisms, characteristic to VPP systems. This is one of the very attractive research directions left for future work.

As for the VPP dampers, the next step is to calibrate the model with real experimental data. If succeeded, and the *quantitative*, not only qualitative, agreement will be achieved, this will prove the validity of the presented DEM approach.

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