JST: Engineering and Technology for Sustainable Development
Volume 33, Issue 3, July 2023, 010-017

Influence of Damping Particles on the Vibration of Spur Gear Transmission Using Numerical Modelization

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Abstract

The article numerically simulates the vibration reduction of a spur gear transmission by using damping particles placed in technological holes designed on the gear itself. The vibration of the gear transmission is reduced based on friction and inelastic collision which eliminates the vibrational energy by the loss during the motion of the damping particles within the technological holes. The kinematic processing of the gear system is analyzed using Adams software. The displacement acceleration data at the survey site is obtained from the Adams instrument which is valuable for evaluating the vibration level of the gear transmission. The interaction between the damping particles as well as the interaction between the particles with the gear model is simulated using EDEM software based on the discrete element method. The vibration of the gear transmission is assessed by the acceleration of the driven gear's center of mass. The results show that the center of mass acceleration is remarkably reduced when particles are used at the rotation speed of 500 rpm and of 700 rpm. However, at the rotation speed of 1000 rpm, the vibration reduction is not much. This can be explained by the high speed and high inertia which cause the damping particles to rotate along with the gear, resulting in almost no collision between damping particles. The study also assesses the vibration reduction efficiency of the gear transmission according to the number of damping particles in each cavity and found that the number of particles accounting for 45.5% to 47.2% of the fill volume would reduce vibration most effectively. The three-millimeter diameter damper particles provide the most effective damping effect, at second place are the particles in four-millimeter diameter, and the least effective are those with two-millimeter diameter.

Keywords: Gear transmission, vibration, particle, discrete element method, multi-body.

1. Introduction

Gear transmissions are widely used in many mechanical structures and devices due to their more compact size and higher load capacity than other transmissions when operating with the same power, number of revolutions and gear ratios. The inherent point of the gear transmission is the vibration factor. This vibration comes from many reasons such as the tooth profile, the mounting system, the operating regimes, the working environment, etc., which affects the optimal working ability of the device. Therefore, reducing the vibration of the gear transmission is always of interest of scientists and manufacturers.

Particle damping technology is a passive technology to reduce vibration, which has been used in many fields, such as civil engineering [1-3], mechanical engineering [4-6] and aeronautical engineering [7]. Lu *et al*. [3] conducted dynamic experiments to investigate the effect of buffer bead dampers fastened to a three-stage steel frame. Properly designed particle dampers can reduce the effects of vibrations, especially when subjected to random excitation. Ahmad *et al*. [7] performed numerical and experimental studies on honeycomb beams filled with damping particles. Reduces vibration by giving proper mass ratio and partial filling of damping particles. Particle damping technology is further applied to gear transmission problems [8, 9]. The authors used multiple-body dynamics simulation (MBD) - One-dimensional discrete element method (DEM) to determine the influence of damping particles on the dynamic response of gear motion. Experimental study by Xiao *et al*. [8] shows that the bead damping with the appropriate filling ratio effectively reduces the vibration of the gear transmission.

Some other studies on the combined MBD-DEM dynamic model, especially in the field of mechanical engineering. This study establishes a two-dimensional combined MBD - DEM dynamic model for a gear and bearing system in which the holes in the gear body are filled with damping particles. The predictive dynamics model considers contact stiffness, damping, and friction between mechanical components and between gears and damping particles. Hertz contact theory [9] and Coulomb friction [10] are used to model these contacts. Yun-Chi C. and Yu-Ren W. [11] provided a dynamic model for a gear transmission system containing damping particles inside holes in the gear

ISSN 2734-9381
https://doi.org/10.51316/jst.167.etsd.2023.33.3.2
Received: June 14, 2022; accepted: May 23, 2023

body, using a two-way coupling with multi-body dynamics and discrete element methods. The study considers the influence of particle radius, coefficient of friction and coefficient of recovery on the dynamic properties.

This paper introduces the numerical simulation of the vibration of the gear transmission with and without damping particles placed inside the technological cavities of the gear. By using two softwares Adams View and EDEM to support the analysis of kinematics, dynamics and problem solving by discrete element method.

2. Gear Transmission Overview

The gear system (Fig. 1) consists of two geared spur gears (2, 4) which are fitted together and are fixedly mounted on their respective shafts (1, 3). The gear is designed with 6 technological holes (5) evenly divided on the gear body to accommodate the damping particles (6) (Fig. 2). The damping particles are filled in the technological cavities with a certain ratio. When the two gears are engaged, the mutual collision of the damping particles and the cavity wall reduces the vibration of the system through a loss mechanism including friction and momentum exchange.

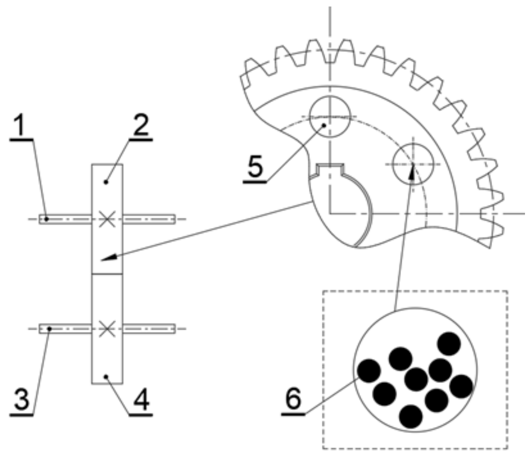

Fig. 1. The gear system is engaged.

3. Theoretical Basis

The interaction of damping particles is modelled according to Rayleigh principle [9, 11] as shown in Fig. 3. Discrete element method studies the interaction between two matter particles i and j corresponding to each micro speed v_i and v_j.

The equation of motion of the particle during the collision, characterized by the displacement quantity x, has the following form:

$$m\ddot{x} + Dx^{\xi}\dot{x} + kx^{\eta} = 0 \quad (1)$$

This is a non-linear collision model, so

$$\xi = \frac{1}{4}\ ;\ \ \eta = \frac{3}{2} \quad (2)$$

We get the following non-linear equation of motion:

$$m\ddot{x} + Dx^{\frac{1}{4}}\dot{x} + kx^{\frac{3}{2}} = 0 \quad (3)$$

where, D is the damping coefficient, k is the stiffness of the particle, m is the mass of the element, x is the amount of displacement of the element with time.

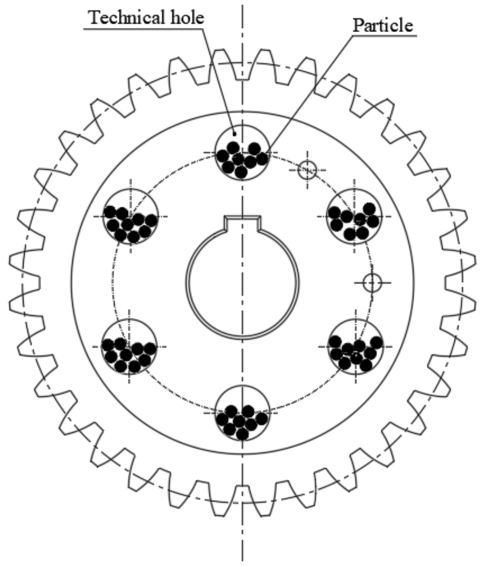

Fig. 2. Technological recesses containing dampers

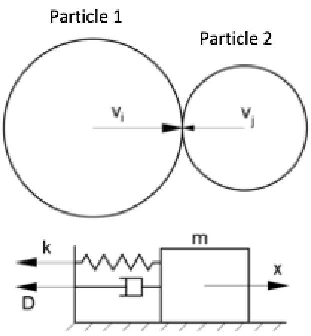

Fig. 3. Rayleigh's principle for collision model.

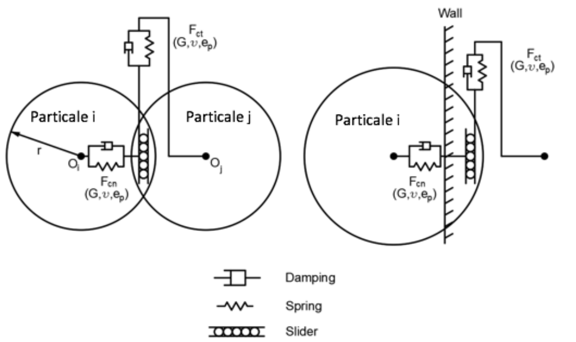

Fig. 4. Computational model of collisions between particles and walls according to the Hertz-Mindlin theory.

Collision model of the shock absorbers and dampers with the wall follows the Hertz-Mindlin contact force model [11, 12] as shown in Fig. 4.

The force of interaction between the body systems is represented by the component of the tangential force and the normal [10] by the equation:

$$F_{CN} = F_{CN,s} + F_{CN,D} \tag{4}$$

with $F_{CN,s} = \frac{-4G\sqrt{r}}{3(1-\nu)}\delta_n^{\frac{3}{2}}$

$$F_{cn,d} = -2\sqrt{\frac{5}{6}}\xi_d\sqrt{M \times k_n}\delta_n^*$$

where: F_{CN} is the total interaction force, $F_{CN,s}$ is the spring force in the tangent direction, $F_{CN,D}$ is the damping force according to the linear method. δ_n is the normal tangent displacement, δ^*_n is the relative normal velocity of the particle *i* with the particle *j*, G is the shear modulus of the particle, and ν is the Poisson coefficient; k_n is the normal contact stiffness coefficient, ξ_d is the damping coefficient of vibration, M is the particle mass, r is the grain radius.

$$F_{CT} = F_{CT,s} + F_{CT,D} \tag{5}$$

with $F_{CT,s} = F_{CT,s,(n-1)} + \Delta F_{CT,s}$

$$F_{CT,D} = -2\sqrt{\frac{5}{6}}\xi_d\sqrt{M \times k_n}\delta_t^*$$

where, $F_{CT,s}$ is an increasing function, $F_{CT,s,(n-1)}$ is the spring force at time step $(n - 1)$, $\Delta F_{CT,s}$ is the increment of the tangential spring force calculated by the formula $\Delta F_{ct,s} = -k_t\Delta\delta_t$, where k_t is the tangent stiffness, which δ_t is the tangent displacement. $\Delta\delta_t$, the increasing tangent displacement is expressed $\Delta\delta_t = \delta_t\ \Delta t$ as δ_t^* relative tangential velocity and Δt time step.

4. Numerical Simulation

4.1. Setup of Simulation by Adams View

The dynamic model of the research gear system is established by using Adams View software. To simplify the mechanism as well as optimize the simulation process, the shaft and gear are set up as shown in the Fig. 5.

The model of gear transmission system is placed in the Adams View software as shown in Fig. 6. Set the gravity for the survey system in the -*Y* direction and set the value to 9.8 m/s^2. Each gear and two ball bearings are set to have any relative movement with the shaft by blocking these details on the shaft to form a rigid system. The material of the details is steel. Set the rotation for the shaft at “Connector”, set the angular velocity value, the axis of motion for the driving gear at “Motion”. Set the correlation relationship between the two gears in “Contact” with the Solid to Solid selection feature. At the same time, set the interaction forces on the gears in "Force", especially set "Gforce" - a necessary condition to run two softwares Adams and EDEM at the same time.

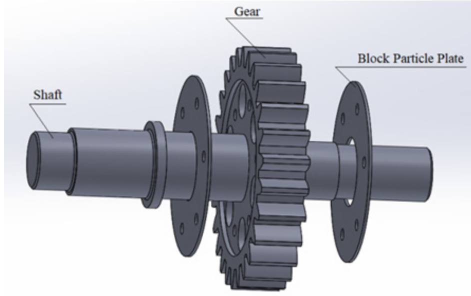

Fig. 5. Modelling shafts and gears in the Adams View software

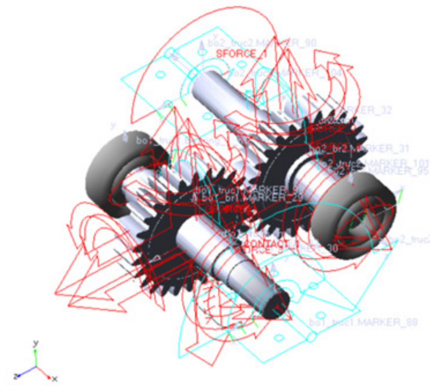

Fig. 6. System model in the Adams View software

4.2. Simulation Setup on EDEM

Set up simulation model of gear system in EDEM by Importing CAD model in *.step* format, set gear material in “Equipment Material” with parameters are Poisson's Ratio $\nu = 0.3$, Solid Density take the same in Adams, Coefficient of Restitution of 0.8, Coefficient of Static Friction of 0.2, Coefficient of Rolling Friction of 0.01. Set the material parameters of the damping particles and the gear material in “Bulk Material”, the number and dimension of particles are optional in “Add Particle”, the particle radius r = 1.5 mm, the number of particles 180 pcs/hole (accounting for 50% of the cavity volume). Particle elements will be formed from “Factory”. There are two “Factory” modes: Dynamic Factory and Static factory. The simulation time is calculated according to Rayleigh time with a value of 20%. The minimum radius of the calculated grid is set between 0.002 m and 0.003 m. Fig. 7 presents the simulation model of the gear system in the EDEM software.

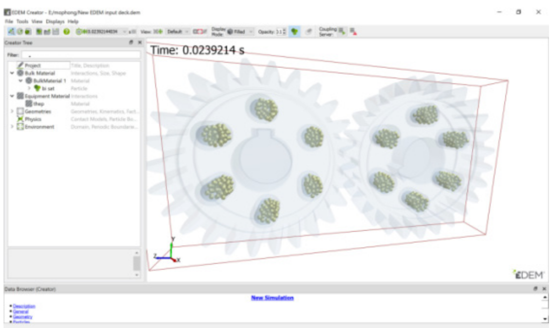

Fig. 7. Simulation in the EDEM software

4.2. Setup of EDEM-Adams Simulation

In order to simulate accurately the behaviour of the gear system in the presence of a damping particle, it is necessary to process data on the dynamics as well as to simulate the collision of the particle system. Therefore, it is necessary to combine the two softwares Adams View and Altair EDEM at the same moment. During the simulation, the two softwares will interact with each other, exchanging information about materials and dynamics (Fig. 8).

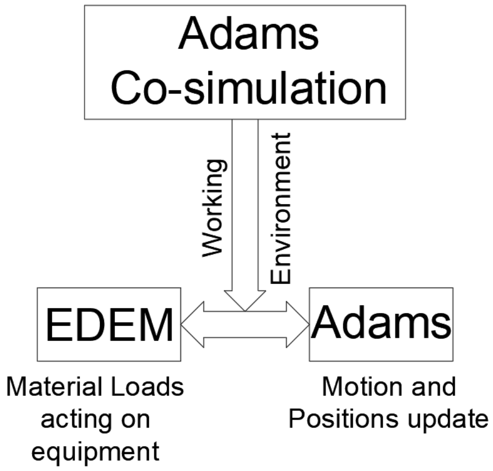

Fig. 8. Exchange of processing information of two softwares Adams and EDEM.

Adams software will give information about the system's motion, position, velocity, acceleration, then EDEM will take that data to calculate and will return data about materials and interaction forces to Adams. For analysis, this exchange takes place continuously during the simulation process.

To combine two softwares at the same time, a middleware is required, which is Adams-Co simulation Interface (ACSI) to exchange data. Setting parameters to run Adams software and EDEM software at the same time will be managed by ACSI. EDEM software will get GFORCE data from Adams by ACSI and use the same *.cosim* file format as the simulation environment. From Adams *.acf* and *.adm* files will be exported as simulation data. The *.adm* file contains the system dynamics data, and the *.acf* file gives information about the simulation time. The modelization results are the acceleration of the driven gear's center of mass and the rolling bearing located on the drive shaft.

5. Results

The experiment had simulated the operation of the gear system both with and without the damper particles at three different rotational speed of 500, 750 and 1000 rpm. The number of damping particles were varied into four cases: 190, 180, 170, and 160 particles per hole. The role of the damping particles' diameter was also taken into account with three variation of diameter being 2, 3, and 4 millimeters.

5.1. Acceleration of the Driven Gear's Center of Mass, 180 Particles per Hole

Fig. 9 represents the acceleration of the driven gear's center of mass (CM) in the absence of the damping particles at three rotational speeds of 500 rpm, of 750 rpm and of 1000 rpm. It shows that, the acceleration increases with the rotational speed. At 500 rpm of rotational frequency, only one abnormal value appears, the two other rotation speeds, the number of acceleration values increases suddenly but the magnitude value is lower. The appearance of these sudden acceleration values is due to the resonance of the individual vibrational frequencies of each part in the system.

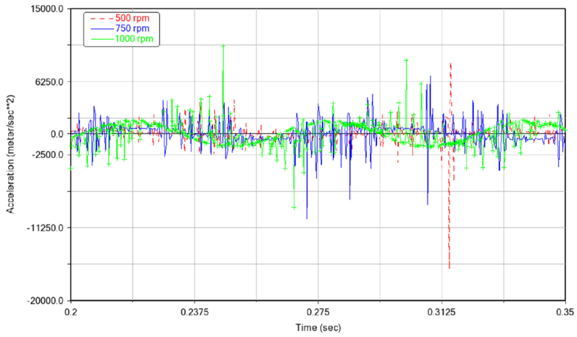

Fig. 9. Acceleration of the driven gear's CM without damper at rotational speeds

Fig. 10 shows the acceleration driven gear's CM with and without the damper at a rotational speed of 500 rpm in steady - state operation, the gear making one full revolution of the engaged movement, for 0.15 seconds. It can be seen that when the model uses damping particles, the acceleration of the CM decreases remarkably. The oscillation amplitude of the acceleration value when there is a particle is smaller and more stable than the amplitude of the acceleration value when there is no damping particle. The maximum acceleration value when there is no damping particle is up to 16250 m/s^2, this value decreases more than 8 times, nearly by 2000 m/s^2 when using particles.

Fig. 11 shows the acceleration of the driven gear's CM with and without the damper at a rotational speed of 750 rpm in steady operation, the gear moving in 0.15 seconds. Similar to the case of rotational speed at 500 rpm, the oscillation amplitude of the acceleration value when damping particles were used is also smaller and more stable than that of the case when no particles were involved. When there is a shock absorber, the maximum acceleration value is reduced by more than 3 times compared to when the damper is not used, from 9500 m/s^2 to nearly 2600m/s^2.

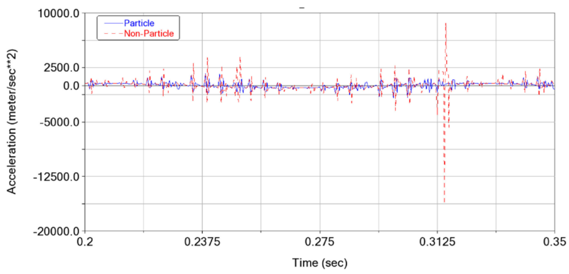

Fig. 10. Acceleration of gear's CM with and without particles, 500 rpm.

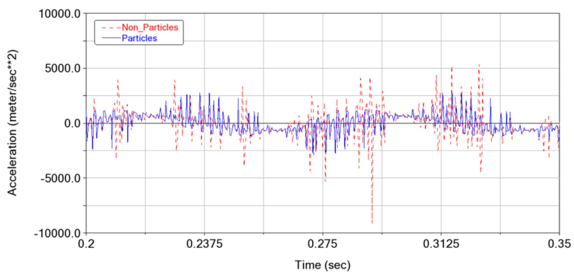

Fig. 11. Acceleration of gear's CM with and without particles, 750 rpm.

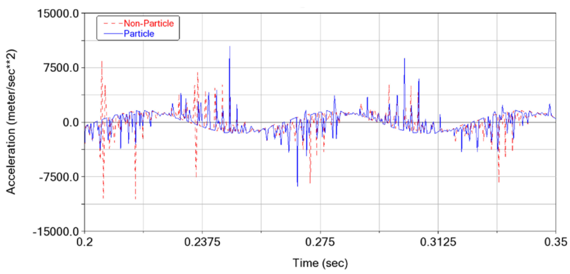

Fig. 12. Acceleration of gear's CM with and without damper, rotational speed 1000 rpm/min.

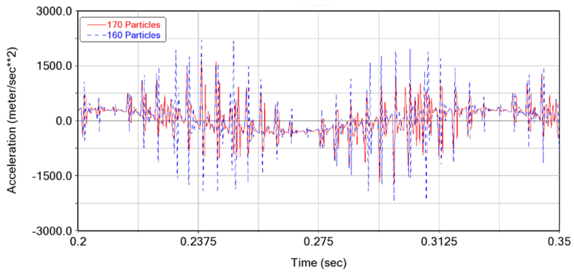

Fig. 13. Comparison of gear's CM using 160 and 170 particles at 500 rpm.

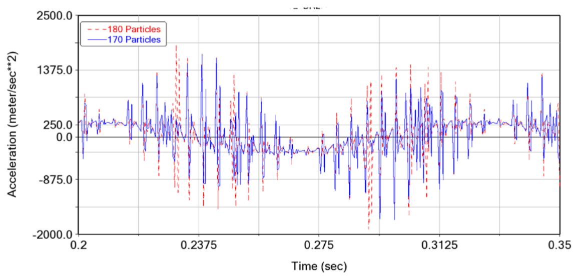

Fig. 14. Comparison of gear's CM using 170 and 180 particles at 500 rpm

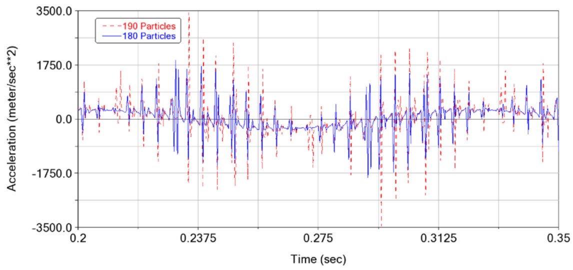

Fig. 15. Comparison of gear's CM using 180 and 190 particles at 500 rpm

When the rotational speed increases to 1000 rpm, the damping effect is negligible (Fig. 12). The amplitude of vibration of the acceleration value and the maximum value of acceleration (10488m/s^2 and 10487.6 m/s^2 with and without damping particles) in both cases are approximately the same. This can be explained that due to the condition of high speed and high inertia, the particles will rotate with the gear by sticking to the cavity wall instead of moving relatively to it. Therefore, this leads to almost no collisions between particles.

In the absence of damping particles at different rotational speeds, the CM acceleration oscillates around a certain amplitude (2500 m/s^2 for 500 rpm, 5000 m/s^2 for 750 rpm, 5600 m/s^2 for rotational speed of 1000 rpm), many peak values spike with a marked jump compared to neighboring times. On the other hand, when there are damping particles, the acceleration of the center of mass oscillating around 1250 m/s^2 is reduced by 50% at 500 rpm, 2500 m/s^2 is reduced by 50% at 750 rpm, 3800 m/s^2 is reduced by 32.14% compared with the case of without particles, and the difference between the peak values is not significantly reduced. Thus, in terms of the values of the peaks and the overall variation, the acceleration of the CM decreases, and the stability of the system increases.

5.2. Comparison of Gear's Center of Mass Acceleration by Number of Particles

The vibration of the gear transmission is remarkably reduced in the presence of dampers. However, in order to optimize vibration reduction, it is necessary to find out the number of particles in percent of the fill volume.

Fig. 13, Fig. 14, and Fig. 15 present the comparison of the gear's CM acceleration at the same rotational speed of 500 rpm using 160 particles, 170 particles, 180 particles and 190 particles with 45.5%, 47.2%, 50% and 52% of the fill volume, respectively. The peak amplitude as well as the maximum oscillation of the graph are arranged in descending order corresponding to the number of particles used 170, 160, 180, 190. Acceleration value

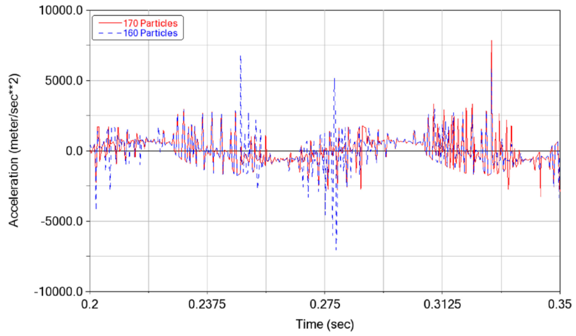

Fig. 16. Comparison of gear's CM using 160 and 170 particles at 750 rpm.

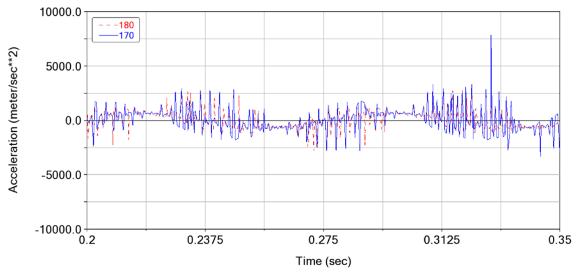

Fig. 17. Comparison of gear's CM using 170 and 180 particles, 750 rpm.

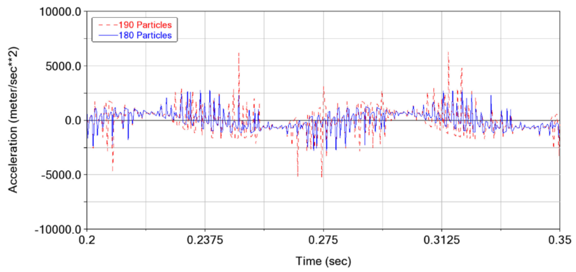

Fig. 18. Comparison of gear's CM using 180 particles and 190 particles, 750 rpm

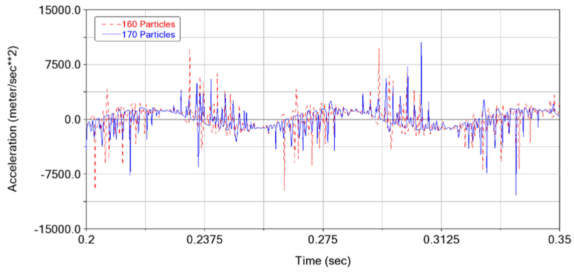

Fig. 19. Comparison of gear's CM using 160 and 170 particles at 1000 rpm.

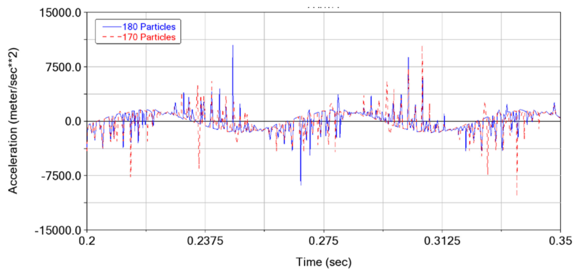

Fig. 20. Comparison of gear's CM using 170 and 180 particles at 1000 rpm

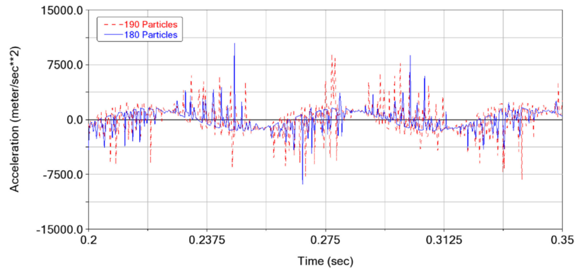

Fig. 21. Comparison of gear's CM using 180 and 190 particles at 1000 rpm

when using the number of 170 vibration damping particles around the value 1600m/s^2, some values are close to the peak value, this value is reduced by 29% compared to using 160 particles (2250 m/s^2), 20% compared to using 180 (2000 m /s^2), 54.28% using 190 (3500 m/s^2). Thus, at 500 rpm, system stability is best when 170 particles are used.

Fig. 16, Fig. 17, and Fig. 18 present the comparison of the gear center of mass acceleration at the same rotational speed of 750 rpm using 160 particles, 170 particles, 180 particles and 190 particles.

The amplitudes of the characteristic curves and the variation of acceleration values were found to increase when the number of particles used per hole are 170, 160, 190, and 180. This shows that the ability to reduce vibration on the gear is most effective when using 170 particles, corresponding to a filling capacity of 47.2%.

Fig. 19, Fig. 20, Fig. 21 represent the comparison of gear's CM acceleration at the same rotational speed of 1000 rpm when using 160, 170, 180, 190 balls per cavity respectively. At this speed, the damping effect between each use of the number of balls is no longer so obvious. The maximum acceleration value of each case fluctuates around 11250 m/s^2, in which there are many peaks approaching the maximum value with a significant jump compared to neighbouring times. But the stability of the acceleration value when using 160 particles and 190 particles is worse than when using 170 particles and 180 particles, especially when using 180 particles the effect is more stable than 170 but not too significant. At 1000 rpm, the number of dampers using 170 to 180 particles equivalent to 47.2% and 50% of the fill volume will increase the stability of the system.

It can be concluded that the best volumetric filling ratio for high vibration efficiency is from 45.5% to 47.2%.

5.3. Comparison of Gear's Center of Mass Acceleration by Particles Diametres

Comparison of gear's CM acceleration at the same rotational speed of 500 rpm and using particles in three different diameters of 2, 3, and 4 millimeters.

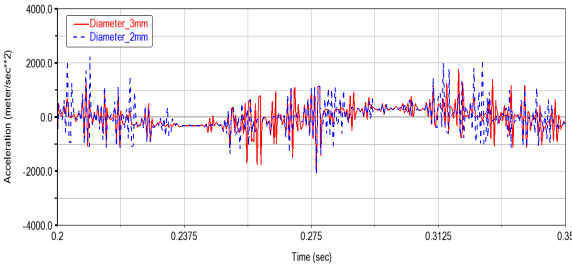

Fig. 22. Comparison of gear's CM acceleration using particles with diameters of 3 mm and 2 mm, 500 rpm

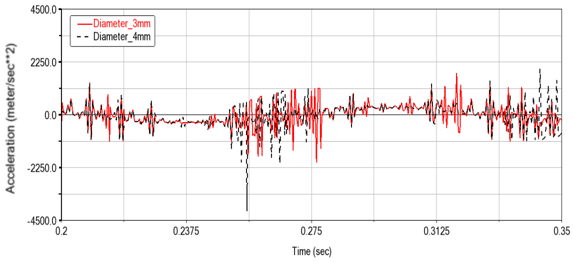

Fig. 23. Comparison of gear's CM acceleration using particles with diameters of 3 mm and 4 mm, 500 rpm

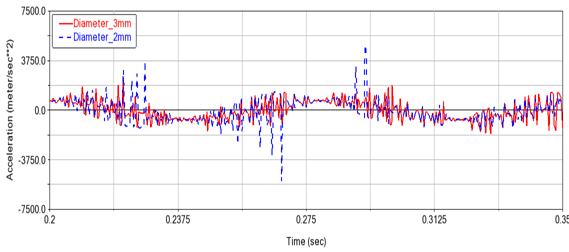

Fig. 24. Comparison of gear's CM acceleration using particles with diameters of 3 mm and 2 mm, 750 rpm

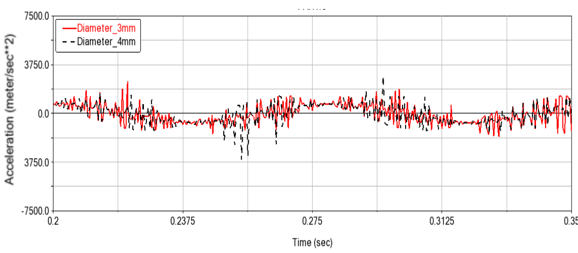

Fig. 25. Comparison of gear's CM acceleration using particles with diameters of 3 mm and 4 mm, 750 rpm

Fig. 22 and Fig. 23 present the comparison between the acceleration at the gear center mass when using particles with a diameter of 3 millimeters (180 particles/hole) with when using particles with a diameter of 2 millimeters (608 particles/hole) and when using particles with diameter of 4 mm (76 particles/hole). It can be seen that, the acceleration value increased suddenly when using particles with diameters of 2 and 4 millimeters. The amplitude variation of the acceleration value when using the 3 millimeters diameter particle is more stable than the two other cases. The maximum value of acceleration when using 4 millimeters diameter particles is 4109 m/s^2, this value decreased by 10.27% (2229 m/s^2) when using 2 millimeters diameter particles and by 51.32% (2000 m/s^2) when using particles with diameter of 3 millimeters.

At 1000 rpm, the acceleration at the center mass of the driven gear did not change significantly when different diameter damper particles were used (Fig. 26 and Fig. 27). The maximum acceleration value when using 2, 3, and 4 millimeters diameter dampers is 10087 m/s^2, 10488 m/s^2, 10157 m/s^2, respectively. This can be explained, at high speed, the inertia of the gear is large, so the damping particles have almost no interaction but tend to rotate with the gear.

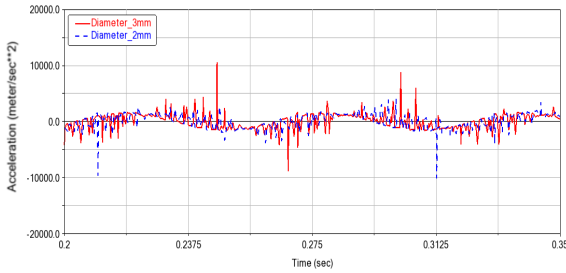

Fig. 26. Comparison of gear's CM acceleration using particles with diameters of 3 mm and 2 mm,1000 rpm

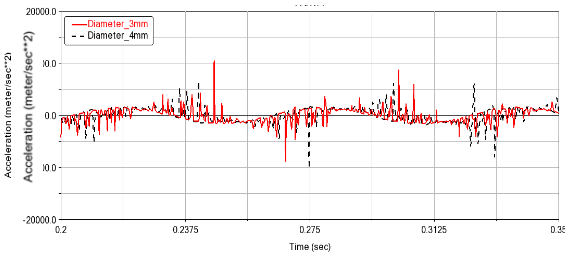

Fig. 27. Comparison of gear's CM acceleration using particles with diameters of 3 mm and 4 mm,1000 rpm

6. Conclusion

Damping particle technology is a method of passive vibration reduction through absorption and loss of vibration energy during the interaction of the damping particle and the mechanical system. The principle of the damping method is based on the discrete element method DEM, the interaction of particles is simulated through EDEM software. The kinematic processing of the gear system is analyzed through Adams software. The result is obtained by continuously updating the interaction position of the gear pair with the processing of the problem of damping particles interacting at the same time.

The vibration of the gear transmission is evaluated through the acceleration of the driven gear's CM. At 500 rpm and 750 rpm, the gear center mass acceleration is significantly reduced when there is a damper, the maximum acceleration value is reduced from 4 to 8 times. However, when the rotational speed increases up to 1000 rpm, the large inertia limits the interaction of the damper, resulting in not very high nor noticeable efficiency at low speeds.

The best vibration reduction efficiency for gear transmission equipment is used when the number of damping particles is used with the filling ratio of each cavity is 45.5% to 47.2% (corresponding to 160 particles and 170 particles). This can be explained that with a reasonable fill volume, when two gears are engaged, the interaction between the damping particles is guaranteed to be consistent with the DEM theory without losing the stability of the system. The vibration damping effect is optimal when using particles with a diameter of 3 millimeters.

Acknowledgements

This research is funded by the Hanoi University of Science and Technology (HUST) under project number T2021-PC-036.

References

[1] Xu, Z., Wang, M. Y., Chen, T., An experimental study of particle damping for beams and plates, J. Vib. Acoust 1 26 (1), pp. 141-148, 2004. https://doi.org/10.1115/1.1640354

[2] Lu, Z., Lu, X. L., Masri, S. F., Studies of the performance of particle dampers under dynamic loads. J. SoundVib. 329 (26), pp. 5415-5433, 2010. https://doi.org/10.1016/j.jsv.2010.06.027

[3] Lu, Z., Lu, X., Lu, W., Masri, S. F., Experimental studies of the effects of buffered particle dampers attached to a multi-degree-of-freedom system under dynamic loads. J. SoundVib. 331, pp. 2007-2022, 2012. https://doi.org/10.1016/j.jsv.2011.12.022

[4] Moore, J. J., Palazzolo, A. B., Gadangi, R., Nale, T.A., Klus-man, S. A., Brown, G. V., Kascak, A. F., A forced response analysis and application of impact dampers to rotor dynamic vibration suppression in a cryogenic environment. J. Vib. Acoust. 117, 300, 1995. https://doi.org/10.1115/1.2874452

[5] Wong, C. X., Daniel, M. C., Rongong, J. A., Energy dissipation prediction of particle dampers. J SoundVib. 319 (1-2), 91-118, 2009. https://doi.org/10.1016/j.jsv.2008.06.027

[6] Yao, B., Chen, Q., Investigation on zero-gravity behavior of particle dampers. J. Vib. Control 21, 124-133, 2013. https://doi.org/10.1177/1077546313488157

[7] Ahmad, N., Ranganath, R., Ghosal, A., Modeling and exper- imental study of a honeycomb beam filled with damping particles. J. SoundVib. 391, 20-34, 2017. https://doi.org/10.1016/j.jsv.2016.11.011

[8] Xiao, W. Q., Huang, Y. X., Jiang, H., Lin, H., Li, J. N.: Energy dissipation mechanism and experiment of particle dampers for gear transmission under centrifugal loads. Particuology 27, 40-50, 2016. https://doi.org/10.1016/j.partic.2015.10.007

[9] Johnson, K. L., Contact Mechanics, Cambridge University Press, Cambridge, 1985.

[10] Coulomb, P. C. A., Theorie des Machines Simples, Bachelier, Paris, 1821.

[11] Yun-Chi Chung, Yu-Ren Wu, Dynamic modeling of a gear transmission system containing damping particles using copled multi-body dynamics and discrete element method, Nonlier Dynamics, Volume 89, pp. 129-149 2019. https://doi.org/10.1007/s11071-019-05177-1

[12] Marius Hromnik, A GPGPU implementation of the discrete element method applied to modeling the dynamic particulate environment inside a tumbling mill, MS thesis. University of Cape Town, 2013.