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Study on the Motion Characteristics of Abrasive Media in Vibratory Finishing

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Study on the Motion Characteristics of Abrasive Media in Vibratory Finishing

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Abstract. In order to investigate the motion characteristics of the abrasive media in the vibratory finishing, the RecurDyn and EDEM coupled simulation method is employed. The simulation results show that the trajectories of the abrasive media are annular spiral motions in general, including a circular motion about the central axis of the vibratory finishing machine and an elliptical motion around the center of the media flow. The reliability of the RecurDyn-EDEM coupled simulation for the vibratory surface finishing process is validated by X-ray real-time detection, which has significance in better understanding of the motion characteristics of abrasive media and the optimal design of the vibratory surface finishing processes.

Keywords. Vibratory finishing; discrete element simulation; motion characteristics; X-ray

1. Introduction

Vibratory finishing is a surface treatment process that uses mechanical vibrations to make products and abrasive media of different sizes and shapes rub each other to remove the burrs, flashes, edges and corners on the mechanical parts, to eliminate the residual stresses in the finished workpiece [1, 2], which can effectively improve the performance and service life of the workpiece. Therefore, vibratory finishing has been widely used for the surface treatment of mechanical products, such as the mechanical parts in hydraulics, wind power equipment, and aerospace [3]. In the last two decades, numbers of scholars have conducted researches on the vibratory surface finishing, due to its industrial processing advantages in terms of large processing volume, low cost, and simple operation.

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The research group from the University of Toronto possibly pioneered the systematic study on the mechanism of vibratory surface finishing. Wang et al. [4] published their experimental study on the mechanism of vibratory finishing of aluminium alloy in 2000. In this study, the normal contact forces between the ceramic media and the aluminium alloy parts was successfully measured by means of a homemade strain gauge sensor under both dry and water-wet conditions. Experimental results show that the changes in hardness and roughness of vibratory finished surfaces were depended significantly on the lubrication condition, the media roughness and size.

Yabuki et al. [5] developed a new force sensor and measured both the contact normal and tangential forces between the abrasive media and workpiece, and calculated the coefficients of friction between the abrasive ceramic media and aluminium alloy AA6061-T6 under dry and water-wet contact conditions in a vibratory finisher. Maciel and Spelt [6] measured the wall-media contact forces and energy in a vibratory finisher using a force sensor embedded in the walls of a vibrating tub finisher loaded with various amounts of steel media in different vibration frequencies, and compared with the DEM predictions. It was found that wall-media contact forces increased with the depth of media above the sensor and with the normal wall velocity, and the average impulse of the wall on the media increased with the increasing of media mass and decreased with the increasing of vibration frequency.

On the other hand, the understanding and measurement of the trajectories of the abrasive media and workpiece is very important to the vibratory finishing process, and significant progress has been made both in mathematical simulations [7, 8] and experimental studies [9-12]. In addition, the discrete element (DME) method has been employed in studies [13-16] for the mass finishing process. Hashemnia et al [17] studied the fluidized granular media at top, middle and bottom of the finisher using DEM simulation method. The effect of parameters such as the grain size of the abrasive media, the operating frequency of the barrel, the loading volume, and the lubrication condition on the surface finishing has been studied for finding the optimal conditions of vibratory finishing [18-21].

This work aims to determine the trajectories of abrasive media and the efficient processing areas in the vibratory surface finishing. The RecurDyn-EDEM coupled simulation method is employed for the vibratory surface finishing process, and it is validated by the X-ray real-time detection, which has significance in better understanding of the motion characteristics of abrasive media and the optimal design of the vibratory surface finishing processes.

2. Development of vibratory finisher model

The vibratory finisher consists of a vibratory barrel, an electric motor, unbalanced weight, 6 springs and a base. Figure 1 shows the schematic diagram of the finisher. In order to study the actual motion of abrasive media during the operation of the vibratory finishing, a three-dimensional model of the vibratory finishing machine with a barrel inner diameter of 0.36 m is established by means of the SolidWorks and is imported into the EDEM software. The dynamic and geometric parameters of the vibratory finisher is listed in Table 1.

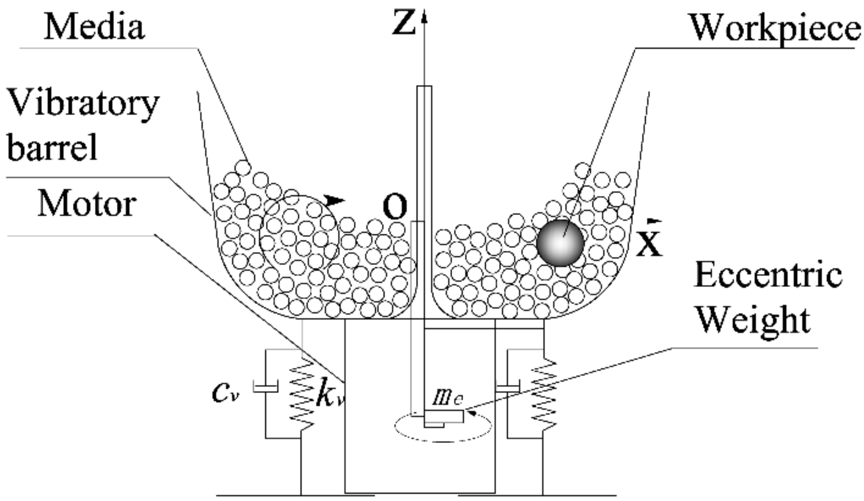

Figure. 1 Illustration of vibratory finishing

Table 1 Dynamical and geometric parameter of the vibratory finisher

Parameter	Value	Unit
Vertical stiffness/k_v	33	N/mm
Horizontal stiffness/k_h	59	N/mm
Vertical damping ratio/c_v	59	Ns/mm
Horizontal damping ratio/c_h	0.0043	Ns/mm
Rotation speed of motor/ω	1500	rpm
Weight of working body/m	15.6	kg
Weight of eccentric weight/m_e	2.4	kg
Distance from spring to OZ axis/a	160	mm
Distance from eccentric weight to body centroid/l	200	mm
Distance from eccentric weight to OZ axis/r	10	mm
Inner diameter of vibrating barrel/R_b	360	mm
Inner height of vibrating barrel /h	150	mm

3. Dynamic measurement of the vibratory finisher

In order to obtain the vibration characteristics of the vibration barrel, the vibratory finishing machine (PU-370S, Shanghai Guangshi Grinding Equipment Co., Ltd.) was taken as the research object. The three-direction acceleration sensor (INV9832-50, Beijing Oriental Institute of Noise & Vibration) was put on the four positions of the finisher, shown in Figure. 2, to collect the vibrations of the finisher during testing. The sampling frequency was 512 Hz, and the measured dynamic responses of the finisher in time and frequency domain are shown in Figure. 3 and 4, respectively.

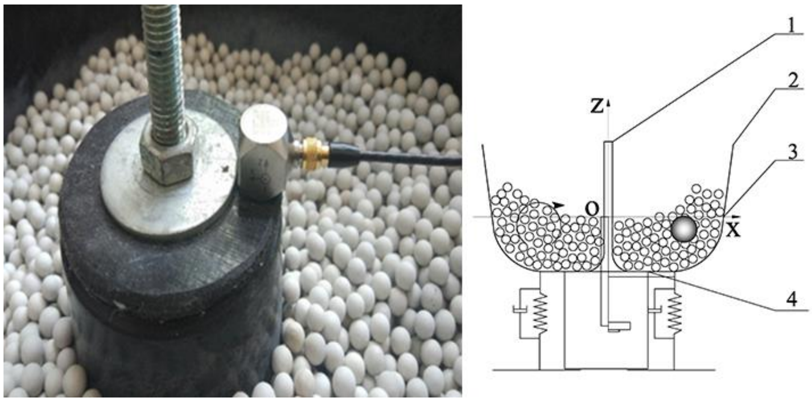

Figure. 2 Vibration measurement of the finisher

Figure 3 shows that in the X direction, the measuring points 2 and 3 have larger vibrations, while the measuring point 1 and 4 have smaller vibrations. In the Y direction, the measuring points 2 and 3 have the largest vibrations, point 4 has the smaller vibrations, but point 1 almost has no vibration. In the Z direction, the measuring point 2 has the largest vibrations; while points 1, 3, 4 have the smaller vibrations and they are similar.

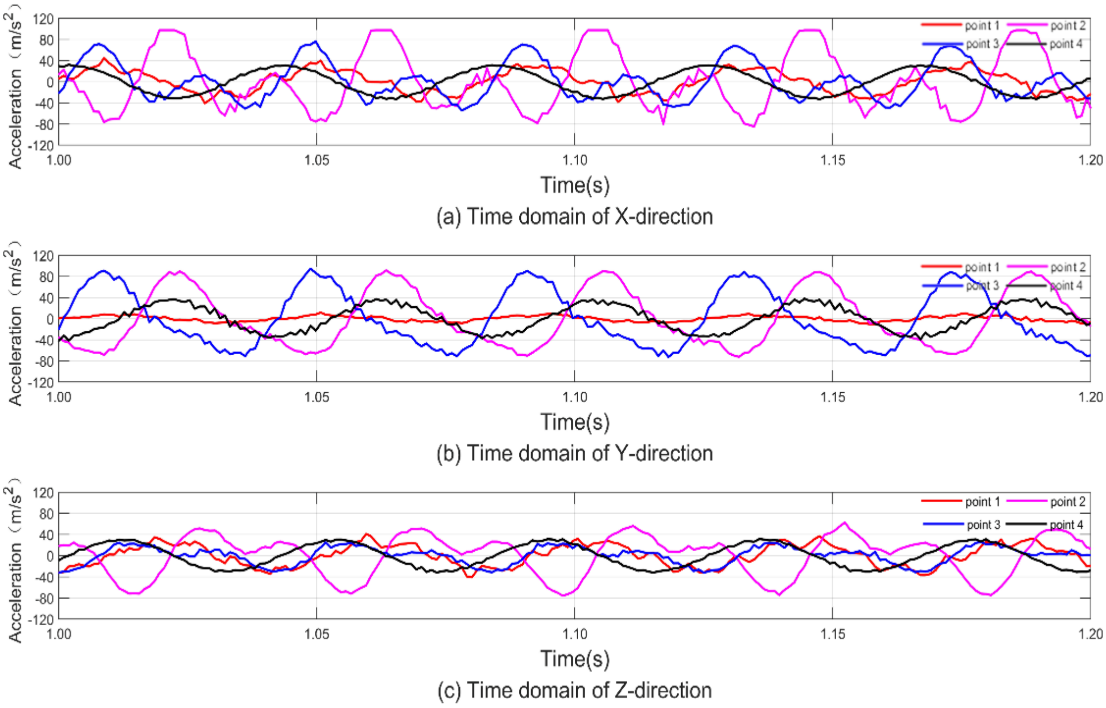

Figure. 3 Measured vibrations of the finisher in time domain, (a) X direction，(b) Y direction，(d) Z direction

Figure 4 presents the measured vibrations in X, Y, and Z directions at 1, 2, 3, and 4 positions in frequency domain. It is observed from Figure. 4 that the resonant frequencies in X, Y, and Z directions are the same, but the peak resonant frequencies in the three directions are different. In the X direction, the dominant resonant frequency is 48 Hz and point 2 has the largest power of vibrations. In the Y direction, the dominant resonant frequency is 24 Hz and point 3 has the largest power of vibrations. However, in Z direction the vibrations at the two resonant frequencies are quite close, but the powers of vibrations at position 2 at the two resonant frequencies are significantly larger than those at positions 1, 3, and 4. It is noticed that the resonant frequency of 24 Hz corresponds to the motor operating speed. In addition, two higher resonant frequencies of 75 Hz and 124 Hz are clearly observed in Figure. 4. All of these measured information about the dynamics of the finisher will be used in the RecurDyn simulation.

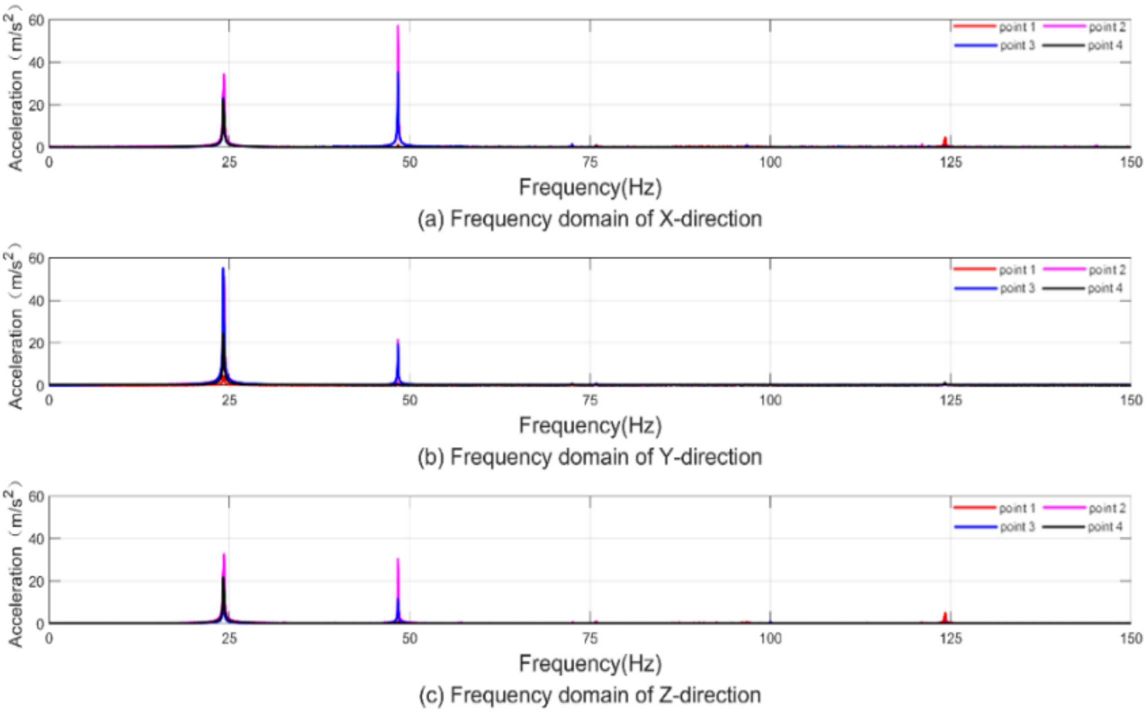

Figure. 4 Measured vibrations of the finisher in frequency domain, (a) X direction，(b) Y direction，(d) Z direction

4. RecurDyn-EDEM coupling simulation

4.1. RecurDyn-EDEM coupling simulation methodology

During the finishing process, the vibrations of the barrel and the motion of the abrasive media will affect each other. Therefore, in order to study the motion of the finishing abrasive media in the finishing machine, RecurDyn-EDEM coupling method is employed. The first step of the coupled simulation is to import the model developed with the SolidWorks software into RecurDyn and set the constraints and driving function of the motion pair, to establish the dynamics model of the vibratory finishing.

The second step is to set the appropriate time step and grid parameters. In each time step, RecurDyn transfers the dynamic simulation information of the vibratory finisher to the EDEM. The change of the model position will cause the abrasive media stress to change; then the EDEM calculates the force and moment of the abrasive media in the vibratory finisher at this step, and transfers the mechanical data back to RecurDyn. Thus, in the next step RecurDyn will jointly calculate the new displacement and velocity information of the vibratory finisher based on the new load information and its own drive. In this way, the data is transferred interactively and cyclically to complete the bidirectional coupling calculation. Since the motion between the abrasive media is a random process of mutual contact, squeezing, collision, rolling, and friction, the Hertz-Mindlin non-slip contact model is selected when setting the particle factory in EDEM, and the time step is set to 4.43×10^{-6}s.

Six kinds of different media in materials, including epoxy resin, glass, silicon carbide, high-alumina porcelain, zirconia and stainless steel were selected. The conical epoxy resin media are used in the simulation, which is the same as that used in the experiments. In order to accelerate the speed of simulations for the comparative study, the other five abrasive media in the simulation studies are set to be spherical. The number of abrasive media is 2000. The size and shape of the abrasive media are shown in Figure 5.

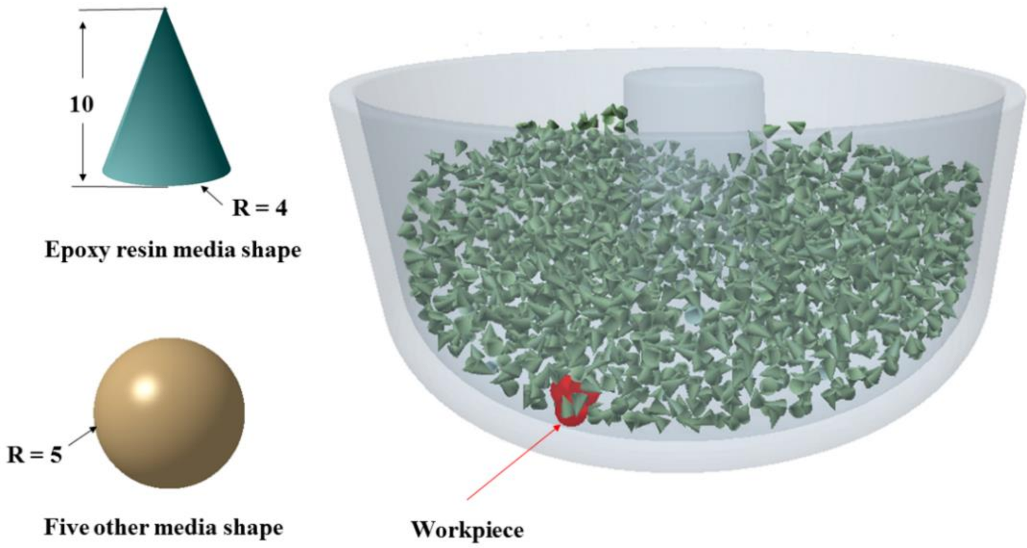

Figure. 5 The simulation setup in EDEM

4.2. Simulation analysis of abrasive media motion

The whole motion of the abrasive media in the vibrating barrel is regarded as a motion cycle. The trajectory of a single abrasive particle in one cycle is extracted. In order to better display the spiral state of media motion, the motion trajectory is observed from a top-view perspective, as shown in Figure 6. It can be seen from Figure. 6 (a) that the epoxy abrasive media exhibits a circular spiral motion in the barrel. One is circular motion around the central axis of the vibrating barrel, and the other is circular motion around the rolling centre of media flow. The trajectory of the glass abrasive media is shown in Figure. 6 (b). Compared with the resin abrasive media and glass abrasive media, the number of spiral turns of silicon carbide abrasive media has increased significantly, and its trajectory is shown in Figure. 6 (c). However, the number of spiral turns of high-alumina porcelain abrasive media has not changed significantly, and its motion trajectory is shown in Figure. 6 (d). The number of spiral turns of zirconia and stainless steel abrasive media increased significantly, and the abrasive media motion cycle is longer, which are shown in Figure. 6 (e) and Figure. 6 (f), respectively. It can be concluded from Figure. 6 that, the abrasive media trajectories of different materials in the vibrating barrel, have the similar motion cycle around the central axis of the barrel, but the number of spirals is different in the same simulation period.

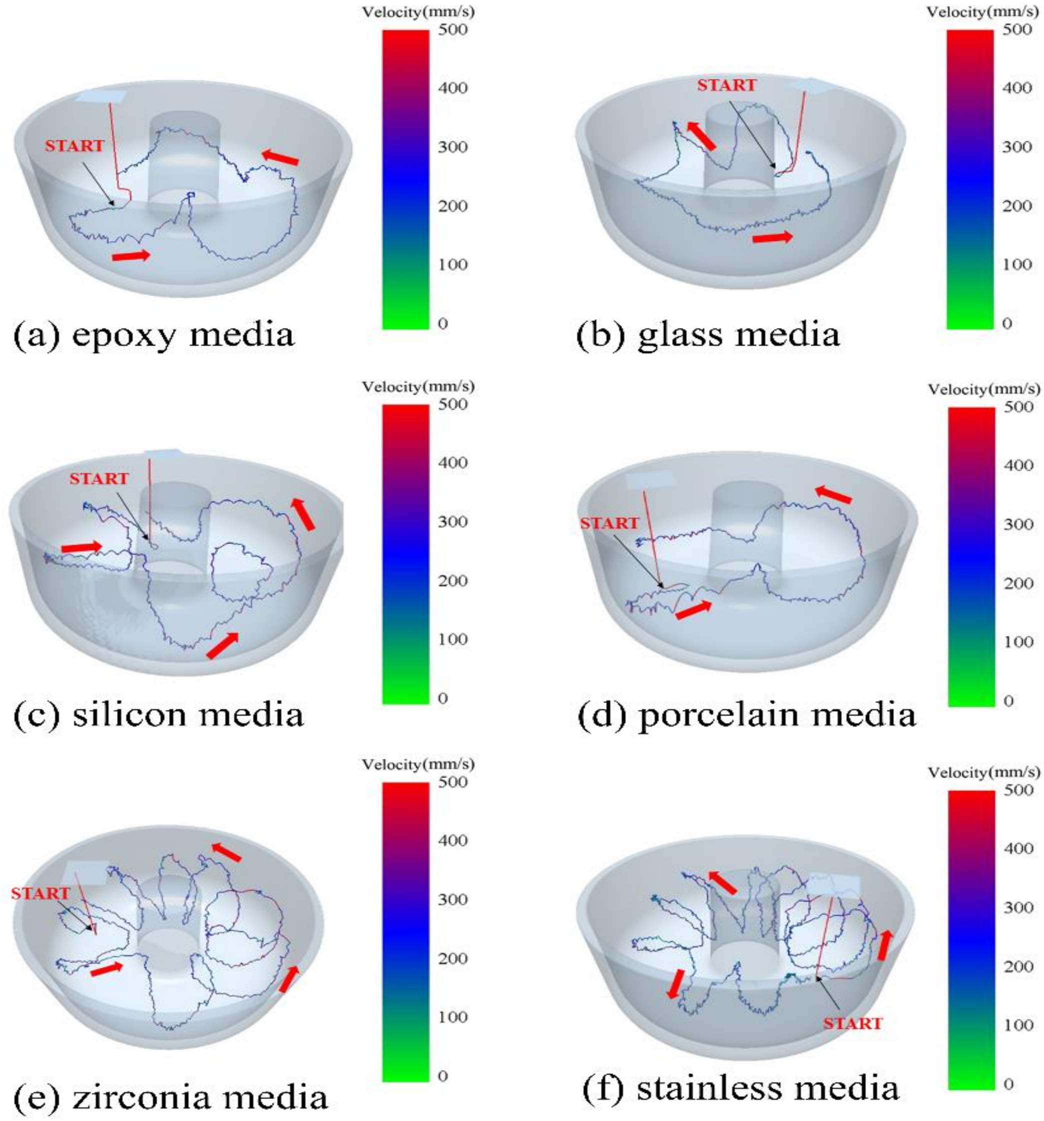

Figure. 6 Simulated trajectories of six different abrasive media

5. Experiment

In order to verify the simulation results of the abrasive media motion trajectories in a vibratory finisher, the X-ray inspection equipment is employed, which consists of a X-ray tube, a receiving board and signal processing system. After the X-ray machine get the images of the targets, the receiving board of the X-ray system receives and transmits them to the computer processing system.

Figure 7 shows the setup of the X-ray inspection system. In order to distinguish specific abrasive media and track the real-time trajectory of specific abrasive media smoothly, select an abrasive media and hollow the bottom of the conical epoxy abrasive media and wrap it with 1.53 mm in thickness of lead, and ensure that the weight was the same as other normal abrasive media, so that the target media had the same motion with those of normal media.

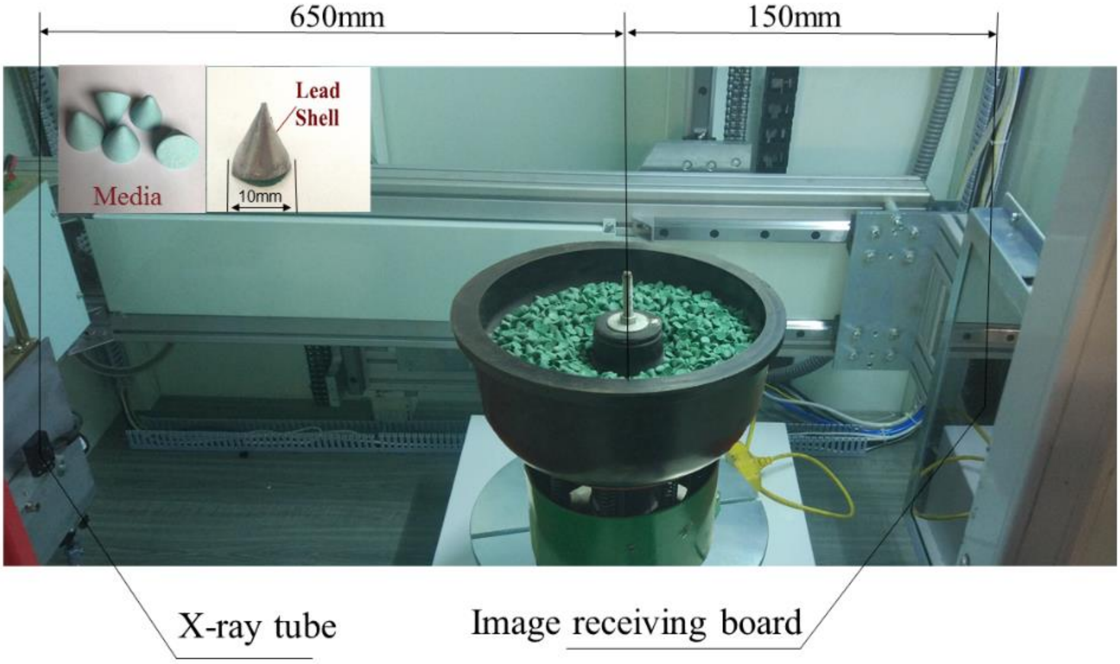

Figure. 7 Setup of X-ray measurement system

Figure 8 (a) presents the trajectory of the media extracted from the X-ray images in a period of 11s. In order to compare the experimental results with simulation results, Figure. 6(a) is rotated 30° clockwise along the vertical axis of the barrel, and observed from a horizontal perspective, as shown in Figure. 8 (b). It can be seen from Figures. 8 (a) and (b) that the media trajectory obtained by the RecurDyn-EDEM coupling simulation is consistent with that from the experimental detection, showing a circular motion around the center of the barrel and 4 consecutive elliptical helical motion.

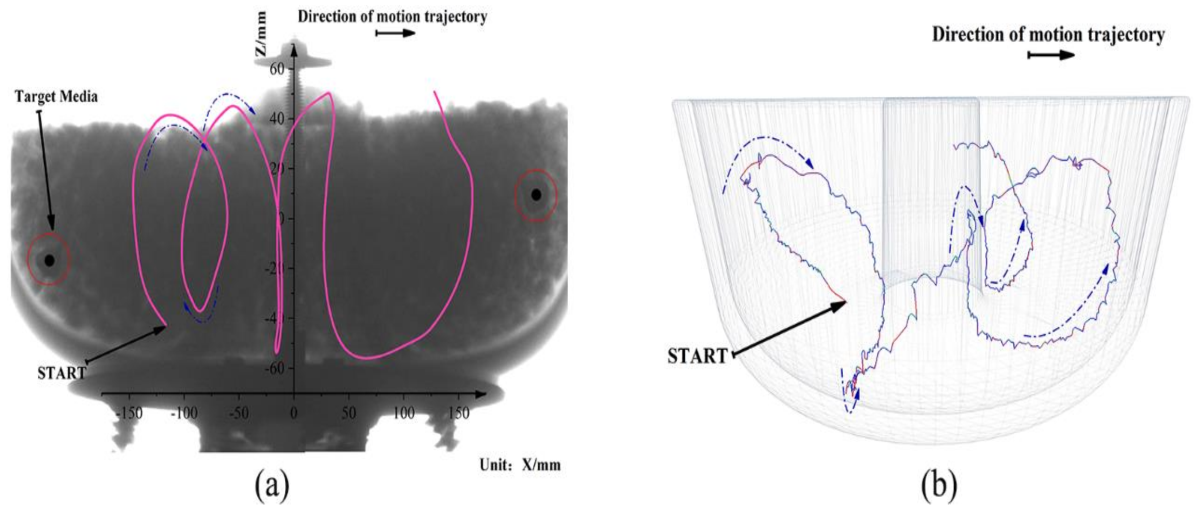

Figure. 8 Media motion image measured by the X-ray inspection system

6. Conclusions

The conclusions of this study can be draw as the follows:

(1) The dynamic responses of the vibratory finisher has been measured, and the fundamental resonant frequency of the finisher is about 24 Hz, corresponding to the motor operation speed of the finisher.

(2) The RecurDyn-EDEM coupling simulation methodology can be effectively used to simulate the motions of abrasive media in a vibratory finisher.

(3) The trajectories of the target abrasive media can be detected by means of the X-ray inspection system, which validated the RecurDyn-EDEM coupling simulation methodology. This study has significance in the understanding of the mechanism of vibratory surface finishing, and provides a fundamental reference for the improvement of the existing vibratory finishing technology and the design of the next-generation of mass finishing process.

7. References

[1] Sofronas A, Taraman S (1979) Model development and optimization of vibratory finishing process. International Journal of Production Research 17 (1):23-31. doi:10.1080/00207547908919592
[2] Hashimoto F, DeBra DB (1996) Modelling and Optimization of Vibratory Finishing Process. CIRP Annals 45 (1):303-306. doi:10.1016/s0007-8506(07)63068-6
[3] Mediratta R, Ahluwalia K, Yeo SH (2015) State-of-the-art on vibratory finishing in the aviation industry: an industrial and academic perspective. The International Journal of Advanced Manufacturing Technology 85 (1-4):415-429. doi:10.1007/s00170-015-7942-0s
[4] Wang S, Timsit RS, Spelt JK (2000) Experimental investigation of vibratory finishing of aluminum. Wear 243 (1):147-156. doi:10.1016/S0043-1648(00)00437-3
[5] Yabuki A, Baghbanan MR, Spelt JK (2002) Contact forces and mechanisms in a vibratory finisher. Wear 252 (7-8):635-643. doi:10.1016/S0043-1648(02)00016-9
[6] da Silva Maciel L, Spelt JK (2020) Measurements of wall-media contact forces and work in a vibratory finisher. Powder Technology 360:911-920. doi:10.1016/j.powtec.2019.10.066
[7] Mamalis AG, Grabchenko AI, Mitsyk AV, Fedorovich VA, Kundrak J (2013) Mathematical simulation of motion of working medium at finishing–grinding treatment in the oscillating reservoir. The International Journal of Advanced Manufacturing Technology 70 (1-4):263-276. doi:10.1007/s00170-013-5257-6
[8] Naeini SE, Spelt JK (2009) Two-dimensional discrete element modeling of a spherical steel media in a vibrating bed. Powder Technology 195 (2):83-90. doi:10.1016/j.powtec.2009.05.016
[9] Tian YB, Zhong ZW, Tan SJ (2016) Kinematic analysis and experimental investigation on vibratory finishing. The International Journal of Advanced Manufacturing Technology 86 (9-12):3113-3121. doi:10.1007/s00170-016-8378-x
[10] Fleischhauer E, Azimi F, Tkacik P, Keanini R, Mullany B (2016) Application of particle image velocimetry (PIV) to vibrational finishing. Journal of Materials Processing Technology 229:322-328. doi:10.1016/j.jmatprotec.2015.09.017
[11] Zhang C, Liu W, Wang S, Liu Z, Morgan M, Liu X (2019) Dynamic modeling and trajectory measurement on vibratory finishing. The International Journal of Advanced Manufacturing Technology 106 (1-2):253-263. doi:10.1007/s00170-019-04644-8
[12] Hashemnia K, Mohajerani A, Spelt JK (2013) Development of a laser displacement probe to measure particle impact velocities in vibrationally fluidized granular flows. Powder Technology 235:940-952. doi:10.1016/j.powtec.2012.12.001
[13] da Silva Maciel L, Spelt JK (2020) Comparison of DEM predictions and measured wall-media contact forces and work in a vibratory finisher. Powder Technology 366:434-447. doi:10.1016/j.powtec.2020.02.014

[14] Hashemnia K, Pourandi S (2018) Study the effect of vibration frequency and amplitude on the quality of fluidization of a vibrated granular flow using discrete element method. Powder Technology 327:335-345. doi:10.1016/j.powtec.2017.12.097
[15] Wan S, Liu YC, Woon KS (2016) A simple general process model for vibratory finishing. The International Journal of Advanced Manufacturing Technology 86 (9-12):2393-2400. doi:10.1007/s00170-016-8379-9
[16] Djender K, Hamouda K, Keddam M, Amrou MHE (2020) Statistical modelling and optimisation of the factors affecting the surface roughness of C45 steel treated by the centrifugal disk mass finishing process. Int J Materials Engineering Innovation 11 (1):70-89. doi:10.1504/IJMATEI.2020.104794
[17] Wong BJ, Majumdar K, Ahluwalia K, Yeo S-H (2020) Minimum surface roughness using rule-based modeling of the vibratory finishing process in a high-frequency bowl system. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture. doi:10.1177/0954405420911282
[18] Malkorra I, Salvatore F, Rech PA J, Tardelli AM J(2020) Influence of lubrication condition on the surface integrity induced during drag finishing. Procedia CIRP 87:245-250. doi:10.1016/j.procir.2020.02.087
[19] Sutowski P, Plichta J, Kałduński P (2019) Determining kinetic energy distribution of the working medium in a centrifugal disc finishing process—part 1: theoretical and numerical analysis with DEM method. The International Journal of Advanced Manufacturing Technology 104 (1-4):1345-1355. doi:10.1007/s00170-019-03872-2
[20] Sutowski P, Plichta J, Kałduński P (2019) Determining kinetic energy distribution of the working medium in a centrifugal disc finishing process—part 2: experimental analysis with the use of acoustic emission signal. The International Journal of Advanced Manufacturing Technology 104 (1-4):687-704. doi:10.1007/s00170-019-03937-2
[21] Kang YS, Hashimoto F, Johnson SP, Rhodes JP (2017) Discrete element modeling of 3D media motion in vibratory finishing process. CIRP Annals 66 (1):313-316. doi:10.1016/j.cirp.2017.04.092

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