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Random Dynamic Analysis of Ring Die Pellet Mill

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Abstract

Ring die pellet mills are widely applied in feed and biomass fuel. Particles are formed by rotating ring die, so torsional vibration is essential. Because the material has randomness in the extrusion process, the torsional vibration of ring die pellet mills is random, which affects the life, stability, and reliability. Using Lagrange equations and the lump-mass method, the torsional dynamic model of the ring die pellet mill is established. Based on the stochastic volatility model, the extrusion force is created. The dynamic equation of the ring die pellet mill is solved using the Runge-Kutta integration method, and the results show that the torsional vibration is related to the extrusion force, rotational speed, errors in installation, and fabrication. The torsional vibration and the torque of the ring die have similar changes in trend. The error affects the torsional vibration when it reaches a certain level.

Keywords: ring die pellet mill; random dynamic analysis; torsional vibration

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1. Introduction

With the gradual maturation of biomass technology, biomass energy has developed into a new energy that has a pivotal position after petroleum, natural gas, and coal. It has the advantages of abundant reserves, reproducibility, no pollution, environmental protection, and so on. The transport and storage of biomass causes issues with the development of biomass energy. Biomass forming technology solves these problems, reduces biomass volume, and increases its energy.

Ring die pellet mills have the advantages of granulating efficiency and favourable forming effect, and they are important processing equipment in biomass energy. At present, research on ring die pellet mills mainly concentrates on the principle of extrusion molding, mechanical analysis of core components, quality of pellets, and so on. Holm [1-2] established a mechanical model of biomass pellets through theoretical analysis and experimental research. Castellano [3] experimented with different sizes of different materials to analyse the effect of material composition and size on palletization parameters. Stelte [4] identified key factors affecting the pelletizing pressure in biomass palletization processes as raw material type, pellet length moisture content, and particle size. He also studied the relationship between them and biomass pelletization pressure using a single pellet press unit. Wu [5] developed a torque model in the pelleting process through mathematical analysis, FEA simulation, and testing research. Shen [6] analysed the vibration of the ring die pellet mill with the eccentric rotor and optimized its structure. The above works provide a theoretical basis for the dynamic analysis of the ring die pellet mill. However, stochastic vibration caused by random squeezing pressure is not analysed in these works.

The material has randomness-caused squeezing pressure to stochastic change in the extrusion forming process. Random vibration affects the pellet quality, the lifetime of the core component, and the stability and reliability, and it directly results in frequent failure and hidden danger. Therefore, it is necessary to analyse the dynamics of the ring die pellet mill with random squeezing pressure.

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2. Dynamic Model of Ring Die Pellet Mill

2.1. Mechanical Analysis of Ring Die

At present, most pellets are produced in pellet mills of the ring die type, and the double-roller ring die pellet mill has a very wide range of applications in biomass energy. To establish the dynamic model of the ring die pellet mill, force analysis is the foundation, and the mutual squeeze force between the ring die and roller is the key to study the dynamics model. After the material enters the extrusion forming zone, it is subjected to the mutual squeeze force of the ring die and the roller, and its direction points to the roller's rotation center. At the same time, the relative movement between the material and the ring die produces a friction to hinder the rotation of the ring die. The bonding forces between particles ensure the highly density of biomass.

The bonding forces of biomass in the extrusion process have been classified into five major categories [7]: solid bridges, mechanical interlocking, adhesion and cohesion, interfacial forces and capillary pressure, and attraction forces between solid particles. The bonding forces occur throughout the extrusion process and have been described well by Stelte [8]. The process is shown in Figure 1. Particle rearrangement is the first step in the extrusion process. When the pressure between the particles gradually increases, the gap between the particles is filled. When the gaps between the particles are filled, elastic and plastic deformations of the particles occur. As the extrusion pressure increases, the biomass cells are destroyed and the bonding forces between the particles increase. When the cell-walls are broken up, the empty space inside the cell (vacuole) of dry biomass is compressed [9]. Because of the viscoelastic properties of biomass, when the biomass is compressed for a period of time, creep and plastic flow occur, and the stress relaxation phenomenon is produced.

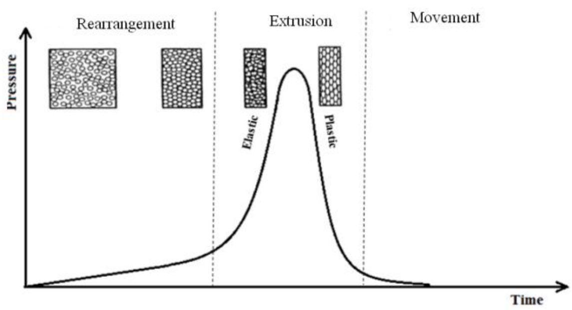


Figure 1. The bonding forces curve in the extrusion process

According to the bonding forces curve in the extrusion process, the material is divided into three processes shown in Figure 2 in the extrusion process: feeding process, deformation extrusion process, and extrusion forming process [10]. In the deformation extrusion zone and extrusion forming zone, the material is extruded and formed under the mutual squeeze force of the ring die and the roller. In the deformation extrusion zone, the material undergoes a series of elastic and plastic deformation, reaches a certain density, and then produces irreversible plastic deformation. In the extrusion forming zone, the clearance between the ring die and the roller rapidly becomes narrower, causing the extrusion pressure to increase rapidly. The material is further plastically deformed, and the density continues to increase. Finally, the material is squeezed into the ring die's hole until the extruding ring die. According to the mechanical model of extrusion force proposed by Wu, the relation function of squeeze pressure and material density conforms to the exponential model [11], and its formula is as follows:

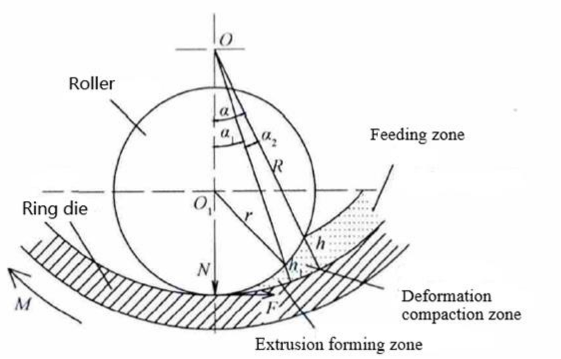


Figure 2. Pelleting process and principle

$$P_L(\theta) = kP_{r0}e^{-r(\theta)/\rho} \tag{1}$$

$$P_L = kP_{r0}e^{-r/\rho} \tag{2}$$

Where $P_L(\theta)$ is the pressure at section θ in the deformed extrusion zone, P_L is the pressure in the extrusion forming zone, P_{r0} is the prestress pressure, k is the coefficient of force and density and is related to pressure and the particle size coefficient, and $r(\theta)$ is a particle function that is related to particle size, coefficient of friction, Poisson's ratio, and compression ratio. Therefore, the extrusion force between the ring die and the roller is obtained by integrating the pressure of the deformation extrusion zone and the extrusion forming zone, as follows:

$$F = P_L Br\alpha_1 + \int_{\alpha_1}^{\alpha_1+\alpha_2} P_L(\theta)Br\theta \mathrm{d}\theta \tag{3}$$

Where F is the extrusion force between the ring die and the roller, B is the width of the ring die, r is the radius of the ring die, α_1 is the angle of the deformed extrusion zone, and α_2 is the angle of the extrusion forming zone.

The force of the ring die is shown in Figure 3. The ring die is affected by the extrusion forces F_1 and F_2, the friction F_{f1} and F_{f2}, and the driving moment M_n. It is obvious that the relationship between the driving moment and the extrusion force and friction satisfies the equations as follows:

$$M_n = F_{f1}R + F_{f2}R \tag{4}$$

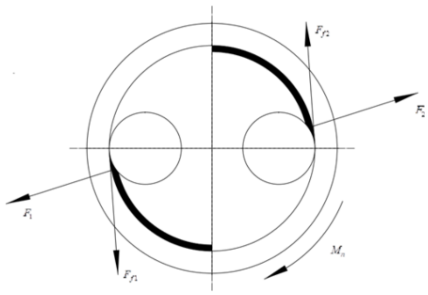


Figure 3. The force of ring die

2.2. Layer Design of Web

The ring die pellet mill's transmission structure is ordinarily helical gear as shown in Figure 4, and the ring die is driven by the helical gear. The ring die pellet mill relies on the ring die rotating to bring the material into clearance between the ring die and roller. The material is subjected to the extrusion force of the ring die and roller and enters the ring die hole until the extruding ring die.

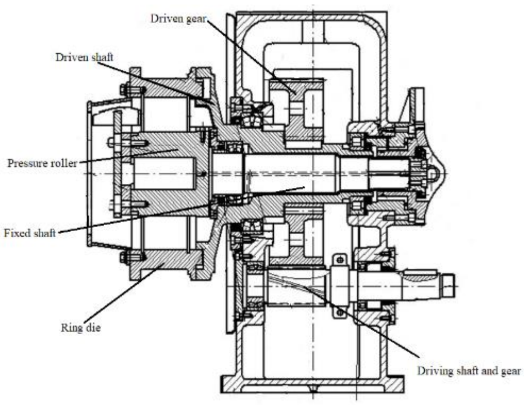


Figure 4. Ring die pellet mill

According to the structure of the ring die pellet mill, the dynamic model of the torsion direction is established by the lump-mass method as shown in Figure 5. In Figure 5, the inertia moment of the input is J_d, the inertia moment of the ring die is J_l, and the inertia moment of the driving gear and driven gear is J_1 and J_2, respectively. To establish the dynamical model of the ring die pellet mill, the first step is to analyse its motion. The relation of the rotation between the input, ring die, driving gear, and driven gear is as follows:

$$\begin{aligned} \phi_d &= \omega_1 t + \theta_d,\ \phi_1 = \omega_1 t + \theta_1 \\ \phi_2 &= \omega_2 t + \theta_2,\ \phi_l = \omega_2 t + \theta_l \end{aligned} \tag{5}$$

Where the rotation of the input is ϕ_d and the vibrational rotation is θ_d; the rotation of the driving gear is ϕ_1 and the vibrational rotation is θ_1; the rotation of the driven gear is ϕ_2 and the vibrational rotation is θ_2; and the rotation of the ring die is ϕ_l and the vibrational rotation of the input is θ_l.

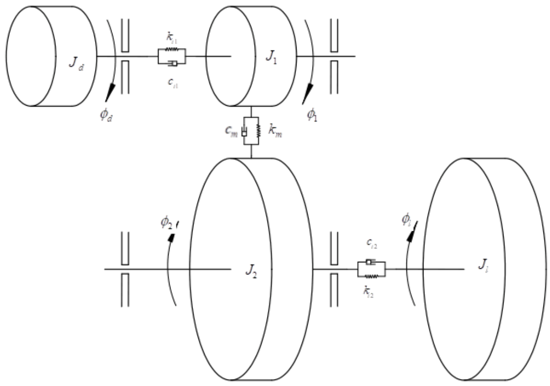


Figure 5. Torsional vibration model of ring die pellet mill

The helical gear pairs are considered a pair of rigid discs connected by a spring and a damper [12], the stiffness coefficient in the direction of the meshing force is expressed as k_m, and the damping coefficient is expressed as c_m. The fear meshing force closely relates to gear deformation in the direction of the meshing force, and their relationship is as follows:

$$F = c_m \cos\beta_b \dot{\delta} + k_m \cos\beta_b \delta \tag{6}$$

Where the spiral angle of the basic circle is β_b, the gear deformation in the direction of the meshing force is δ, and it is as follows:

$$\delta = r_{b1}\theta_1 - r_{b2}\theta_2 - e(t) \tag{7}$$

Where the radius of the driving gear and driven gear is r_{b1} and r_{b2}, respectively, and the meshing error is $e(t)$.

To research the torsional vibration of the ring die pellet mill, the torsional dynamic equation is established by the Lagrange equation as follows:

$$\begin{aligned} &J_d \ddot{\theta}_d + c_{t1}(\dot{\theta}_d - \dot{\theta}_1) + k_{t1}(\theta_d - \theta_1) = T_d \\ &J_1 \ddot{\theta}_1 + c_{t1}(\dot{\theta}_1 - \dot{\theta}_d) + k_{t1}(\theta_1 - \theta_d) = Fr_{b1} \\ &J_2 \ddot{\theta}_2 + c_{t2}(\dot{\theta}_2 - \dot{\theta}_i) + k_{t2}(\theta_2 - \theta_i) = -Fr_{b2} \\ &J_l \ddot{\theta}_i + c_{t2}(\dot{\theta}_i - \dot{\theta}_2) + k_{t2}(\theta_i - \theta_2) = -M_n \end{aligned} \tag{8}$$

Where the torsional stiffness of the driving shaft and driven shaft is k_{t1} and k_{t2}, respectively, and the torsional damping is c_{t1} and c_{t2}. Equation (9) is expressed in the matrix as follows:

$$
\begin{aligned}
&M\ddot{x}+C\dot{x}+K(t)x=T(t)\\
&x=\begin{bmatrix}\theta_d & \theta_1 & \theta_2 & \theta_l\end{bmatrix}^T\\
&M=\begin{bmatrix}J_d & & & \\ & J_1 & & \\ & & J_2 & \\ & & & J_l\end{bmatrix}\\
&C=\begin{bmatrix}c_{t1} & -c_{t1} & & \\ -c_{t1} & c_{t1} & & \\ & & c_{t2} & -c_{t2} \\ & & -c_{t2} & c_{t2}\end{bmatrix}\\
&K=\begin{bmatrix}k_{t1} & -k_{t1} & & \\ -k_{t1} & k_{t1} & & \\ & & k_{t2} & -k_{t2} \\ & & -k_{t2} & k_{t2}\end{bmatrix}\\
&T(t)=\begin{bmatrix}T_d & Fr_{b1} & -Fr_{b2} & -M_n\end{bmatrix}^T
\end{aligned}
\tag{9}
$$

Where x is the torsional displacement, M is the quality matrix, C is the damping matrix, K is the stiffness matrix, and $T(t)$ is the moment.

3. Excitation Analysis

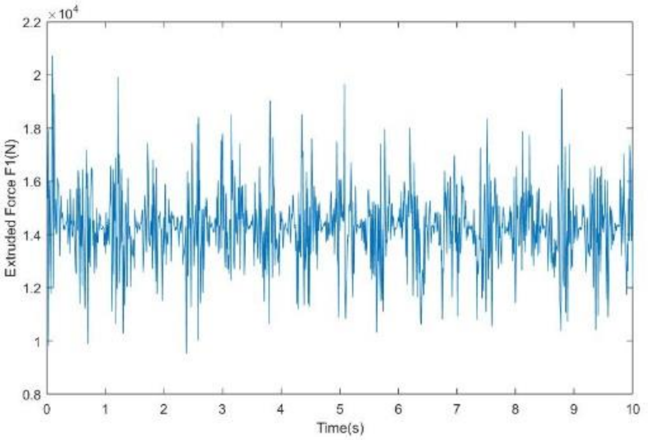
3.1. External Excitation Analysis

Changes in the extrusion force are the main reason of the vibration for the ring granulator. After entering the granulating chamber, the material enters the extrusion zone with the ring die rotating and is squeezed and extruded under the action of the extrusion force. However, the thickness of the material is random in the actual extrusion process, resulting in a randomly changing extrusion force. The material will be crushed, mixed, burden, and cured before the material is squeezed, and some metal and sandstone are added into the material. In the process of material extrusion, the metal and sandstone make the extrusion force increase. Some particles' diameters are larger than the clearance between the ring die and the roller, leading to a sharp extrusion force.

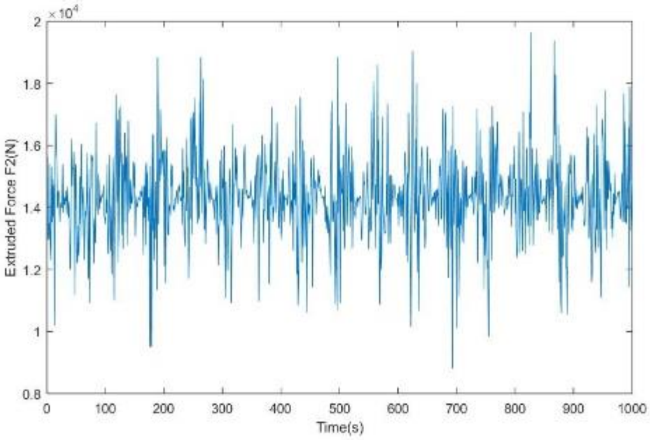
The extrusion force between the ring die and the roller is random and not predetermined, so only the probabilistic method is used to describe its change rule. The stochastic volatility model is a time-series analysis method [13] that regards volatility as an implicit variable. The extrusion force of ring die is established by the stochastic volatility model, and its expression is as follows:

$$
\begin{aligned}
&F(t)=\varepsilon_t+E(y_t\,|\psi_{t-1})+\sigma_t z_t\\
&\ln(\sigma_t^2)=a+\varphi\ln(\sigma_{t-1}^2)+\sigma_\eta\eta_t
\end{aligned}
\tag{10}
$$

Where $F(t)$ is the amplitude of extrusion force fluctuation, ε_t is the peak of extrusion force fluctuation, $E(y_t\,|\psi_{t-1})$ is the conditional mean of extrusion force fluctuation obtained by using the information from the previous moment, σ_t is the conditional variance, a is a constant that reflects the average of volatility, φ is a persistence parameter, σ_η is the average variance of volatility, and z_t and η_t are the normal distribution. According to the stochastic volatility model, the extrusion force is shown as Figure 6.



(a) The extrusion force F_1



(b) The extrusion force F_2

Figure 6. The extrusion force

3.2. Intrinsic Excitation Analysis

The variation of the intrinsic excitation is mainly aroused by the change of gear meshing stiffness and the error of manufacture and installation. In the process of gear transmission, the number of gear teeth engaged in meshing varies with time periodically, which causes the meshing stiffness of gears to change and leads to the dynamic change of the meshing force. When the contact ratio is less than or equal to 1, the meshing stiffness is single tooth. When the contact ratio is greater than 1, the meshing stiffness is multiple teeth. For helical gear, the meshing process is when a surface of the tooth begins to engage, gradually expands to the entire tooth surface, and finally pulls out when the other tooth begins. Thus, the meshing stiffness of the helical gear is time-varying [14], and it is shown in Figure 7.

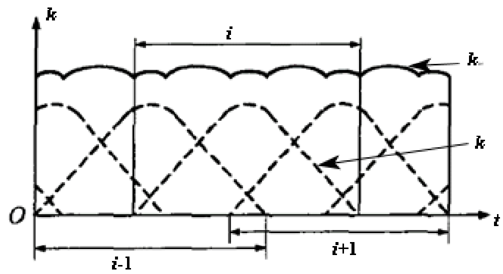


Figure 7. The meshing stiffness

The error caused by the machining and installation brings about changes in the displacement period between the meshing teeth and makes the meshing force change periodically. The error excitation is related to the accuracy of gears. It is represented by the superposition of the sine function and random fluctuation [15], as follows:

$$e(t) = e_m + e_r \sin(\omega_e t + \varphi_e) + \varepsilon \tag{11}$$

Where e_m is the average of error excitation, e_r is the amplitude of error excitation, ω_e is the angular frequency corresponding to the gear meshing frequency, φ_e is the initial phase of error excitation, and ε is the integrative transmission error.

4. Random Dynamic Response Analysis

4.1. Influence of External Excitation on Random Dynamic Response

Using the stochastic volatility model of the extrusion force, the driving torque is obtained by formula 4, and its time curve is shown in Figure 8. For each random excitation, the dynamic equation of the ring die pellet mill is solved by the Runge-Kutta integration method, and the torsional vibration of the ring die pellet mill is obtained as shown in Figure 9.

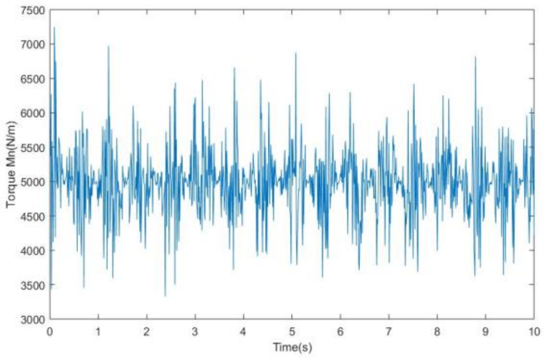
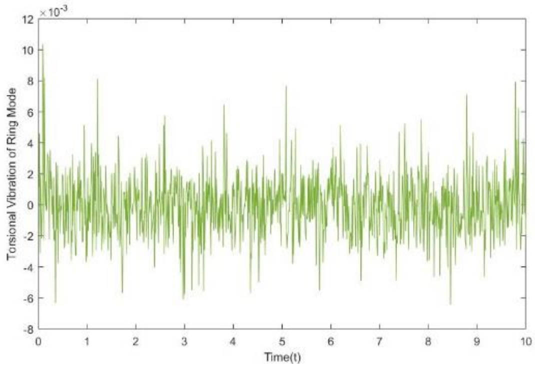
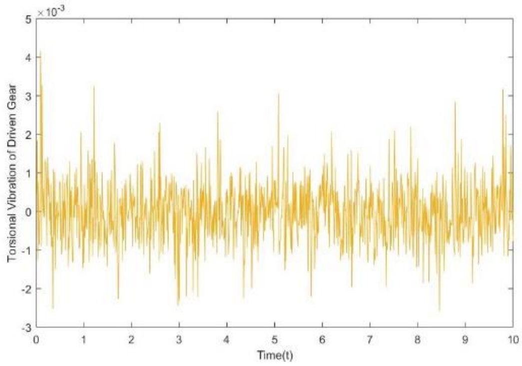


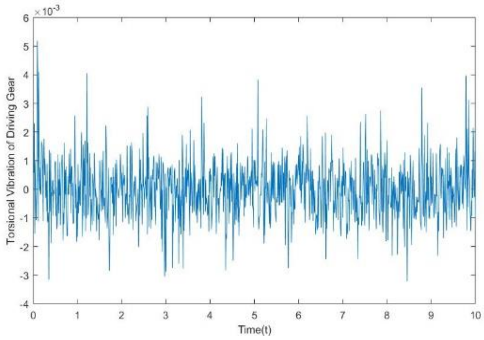
Figure 8. The driving torque of ring die



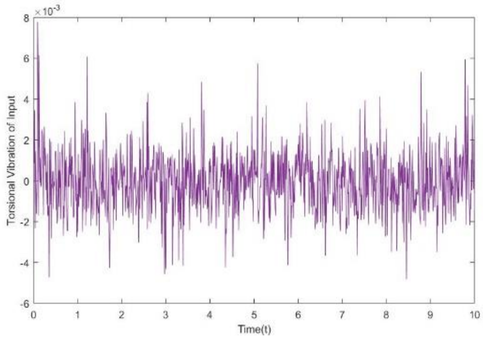
(a) The torsional vibration of ring die



(b) The torsional vibration of driven gear



(c) The torsional vibration of driving gear



(d) The torsional vibration of input

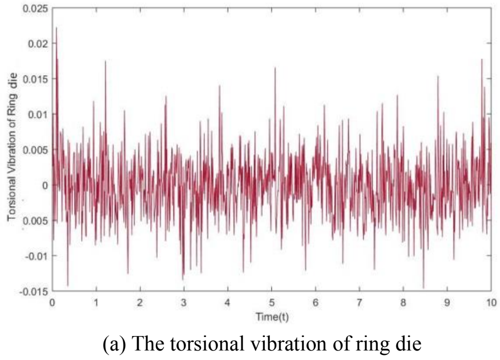
Figure 9. The time response curve of torsional vibration

According to the torsional vibration of the ring die pellet mill, the torsional vibration and the driving torque have similar changes in trend. The greater the driving torque, the greater the torsional vibration fluctuation of the ring die pellet mill. The torsional vibration of the ring mode is a maximum, and the torsional vibration amplitude of driving gears is larger than that of the driven gears.

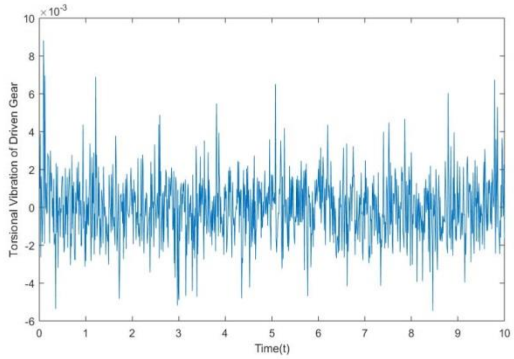
4.2. Influence of Intrinsic Excitation on Random Dynamic Response

The intrinsic excitation is divided into stiffness excitation and error excitation, and the stiffness excitation is deterministic. The error excitation is random, assuming it accords with the normal distribution as follows: $\varepsilon \sim N(\varepsilon, \sigma^2)$. σ describes the dispersion degree of the normal distribution, which depends on the manufacturing and installation accuracy. The higher the precision, the smaller the discrete degree.

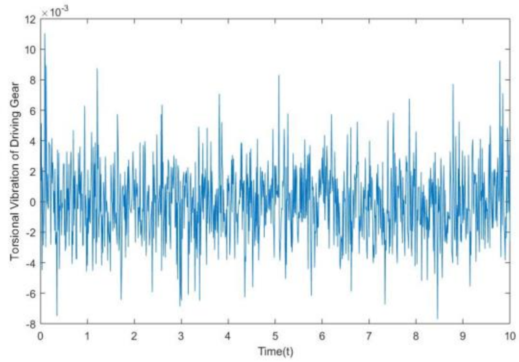
Assuming the average equals 0, the dynamic equation of the ring die pellet mill is solved when the dispersion degree is 0.02 and 0.05, and it is obtained as shown in Figures 10 and 11. When the random error excitation is considered, the torsional vibration of the ring die pellet mill increases according to Figures 10 and 11. When the dispersion degree is 0.02, the torsional vibration is almost identical without considering the error excitation, and the error excitation has less influence on torsional vibration. When the dispersion degree is 0.05, the torsional vibration is increased and is significantly different without considering the error excitation, and the error excitation influences the torsional vibration of the ring die pellet mill. Therefore, the dispersion degree of error excitation affects the torsional vibration when it reaches a certain level.



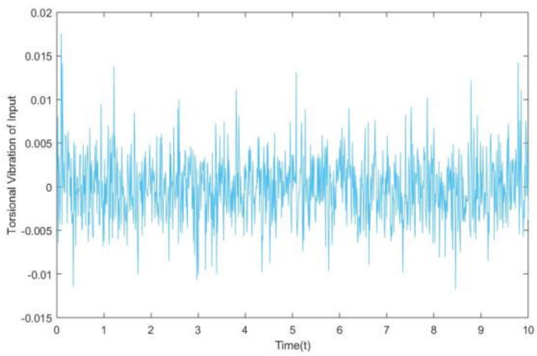
(a) The torsional vibration of ring die



(b) The torsional vibration of driven gear

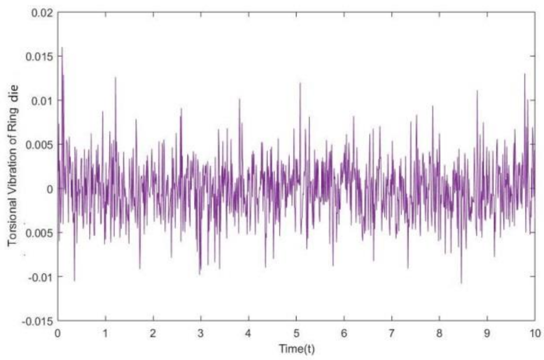


(c) The torsional vibration of driving gear

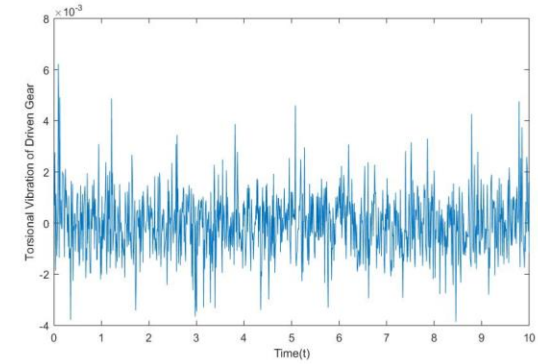


(d) The torsional vibration of input

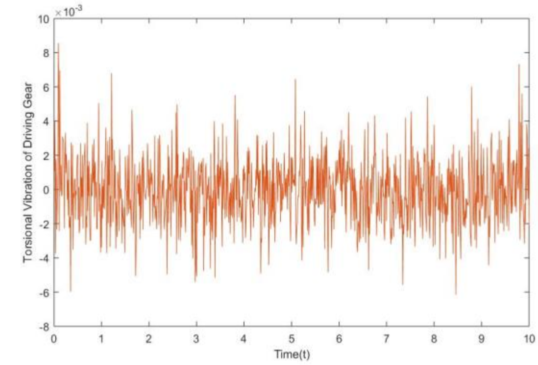
Figure 10. The time response curve of torsional vibration when the dispersion degree is 0.02



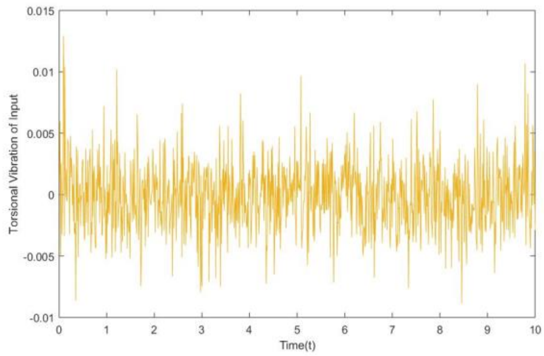
(a) The torsional vibration of ring die



(b) The torsional vibration of driven gear



(c) The torsional vibration of driving gear



(d) The torsional vibration of input

Figure 11. The time response curve of torsional vibration when the dispersion degree is 0.02

5. The Dynamic Simulation Analysis of Ring Die Pellet Mill

In order to verify the correctness of the random dynamic analysis of the ring die pellet mill, the dynamic simulation model shown in Figure 12 is established by utilizing the Adams software. The ring die is a complex component with numerous ring die holes, but the force of ring die holes has no obvious influence on the random dynamic analysis of the ring die pellet mill. The ring die is considered as a thick wall ring with a cross-section. The ring die pellet mill is composed of many components. In order to reduce the computational cost, the dynamic simulation model only retains the main components such as the ring die, gears, driven shaft, and driving shaft. The constraint, material, contact, and damping of each component are set up according to the actual structure. Finally, the data of frictional moment is imported into the spline function of Adams, and the friction moment and the driving moment are respectively applied to the ring die and driving shaft.

The dynamic simulation model of the ring die pellet mill is solved. When the integrator is set to the HHT integrator, the end time is 10s and the step number is 1000. The torsional motion of ring die is shown in Figure 13. The torsional vibration is consistent with the random dynamic analysis results.

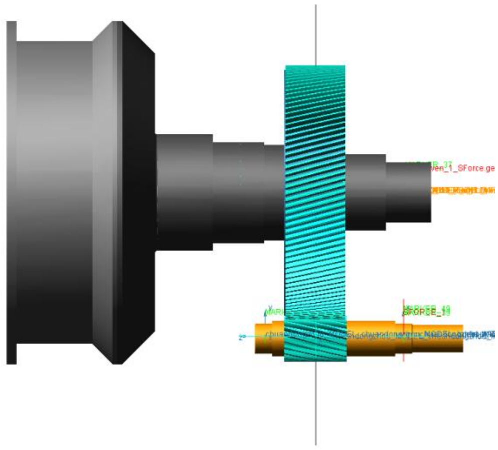
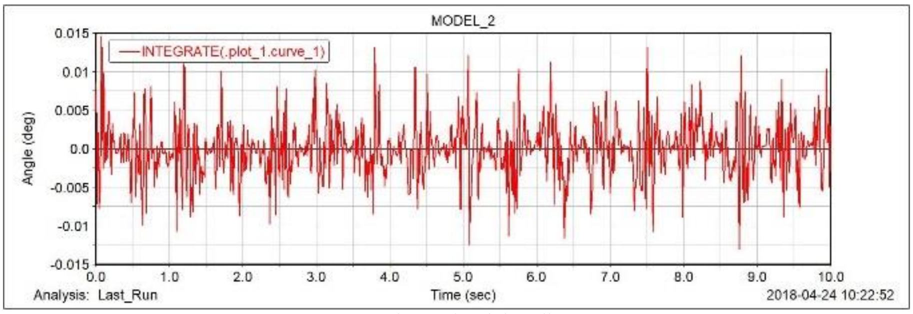
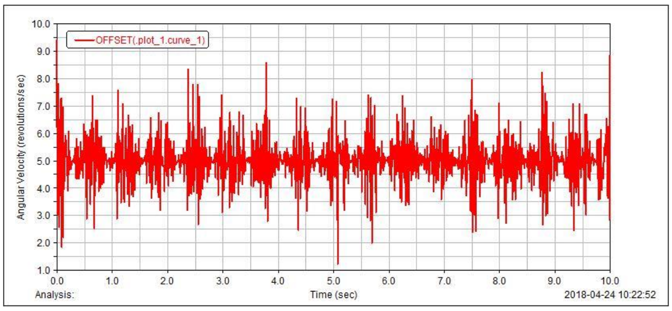


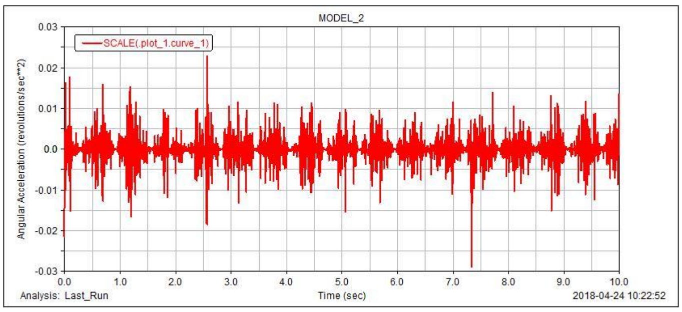
Figure 12. The dynamic simulation model of ring die pellet mill



(a) The angle of ring die



(b) The angular velocity of ring die



(c) The angular acceleration of ring die

Figure 13. The torsional motion of ring die

6. Conclusions

The particle is formed by rotating ring die, and the torsional vibration of ring die affects the quality of the particles, energy consumption, and so on. To study the torsional vibration of ring die, a dynamic model is established by Lagrange equations and the lump-mass method, and the extrusion force is created. Through random dynamic analysis, the following conclusions are obtained:

(1) The torsional vibration of the ring die, driven gear, driving gear, input, and driving torque have similar changes in trend, in which the torsional vibration of ring die is a maximum.

(2) The torsional vibration of ring die is connected to the rotational speed. The rotational speed of the driving gear is larger than that of the driven gear, so the torsional vibration amplitude of driving gears is larger than that of driven gears.

(3) The dispersion degree of error excitation affects the torsional vibration when it reaches a certain level.

The research results lay a foundation for the reliability and stability of the ring die pellet mill and play an important role in reducing the vibration.

Acknowledgements

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