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Article

Structural modal study of vertical system vibration based on large axial Cross-Wedge rolling mill

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Abstract: With the surge in demand for large shaft components in the railway transportation industry, traditional rolling mills are insufficient to meet actual production needs, leading to the development of wedge cross-rolling mill equipment suitable for producing large shaft components. This paper focuses on the study of the vibration characteristics of the vertical system of large axial Cross-Wedge rolling mill. By constructing a four-degree-of-freedom (4-DoF) vertical vibration dynamic model of the mill frame structure, the vibration characteristics of the vertical system were investigated, and the natural frequencies and main vibration modes of each order were obtained. To facilitate subsequent research and optimization of the overall mill structure, the 4DoF vertical system model was simplified into a symmetric single-degree-of-freedom (SDoF) model, and the sensitivity of the second-order mode to stiffness was explored. At the same time, finite element analysis (FEM) was used to conduct modal analysis on the mill vertical system, and vertical system velocity signals were obtained through on-site data collection. The results indicate that the simplified vertical system structural model matches the vibration characteristics of the mill's vertical system, and the natural frequencies of the vertical system calculated are basically consistent with the results from modal analysis and on-site data collection. This study provides a theoretical basis for the prediction, diagnosis, and structural parameter optimization of vertical vibration in large axial Cross-Wedge rolling mill.

Keywords: rolling mill vertical system; dynamic modeling; vibration characteristics; modal analysis

1. Introduction

With the rapid development of railways, urban subways, and large engineering machinery, the market demand for large shaft parts has grown exponentially. Traditional manufacturing processes for large shaft parts are primarily dominated by rapid forging and precision forging. However, these technologies suffer from low efficiency, poor dimensional accuracy, and unstable product quality, making them inadequate for meeting the ever-growing industrial demands [1,2]. In contrast, cross wedge rolling technology, with its prominent advantages such as high material utilization, fast production efficiency, and excellent forming quality, has become a vital method for the efficient plastic forming of shaft parts. Consequently, our project team has adopted cross wedge rolling technology to manufacture large axles [3–5] and independently developed the “Large Shaft Intelligent Cross Wedge Rolling Mill” [6]. This mill features rolls with a maximum outer diameter of 1,800 mm and can roll products with a maximum diameter of up to 250 mm. The successful development of this mill has provided reliable and highly efficient equipment for the rapid production of large shaft parts, making a significant contribution to the advancement of China’s rail transit industry.

At the initial stage of equipment development, fully considering its structural operational stability and reliability plays a crucial role in ensuring production efficiency and product quality [7, 8]. Based on conventional experience, it is understood that such a massive rolling mill is accompanied by complex vibration phenomena during operation. These vibrations not only affect the machining accuracy of the rolling mill but may also lead to premature wear or even failure of the equipment, thereby posing potential risks to production safety and economic benefits. Therefore, investigating the vibration characteristics of the large shaft intelligent cross wedge rolling mill is particularly important for the stable operation of the equipment.

At present, many scholars have conducted in-depth research on the vibration characteristics of strip steel rolling mills or medium and small-sized wedge cross-rolling mills. He et al. [9, 10] conducted in-depth investigations into rolling mill vibration theory, studying the vibration characteristics and vibration suppression of the rolls in a two-high rolling mill. They elaborated in detail on the typical dynamic characteristics existing in rolling mill vibration systems, including multi-degree-of-freedom coupling, parametric excitation, and nonlinear instability, and summarized the current research status of active control and passive suppression strategies. This work has laid a solid theoretical foundation for the dynamic characteristic analysis of rolling mills. Liu et al. [11] addressed the problem of rolling mill vibration under the constraints of nonlinear spring force and friction force in the hydraulic cylinder, and established a vertical vibration dynamic model that incorporates nonlinear constraints. Simultaneously, by employing the averaging method to solve the amplitude-frequency response of the system, they analyzed the influence of external excitation on system stability and bifurcation behavior, and revealed the evolution laws among periodic motion, period-doubling motion, and chaotic vibration, thereby providing a theoretical basis for the stability analysis of rolling mill vibration. Peng et al. [12] established a roll vibration model for a hot rolling mill that accounts for elastoplastic hysteretic deformation, and incorporated the dynamic rolling force into the vibration analysis. They investigated the effects of rolling speed, tension, roll diameter, and other parameters on the vibration response. The results revealed that the nonlinear stiffness variation induced by the dynamic rolling force affects the subharmonic resonance and internal resonance characteristics. Moreover, bifurcation diagrams, Lyapunov exponents, and other tools were employed to analyze the complex dynamic behaviors of the system. Chen et al. [13] took a four-high cold rolling mill as the research object, established a multi-degree-of-freedom dynamic model for the vertical vibration system incorporating the rolls, the mill stand, and the rolling interface, and conducted a theoretical investigation of the vertical vibration model using the stochastic averaging method. The study demonstrated that the vertical vibration of the cold rolling mill exhibits strong parameter sensitivity under random disturbances. Zhang et al. [14] established a horizontal-vertical-torsional coupled vibration model by incorporating nonlinear friction force and structural clearance factors in the rolling process. They analyzed the amplitude-frequency characteristics and bifurcation behavior of the work roll vibration under different clearance conditions. The study indicates that structural clearance enhances the nonlinear response of the system and is a significant factor inducing rolling mill vibration. Li et al. [15] established a nonlinear excitation vertical vibration model based on dynamic rolling force, and analyzed the effects of nonlinear factors on system stability and vibration characteristics. The results show that nonlinear stiffness has a significant effect on system stability, while increasing system damping can effectively reduce vibration amplitude and narrow the resonance region. Meanwhile, by employing the averaging method and singular value theory, the stability of the cold rolling mill roll system under non-autonomous and autonomous states was analyzed. Zhang et al. [16] established a horizontal-torsional vibration model for hot rolling, and calculated the dynamic rolling force and rolling torque increment by inputting the TCN-LSTM cascaded transfer model. The horizontal vibration displacement and torsional vibration displacement were simulated and analyzed. By reasonably adjusting the process parameters, the goal of vibration suppression was ultimately achieved. Jia et al. [17] established the dynamic model of a single-stand rolling mill system conducted simulation studies to explore the multi-factor influencing mechanism of vibration amplitude and frequency, and determined the cooperative vibration mechanism and control strategy of the cold rolling mill. Zhang et al. [18] calculated the vibration response of the cold rolling mill system by establishing a vertical nonlinear vibration model of structural clearance and dynamic rolling force and carried out a numerical simulation. The research results revealed the law of the influence of system parameters on the vertical nonlinear vibration of the cold rolling mill. Regarding the vibration characteristics of cross wedge rolling mills, Zhao and Shu [19] applied the finite element dynamics analysis module to determine the natural frequencies and mode shapes of the roll system of an automotive half-shaft cross wedge rolling mill under existing boundary conditions. The variation rules of the natural frequencies and mode shapes of the roll system with respect to different center distances and different constraint conditions were analyzed. Lin et al. [20] elaborated the principle of the cross wedge rolling (CWR) process in detail. Through finite element simulations and experiments, they investigated the forming process of shaft parts. Finite element models, rolling mill trials, and performance characterizations were systematically conducted to study the process.

Compared with strip rolling mills and small- and medium-sized cross wedge rolling mills, the vertical system of the large cross wedge rolling mill described in this paper exhibits prominent features such as enormous structural scale, complex overall vibration characteristics of the mill, and uneven mass distribution among components. Its vibration modes are not only influenced by the dynamic interaction between the rolls and the billet, but also strongly constrained by the overall frame stiffness and the connection stiffness of each substructure [21]. Systematic research and reports on the vibration characteristics of large shaft cross wedge rolling mills remain scarce. Therefore, on the basis of summarizing the aforementioned theoretical studies on rolling mill vibration, this paper conducts a systematic investigation into the structural vibration modes of the vertical system of the large shaft cross wedge rolling mill. The vibration characteristics are analyzed by constructing a dynamic model of the mill vertical system, and the vertical vibration behavior of the mill stand is analyzed by simplifying the vertical system vibration model in combination with a spring-mass system [22,23]. In addition, this paper also uses the finite element method to perform structural modal analysis on the rolling mill frame system, extracting the first four modes and natural frequencies, revealing the coupled vibration characteristics of the frame and roll system under different modes, and providing a basis for further study of the overall vibration characteristics and design optimization of large shaft-type wedge cross rolling mills [20].

2. Structural modeling of the vertical system

2.1. Introduction to the main structure of the rolling mill

The structural schematic of the large axial Cross-Wedge rolling mill investigated in this paper is shown in **Figure 1**. It mainly comprises the worm gear screw-down device, the mill stand structure, the roll system assembly, and the main drive system. During the rolling process, factors such as periodic fluctuations in rolling force, roll eccentricity, and torsional impact from the drive system cause complex coupled vibrations in various components of the equipment, which directly affect rolling accuracy and equipment service life. To this end, this paper focuses on the structural vibration model of the rolling mill, with modeling and analysis work primarily directed at the main structure of the mill.

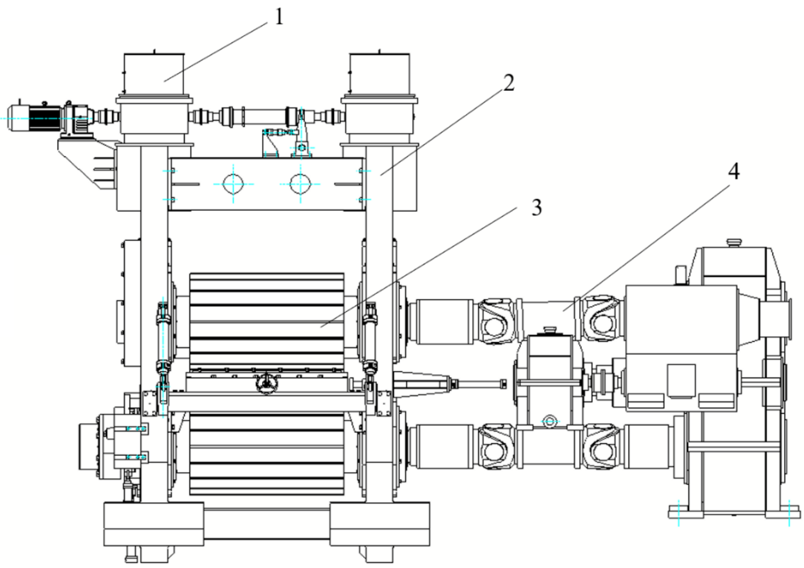

Figure 1. Schematic diagram of rolling mill structure: 1. Worm gear and worm pressing device; 2. Frame structure; 3. Roll assembly; 4. Main drive unit.

Figure 2 shows the model diagram of the large axial Cross-Wedge rolling mill. As shown in **Figure 2b**, the upper and lower roll systems of the mill mainly include the upper and lower work rolls (**Figure 2c**) and their corresponding bearings and bearing chocks. They are part of the vertical system of the mill and, together with the hydraulic system and the mill stand, constitute the supporting structure. **Figure 2d** shows the mill stand structure, which mainly consists of the upper and lower crossbeams, the left and right frames, and the worm gear screw-down hydraulic system, serving as the main supporting structure of the mill.

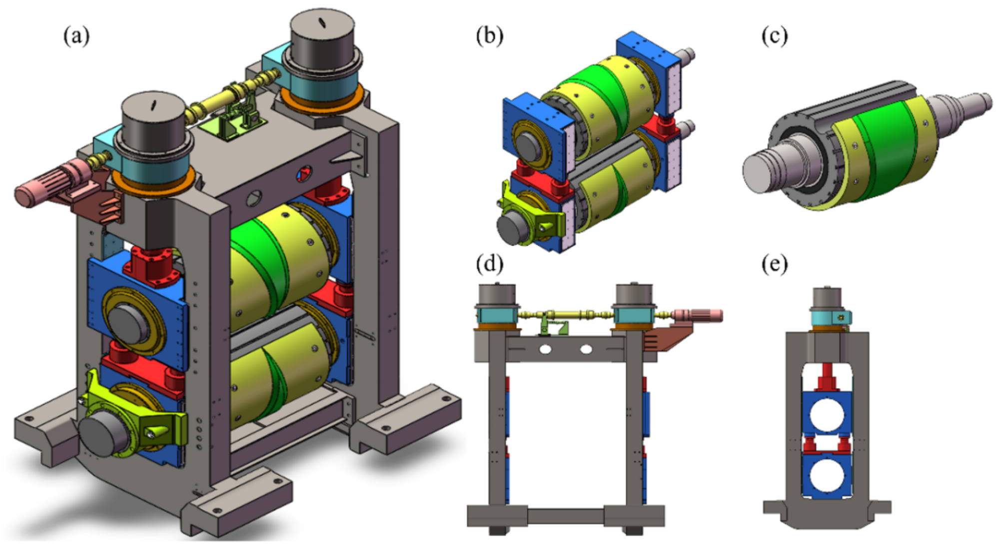

Figure 2. The large axial Cross-Wedge rolling mill main structure detailed explanation **(a)** Rolling mill main structure; **(b)** Roll system; **(c)** Roll; **(d)** Frame; **(e)** Support structure.

2.2. Establishment of the vertical vibration system model

Analyzing the force conditions of the mill stand structure during the operation of the rolling mill helps to explore and optimize the dynamic response and vibration characteristics of the mill stand, which is of great importance for establishing the structural model of the rolling mill. The force conditions of the mill stand structure are shown in **Figure 3**, where the mill stand is subjected to a resultant vertical force within it. This resultant vertical force is caused by the rolling force exerted on the mill stand by the roll system of the rolling mill, and it is uniformly shared by the upper and lower crossbeams and other supporting structures of the mill stand. Meanwhile, the hydraulic system also plays a key role in supporting the mill stand structure. Therefore, in establishing the vertical system of the rolling mill, the equivalent stiffness of the closed-frame mill stand structure, as well as the stiffness of the hydraulic system and the bearing chocks and other parts, are mainly considered.

Based on the force analysis of the vertical structure of the mill stand and in combination with dynamic principles, a simplified mass-spring system model is adopted to establish the vertical vibration system model of the cross wedge rolling mill. To facilitate the calculation of the natural frequencies of the mill vertical system, as well as the analysis of vibration characteristics and modal sensitivity, the mill model is further simplified to obtain a four-degree-of-freedom vertical vibration system model [22], as shown in **Figure 4**.

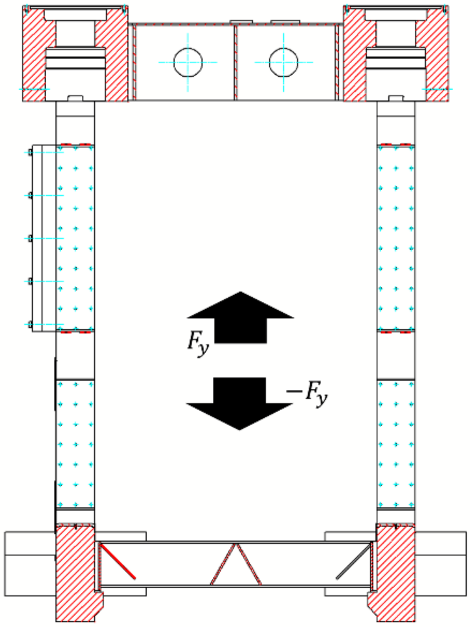

Figure 3. Force analysis of the vertical structure of the mill stand.

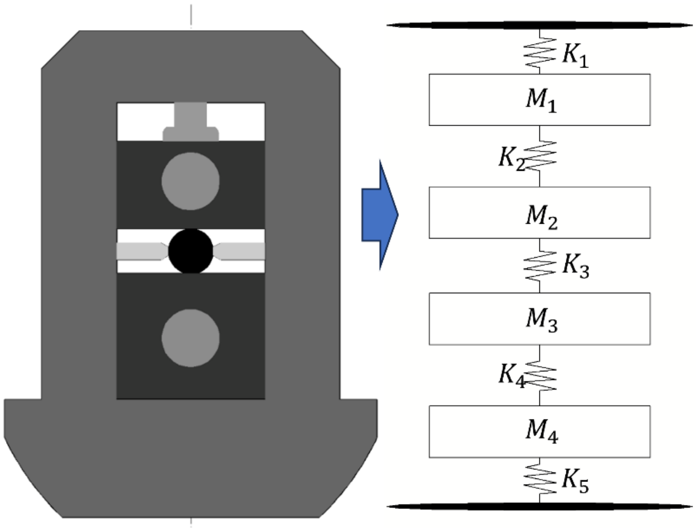

Figure 4. The vertical vibration system model.

Among them: M_1—the equivalent mass of the upper part of the stand and the upper part of the pressing device and locking device; M_2—the equivalent mass of the upper working roller system; M_3—the equivalent mass of the lower working roller system; M_4—the mass of the lower part of the stand and the lower part of the locking device; K_1—the equivalent stiffness of the upper part of the stand and the pressing device; K_2—the equivalent stiffness of the upper working roller bearing seat and hydraulic cylinder; K_3—the equivalent stiffness of the pre-tightening hydraulic cylinder; K_4—the equivalent stiffness of the lower working roller bearing seat; K_5—the bending equivalent stiffness of the lower part of the stand and the crossbeam.

Based on the principles of rolling mill structural dynamics, the dynamic differential equation for establishing the vertical vibration system model is:

$$[M]\{\ddot{y}_i\} + [C]\{\dot{y}_i\} + [K]\{y_i\} = \{F_y\} \tag{1}$$

$$[M] = \begin{bmatrix} M_1 & & & \\ & M_2 & & \\ & & M_3 & \\ & & & M_4 \end{bmatrix} \tag{2}$$

$$[C] = \begin{bmatrix} c_1+c_2 & -c_2 & & \\ -c_2 & c_2+c_3 & -c_3 & \\ & -c_3 & c_3+c_4 & -c_4 \\ & & -c_4 & c_4+c_5 \end{bmatrix} \tag{3}$$

$$[K] = \begin{bmatrix} k_1+k_2 & -k_2 & & \\ -k_2 & k_2+k_3 & -k_3 & \\ & -k_3 & k_3+k_4 & -k_4 \\ & & -k_4 & k_4+k_5 \end{bmatrix} \tag{4}$$

$$\{y_i\} = \begin{Bmatrix} y_1 & y_2 & y_3 & y_4 \end{Bmatrix}$$

Where, $[M]$, $[C]$, and $[K]$ are mass, damping, and stiffness matrices respectively; and y_1, y_2, and y_3 are the component acceleration, velocity, and displacement series respectively.

2.3. Vertical system vibration characteristics analysis

To calculate the natural frequency and principal mode of the system, the problem of solving undamped free vibration is transformed into the problem of finding eigenvalues [24]. Then, let $[C] = \{y_i\} = 0$, the system can be used as the differential equations of undamped vibration:

$$[J]\{\ddot{y}_i\} + [K]\{y_i\} = \{0\} \tag{5}$$

$$[K]\{A\} = \omega^2[M]\{A\} \tag{6}$$

Where ω is the frequency vector when vibrating; $\{A\}$ is the master mode of each order frequency of the vertical vibration system.

The equivalent stiffness relationships of the vertical system of the rolling mill frame are shown in **Figure 5**.

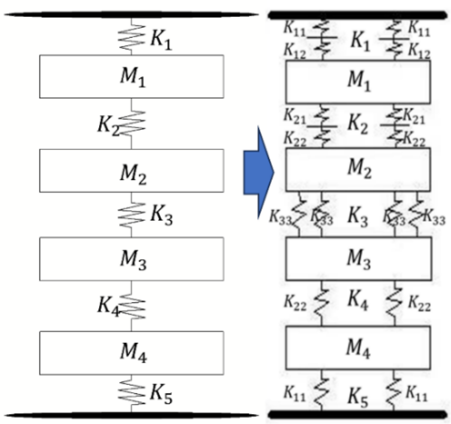

Figure 5. Schematic diagram of equivalent stiffness.

The equivalent masses of each component in the vertical system are calculated as follows:

$$M_1 = \frac{M_\mathrm{P}}{2} \times 2 + M_\mathrm{Y} + M_\mathrm{S} \tag{7}$$

$$M_4 = \frac{M_\mathrm{P}}{2} \times 2 + 2M_\mathrm{G} + M_\mathrm{X} \tag{8}$$

$$M_2 = M_\mathrm{R} + 2M_\mathrm{Z} \tag{9}$$

$$M_3 = M_\mathrm{R} + 2M_\mathrm{Z} + M_\mathrm{T} \tag{10}$$

Where, M_Y is the equivalent mass of the press device, M_S is the equivalent mass of the upper part of the locking device, M_R is the equivalent mass of the roll, M_Z is the equivalent mass of the bearing and bearing seat, M_T is the equivalent mass of the push-back bearing seat, M_G is the equivalent mass of the rail seat, M_X is the equivalent mass of the lower part of the locking device, M_P is the equivalent mass of the stand archway. $M_\mathrm{P} = K_p/\omega^2$, where K_p is the equivalent stiffness of the stand, ω is the natural frequency, $\omega = 2\pi f = \sqrt{(K/M)}$, then $M_P = K_p/(4\pi^2 f^2)$.

The upper and lower parts of the arch are respectively stressed F, and the displacements of the upper and lower parts are recorded as s_1 and s_2, then the stiffness of the stand is:

$$K_P = \frac{F}{|s_1 - s_2|} \tag{11}$$

The equivalent stiffness of each component in the vertical system is calculated as follows:

$$\frac{1}{K_1} = \frac{\frac{1}{K_{11}} \quad \frac{1}{K_{12}}}{2} \tag{12}$$

$$\frac{1}{K_2} = \frac{\frac{1}{K_{21}} \quad \frac{1}{K_{22}}}{2} \tag{13}$$

$$K_3 = 4K_{33} \tag{14}$$

$$K_4 = 2K_{22} \tag{15}$$

$$K_5 = 2K_{11} \tag{16}$$

Where, $K_{11} = 2K_p$ is the equivalent stiffness of the half-stand, K_{12} is the stiffness of the drive screw, K_{21} is the stiffness of the pushdown hydraulic cylinder, K_{22} is the stiffness of the roll bearing seat, and K_{33} is the stiffness of the pre-loaded hydraulic cylinder.

To obtain the equivalent stiffness and natural frequency of the stand archway, the finite element method is used to carry out a modal analysis of the stand archway. The rolling mill is divided into two parts uniformly, and the displacement of the upper and lower parts is solved by applying uniform load on the rolling mill, and then the equivalent stiffness is solved. The modal analysis results of the natural frequency model of the stand archway in the vertical direction are shown in **Figure 6**, and the finite element displacement results of the stand archway after loading are shown in **Figure 7**. It is known that the corresponding natural frequency in the vertical direction is 106.33 Hz.

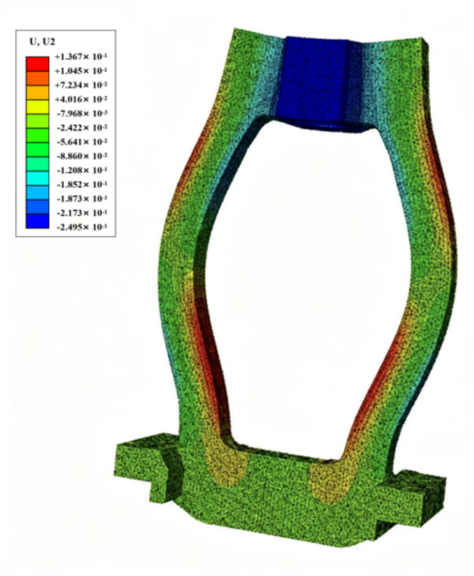

Figure 6. Finite element modal analysis of stand archway.

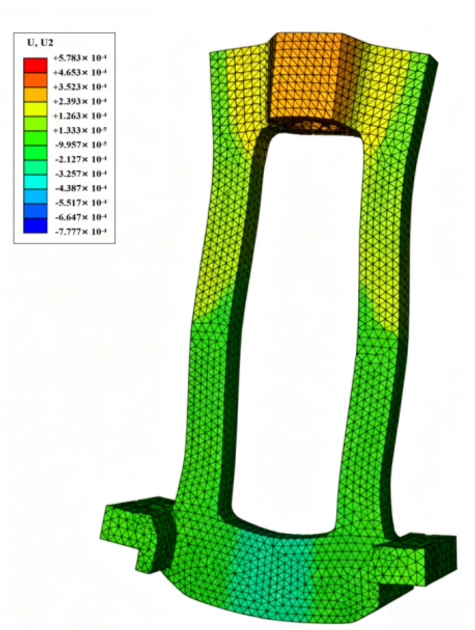

Figure 7. The result of the finite element displacement of the stand archway.

The equivalent mass and equivalent stiffness of the rack vertical system were solved through numerical analysis software, and the vertical system model parameters were obtained through calculation, as shown in **Table 1**.

Table 1. The parameters of the vertical system model.

Equivalent mass	Value (kg)	Equivalent stiffness	Value (10^9N/m)
M_1	109,061	K_1	6.1
M_2	75,640	K_2	3.1
M_3	75,640	K_3	0.7
M_4	94,543	K_4	2.9
—	—	K_5	5.9

The natural frequency of the vertical system is shown in **Table 2**. The first-order natural frequency is 149 Hz, and the vibration mode of the whole rolling mill in the vertical direction is downward at the same time. In the second stage, the natural frequency is 190.8 Hz, and the vibration mode of the rolling mill is symmetrical and the amplitude is similar along the upper and lower rolls. The third-order natural frequency is 320.1 Hz, and the displacement direction of the upper and lower rolls is the same, which is opposite to the displacement of the upper and lower stands. The fourth-order natural frequency is 335.3 Hz, when the vibration direction of the upper and lower rolls is opposite, and the vibration direction of the upper and lower stands is opposite.

Table 2. The natural frequencies of vertical systems (Hz).

Frequency	f_1	f_2	f_3	f_4
Natural frequency	149.0	190.8	320.1	335.3

At the same time, it is calculated that the master mode corresponding to each order frequency of the vertical system structure model of the rolling mill and the master mode diagram are shown in **Table 3** and **Figure 8**.

Table 3. The principal vibrational modes corresponding to natural frequency of each order.

Number	1	2	3	4
f_1	−0.4267	−0.9679	−1	−0.4328
f_2	0.5768	1	−0.9925	−0.5374
f_3	−1	0.7501	0.0976	−0.3188
f_4	0.2047	−0.2305	0.6320	−1

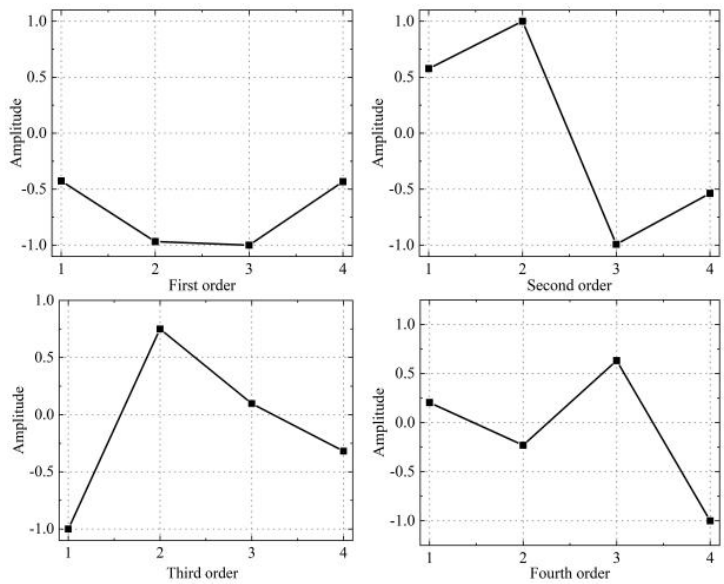

Figure 8. Diagram of the principal vibrational modes corresponding to natural frequency of each order.

2.4. Simplification of the rolling mill vertical system model

By using the spring-mass system, the equivalent mass and equivalent stiffness of the vertical vibration system are simplified, the structure model of the 4-DoF vertical vibration system is constructed, and its natural frequency and mode are calculated. In order to reduce the calculation amount of the subsequent research process of the vibration characteristics of the whole structure of the rolling mill, in order to better analysis and optimization, this paper simplifies the vertical vibration system model based on the 4-DoF.

Through the above analysis, it can be seen that when the second order natural frequency is 190.8 Hz, the displacement direction of the upper roll and the upper stand is the same, while the displacement direction of the lower roll and the lower stand is opposite, and the second order natural frequency is within the frequency range of the third-octave vibration (100 Hz–240 Hz), so the vibration in the second order mode is the most harmful to the rolling parts. By analyzing the stiffness sensitivity of the vertical system in the second mode, the structural model of the vertical system is further simplified. The sensitivity of the system to stiffness is:

$$\frac{\partial f_r}{\partial k_m} = \frac{1}{2f_r}\{A_r\}^T \frac{\partial K}{\partial k_m}\{A_r\} \tag{17}$$

Where k_m is each stiffness in the system; K is the stiffness matrix; f_r and $\{A_r\}$ are the natural frequencies and principal modes of the R-order modes.

Substituting the system structural parameters constructed previously into the above formula, the sensitivities of various stiffnesses to the second-order vertical system mode are obtained through numerical analysis, as shown in **Figure 9**. Among them, the sensitivity of K1 is 0.87×10^{-3}, K2 is 0.11×10^{-3}, K3 is 6.4×10^{-3}, K4 is 0.54×10^{-3}, and K5 is 0.75×10^{-3}, indicating that the most sensitive stiffness in the second-order mode is the equivalent stiffness K3, which is most sensitive to the pre-stressed hydraulic cylinder stiffness. The effects of stiffness K1 and K5 are also relatively significant, while K2 has almost no influence.

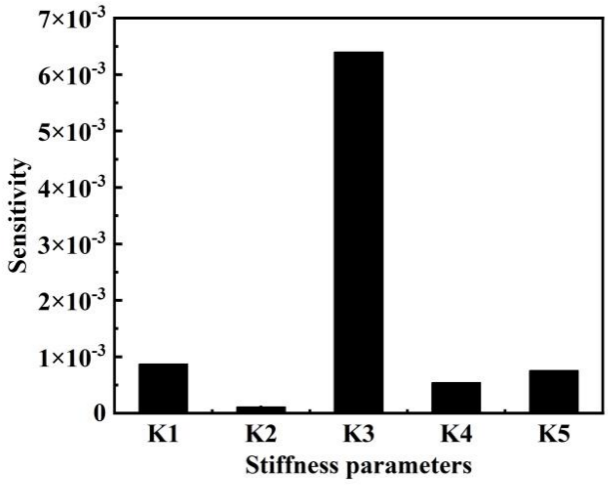

Figure 9. Sensitivity of various stiffnesses to the second mode of the vertical vibration system.

By means of stiffness sensitivity analysis, the vertical structure model established above is simplified. However, according to the introduction, the 4-DoF structure model can be simplified into a two-degree-of-freedom (2-DoF) vibration system structure model according to its vibration characteristics, so the frequency corresponding mode diagram is made according to the above calculation data. **Figure 8** is the master mode corresponding to each order frequency of the vertical system structure model of the rolling mill.

From the second-order mode shape shown in **Figure 8**, it can be seen that the upper and lower parts of the vertical system have basically the same vibration pattern, and the upper and lower roll sets as well as the left and right bearing housings correspond basically in mass and stiffness. Therefore, assuming a symmetric distribution of the upper and lower parts, the 4-DoF structural model is simplified into a 2-DoF vibration system model. According to the stiffness sensitivity analysis of this mode based on the second-order mode, since the stiffness K2 has little effect on this mode, K2 is neglected, and the 2-DoF structural model is further simplified into a symmetrical SDoF structural model, with k1 = K1 and k2 = K3. From the mode shape, it can be seen that the vibration of the upper half of the frame and the upper roll set is in the same direction, so the two parts can be regarded as a whole and further simplified, letting m1 = M1 + M2, and ultimately obtaining a symmetrical SDoF. The simplification process is shown in **Figure 10**.

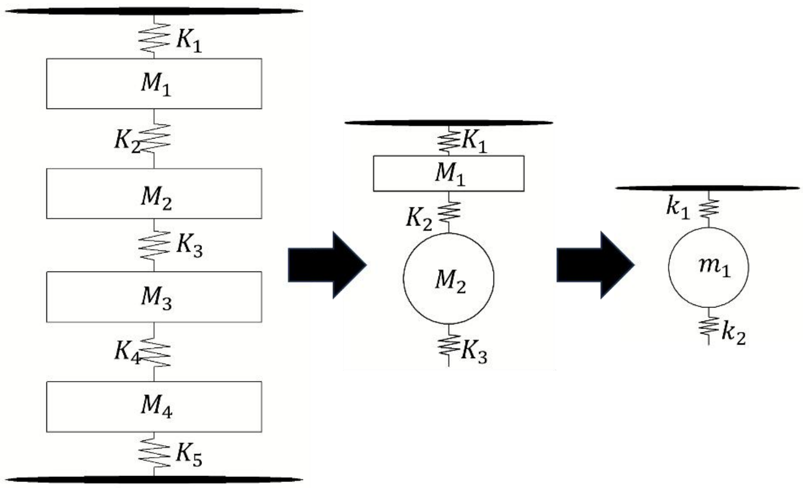

Figure 10. Schematic diagram of simplification process for the vertical subsystem.

The natural frequency of the simplified SDoF structural model was calculated as:

$$f = \frac{1}{2\pi}\sqrt{\frac{k_1 + k_2}{m_1 k_1 k_2}} = 196.76 \text{ HZ} \tag{18}$$

The result closely matches the second natural frequency of the original structural model, demonstrating that the simplified structure accurately captures the dynamic characteristics of the rolling mill vertical vibration system.

3. Modal analysis and data acquisition of the vertical housing system structure

The mill stand system is an important structure for supporting and retaining mechanical equipment. Through modal analysis, the vibration modes of the mill stand system at different frequencies can be evaluated to determine the structural stability, which helps to ensure that the mill stand will not experience excessive vibration or instability under operating conditions, thereby guaranteeing the safe operation of the equipment. Certain components of the mill stand system may resonate at specific frequencies, leading to increased amplitudes and potentially causing structural damage.

Through modal analysis, the natural frequencies of the mill stand system can be determined, and the structural design of the mill stand system can be evaluated to identify possible vibration issues, while also providing a basis for the overall lightweight design of the mill stand [25–27].

The finite element model of the rolling mill frame system is shown in **Figure 11**, where the pedestals, upper and lower beams, bearing housings, rolls, downshot screws, and supporting hydraulic cylinders are all modeled as solid elements. When modeling the rolls, their molds are omitted, and each roll assembly is represented as an integrated roll, which is discretized with solid elements and boundary conditions are applied. The frame, bearing housings, upper and lower roll sets, upper and lower connecting beams, and supporting hydraulic cylinders are all meshed using hexahedral elements. The overall system mesh size is set to 20 mm, with local refinement to 10 mm in stress-concentrated areas. The final model contains approximately 750,000 elements and about 1.34 million nodes.

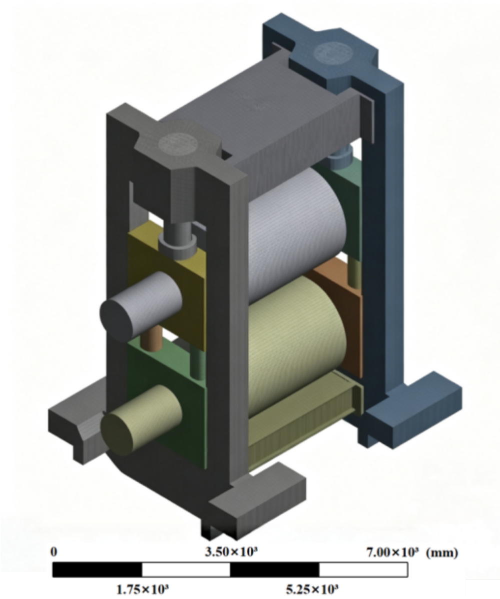

Figure 11. Finite element of the rolling mill stand system.

The contact between the roller and the bearing seat is simulated by a spring element, which is applied between the roller and the bearing seat according to the grid division. The elastic modulus of each part in the model is E = 206 GPa, Poisson's ratio is 0.3, the stiffness of the spring element is $1.8 \times 10^9\ N/M$, and the spring stiffness direction is along the radial direction of the roller system. The pressure device is simplified to a concentrated mass uniformly applied above the stand archway; Anchor bolts secure the entire stand system by fixing the stand archway to the base, so the bottom surface of the frame is fully constrained.

Using the above finite element model and boundary conditions, modal analysis was conducted on the vertical system of the frame, and the natural frequencies of each order were extracted as shown in **Table 4**. The first-order frequency is approximately 148.6 Hz, the second-order frequency is approximately 194.6 Hz, and the third and fourth-order frequencies are 317.1 Hz and 332.4 Hz, respectively. The simulated mode shapes of each order are shown in **Figure 12**, indicating that the lower-order modes are dominated by overall vertical motion, while the higher-order modes exhibit local flexibility characteristics.

Table 4. Natural frequencies of the rolling mill stand system (Hz).

Order	1st	2nd	3rd	4th
Natural Frequency	148.6	194.6	317.1	332.4

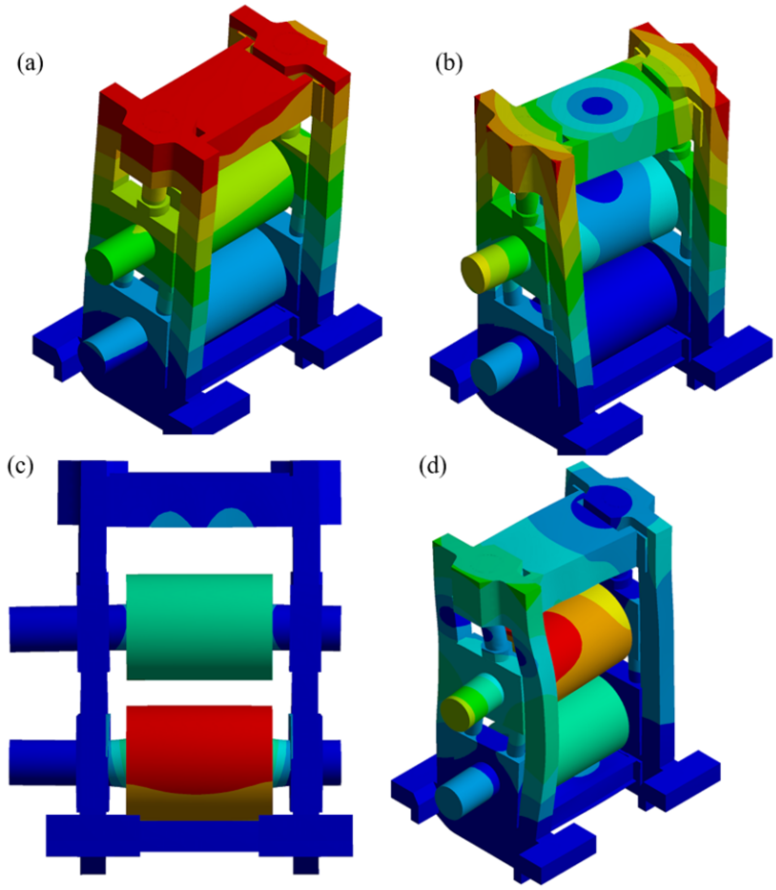

Figure 12. The modal analysis results of the stand system structure **(a)** 1st order; **(b)** 2nd order; **(c)** 3rd order; **(d)** 4th order.

Based on the modal analysis results shown in **Figure 12**, combined with the natural frequencies of each order in **Table 4**, the vibration mode characteristics of the rack structure's vertical system are analyzed. In the first-order mode, the inner rack and crossbeam vibrate in the horizontal direction of the rolling mill, indicating that this mode is dominated by the lateral motion of the rack structure. In the second-order mode, the rack and the upper and lower crossbeams vibrate in the vertical direction of the rolling mill, representing the main working mode of the rolling mill's vertical system. In the third-order mode, the entire rack vibrates in the axial direction of the rolling mill, indicating that the rollers, as the main components, participate in axial oscillation. After the fourth-order mode, the vibration patterns are mostly compound vibrations. The third- and fourth-order mode shapes both feature composite vibration of the rollers and the rack, with the rolling set serving as the main moving structure in the rolling mill system. According to this analysis, when comparing the vibration frequencies of the rolling mill's vertical system with the calculated values from the

4-DoF dynamic model in **Table 2**, the error for each order does not exceed 2%, further validating the rationality of the theoretical model.

4. Data acquisition and comparison

The intelligent production line of the large rolling-shaft-type wedge cross-rolling mill is equipped with a data acquisition system and a production process quality diagnosis model, allowing direct acquisition of relevant data from the mill's vertical system through its data acquisition system. First, test points are arranged at four locations: the vertical direction of the upper and lower roll bearing housings, the middle of the frame columns, and the top of the frame arch. Each measurement point is measured three times, and the average value is taken. **Figure 13** shows the rolling site and the signal acquisition platform. To verify the above conclusions, under steady-state rolling conditions, vertical system velocity response diagrams were obtained by collecting the mill monitoring velocity signals during the rolling process, as shown in **Figure 14**.

Figure 13. Intelligent control platform for rolling mill site.

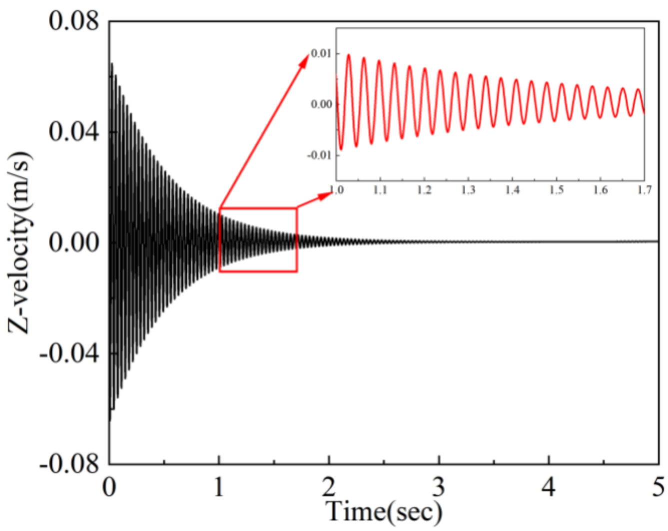

Figure 14. System vertical speed signal diagram.

As shown in **Figure 14**, the rolling mill has a vibration frequency of about 200 Hz in the vertical direction, and the amplitude converges from 0.6 m/s to a stable state. This indicates that in the initial stage, vibration occurs in the vertical direction of the rolling mill, but it quickly tends to converge.

Due to deviations in boundary conditions such as the preloading force and foundation stiffness during on-site rolling compared to the idealized conditions set in the finite element model, there is a certain error in the vibration frequency in the vertical direction, approximately 1.62%. The results validate the accuracy of the vertical dynamic system model of the rolling mill constructed in this study in describing the rolling mill's motion.

5. Conclusion

(1) Based on dynamic principles, the equivalent mass and stiffness of the rolling mill vertical system were calculated, establishing a 4-DoF vertical vibration model. By solving the governing differential equations, the natural frequency of the vertical vibration system was determined to be 190.8 Hz.

(2) Analysis of mode shapes corresponding to each natural frequency revealed that the second-order mode exhibits the highest sensitivity to stiffness variations. Consequently, the vertical vibration system was simplified into a symmetric SDoF model for enhanced analytical and optimization efficiency. The simplified model yielded a natural frequency of 196.76 Hz, consistent with the dynamic characteristics of the vertical vibration system.

(3) Finite element modal analysis identified the natural frequency of the vertical structure as 194.6 Hz. Field data acquisition further demonstrated rapid convergence of vertical vibration velocity, with a measured natural frequency of approximately 200 Hz. The error between the data collection results and the calculation results of the constructed model is approximately 4.6%, and it further proves the accuracy of the vibration model of the vertical system of the rolling mill constructed in this paper.

Author contributions: CM conceptualized the paper as a whole, designed and analyzed the results of the study. XZ contributed to the collection of experimental data and equipment stability verification. WZ modeled and simulated the cross wedge rolling process. JW participated in the graphic production. JX provided guidance on the cross wedge rolling process and verified the dynamics model. YZ contributed in analyzing the data and data visualization presentation. ZC gave overall guidance, was responsible for the conceptualization, project management and financial support, and can serve as the corresponding author. All authors have read and agreed to the published version of the manuscript.

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References

1. Yang Y, Chen X, Zhang B, et al. Precision roll forging process for axles for rail transit. Forging & Stamping Technology. 2022; 47(5): 33–37. (in Chinese)
2. Shi Y, Yang Y, Li H, et al. 1600 mm roll forging machine and its application in the production of axles for rail transit. Forging & Stamping Technology. 2022; 47(6): 209–213. (in Chinese)
3. Cheng M, Shi M, Vladimir P, et al. Novel evaluation method for metal workability during cross wedge rolling process. Advances in Manufacturing. 2021; 9: 473–481.
4. Merkel P, Budde L, Grajczak J, et al. Feasibility study for the manufacturing of hybrid pinion shafts with the cross-wedge rolling process. International Journal of Material Forming. 2023; 16: 45.
5. Lin L, Peng W, Titov V, et al. Interface phenomena and bonding mechanism in the new method of cross wedge rolling bimetallic shaft. Journal of Materials Research and Technology. 2023; 24: 1132–1149.
6. Zhong L, Huang Q, Yuan S, et al. Major breakthrough and progress in metal forming technology and equipment of China in the last 30 years. Journal of Plasticity Engineering. 2024; 31(4): 2–45.
7. Li J, Chu W, Feng P, et al. Numerical and experimental research on shafts with elliptical sections formed by cross wedge rolling. The International Journal of Advanced Manufacturing Technology. 2023; 127: 2969–2978. (in Chinese)
8. Shi M, Cheng M, Liu J, et al. Numerical and experimental analysis of defects control in cross wedge rolling for titanium alloy workpieces. The International Journal of Advanced Manufacturing Technology. 2024; 134: 3829–3843.
9. Xu H, Ren C, He D, et al. Coupling vibration characteristics and vibration suppression of rolling mill rolls with dynamic vibration absorber. Journal of Manufacturing Processes. 2024; 120: 1157–1179.
10. He D, Wang T, Liu Y, et al. Review of theoretical studies on vibration in strip rolling mill. Journal of Mechanical Engineering. 2024; 60(7): 93–113. (in Chinese)
11. Liu Z, Pan G, Jiang J, et al. Vibration characteristics of rolling mill system under constraints of the nonlinear spring force and friction force from hydraulic cylinder. Shock and Vibration. 2021; 2021: 6632714.
12. Peng R, Zhang X, Zhang X, et al. Vibration characteristics of hot rolling mill rolls based on elastoplastic hysteretic deformation. Metals. 2021; 11(6): 869.
13. Chen X, Li J, Ma J. Dynamical responses for a vertical vibration model of a four-roller cold rolling mill under combined stochastic and harmonic excitations. Probabilistic Engineering Mechanics. 2023; 73: 103480.
14. Zhang G, Bao J, Li W, et al. Coupled vibration characteristics analysis of hot rolling mill with structural gap. Shock and Vibration. 2021; 2021: 5581398.
15. Li L, Zhong C. Research on nonlinear dynamic vertical vibration characteristics and control of roll system in cold rolling mill. Scientific Reports. 2024; 14: 29503.

16. Zhang M, Huang Z, Yang Y. Model of dynamic mechanical parameters and vibration analysis in hot rolling. Metals. 2024; 14(11): 1257.
17. Jia X, Wang S, Yan X, et al. Research on dynamic response of cold rolling mill with dynamic stiffness compensation. Electronics. 2023; 12: 599.
18. Zhang H, Zhao W, Huang D, et al. Vertical nonlinear vibration analysis of cold rolling mill considering structural gap and dynamic rolling force. Journal of Manufacturing Processes. 2023; 108: 280–291.
19. Zhao P, Shu X. Analysis of dynamic characteristics of roll system of automobile half-shaft wedge horizontal rolling mill. Modern Manufacturing Engineering. 2007; (1): 1–3, 19. (in Chinese)
20. Lin L, Peng W, Zhu S, et al. Cross wedge roll bonding process for laminated shafts forming: Interface microstructure, bonding mechanism, and parameter influence. Journal of Materials Processing Technology. 2023; 317: 117971.
21. Liu Y, Shen W, Wang X, et al. Research on multi-system coupling vibration of a hot tandem mill. Machines. 2024; 12: 302.
22. Zhou X, Sun C, Wang B, et al. Investigation and prediction of central cracking in cross wedge rolling. The International Journal of Advanced Manufacturing Technology. 2022; 123: 145–159.
23. Zhu L, Sun C, Wang B, et al. Cross wedge rolling deformation law and bonding mechanism of 304 stainless steel/Q235 carbon steel bimetallic shaft. Journal of Iron and Steel Research International. 2024; 31: 2423–2437.
24. Peng R, Zhang X, Shi P. Vertical–horizontal coupling vibration of hot rolling mill rolls under multi-piecewise nonlinear constraints. Metals. 2021; 11(1): 170.
25. Meng D, Li Y, He C, et al. Multidisciplinary design for structural integrity using a collaborative optimization method based on adaptive surrogate modelling. Materials & Design. 2021; 206: 109789.
26. Meng D, Yang S, Zhang Y, et al. Structural reliability analysis and uncertainties-based collaborative design and optimization of turbine blades using surrogate model. Fatigue & Fracture of Engineering Materials & Structures. 2019; 42: 1219–1227.
27. Meng D, Yang S, Abílio M.P., et al. A novel Kriging-model-assisted reliability-based multidisciplinary design optimization strategy and its application in the offshore wind turbine tower. Renewable Energy. 2023; 203: 407–420.