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Research Article

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Posted Date: March 16th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1441429/v1

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Vibration monitoring and analysis of strip rolling mill based on the digital twin model

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Abstract

This paper presents a monitoring method of strip rolling mill based on the digital twin model. Compared with the traditional monitoring methods, this method effectively reduces structure complexity and test cost of the monitoring system. In this paper, the coupling vibration mechanism model of the dynamic characteristics of roll system and bearings of four-high mill was established, and the digital twin model of strip rolling mill vibration was built based on the mechanism model. Consequently, the traditional monitoring test of the rolling mill was carried out to verify the accuracy of the digital twin model. Through analyzing the test results, it can be found that when the rolling force fluctuation is more obvious, the rolling mill roll system vibration becomes more intense. According to this phenomenon, the measures were put forward to suppress rolling mill vibration. In conclusion, the rolling mill vibration monitoring theory based on digital twin model provides technical support and theoretical basis for improving equipment operation stability, reducing test cost and improving product quality.

Keywords: Digital twin, Mill dynamic model, Rolling mill vibration, Monitoring

1. Introduction

With the aim of the reliability and economics of complex equipment operation, failure prediction and health management (prognostics and health management, PHM) have received more and more attention and gradually developed into an important technical basis for autonomous logistics support of complex equipment [1]. Condition monitoring, abnormal detection, fault diagnosis, degradation, life prediction, and system health management for online operation have become current research hotspots and fields [2-3]. Rolling mill is the most essential machine in the process of producing plate and strip. Roll system vibration of strip mill is an essential factor affecting strip thickness accuracy and surface quality. Therefore, online monitoring of rolling mill vibration is of great significance to improving strip product quality stability [4].

Modern monitoring theories and methods mainly include intelligent detection and virtual instrument technology. In the aspect of intelligent monitoring, Martin and Paya [5] respectively studied the application of wavelet transform in the analysis of vibration signals of bearings and gearboxes. The vibration signal decomposed by wavelet is input into a multilayer neural network for fault diagnosis. The system can accurately identify single or multiple faults. Garcia [6] and others established an intelligent system for condition monitoring and fault prediction of wind turbine gearboxes. Garcia proposed that the application of artificial intelligence is mainly embodied in: using artificial neural networks to model dynamic nonlinear processes, using artificial neural networks and expert systems to express quantitative historical data and qualitative knowledge, using genetic algorithms for virtual instruments. Huang [7] completed the measurement of the relevant parameters of the vibration test bench, digital signal processing, and the development of control software through the monitoring system built with LabVIEW software and NI data acquisition equipment. This type of detection principle focuses on the processing of data and the extraction of information. The process requires the assistance of professionals, and the results are not intuitive.

At present, relatively mature monitoring systems include Westinghouse's PSD system, Denmark's B&K's B&K3450 system, ENTECK & IRD's 5911 system, and Mitsubishi's MHM system [8]. The manufacturer of special test equipment for rolling mills is represented by Auber Technology Company, a subsidiary of China Iron and Steel Metallurgy Automation Research and Design Institute. The EN8000 large-scale mechanical vibration monitoring and fault diagnosis expert system produced by Inventec was adopted in the 2250 mm hot strip mill of Wuhan Iron and Steel No. 2 Hot Strip Mill. Online monitoring and diagnosis of the whole process of the hot rolling production line. The monitoring objects include dozens of reducers, fans, and gear bases. Use Process Control judgment rules to eliminate systematic influencing factors, effectively reduce the risk of quality defects, and improve production efficiency and product quality stability. However, these monitoring systems are usually aimed at a single function. When multiple monitoring instruments are combined, they can only accumulate, which significantly increases the complexity of the system. And in the process of vibration monitoring of the rolling mill roll system, the acceleration sensor needs to be soaked in emulsion for a long time, resulting in profound sensor loss.

The emergence and rapid development of digital twin technology provide new ideas for solving the above problems. The conceptual model of digital twins first appeared in 2003 by Grieves M. W. The professor proposed it in the product lifecycle management (PLM) course of the University of Michigan in the United States, which was called the "mirror space model" [9], and was later defined as the "information mirror model" in the literature [10] And "digital twins." In 2010, the National Aeronautics and Space Administration (NASA) introduced the concept of digital twins for the first time in the space technology roadmap [11], which is intended to use digital twin technology to achieve comprehensive diagnosis and prediction functions of the flight system to ensure the entire system's service life. Achieve continuous and safe operation. In recent years, Tao Fei et al. [12-13] proposed a five-dimensional digital twin model that includes physical entities, virtual entities, connections, twin data, and services. Zhuang C [14] proposed a digital model framework based on real-time data for the intelligent production management and control of complex product assembly workshops.

This paper proposes a vibration monitoring method（Figure 1） based on a digital twin system for a 1400mm strip rolling mill in a factory. Compared with the traditional rolling mill vibration monitoring method (Figure 2), It reduces the use of monitoring hardware equipment, simplifies the vibration monitoring system, avoids the problem that the acceleration sensor needs to be soaked in emulsion for a long time, resulting in severe sensor loss, and effectively solves the problem that cannot monitor the running state of rolling mill roll system for a long time due to the surge of test cost in the traditional rolling mill vibration test process. A new solution is proposed for online monitoring of rolling mill operations.

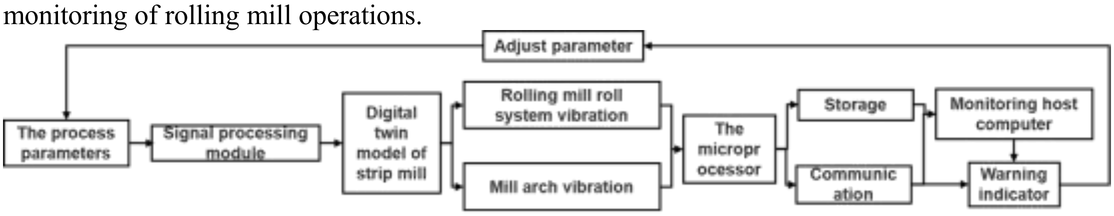

Fig. 1 Monitoring method of strip rolling mill based on digital twin model

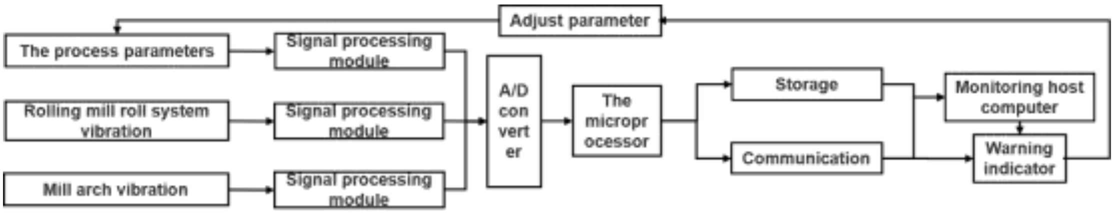

Fig. 2 Traditional plate and strip mill vibration method

2. Research methods

Figure 3 shows the research method in this paper: the rolling force and the rolling speed are extracted from the AGC control system by the rolling process data acquisition system to drive the virtual rolling mill to obtain the rolling mill rolling vibration and rolling mill housing vibration and the physical rolling mill measured by the acceleration sensor The rolling system vibration of the rolling mill is compared with the vibration of the mill housing. If the results do not match, adjust the virtual rolling mill parameters until the results match. According to the results, the vibration suppression measures are given feedback to the physical rolling mill to realize the daily maintenance of the rolling mill.

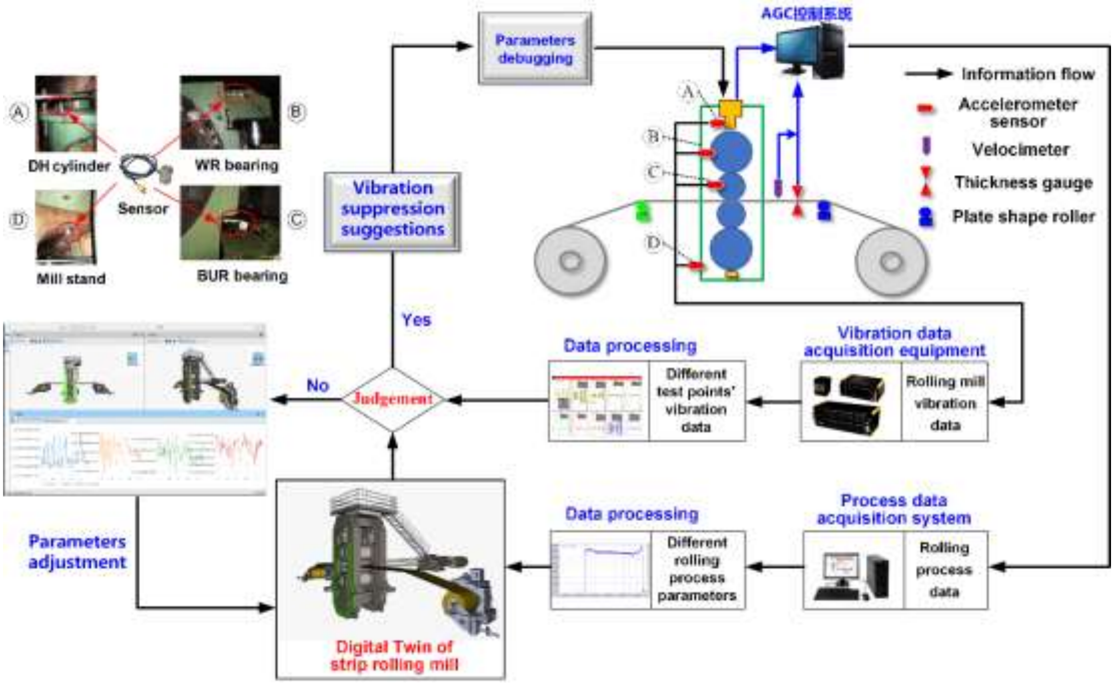

Fig. 3 Research roadmap

3. Digital twin model

Figure 4 shows the framework of the digital twin system, which is mainly divided into three parts, the virtual environment, the data layer, and the physical environment.

The virtual environment takes the rolling force and rolling speed measured by the sensors in the data layer as input and outputs the rolling vibration of the virtual rolling mill and the vibration of the rolling mill casing to the data layer. The physical environment realizes vibration suppression through the vibration suppression corrected rolling force and rolling speed obtained from the data layer and outputs the rolling mill rolling vibration, rolling force, rolling speed, and rolling mill casing vibration from the sensor data to the data layer. Data layer A data integration system is built in the system to integrate the data between the physical environment and the virtual environment and perform visual display and analysis.

3.1 Establishment of Rolling Mill Dynamics Model

The dynamics model of the rolling mill built by considering the dynamic characteristics of the rolling mill rolling system and bearings is shown in Figure 5.

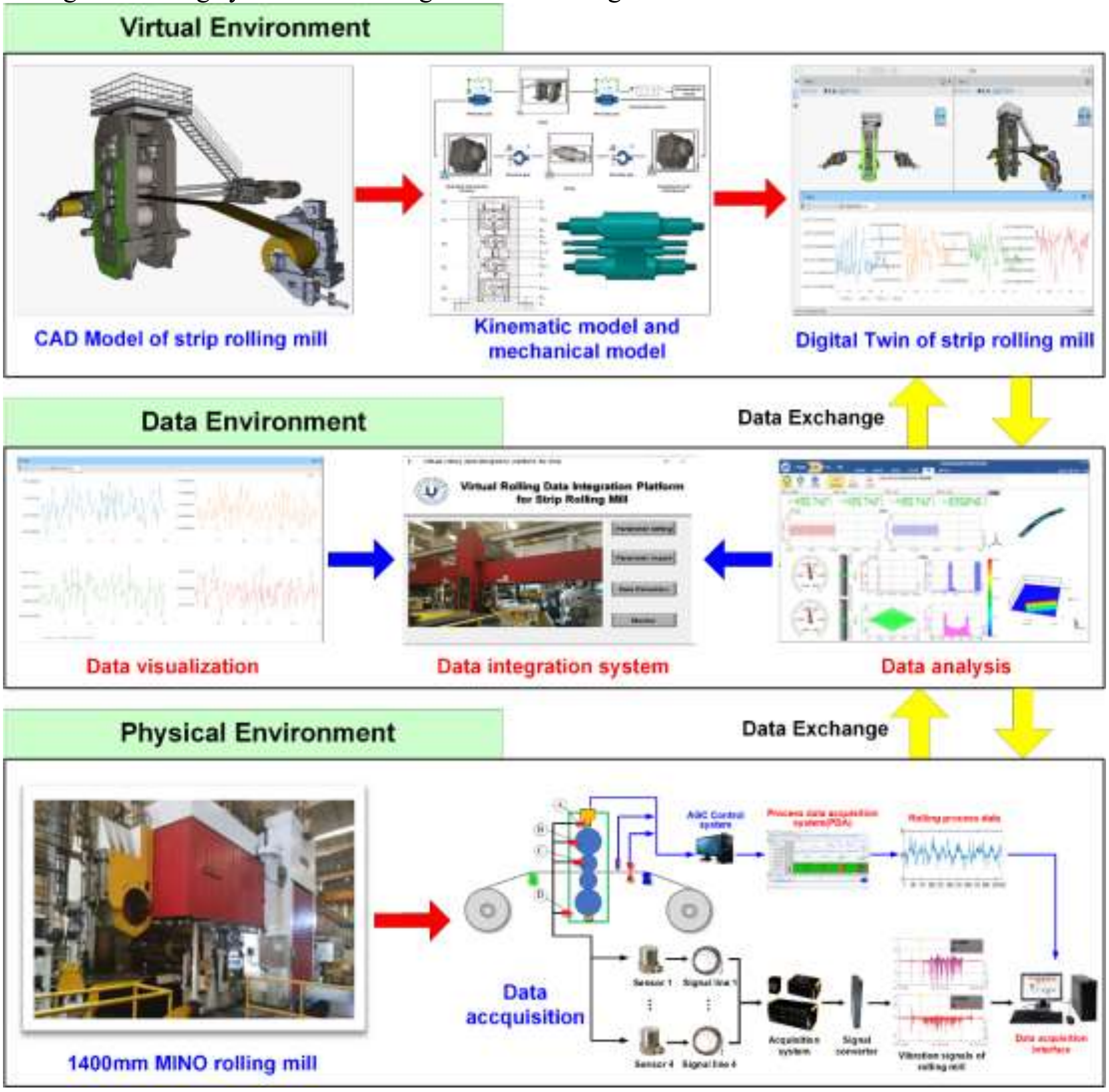

Fig. 4 Digital Twin System

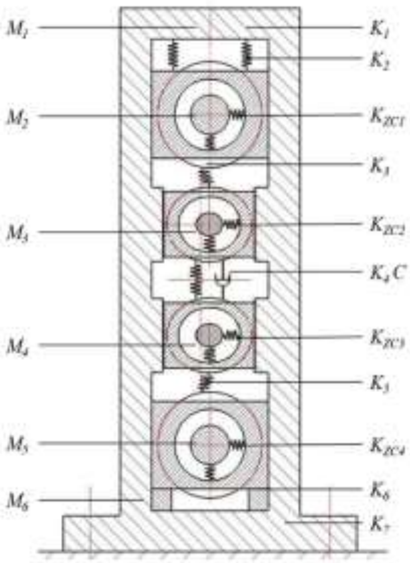

Fig. 5 Rolling Mill Dynamics Model

In Figure 5, M_1 is the equivalent mass of the upper column, upper beam, and hydraulic cylinder of the machine frame; M_2 is the equivalent mass of the upper support rolling system; M_3 is the equivalent mass of the upper work rolling system; M_4 is the equivalent mass of the lower work roll system Equivalent mass; M_5 is the equivalent mass of the lower support roller system; M_6 is the equivalent mass of the lower column, lower beam, and cushion block of the frame; K_1 is the equivalent stiffness of the frame and upper beam; K_2 is the upper support roller and The equivalent stiffness of the upper beam; K_3 is the contact stiffness between the upper support roller and the upper work roll; K_4 is the stiffness between the work rolls (considering the rolled piece); K_5 is the contact stiffness between the lower work roll and the lower support roll; K_6 is the equivalent stiffness of the lower support roller and the lower beam; K_7 is the equivalent stiffness of the lower column, lower beam, and cushion block of the frame; C is the equivalent damping between the work roller (considering the rolled piece); K_{zc1} is the upper The equivalent stiffness in the horizontal direction of the four-row cylindrical roller bearing of the backup roller; K_{zc2} is the equivalent stiffness in the horizontal direction of the four-row tapered roller bearing of the upper work roller; K_{zc3} is the equivalent stiffness in the horizontal direction of the four-row tapered roller bearing of the lower work roller; K_{zc4} is the horizontal equivalent stiffness of the four-row cylindrical roller bearing of the lower support roll; K_{x1} is the equivalent stiffness between the upper work roll chock and the frame; K_{x2} is the equivalent stiffness between the bottom work roll chock and the frame.

The dynamics of the rolling mill roll system vibration system can be described by the motion equation given by the Eq. (1).

$$\begin{gathered}[M]\{x^n\}+[K]\{x\}=0\\ [M]\{y^n\}+[K]\{y\}=0\end{gathered} \tag{1}$$

Where [M] means the system mass matrix, [K] means the system stiffness matrix, $\{x^n\}$ means the horizontal direction acceleration column vector, {x} means the horizontal direction displacement column vector, $\{y^n\}$ means the vertical direction acceleration Column vector, {y} means vertical displacement column vector.

The model considering the dynamic characteristics of the bearing is shown in Figure 6.

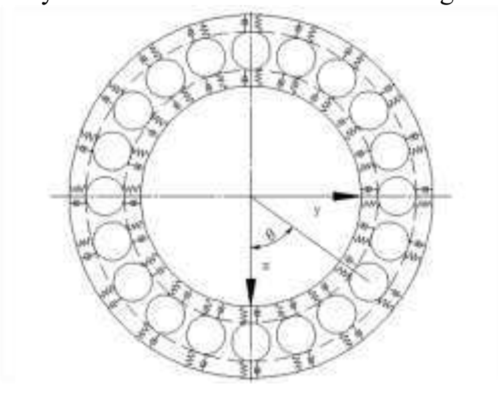

Fig. 6 Bearing dynamics model

The dynamics of the rolling mill bearing system can be described by the equation of motion given by Eq. (2).

$$\begin{gathered}M\ddot{x}_i + c\dot{x}_i + k_n \cos\theta_i[(x_i cos\theta_i + y_i \sin\theta_i)\cos\alpha - u_r]^{1.11} = Q_{\theta i}\cos\theta_i\\ M\ddot{y}_i + c\dot{y}_i + k_n \cos\theta_i[(x_i cos\theta_i + y_i \sin\theta_i)\cos\alpha - u_r]^{1.11} = Q_{\theta i}\cos\theta_i\end{gathered} \tag{2}$$

Where M is the mass of the rolling element; c is the viscous damping between the rolling element and the inner and outer rings; x_i is the horizontal displacement of the i-th moving body center of the tapered roller; y_i is the i-th rolling element of the tapered roller The displacement of the center in the vertical direction.

3.2 Calculation of equivalent mass M

Eq. (3) represents the equivalent mass M_1 of the upright column, upper beam, and hydraulic cylinder of the frame.

$$M_1 = M_{LZ} + M_L + M_{DKt} + M_{hs} \tag{3}$$

Eq. (4) represents the equivalent mass M_2 of the upper support roller system.

$$M_2 = \frac{2}{\delta_{2t}^2}\left[\begin{array}{l}\frac{\pi D_2^2}{4}\rho\int_0^{\frac{L_b}{2}} f_2^2(x)dx + \frac{M_{gjb}}{l_b - L_b}\int_{\frac{L_b}{2}}^{\frac{l_b}{2}} f_2^2(x)dx + M_{yg}\left(1/K_1 + 1/K_y\right)^2 + \\ M_{Zt}\left(1/K_1 + 1/K_y + 1/K_{gt}\right)^2 + M_r\left(1/K_1 + 1/K_y + 1/K_{gt} + 1/K_{Zt} + 1/K_{Zy}\right)^2 + M_{ph}/\left(2K_1^2\right)\end{array}\right] \tag{4}$$

Eq. (5) represents the equivalent mass M_3 of the upper work roll system.

$$M_3 = \frac{2}{\delta_{1t}^2}\left[\frac{M_{b1}}{L_w}\int_0^{\frac{L_w}{2}} f_1^2(x)dx + M_{zc}f_1^2\left(\frac{l_1}{2}\right) + M_{gjw}f_1^2\left(\frac{l_w + L_w}{4}\right)\right] \tag{5}$$

Eq. (6) represents the equivalent mass M_4 of the lower work roll system.

$$M_4 = \frac{2}{\delta_{1d}^2}\left[\frac{M_{b2}}{L_w}\int_0^{\frac{L_w}{2}} f_1^2(x)dx + M_{zc}f_1^2\left(\frac{l_1}{2}\right) + M_{gjw}f_1^2\left(\frac{l_w + L_w}{4}\right)\right] \tag{6}$$

Eq. (7) represents the equivalent mass M_5 of the lower support roller system.

$$M_5 = \frac{2}{\delta_{2d}^2}\left[\frac{\pi D_2^2}{4}\rho\int_0^{\frac{L_b}{2}} f_2^2(x)dx + \frac{M_{gjb}}{l_b - L_b}\int_{\frac{L_b}{2}}^{\frac{l_b}{2}} f_2^2(x)dx + M_{zd}\left(1/K_7\right)^2 + M_r\left(1/K_7 + 1/K_{Zd} + 1/K_{Zy}\right)^2\right] \tag{7}$$

Eq. (8) represents the equivalent mass M_6 of the lower column, lower beam, and spacer of the frame.

$$M_6 = M_{LZd} + M_{Ld} + M_{cy} + M_{DKd} \tag{8}$$

As shown in Table 1, the equivalent quality results are calculated by MATLAB:

Table 1 The equivalent quality results are calculated

Equivalent mass	Value/kg	Equivalent mass	Value/kg
M_1	9321.943	M_4	3094.684
M_2	59716.884	M_5	42200.563
M_3	1888.705	M_6	4663.290

3.3 Calculation model parameters

Eq. (9) expresses the equivalent stiffness K_1 of the frame and the upper beam.

$$\frac{1}{K_1} = \frac{1}{K_{LZ}} + \frac{1}{K_L} + \frac{1}{K_{HS}} + \frac{1}{K_{DKt}} \tag{9}$$

Eq. (10) expresses the equivalent stiffness K_2 of the upper support roller and the upper beam.

$$\frac{1}{K_2} = \frac{1}{K_{ZW}} + \frac{1}{K_{Zy}} + \frac{1}{K_y} + \frac{1}{K_{gt}} + \frac{1}{K_{zt}} \tag{10}$$

Considering the influence of the elastoplastic deformation of the rolling stock on the work roll, the calculation process is extremely complicated, and it is not easy to use mathematical models. Use the finite element method to calculate the stiffness K4 between the upper work rolls (considering the rolled piece).

The establishment of a roller model in Abaqus is shown in Figure 7.

Fig. 7 Finite element model of rolling mill roll system

The material used in the roll system of the rolling mill is 70Cr3NiMo wear-resistant cast steel, which has high wear resistance and good impact resistance. It can be used in a high-speed and heavy-duty environment for a long time. It has good mechanical properties. The physical parameters of the roll are shown in Table 2.

Table 2 Physical parameter table of rolling mill roll system

Mechanical properties	value
Elastic Modulus /MPa	2.7e5
Poisson's ratio	0.28
Coefficient of thermal expansion /K	1.3e5
Mass density（T/mm2）	7.7e-9
friction coefficient	0.2

The process parameters of the rolling process are shown in Table 3.

Table 3 Process parameters of rolling process

V_r/rad/s	v/m/s	h_1/mm	h_2/mm
1.4	4	8	5

Extract the force and displacement data on the path nodes, respectively calculate the ratio of the relative displacement of each node under the action of the contact force, and then obtain the stiffness value of each point when the surface is in contact. Figure 11 shows the stiffness K4 stiffness fitting curve between the work rolls.

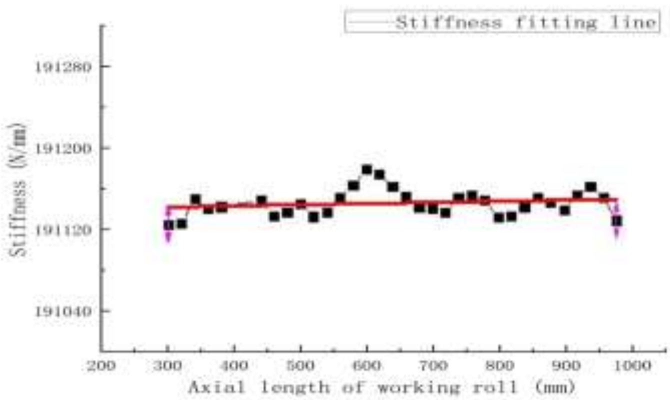

Fig. 8 K4 stiffness fitting curve

Since the distance between the two sides of the roll exceeds the length of the contact zone of the rolling piece, the unreasonable nodes on both sides are removed, and a relatively stable value in the middle area is selected to fit it. The contact stiffness K4 between the upper work roll and the rolling piece is 1.91141e5KN/mm.

The same as the calculation method of K4, the stiffness K3 between the upper work roll and the upper support roll is 7.53399e5KN/mm, and the stiffness K5 between the lower work roll and the lower support roll is 6.58293e5KN/mm.

Eq. (11) expresses the equivalent stiffness of K6 lower support roller and lower beam.

$$\frac{1}{K_6}=\frac{1}{K_{ZW}}+\frac{1}{K_{Zy}}+\frac{1}{K_{Zd}} \tag{11}$$

Eq. (12) represents the equivalent stiffness of the lower column, lower beam, and cushion block of the K7 frame.

$$\frac{1}{K_7}=\frac{1}{K_{LZ\mathrm{d}}}+\frac{1}{K_{Ld}}+\frac{1}{K_{DKt}} \tag{12}$$

The rolls of the 1400mm four-high mill adopt four-row tapered roller bearings. The number of rolling elements in the bearing is large and the force of each rolling element is different. It is difficult to calculate the equivalent stiffness of the roll bearing Kzc1, Kzc2, Kzc3, Kzc4 using numerical calculation methods, so this paper uses the finite element analysis method to solve the equivalent stiffness of the roll bearing.

As shown in Figure9, the finite element model of the bearing is established in Abaqus.

Fig. 9 Finite element model of four-row tapered bearing

The 1400mm four-high mill selects four-row tapered roller bearings. The material used is GCr9SiMn. Table 4 shows the physical parameters of the four-row tapered roller bearings.

Table 4 Physical parameter table of four-row tapered roller bearings

Parameter	Value	Parameter	Value
Outer ring D/mm	355.6	Density /Ton/mm^3	7.81e-9
Inner ring d/mm	266.7	Number of rolling elements	156
Cone angle of rolling element / degree	2.5	Elastic modulus /MPa	2.08e5
Rolling element length /mm	33.4	Poisson's ratio	0.3

Under the action of radial load, the stiffness of the bearing is the sum of the radial stiffness of each rolling element, that is, the force of the rolling elements of the four-row tapered roller bearing and the corresponding elastic change are obtained, and the stiffness value of each row of the forced rolling elements is calculated. After fitting it, the total stiffness of the integral bearing is calculated [12,13]. Figure 10 shows the fitted value of the bearing stiffness.

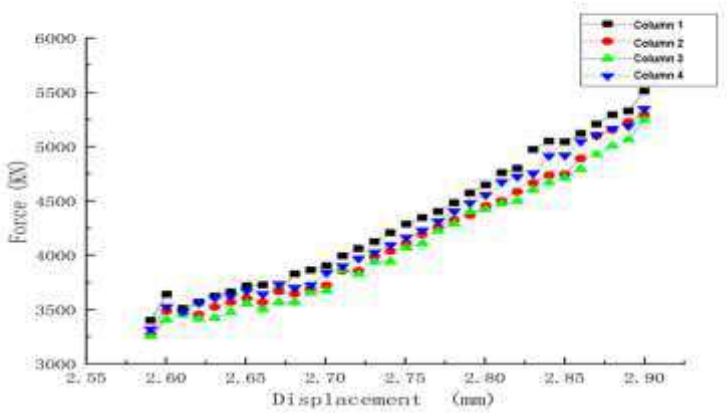

Fig. 10 Bearing stiffness fitting curve

Calculate the stiffness values of the first to fourth rows of rolling elements as: 6.78395e5N/mm, 6.37958e5N/mm, 6.23286N/mm and 6.47685e5N/mm. Eq. (13) indicates that the total radial stiffness of the bearing is the sum of the stiffness of the four rows of rolling elements.

$$\mathrm{K_{zc1}}=\mathrm{K_{zc2}}=\mathrm{K_{zc3}}=\mathrm{K_{zc4}}=2.01e4\ \mathrm{K}N/mm \tag{13}$$

In this study, the damping is not considered temporary, and the equivalent damping between the work rollers (considering the rolled parts) is 0.01 times of K4 for the convenience of calculation.

$$\mathrm{C}=1.91141\mathrm{e}2\ \mathrm{K}N/mm \tag{14}$$

Table 5 shows the calculation results of model parameters.

Table 5 Model parameter calculation results.

Equivalent stiffness	value	Equivalent stiffness	value
K1/KN/mm	6.3086e3	K7/KN/mm	6.8789e3
K2/KN/mm	1.0233e4	Kzc1/KN/mm	2.01e4
K3/KN/mm	7.53399e5	Kzc2/KN/mm	2.01e4
K4/KN/mm	1.91141e5	Kzc3/KN/mm	2.01e4
K5/KN/mm	6.58293e5	Kzc4/KN/mm	2.01e4
K6/KN/mm	2.9301e4	C/KN/mm	1.91141e2

3.4 Modelica modeling

In Maplesim, the CAD model of the 1400mm rolling mill is combined according to the rolling mill dynamics model in Figure 5, and the CAD model parts are divided into blocks, and then the rotation pair, the moving pair, the damping spring and the contact element in the Modelica mechanical library are used to complete the vibration The description of the simplified rolling model is programmed to obtain the vibration model of the 1400mm rolling mill. Figure 14 shows the direct connection between the upper support roller and the bearing housing on the operating side of the upper support roller.

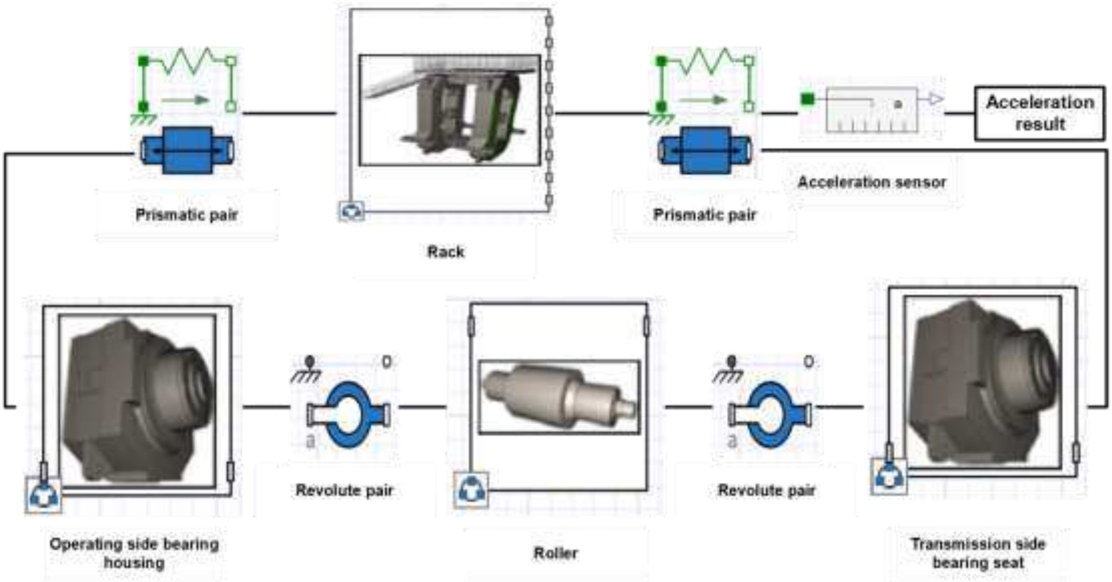

Fig. 11 Part of modelica model

Realizing real-time interaction with data is mainly through python for the secondary development of Maplesim and the establishment of connection with the data layer. The first step is to configure the virtual environment for running Python, and install the Pandas library required for processing data in the virtual environment; the Fmpy library required for processing fum files, and the Tkinter library required for the data service GUI interface. The second step is to convert the 1400mm rolling mill vibration modelica model established in the virtual environment into a fum file through the FMI interface in Maplsim. When converting into a fum file, select rolling force and rolling speed as input, roll vibration acceleration as output, and make the model parameters adjustable to facilitate subsequent debugging. Choose fum version 2.0 and fum type Co-Simulation , Co-Simulation Solver is the Implicait Euler solver.The third step is to put the exported fum file into the configured virtual environment, and realize real-time control of the model by programming the custom model calculation process. Finally, as shown in Figure 12. Develop a virtual rolling data integration platform for rigid strips.

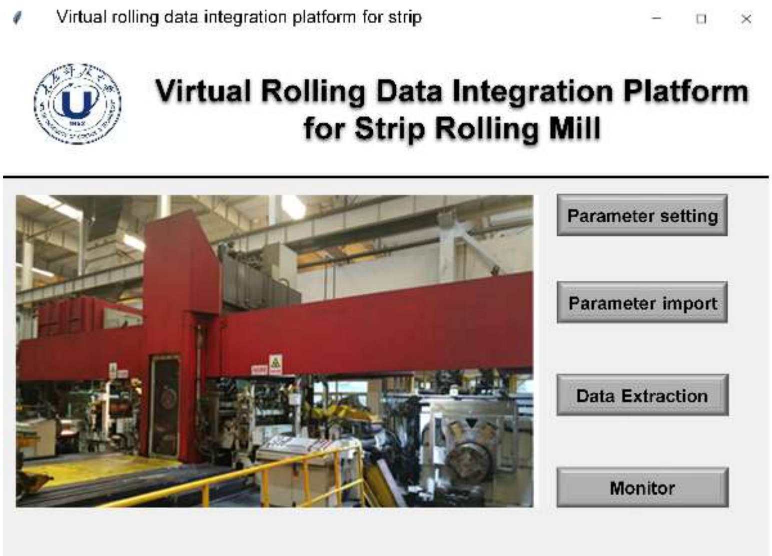

Fig. 12 Virtual rolling data integration platform for strip

4. Experiments and Results

In this study, the traditional monitoring method and the monitoring method based on the digital twin model were used on a 1400mm four-high mill for two-pass rolling process tests. Figure 13 shows the traditional monitoring method, 1400mm four-high mill equipped with AGC control system and DHDAS dynamic signal recorder for routine vibration monitoring.

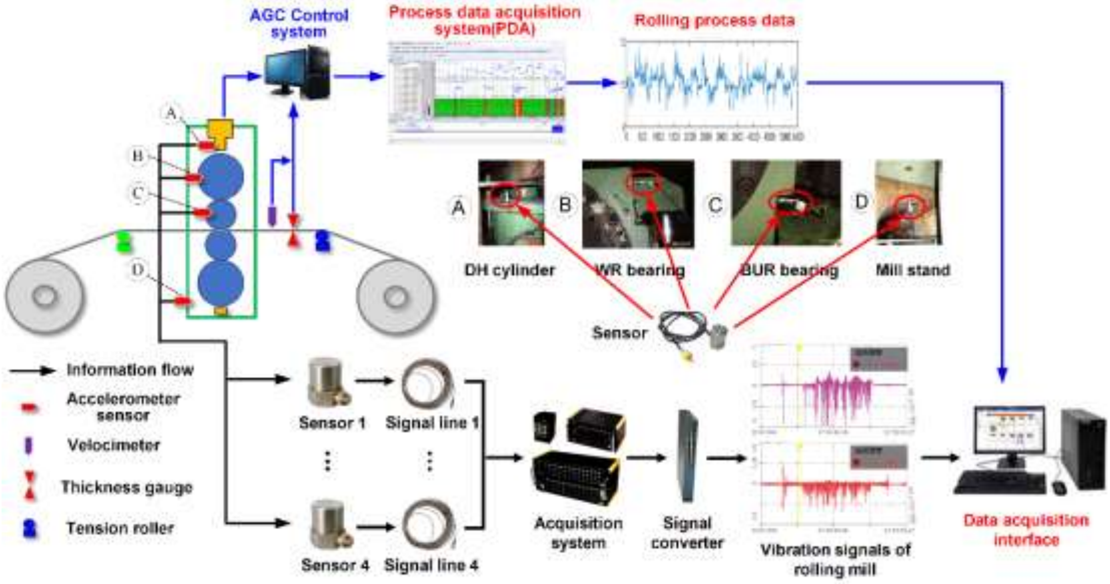

Fig. 13 Information Collection System

Figures 14 and 19 show the rolling forces of the two rolling processes, which drive the digital twin model. Figures 15-16 and 20-21 show the results obtained by traditional monitoring methods. Figures 17-18 and Figures 22 and 23 show the results obtained based on the digital twin model monitoring method.

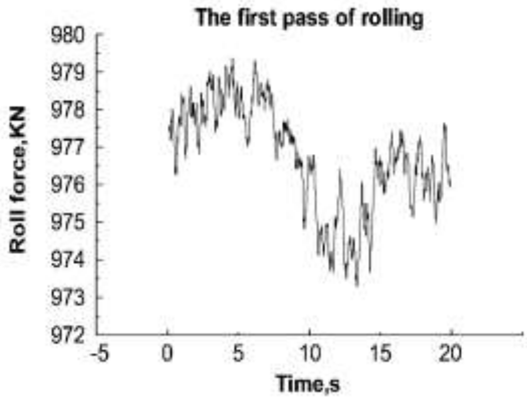

Fig. 14 First pass rolling force

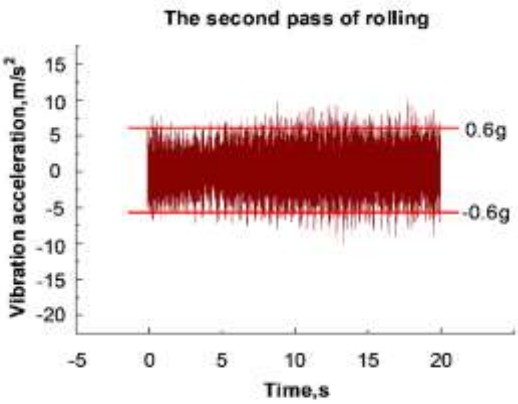

Fig. 15 Traditionally monitored vibration acceleration of upper work roll

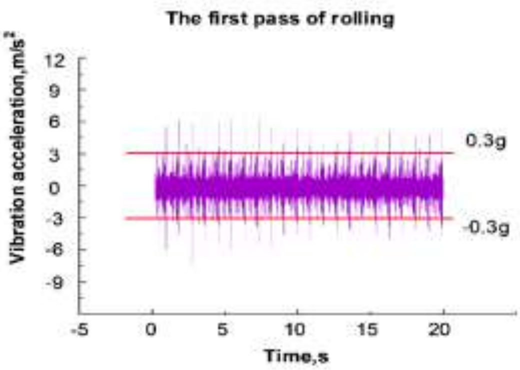

Fig. 16 Traditionally monitored vibration acceleration of the lower work roll

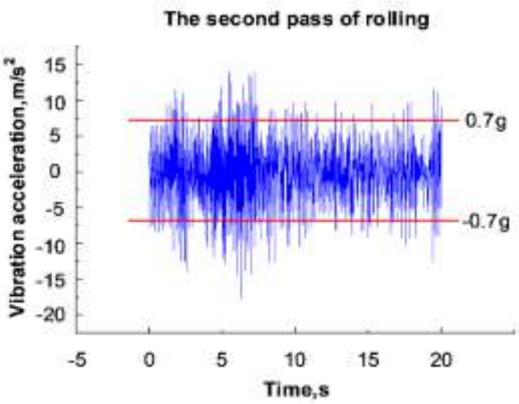

Fig. 17 Digital twin models monitor the acceleration of the upper work roll

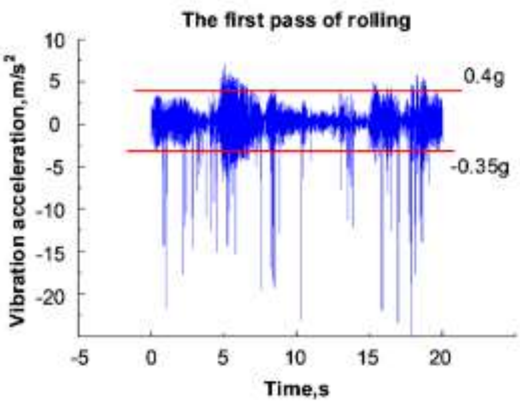

Fig. 18 Digital twin models monitor the acceleration of the lower work roll

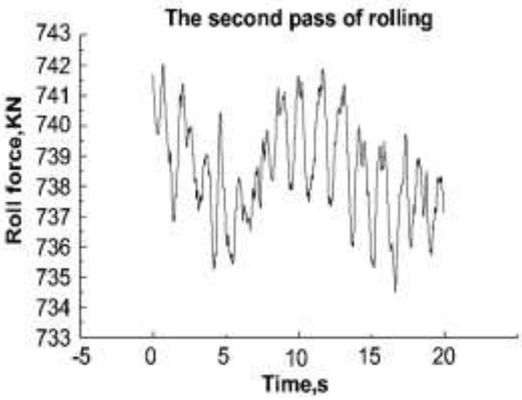

Fig. 19 Second pass rolling force

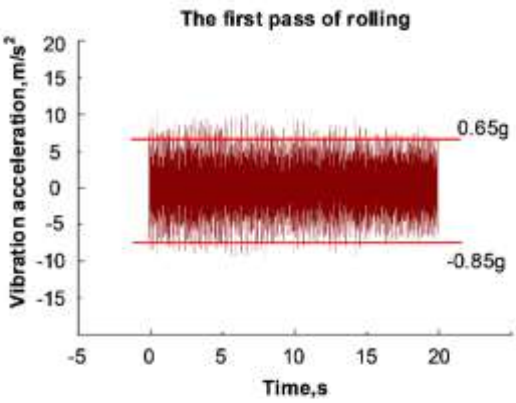

Fig. 20 Traditionally monitored vibration acceleration of upper work roll

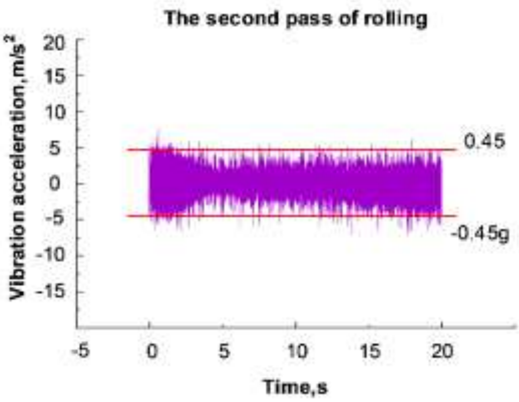

Fig. 21 Traditionally monitored vibration acceleration of the lower work roll

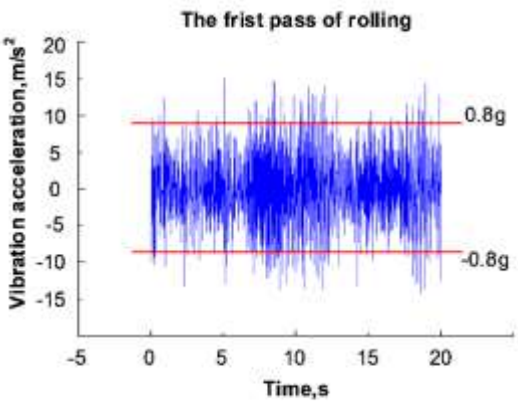

Fig. 22 Digital twin models monitor the acceleration of the upper work roll

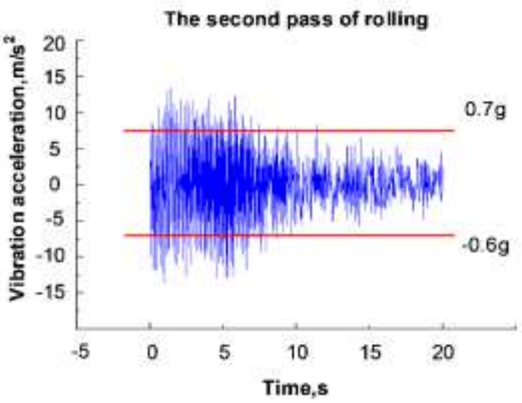

Fig. 23 Digital twin models monitor the acceleration of the lower work roll

According to the figure above, in the first working condition, based on the traditional detection method， the amplitude of vibration acceleration of the upper work roll is 1.2g, and that of the lower work roll collected is 0.6g. Based on the monitoring method of the digital twin model, the amplitude of vibration acceleration of the upper work roll is 1.4 g, and that of the lower work roll is 0.75g. Under the second working condition, the amplitude of vibration acceleration obtained by the traditional detection method is 1.5g for the upper work roll, and 0.9g for the lower work roll. Based on the digital twin model monitoring method, the amplitude of vibration acceleration of the upper work roll is 1.6g, and that of the lower work roll is 1.3g.

5. Discussion

Under the first working condition, the maximum rolling force is 979.537KN, the minimum is 972.898KN, and the fluctuation amplitude is 6.639KN. Under the second working condition, the maximum rolling force is 742.28KN, the minimum is 733.705kN, and the fluctuation amplitude is 8.575kN. Although the rolling force of the first pass is larger than that of the second pass but regardless of the results of the traditional monitoring method or the monitoring method based on the digital twin model, it can be clearly seen that the vibration amplitude of the second pass is larger than that of the first pass. Through analyzing the test results, it can be found that when the rolling force fluctuation is more obvious, the rolling mill roll system vibration becomes more intense. According to this phenomenon, the measures were put forward to suppress rolling mill vibration. In conclusion, the rolling mill vibration monitoring theory based on digital twin model provides technical support and theoretical basis for improving equipment operation stability, reducing test cost and improving product quality.

Under the same working conditions, comparing the vibration monitored by the traditional monitoring method and the monitoring method based on the digital twin model, it is found that the vibration amplitude monitored by the digital twin model is generally larger than the collected vibration amplitude. This phenomenon may be caused by the fact that the equivalent stiffness parameter of the established digital twin model is a specific value, while the actual equivalent stiffness changes during the rolling process.

6. Conclusion

The following conclusions are derived from this research:

(1) In this paper, the vibration monitoring theory of rolling mill based on digital twin model is proposed to provides technical support and theoretical basis for improving equipment operation stability, reducing test cost and improving product quality.

(2) Based on the dynamic characteristics of the rolling mill roll system and bearing, the dynamic model of the four-high mill is proposed, and the digital twin model of the four-high mill is

established according to the dynamic model of four-high mill.

(3) Through analyzing the test results, it can be found that when the rolling force fluctuation is more obvious, the rolling mill roll system vibration is more intense. According to this phenomenon, it is proposed that maintaining the stability of rolling force can realize the vibration suppression effect.

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Statements and Declarations

Funding

The authors are grateful for the supports of the National Natural Science Foundation of China (Grant No. 51905365), the Grant From of Shanxi Major Science and Technology Projects (No. 20181102015) and the National Key R&D Program of China (No. 2018YFA0707305).

Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by [Yang Zhang], digital twin modeling by [Weizhong Wang], finite element analysis by [Han Zhang], [Haichao Li], and material curation by [Cuirong Liu] and [Xiaozhong Du] to proceed and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.