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Spatial vibration of rolling mills

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ABSTRACT

The analysis of rolling mill vibrations is usually limited to simple planar or low DOF vibrations. In reality, however, rolling mill vibrations take place in six DOF leading to spatial behaviors involving vertical, horizontal, axial, reverse, cross and swinging vibration modes resulting in complex relative motions between the rolls. In this paper, a complete spatial vibration characteristic analysis will be presented based on the modified Riccati-overall transfer matrix method. The proposed methodology will be applied to two distinct mill configurations, namely two high-stiffness mills with and without clearance in the chocks. Coupled vibration characteristics of cross and sway motions will be presented along with the complex mode shape analysis of the mills. Experimental results will be presented to prove the validity of the proposed method for spatial vibration analysis.

1. Introduction

Vibration phenomena in rolling mills are very common and complicated. For rolling mill vibrations, there are more studies on conventional vibration behaviors involving vertical, axial and torsional vibration modes of the rolls. However, as shown in Fig. 1, some more important unusual vibration behaviors, including horizontal, cross and swinging vibration modes of the rolls illustrated by Shen and Li (2009), exist as well in practical production of high-stiffness bar and rod mills, large four-high and six-high plate rolling mills. In reality, these vibration behaviors demonstrate that rolling mill vibrations are spatial behaviors in 6-DOF involving three displacements and three rotation angles. The horizontal, cross and swinging behaviors of the rolls result in minor variation of roll gap that affects dimensional accuracy of rolled product, and break the state of equilibrium of roll system that leads to occurrence of abnormal excitation forces threatening safety of rolling mill structure.

The traditional research about vibration phenomena in rolling mills, including such a single vibration mode or coupling vibration modes of the rolls, belongs to planar vibration analysis based on some simplifications. It mainly includes torsional vibration analysis about axis of the rolls studied by Toshifumi (2011), vertical vibration analysis of the rolls in vertical plane passing though axis of the rolls studied by Nizio (2005) and vertical–torsional coupling vibration analysis studied by Yan (2008), horizontal vibration analysis of the rolls in horizontal plane parallel to the rolling direction studied by Alok (2010) and vertical–horizontal coupling vibration analysis in vertical plane passing through cross-sectional areas of rolls studied by Yun and Wilson (1998), etc. However, during rolling process, phenomena such as elliptical cross-section of rolled product in two high rolling mill and chatter marks with blurry edge on the strip described by Zhong (2002) in four high or six high rolling mill always occur and the planar vibration analysis cannot reveal these phenomena well. The reason lies in spatial behaviors of rolling mill accompanied by cross and swinging vibration modes of the rolls caused by micro-scale parameters including structural clearance between components or the offset distance between the rolls studied by Shen et al. (2010). The planar vibration model and theory cannot completely reveal a complete spatial vibration characteristic and its effect on quality of rolled product. Therefore, it is very essential for a rolling mill to study its spatial vibration involving vertical, horizontal, axial, reverse, cross and swinging vibration modes and the key is to establish the corresponding numerical method.

A spatial vibration analysis for two high-stiffness rolling mills with different stability is conducted using modified Riccati-overall transfer matrix method to prove the validity of the proposed method.

2. 250 high-stiffness rolling mill

To develop an analytical method for spatial vibration analysis of rolling mill, a 250 mm (diameter of the roll) high-stiffness rolling

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Nomenclature

$k_{x'}, k_{y'}, k_{z'}$	spring constant in x', y' and z' direction
$k'_{x'}, k'_{y'}, k'_{z'}$	torsional spring constant in x', y' and z' direction
P_i	state vector of connection point i in modal coordinates
P_d	generalized displacements state vector
P_f	generalized force state vector
A	upper roll
B	lower roll
P_A, P_B	state vector of upper roll and lower roll
P_{dA}, P_{dB}	generalized displacements state vector of upper roll and lower roll
P_{fA}, P_{fB}	generalized force state vector of upper roll and lower roll
U	transfer matrices
U_A, U_B	field transfer matrices of upper roll and lower roll
$K_{AA}, K_{AB}, K_{BA}, K_{BB}$	stiffness matrices between the rolls
$M_{Ch}, M_{Ch'}$	mass matrix of upper roll and lower chocks
C_1–C_{10}	coefficient matrices
E	Young's modulus
D	cross-sectional area
I_y, I_z	moment inertia around y and z axis
$\bar{m}$	linear density
L	length of the roll element
G	shear modulus
$\bar{J}$	rotational inertia per unit
$T_{11}, T_{12}, T_{21}, T_{22}$	sub matrices of the rearrange of transfer matrix U
S_i	Riccati transfer matrix of point i
C	coefficient of equivalent viscous damping
f	frictional damping force
μ	frictional coefficient
N	rolling load
ω	vibration frequency
λ	complex frequency
H_0	initial roll gap
H_1	roll gap after horizontal displacement vibration

mill (without housing) is taken as an object for analysis. As shown in Fig. 2, the upper and lower chocks are connected by two square columns and two rods with left and right threads. Connections between chocks and square columns are slots and the square column can regard as a fixed device in horizontal and axial direction and a guide column in vertical direction for the rolls. Chocks and rods are connected by screw nut and spherical pad. The radial roller bearings are fixed on both ends of the roll and an end-thrust roller bearing is fixed on operation side. The heavy rolling load is transferred from roll body to rods by radial roller bearings and chocks. Rods and square columns are fixed on the base through the frame leg.

In initial structure of this rolling mill, there is a small clearance Δ, of 2 mm between chock bore and spherical pad, thus the rolling mill is unstable in the rolling process and the unusual vibration behaviors involving horizontal, cross and swinging vibration modes of the rolls introduced in Section 1 are easy to occur. These behaviors decrease dimensional accuracy and ellipticity of cross-section of the bar and affect safe running of rolling mill. More important, cross and swinging behaviors of the rolls cannot be illustrated by previous planar vibration analysis. Then, an improved structure is designed. The difference is that the clearance Δ between chock bore and spherical pad is removed and another double-sphere pad is added to realize a statically determinate rolling mill structure and ensure safe running of the rolling mill.

3. The modified Riccati-overall transfer matrix method

Corresponding to spatial vibration of rolling mill, the traditional 3-DOF vibration model, including the discrete system model in which the roll is simplified as lumped mass in vertical or horizontal plane or the continuous system model in which the roll is simplified as a continuous elastomer and vibrates only in vertical plane passing through axis of the rolls, must be upgraded to 6-DOF involving three displacements and three rotation angles spatial vibration model.

Mechanical model of high-stiffness rolling mill is shown in Fig. 3. This model is decomposed into two parts: main system and branch system. The main system is composed of the upper and lower rolls, and the branch system is composed of chocks (including roller bearings), rods and square columns. The main system is defined in global coordinate system *oxyz* and the branch systems of operation side and drive side are described in local coordinate systems o' x' y' z' and o'' x'' y'' z'' respectively.

In the model, rods and square columns are simplified as continuous elastomer, however, considering the effect of rotation inertia and shear deformation, the roll is modeled as Timoshenko-beam illustrated by Timoshenko (1955). The chock is taken as a rigid body. Because the width of bar is much smaller than length of the roll, the bar is regarded as a spring in vertical direction between the rolls. For the operation side, connections between rods and chocks are indicated by red points of number 1 and 2 on upper and lower chocks and the spatial constraint of the red point is a spatial spring-damper joint shown in Fig. 3a. Similarly, connections between square columns and chocks are indicated by green points of number 3 and 4 on upper and lower chocks, connections between square columns and frame legs are indicated by green point of number 5 and 6 and connections between rods and frame legs are indicated by green point of number 7 and 8. The spatial constraint of the green point is a spatial spring joint shown in Fig. 3a. There is frictional damping between chock bore and spherical pad

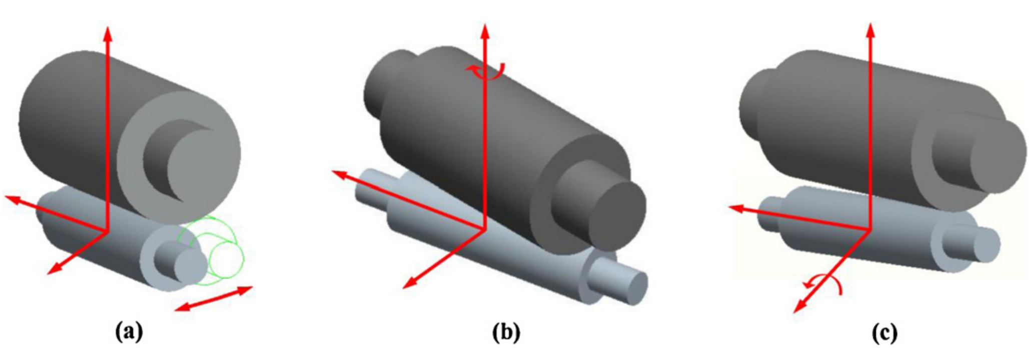

Fig. 1. The unusual vibration behaviors of rolls: (a) horizontal vibration, (b) cross vibration and (c) swinging vibration.