VIBRATION AND CONTROL IN RING ROLLING PROCESS①

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ABSTRACT The vibration characteristics and mechanisms of ring rolling process were analysed, a physical vibration model for the ring rolling process was proposed, and the dynamical vibration equations were established. Based on the contact state between ring and roller, the conditions of linear and non-linear vibrations corresponding to small and large amplitude respectively were determined, and the related stability conditions of vibration were derived. The factors which influence the vibration stability of ring rolling were discussed, which provides theoretic basis for the design, prediction and control of steady ring rolling.

Key words ring rolling vibration stability process control

1 INTRODUCTION

Ring rolling is an important mechanical processing process which is suitable for producing d 50 ~ 100 mm ring parts of different materials[1-3]. The vibrations in the ring rolling process directly affects the geometric precisions of the rolled rings, the service life of rolling groove and the working conditions of the ring roller, serious vibrations even make the rolled rings scrap by flattening, the rolling groove rupture and the power transmission shaft break[4]. How to predict and control the vibrations in the ring rolling process is an urgent problem to be solved for the application and development of the ring rolling technology. However, no study concerning the vibration law of ring rolling has been carried out, thus no reasonable explanations can be supplied for its vibration phenomena, and it is needless to say how to predict and control the vibrations. The vibrations in the ring rolling process are affected by many factors such as material, technology and equipment, and some of which represent strong non-linear geometric and physical characteristics[5,6]. Based on the linear and non-linear theories, this article aims to study the vibration law in the ring rolling process so as to provide theoretic basis for the prediction and control of the vibrations in this process and find suitable technological process for producing high-quality rings.

2 VIBRATIONS IN RING ROLLING, MECHANISMS AND PHYSICAL MODEL

Take a vertical ring rolling mill as an example, the ring rolling is shown in Fig.1. The driven roller makes rotational rolling movement and rectilinear feed movement, while the core roller is an idler roller with the shaft line fixed. Under the action of the driven roller, the ring is continuously nipped into the groove between the driven roller and the core roller, and produces continuous local plastic deformation in which the wall thickness of the ring gets thinner and thinner while its diameter gets larger and larger, and finally becomes a ring part of definite cross-section shape and geometric dimensions. In the

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Fig.1 Physical model of ring rolling

stable rolling process without vibrations, the external outline of the ring is a left-handed Archimede′s spiral, and its internal outline is a right-handed Archimede′s spiral[7]. In each revolution of rolling, the feed amounts of the external and internal surfaces are S_{01} and S_{02} respectively, whose sum is the total feed amount of the ring per revolution, S_0. When there occurs vibration in the ring rolling process, the external and internal outlines of the rolled ring are waveform lines which fluctuate along the Archimede′s spirals. The instantaneous feed amount of the ring per revolution of rolling is

$$S(t) = S_1(t) + S_2(t) \tag{1}$$

where $S_1(t)$ and $S_2(t)$ are the instantaneous feed amounts per revolution of the external and internal surfaces of the ring, respectively.

If the external outline of the ring as shown in Fig.1 is developed, then the developed view of Archimede′s spiral in steady rolling is a straight line, while the developed view of a waveform line in vibration rolling is still a waveform line which fluctuates along a straight line, as shown in Fig.2. It can be seen from Fig.2 that the distance between two developed external outlines is the instantaneous feed amount per revolution of the external surface of the ring, i.e.

$$S_1(t) = x_1(t) - y_1(t) \tag{2}$$

where $x_1(t)$ and $y_1(t)$ are the external outlines of the ring in the present and the last revolutions, respectively. If the critical state between steady and unsteady rolling is studied, then the external outline of the rolled ring at this moment is a persistent harmonic wave[8,9]. Assume the external outline of this revolution rolling

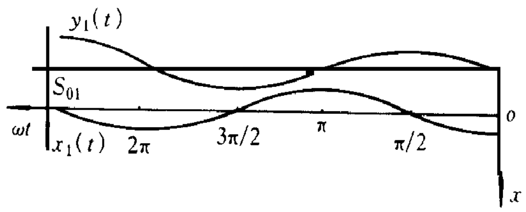

Fig.2 Developed view of external outline of ring

$$x_1(t) = a_{01}\cos\omega_1 t \tag{3}$$

where a_{01} and ω_1 are respectively amplitude and angular frequency of the harmonic wave curve of the external ring outline. Let T be the time interval per revolution of the ring rolling, then the external ring outline of the last revolution can be derived by

$$y_1(t) = x_1(t - T) - S_{01} = a_{01}\cos(\omega_1 t - \omega_1 T) - S_{01} \quad (4)$$

Substituting equations (3) and (4) into equation (2) and rearranging yields

$$S_1(t) = S_{01} + A_1 x_1(t) + (B_1/\omega_1)\dot{x}_1(t) \quad (5)$$

where $A_1 = 1 - \cos\omega_1 T$, $B = \sin\omega_1 T$, and $\dot{x}_1 = -\omega_1 a_{01}\sin\omega t$.

The instantaneous feed amount per revolution of the internal ring surface, $S_2(t)$, can be obtained by similar analysis, namely

$$S_2(t) = S_{02} + A_2 x_2(t) + (B_2/\omega_2)\dot{x}_2(t) \quad (6)$$

where $A_2 = 1 - \cos\omega_2 T$, $B_2 = \sin\omega_2 T$, $x_2 = a_{02}\cos\omega_2 t$, and $\dot{x}_2 = -\omega_2 a_{02}\sin\omega_2 t$.

Because the waveform lines of the external and internal outlines of the ring are produced simultaneously by the feed vibration of the driven roller, the frequencies of both waveform lines can be considered equal, thus

$$\left.\begin{aligned} \omega_1 &= \omega_2 = \omega \\ A_1 &= A_2 = A = 1 - \cos\omega T \\ B_1 &= B_2 = B_2 = \sin\omega T \end{aligned}\right\} \quad (7)$$

Substituting equations (5) ~ (7) into equation (1) and rearranging yields the total instantaneous feed amount of the ring rolling per revolution, i.e.

$$S(t) = S_0 + Ax(t) + (B/\omega)\dot{x}(t) \quad (8)$$

where $S_0 = S_{01} + S_{02}$, $x(t) = a_0\cos\omega t$, and $\dot{x}(t) = -\omega a_0\sin\omega t$. Here $a_0 = a_{01} + a_{02}$.

The dynamical increment of the instantaneous feed amount per revolution respective to the average value is

$$\Delta S(t) = S(t) - S_0 = Ax(t) + (B/\omega)\dot{x}(t) \quad (9)$$

In the vertical ring rolling mill, the driven roller is driven by hydraulic or pneumatic press, the rigidity of the driven roller in the feeding direction is much smaller than that of the core roller with the shaft line fixed, as a result the vibration in the ring rolling process is mainly the vibration of the driven roller in the feeding direction, therefore it can be described using the physical model of single degree of freedom vibration as shown in Fig.1. According to the vibration theory[10], the dynamical vibration equation in the ring rolling process is

$$mx(t) + cx(t) + kx(t) = -\Delta F(t) \quad (10)$$

where $F(t)$ is the rolling force acted on the driven roller, $x(t)$ is the displacement of the driven roller with respective to the equilibrium point which is on the Archimede′s spiral in the steady rolling, m is the mass of the feeding mechanism of the ring rolling mill (including the driven roller), c is the feed movement damping, k is the rigidity in the feeding direction, $\Delta F(t)$ is the difference between the instantaneous rolling force and the steady rolling force, i.e. the dynamic increment of the rolling force.

3 TWO KINDS OF VIBRATION IN RING ROLLING

3.1 Linear vibration

When the driven roller does not vibrate away from the ring workpiece, the instantaneous feed amount per revolution is not zero, the vibration belongs to small amplitude vibration. According to the geometric condition $S(t) \geqslant 0$, substituting it into equation (9) and rearranging gives the condition that the driven roller does not vibrate away from the ring workpiece:

$$a_0 \leqslant a_{cr} = \frac{S_0}{2|\sin(\omega T/2)|} \quad (11)$$

If the above formula is satisfied, then the driven roller will not vibrate away from the ring workpiece, thus the vibration under this condition is small amplitude vibration and it can be described by the linear vibration theory. It may be assumed that the dynamical increment of the rolling force is linearly related to the dynamical increment of the feed amount per revolution, namely

$$\Delta F(t) = bk_s\Delta S(t) \quad (12)$$

where b is the axial size of the ring; k_s is the characteristic parameter of feed in the rolling process, which represents the increment of rolling force per unit feed area.

Substituting equations (9) and (12) into equation (10) gives the small amplitude linear vibration equation that the driven roller does not vibrate away from the ring workpiece:

$$m\ddot{x}(t) + (c + bk_s B/\omega)\dot{x}(t) + (k + bk_s A)x(t) = 0 \tag{13}$$

The above equation indicates that the linear vibration of the driven roller not vibrating away from the ring workpiece is similar in form to the free vibration of single degree of freedom system. Because the dynamical increment of feed amount, $\Delta S(t)$, is jointly determined by the outlines of the ring in this revolution and the last revolution and the average feed amount per revolution, it naturally includes the factor of displacement delay feedback, thus producing the velocity feedback factor $bk_s B/\omega$ and the displacement feedback factor $bk_s A$ in equation (13), changing the vibration damping and rigidity of the rolling system, and also changing the vibration characteristics under some conditions. Because $B = \sin\omega T \in [-1, 1]$, there may occur negative damping in equation (13). According to the vibration theory, there will appear strong self-excited vibration in this case.

3.2 Non-linear vibration

When the driven roller vibrates away from the ring workpiece, the instantaneous feed amount per revolution is zero, the rolling feed process is discontinuous, and the vibration belongs to large amplitude vibration. At this moment, formula (11) does not hold, hence

$$a_0 > a_{cr} = \frac{S_0}{2|\sin(\omega T/2)|} \tag{14}$$

Because the amplitude of the driven roller is large, it vibrates away from the ring piece, thus the instantaneous feed amount per revolution of the ring rolling is determined by the relative geometric relation of the outlines of the ring of this revolution and several previous revolutions.

Let $x_0(t)$ be the outline of the ring of this revolution, and

$$y_0(t) = \max(x_1(t), x_2(t), \cdots, x_m(t)) \tag{15}$$

then the instantaneous feed amount per revolution in the rolling of this revolution is

$$S(t) = \begin{cases} x_0(t) - y_0(t), & x_0(t) > y_0(t) \\ 0, & x_0(t) \leqslant y_0(t) \end{cases} \tag{16}$$

In the case of large amplitude non-linear vibration, the dynamical increment, $\Delta S(t)$, of the feed amount per revolution is a complex non-linear function. Even if $\Delta F(t) = bk_s \Delta S(t)$ is satisfied, the vibration equation of the ring rolling process (equation (10)) is still a very complex non-linear differential equation. The nature of the non-linearity is that the exciting force, $\Delta F(t)$, is non-linearly related to the vibration displacement, $x_0(t)$. Assuming that the effect of the high-order harmonic waves of the exciting force on the vibration of the ring rolling process is negligible, and only the first harmonic plays the main role, then only the mutual actions between the first harmonic of the vibration (the fundamental wave of the ring outline) and the first harmonic of the exciting force need to be investigated. Assuming the first harmonics of the outlines (i.e. the superimposed curves of the internal and external outlines) of this revolution and several previous revolutions in the self-exciting vibration are as follows:

$$\left.\begin{aligned} x_0(t) &= a_0\cos\omega t \\ x_1(t) &= a_0\cos(\omega t - \omega T) - S_0 \\ &\vdots \\ x_m(t) &= a_0\cos(\omega t - m\omega T) - mS_0 \end{aligned}\right\} \tag{17}$$

According to the geometric relations of the developed views of the ring outlines of different rolling revolutions, there is

$$m = \mathrm{INT}(2a_0/S_0 + 1)$$

where INT means integration. Furthermore, according to the Fourier development, the first harmonic of the exciting force $\Delta F(t) = bk_s \Delta S(t)$ can be written as

$$\Delta F(t) = bk_s(A_0 x_0(t) - (B_0/\omega)\dot{x}_0(t)) \tag{19}$$

where

$$\left.\begin{aligned} A_0 &= \frac{1}{a_0\pi}\int_0^{2\pi}\Delta S(t)\cos\omega t\,d(\omega t) \\ B_0 &= \frac{1}{a_0\pi}\int_0^{2\pi}\Delta S(t)\sin\omega t\,d(\omega t) \end{aligned}\right\} \tag{20}$$

Substituting equation (19) into equation (10) gives the non-linear steady self-exciting vibration equation that the driven roller vibrates away from the ring workpiece:

$$m\ddot{x}_0(t) + (c - bk_s B_0/\omega)\dot{x}_0(t) + (k + bk_s A_0)x_0(t) = 0 \tag{21}$$

4 STABILITY OF VIBRATION IN RING ROLLING AND CONTROL

4.1 Stability of linear vibration

According to the vibration theory[10,11], in the case of small amplitude vibration that the driven roller does not vibrate away from the ring workpiece, the critical stability conditions are composed of zero damping and natural frequency corresponding to the zero damping. Therefore, the stability condition for the linear vibration of ring rolling can be obtained from equation (13):

$$\left.\begin{aligned} c + bk_s B/\omega &= 0 \\ \omega^2 - (k + bk_s A)/m &= 0 \end{aligned}\right\} \tag{22}$$

4.2 Stability of non-linear vibration

For the large amplitude non-linear vibration expressed by equation (21) that the driven roller vibrates away from the ring workpiece, the stability condition of the non-linear vibration can be obtained using harmonic balancing process, namely

$$\left.\begin{aligned} c - bk_s B_0/\omega &= 0 \\ \omega^2 - (k + bk_s A_0)/m &= 0 \end{aligned}\right\} \tag{23}$$

If the vibration amplitude is so small that the driven roller does not vibrate away from the workpiece, then it is thus evident from equation (20) that A_0 and B_0 are equal to A and $-B$, respectively, and the stability condition of non-linear vibration expressed by equation (23) is degenerated to that of linear vibration.

4.3 Influence factors of vibration in ring rolling and control

According to Ref.[12], the time interval for per revolution of ring rolling is

$$T = R/(n_1 R_1) \tag{24}$$

where R is the average radius of instantaneous excircle of the ring workpiece in rolling, R_1 is the working radius of the driven roller, and n_1 is the rate of revolution of the driven roller.

It is clear from equations (7), (20) and (24) that the parameters A, B, A_0 and B_0 are all functions of R, R_1 and n_1. A_0 and B_0 are also related to the amplitude a_0. It can be known from the stability condition of linear vibration (equation (22)) and the stability condition of non-linear vibration (equation (23)) in the ring rolling that the stability conditions of ring rolling are related to the vibration parameters of the rolling system (ω, m, k and c), the feed characteristic parameter of rolling (k_s), the geometric parameter (R_1) and the movement parameter (n_1) of the driven roller, and the stability condition of non-linear vibration is also related to the vibration amplitude of rolling, a_0. Now that the stability of ring rolling is affected by the above multiple factors, it is very difficult to control, but there is also greater degree of freedom for design. In order to control the vibration in the ring rolling process, and realize steady rolling, the reasonable design, real-time observation and control of the various vibration factors are indispensable.

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