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A study on the method of impact mass estimation of loose parts

Li-Xian Fang [a], Tian-Tian Ji [a,*], Fu Zeng [a], Wei Zhang [a], Yong-Cheng Xie [b], Chi-Hu Wang [b], Ke-Feng Zhang [b]

[a] Hangzhou Dianzi University, Hang Zhou 310018, China
[b] Shanghai Nuclear Engineering Research and Design Institute, Shanghai 200233, China

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ABSTRACT

It is a very difficult problem to realize the mass estimation of loose parts in the mechanical equipment. The result of mass estimation will influence the fault diagnosing of equipment, especially in the loose part monitoring system of nuclear power station which can provide important guidance for the type classification of loose parts. This paper is based on experiments, by wavelet energy spectrum method to make estimation for different impact mass, and by using linear interpolation method to establish the scale peak function .The results show that the method has characteristics of small estimation errors and good consistency, strong anti-interference capacity, and it has better actual application value.

1. Introduction

The faults of the mechanical equipment sometimes include loose or loosened parts, such as loose or loosened parts in the primary or secondary side of the reactor coolant system and in the operation of rotating machinery. This kind of fault diagnosis often needs to estimate the mass of loose parts as an important basis for judging the fault type. For the mass estimation, the problems to be solved mainly include: 1) the valuation should be consistent for the different sensors receiving the same signal; 2) the mass estimation for impact signal of different mass should have a clear distinction; 3) mass estimation method is not sensitive to noise. Now, the common use mass estimation method consists of two kinds (Bechtold and Kunze, 1999; Kim and Lyou, 2000; Kim et al., 2001; Mayo, 1999; He and Caoet al, 2012; Figedy and Oksa, 2005; Hoppmann, 1961): One is directly using Hertz contact theory to establish mathematical model in order to calculate the mass of the loose parts. The other one is to estimate the mass of the loose parts by extracting the Fast Fourier spectrum of impact signal. The theoretical significance of the first method is much greater than the actual application value, while the second one usually uses the power spectral density of signal that can reflect the impact signal spectrum structure changes as the basis for mass estimation, such as frequency ratio method. However, in practice there are still large errors and poor uniformity of mass estimation performance, thus affecting the fault type judgment.

2. Collision theory

2.1. Mass estimation method based on Hertz contact theory

Under the assumption of completely elastic collision, the dropping steel ball collides with the steel plate. Hertz has done some researches on the impact process. It is as follows (Fig. 1).

The maximum amplitude of steel plate during the impact time of steel ball and steel plate is shown as Eq. (1) (Liu, 2001):

$$D_{\max} = \left[\frac{15}{16}MV_0^2\left(\frac{1-v_1^2}{E_1}+\frac{1-v_2^2}{E_2}\right)\right]^{0.4}\cdot R^{-0.2} \quad (1)$$

where $D_{\max}$ is the maximum amplitude of the plate after the impact, M is the mass of the ball, V_0 represents the velocity of the ball once it collides with the plate, R is the contact radius, E_1, E_2 is respectively the ball and the plate's elastic modulus, and v_1, v_2 is their Poisson's ratio.

Set:

$$k_h = \left[\frac{15}{16}MV_0^2\left(\frac{1-v_1^2}{E_1}+\frac{1-v_2^2}{E_2}\right)\right]^{0.4} \quad (2)$$

* Corresponding author. Tel.: +86 18868879842.
E-mail address: jitiantian27@163.com (T.-T. Ji).

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where k_h is only related to the material and property of the ball and the steel.

The contact time of the ball and the steel's impact can be calculated through the Eq. (3):

$$T_d = 2.94 \cdot \frac{D_{\max}}{V_0} \tag{3}$$

Set Eq. (1) to Eq. (3), we will get the Eq. (4):

$$T_d = 2.94 \cdot k_h M^{0.4} V_0^{-0.2} R^{-0.2} \tag{4}$$

Based on Newton's second law, the maximum force caused by the impact can be expressed as follows (Liu et al., 2009):

$$F_{\max} = m_{\text{eff}} A_{\max} \tag{5}$$

Here $A_{\max}$ is the maximum acceleration; m_{eff} is the mass of the impacted object responding during the impact contact.

$$m_{\text{eff}} = \pi (c_b T_d)^2 \mathrm{d}\rho \tag{6}$$

$$F_{\max} = k_h^{-1} M^{0.6} V_0^{1.2} R^{0.2} \tag{7}$$

Here C_b is the phase velocity of flexural wave, d is the thickness of the steel plate, ρ is the density of steel plate.

Set Eqs. (6) and (7) to Eq. (5), we will get Eq. (8):

$$F_{\max} = \pi (c_b T_d)^2 \mathrm{d}\rho A_{\max} \tag{8}$$

$A_{\max}$ can be measured by acceleration sensor; if the impact contact time T_d is known, we can get the value of $F_{\max}$.

According to Eqs. (4) and (7), we can get Eq. (9);

$$F_{\max} \cdot T_d^6 = (2.94)^6 k_h^5 M^3 R^{-1} \tag{9}$$

Through deduction we can get the following formula:

$$M = 0.1157 T_d^2 \sqrt[3]{F_{\max} R k_h^{-5}} \tag{10}$$

$$R = \left(\frac{3F_{\max} \cdot r}{4E^*}\right)^{1/3} \tag{11}$$

where $1/E^* = 1 - \upsilon_1^2/E_1 + 1 - \upsilon_2^2/E_1$; r is the radius of the ball, in the Hertz contact experiment r is known. So if we can exactly estimate the impact contact time T_d, we will calculate the mass of the loose parts. We can estimate the impact time from time or frequency domain, and the Eq. (12) shows the relationship between the impact contact time and the frequency of the impact signal (Cai and Yang,1995):

$$f = \frac{0.8}{T_d} \tag{12}$$

Hertz contact theory shows that there is no linear relationship among the impact parameters (such as: mass, velocity, contact radius, momentum and energy). Due to the contact radius of collision process are difficult to obtain, it is impossible to determine the impact parameter according to the impact acceleration or impact time. Hertz contact theory is useful for making researches on impact response as a function of the fundamental variables but has inherent uncertainties in mass estimation for unknown loose parts.

2.2. Mass estimation method based on energy spectrum

According to Hertz collision theory (He and Caoet al, 2012), the frequency components of impact signal caused by collisions between a metal ball and metal plate are related to the metal ball's mass and impact velocity. With the increase of the metal ball's mass, the low frequency components of impact signal increases significantly, and the maximum acceleration of impact gets bigger; with the increase of impact velocity, the high frequency components of impact signal are increased, and the maximum acceleration of impact gets bigger; as shown in Fig. 2. Figedy (Figedy and Oksa, 2005) and others contend that sensor response depends on the impacting loose part mass (and energy), and it is also reflected in the shape of the fast Fourier transform (FFT) spectrum of the burst. The heavier the impacting part is the much lower frequencies can be found in the spectrum .In other words, the FFT spectrum is shifted towards the low frequencies with the mass increasing. So we can use this characteristic of impact signal to estimate the mass of the loosened part, such as the frequency ratio method.

The common use of the frequency ratio method is to extract the energy ratio between the low and high frequency bands as the parameter of mass estimation. The formula of it is as follows:

$$\mathrm{FR} = \sqrt{\frac{\int_L \mathrm{PSD} df}{\int_H \mathrm{PSD} df}} \tag{13}$$

where FR decreases gradually with the increasing of the mass. But since the signal spectrum has been simply divided into high and low two parts to make a comparison with the frequency ratio method, so in practical applications the effort is not good. This method has defects, such as big estimation errors and poor consistency.

3. Wavelet energy spectrum mass estimation method

The energy transforms are equal in the wavelet transform, that is to say the wavelet transform has no energy loss for signal, and the positive and negative transform is conserved, so the following formula is true:

$$\langle f, f \rangle = \int_{-\infty}^{+\infty} |f(t)|^2 dt = \frac{1}{C_\psi} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \left|W_f(a,b)\right|^2 \frac{dadb}{a^2} \tag{14}$$

For the right hand side expression of Eq. (14), we can consider $\left|W_f(a,b)\right|^2 / C_\psi a^2$ as an energy density function in (a, b) plane,

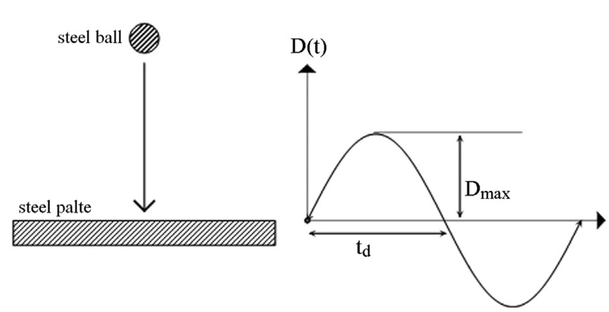

Fig. 1. The process of steel ball and steel plate impact.