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Uncertainty Analysis of Cyclic Force Calibration for Axial Force Fatigue Testing Machines

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Abstract: This article proposes an inertial force calibration method based on correction factors, which can improve the accuracy of correcting inertial forces. Through experiments, taking the calibration of the cyclic force of a certain model of 500kN electromagnetic resonance fatigue testing machine as an example, the calibration results of the cyclic force, the amplitude frequency characteristics of the force sensor, and the correction of the inertial force were analyzed and the uncertainty was evaluated.

Keywords: Cyclic Force Calibration; Inertial Force Correction; Uncertainty Assessment; Fatigue Testing Machine

1. Introduction

The fatigue testing machine is mainly used to study the fatigue performance of various materials in industries such as aerospace, automotive and shipbuilding, and construction and civil engineering under cyclic forces. It can also be used for prefabricated crack and crack propagation tests.[1-4] There are mainly types of fatigue testing machines, including electro-hydraulic servo fatigue testing machines, hydraulic pulsation fatigue testing machines, mechanical fatigue testing machines, and electromagnetic resonance fatigue testing machines. The electro-hydraulic servo fatigue testing machine has the advantages of rich loading waveforms and good control accuracy. However, due to the limitations of servo valves, its operating frequency is generally not high, mostly within 50Hz, and energy consumption is high under long-term fatigue testing. The electromagnetic resonance fatigue testing machine adjusts the frequency of the electromagnetic excitation load to the structural resonance zone, and uses a small excitation load to excite the inertial force of a large weight, thereby acting on the tested piece to achieve a higher working frequency and lower energy consumption. However, the loading waveform of this type of fatigue testing machine is only a sine wave, and the waveform control is not as good as that of the electro-hydraulic servo fatigue testing machine.

For electromagnetic resonance fatigue testing machines, due to their low time and energy consumption, they are widely used in various industries. However, domestically produced electromagnetic resonance fatigue testing machines generally have a working frequency of 50-300Hz and an amplitude of only about 1mm. Therefore, in the long run, most of the metrology industry adopts the method of "using static standards" , assuming that the indication error under dynamic effects is similar to the static error. However, with the development of manufacturing technology in the industry, 500kN high-frequency fatigue testing machines have been produced domestically. Due to the large load, the fixture mass is 100 times that of a typical small load fatigue testing machine. Even if the force sensor of the fatigue testing machine is installed at the fixed end, the inertial force generated by the fixture mass cannot be ignored. Therefore, it is necessary to calibrate the force sensor on the fatigue testing machine separately for static and dynamic forces.[5-8] Therefore, this article will analyze the factors affecting the cyclic force calibration of high load high-frequency electromagnetic resonance fatigue testing machines and the uncertainty during the calibration process.

2. Inertial Force Correction Method in Dynamic Calibration of High Frequency Fatigue Testing Machine with Large Load

According to JJG556-2011[9], during the calibration process of cyclic force, due to the inertia force of large mass blocks, the calibration results of cyclic force should be corrected for inertia force. JJG556-2011 provides the calculation formula for inertia force Fi:

$$F_i = -m(2\pi f)^2 X \tag{1}$$

m is the inertial mass; f is the operating frequency of the fatigue testing machine; X is the displacement of the inertial mass.

However, for the 500kN high load high-frequency electromagnetic resonance fatigue testing machine, due to the large test load and special test sample, the weight of the lower fixture of the fatigue testing machine reaches 300kg, which is more than 100 times larger than the weight of a fixture of 1-3kg for a common small load fatigue testing machine of the same type. According to calculations, the inertia displacement of the fixture is only 0.0087mm, which is much lower than the inertia displacement of about 1mm for ordinary small load fatigue testing machines of the same type. It is difficult to correct it through the improved inertia force calculation formula in JJG556-2011.

By establishing a three degree of freedom linear vibration mechanics model without damping, it was found that the correction factor can be calculated by measuring the mass of the lower fixture of the vibration system, the working frequency of the fatigue testing machine, and the stiffness of the force sensor of the fatigue testing machine. The correction factor is used to correct the calibration results of the high load high-frequency electromagnetic resonance fatigue testing machine. The calculation formula for the correction factor is as follows:

$$\beta = \frac{F_{Fatiguetester}}{F_{reference}} = \frac{k}{k - m\omega^2} \tag{2}$$

Among them, $F_{FatigueTester}$ is the cyclic force value of the force sensor of the fatigue testing machine; $F_{reference}$ is the cyclic force value of the force sensor in the cyclic force calibration device; k is the overall stiffness from the mass of the lower fixture to the base of the fatigue testing machine; m is the quality of the lower fixture; ω is the working frequency of the fatigue testing machine.

3. Measurement Uncertainty Evaluation based on Correction Factor Inertial Force Calibration Method

Analyzing the calibration process of cyclic force range, the measurement mathematical model of cyclic force range calibration process is shown in equation (3). Because the indication error of cyclic force range is essentially the dynamic force measurement error between the fatigue testing machine force sensor and the cyclic force calibration device, for the convenience of analysis, the relative error calculation formula of equation (3) is simplified to equation (4).

Since F_{Cp} 、 F_{Cv} and F_R are independent of each other, the sensitivity coefficients of each influencing variable can be obtained by taking partial derivatives of each influencing variable in equation (5~7).

$$\delta_R = \frac{(F_{Cp} - F_{Cv}) - \overline{F_R}}{\overline{F_R}} \tag{3}$$

$$\delta = (F_{Cp} - F_{Cv}) - F_R \tag{4}$$

$$c(F_{Cp}) = \frac{\partial \delta}{\partial F_{Cp}} = 1 \tag{5}$$

$$c(F_{Cv}) = \frac{\partial \delta}{\partial F_{Cv}} = 1 \tag{6}$$

$$c(F_R) = \frac{\partial \delta}{\partial F_R} = 1 \tag{7}$$

3.1 The Standard Uncertainty and Uncertainty Components Introduced by Each Influencing Variable

(1)The standard uncertainty u_1 introduced by the repeatability of cyclic force measurement results of fatigue testing machine

By conducting 10 independent and repetitive observations on the same measurement, the experimental standard deviation of a single measurement is calculated using the Bessel formula:

$$s(x) = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}} \tag{8}$$

Due to the fact that the arithmetic mean is used as the best estimate of the measurement result in the calibration of the cyclic force range, the standard uncertainty component is:

$$s(\bar{x}) = \frac{s(x)}{\sqrt{n}} \tag{9}$$

Table 1. Measurement Results of 10 Cycles of Force Range

Measurement frequency	Peak cyclic force	Cycle force valley value	Cycle force range
1	142.40	56.99	85.41
2	142.54	57.03	85.51
3	142.38	57.04	85.34
4	142.59	57.05	85.54
5	142.39	57.01	85.38
6	142.66	56.92	85.74
7	142.43	56.99	85.44
8	142.59	56.99	85.60
9	142.45	57.01	85.44

10	142.58	56.93	85.65

After calculating $s(x)=0.1277kN$, $\overline{s(x)}=0.040\,kN$, therefore

$$u_1=\frac{0.040\,kN}{85.505\,kN}=0.05\% \quad (10)$$

(2)The standard uncertainty u_2 introduced by the resolution of the force measuring device of the fatigue testing machine

The force resolution of the fatigue testing machine is 0.01kN. Assuming it is uniformly distributed and includes a factor $k=\sqrt{3}$, the standard uncertainty component introduced by the force resolution of the fatigue testing machine is:

$$u_2=\frac{0.01}{85.05\sqrt{3}}=0.007\% \quad (11)$$

(3)The standard uncertainty u_3 introduced by the amplitude frequency characteristics of cyclic force measurement in electromagnetic resonance fatigue testing machine

Electromagnetic resonance fatigue testing machines usually work based on electromagnetic excitation and resonance principles, and their amplitude frequency characteristics reflect the relationship between the overall system output force value and the excitation frequency. However, for the uncertainty of cyclic force measurement, it is mainly affected by the amplitude frequency characteristics of the measured force sensor. For the measured force sensor, the variation law of its output signal amplitude with the excitation frequency is mainly manifested as the change of amplitude response and phase delay, while the phase delay does not actually affect the error of cyclic force indication. Therefore, the force sensor can be simplified as a second-order system, and the ratio $|H(f)|$ of the sensor output force signal to the actual cyclic force is:

$$|H(f)|=\frac{K}{\sqrt{(1-(\frac{f}{f_n})^2)^2+(2\zeta\frac{f}{f_n})^2}} \quad (12)$$

Among them, f_n is the natural frequency of the force sensor; ζ is the damping ratio of the force sensor; K is the static sensitivity of the force sensor.

The force sensor commonly used in fatigue testing machines is a spoke type strain sensor, with a typical natural frequency of 1kHz~10kHz and a damping ratio of 0.02~0.05. For electromagnetic resonance fatigue testing machines, the natural frequency of the force sensor used is generally between 5kHz~10kHz, calculated with a natural frequency of 5kHz and a damping ratio of 0.05:

$$|H(f)|=0.9964 \quad (13)$$

Therefore, assuming it is uniformly distributed and includes a factor $k=\sqrt{3}$, calculate the standard uncertainty introduced by the amplitude frequency characteristics of the cyclic force measurement of the electromagnetic resonance fatigue testing machine:

$$u_3=\frac{1-0.9964}{\sqrt{3}}\times 100\%=0.207\% \quad (14)$$

(4)The standard uncertainty u_4 introduced by the amplitude frequency characteristics of cyclic force measurement in the cyclic force calibration device

Similarly, based on the standard uncertainty u_3, according to the GTM product manual, the natural frequency of the force sensor of the cyclic force calibration device is 6.1kHz. Therefore

$$|H(f)|'=0.9976 \quad (15)$$

$$u_4=\frac{1-0.9976}{\sqrt{3}}\times 100\%=0.139\% \quad (16)$$

(5)The standard uncertainty u_5 introduced by the measurement uncertainty of the cyclic force calibration device

According to the traceability certificate of the cyclic force calibration device, the force measurement accuracy level of the calibration device meets level 0.1. Assuming that the force measurement indication error follows a uniform distribution, including factor $k=\sqrt{3}$, the standard uncertainty component introduced by the force measurement uncertainty of the cyclic force calibration device is:

$$u_5=\frac{0.1\%}{\sqrt{3}}=0.06\% \quad (17)$$

(6)The standard uncertainty u_6 introduced by inertial force correction

The uncertainty introduced by inertial force correction includes factors such as inertial mass (fixture mass), fatigue testing machine operating frequency, and measurement of overall stiffness between the lower fixture and the fatigue testing machine base. Through experiments, it was found that the uncertainty introduced by inertial force correction mainly comes from the measurement error of the overall stiffness between the lower fixture and the fatigue testing machine base. After estimation, the error of inertial force correction is about ± 0.5%. Assuming it is uniformly distributed and includes the factor $k=\sqrt{3}$, the standard uncertainty component introduced by inertial force correction is:

$$u_6 = \frac{0.5\%}{\sqrt{3}} = 0.289\% \quad (18)$$

3.2 Calculation Results of Synthetic Uncertainty and Extended Uncertainty for Cyclic Force Calibration

According to the measurement uncertainty propagation formula, the composite standard uncertainty expression of the cyclic force measurement results can be derived as follows:

$$u_c^2 = \sum_{i=1}^{n} \left(\frac{\partial \delta}{\partial x_i} \right)^2 u^2(x_i) \quad (19)$$

$$u_c = \sqrt{0.05\%^2 + 0.007\%^2 + 0.207\%^2 + 0.139\%^2 + 0.06\%^2 + 0.289\%^2} \quad (20)$$

$$u_c = 0.39\% \quad (21)$$

The formula for calculating expanded uncertainty is:

$$U = ku_c (k = 2) \quad (22)$$

$$U_{rel} = 0.8\% (k = 2) \quad (23)$$

4. Conclusion

This article proposes an inertia force correction method for the cyclic force calibration of a high load high-frequency fatigue testing machine. Taking the cyclic force calibration of a 500kN electromagnetic excitation resonant high-frequency testing machine as an example, the uncertainty of the calibration results based on the correction factor inertia force correction is analyzed. It is found that the amplitude frequency characteristics of the force sensor of the fatigue testing machine and the cyclic force calibration device, as well as the uncertainty component introduced by the inertia force correction, are the main contributors to the uncertainty of the cyclic force calibration results of the axial force fatigue testing machine.

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