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The fatigue damage evaluation of gear in sugarcane presser using higher order ultrasonic nonlinear coefficients

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ABSTRACT

The fatigue damage of gear in sugarcane presser is one of the most common damages, which is very difficult to detect in sugar factory. The nonlinear ultrasonic technique is used to evaluate the fatigue damage of gear in this paper. The perturbation method is applied to solve the nonlinear wave equation, the relationship between relative nonlinear coefficient and higher harmonics is analyzed which the second and third order relative nonlinear coefficients are applied to evaluate the fatigue damage. The gear in sugarcane presser after three years service is the research objective, which thirty-two points at tooth root and sixteen points at tooth centre are conducted the nonlinear ultrasonic experiment. Experimental results indicate different detection points have different damage degree, and the fatigue damage degree of tooth No. 14 and 15 are more serious than other teeth. While for the same tooth, the damage degree of tooth root is much severer than the tooth centre. Therefore, the measured relative nonlinear coefficients could be applied to evaluate the fatigue damage of gear, which provides the practical method for internal damage evaluation of gear in sugar factory.

Introduction

Gear is one of the most important rotary components in sugar-making factory. Because the service condition in sugar-making factory is very complex, the failure form of mechanical parts would be very complex, like residual stress, fatigue damage, plastic damage and so on. According to related statistics, gear failure is accounted for 60% in all kinds of parts failure [1]. Related studies have shown that the fatigue life before the macroscopic crack formation accounts for about 80%-90% of total life, which would cause serious accidents of mechanical equipments and engineering structures [2,3]. If the damage or defects of gears can find out in time, the enormous economic loss and catastrophic accidents would be effectively avoided. Therefore effective detection the fatigue damage of gear at an early stage is vital important.

For the damage detection of metal components, there are many kinds of methods, such as eddy current testing (ET) [4,5], magnetic particle testing (MT) [6,7], radiographic testing (RT) and ultrasonic testing [8,9]. Comparing with other detection methods, MT has some advantages, which can visually show the shape, location, size and severity of defects [4]. But this method has some limitations. Firstly, it can only detect the surface defects of gear; secondly, because the magnetic force line at two poles of magnetic detector is cut by the tooth root, the defects at tooth root cannot be detected [10]. ET is another useful method for damage detection, which has a relatively high requirement for the surface condition of inspected components. Because ET is sensitive to the gap between the probe and components, this has great influence on the sensitivity of detection. RT can also detect the damage of gear, but the radiation biological effect is harmful to human body; in addition the detection cost is high and the operation is inconvenient. Compared with ET, MT and RT, the ultrasonic method [11,12] has the characteristics of directivity, high sensitivity, stable performance and free of electromagnetic interference, therefore it has been widely applied for damage detection.

The nonlinear ultrasonic technique applies the nonlinear properties of ultrasonic when it propagates in the solid medium with damage, it has higher sensitivity to detect and evaluate the fatigue damage in the early stage [13–16]. Recently, the related experimental and theory studies indicate that the fatigue damage of metal materials has a close relationship with the nonlinear properties of ultrasonic wave [17–20]. Shui et al. [20] evaluated the fatigue damage of an adhesive joint using the nonlinear ultrasonic method, the ultrasonic nonlinear parameter increased with the fatigue cycles, and a theoretical model with different

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interfacial compression and tension stiffness was proposed to interpret the generation of second harmonic. Jaya Rao et al. [21] studied the relationship between the ultrasonic nonlinear coefficient and strain level of aluminum alloy, two stage dislocation dynamics were observed. Nagy [13] verified that the ultrasonic nonlinear parameter was more sensitive than linear ultrasonic parameters.

Based on related studies, the nonlinear ultrasonic technique is applied to evaluate the fatigue damage based on the second order relative nonlinear coefficient, yet there are very few examples of applying the third order relative nonlinear coefficient to evaluate the fatigue damage of materials. Furthermore, in practical application, there is little study about the fatigue damage evaluation of gear in sugar factory applying the nonlinear ultrasonic technique.

Therefore in this paper, based on the nonlinear ultrasonic theory, the gear of sugarcane presser after three years service in the sugar factory is the research object. The nonlinear ultrasonic experiments are conducted on gear, including thirty-two detection points at tooth root and sixteen detection points at tooth centre, the second and third order relative nonlinear coefficients are calculated to evaluate the fatigue damage of different detection positions. Thus the nonlinear ultrasonic theory is attempted to detect the fatigue damage of gear, which may provide an effective analysis method for the current detection of sugar-making equipments.

Ultrasonic nonlinear coefficient

The nonlinear property of solid can be described by higher elastic constants, such as the second and third order elastic constants. The metal material with damage has nonlinear property, when the ultrasonic propagates in metal material, the nonlinearity of material can be characterized by the nonlinearity of ultrasonic [22].

When the ultrasonic wave propagates in nonlinear medium, under the condition of small strain, the wave equation could be defined as

$$\frac{1}{\rho}\cdot\frac{\partial\sigma}{\partial x}=\frac{\partial^2 u}{\partial t^2} \tag{1}$$

where u is the displacement at x direction, ρ is the density of solid, $\sigma(x,t)$ is the normal stress at x direction.

When the strain is very small, the normal stress is described as

$$\varepsilon=\frac{\partial u}{\partial x} \tag{2}$$

If the nonlinear constitutive relation is

$$\sigma=E\cdot f(\varepsilon) \tag{3}$$

where E is the elastic modulus, $f(\varepsilon)$ is the function of strain ε. Eqs. (2) and (3) are substituted into Eq. (1) and it can be obtained

$$\frac{\rho}{E}\cdot\frac{\partial^2 u}{\partial t^2}=f'(\varepsilon)\frac{\partial^2 u}{\partial x^2} \tag{4}$$

If $f'(\varepsilon)$ is known, Eq. (4) can be solved by the numerical or approximate method. The constitutive relation through power series expansion is

$$\sigma=E\cdot f(\varepsilon)\approx E\varepsilon\left(1+\frac{1}{2}\beta\varepsilon+\frac{1}{3}\delta\varepsilon^2\cdots\right) \tag{5}$$

where β and δ is second and third order nonlinear coefficient which are related to second, third and fourth order elastic constants of material. Eq. (4) can be described as [22]

$$c^2\cdot\frac{\partial^2 u}{\partial t^2}=f'(\varepsilon)\frac{\partial^2 u}{\partial x^2}=\frac{\partial^2 u}{\partial x^2}+\beta\frac{\partial u}{\partial x}\cdot\frac{\partial^2 u}{\partial x^2}+\delta\left(\frac{\partial u}{\partial x}\right)^2\cdot\frac{\partial^2 u}{\partial x^2} \tag{6}$$

where c is the wave velocity of ultrasonic in solid. According to the perturbation theory, if the solution of Eq. (6) is

$$u(x,t)=u_0(x,t)+xu_1(x,t)+x^2u_2(x,t) \tag{7}$$

where u_0, u_1 and u_2 represent the initial driving wave, the first and second order perturbation solution. If the driving signal is a sinusoidal wave, that is

$$u_0(x,t)=A_1\cos(kx-wt) \tag{8}$$

where w, k and x is the angular frequency, wave number and propagation distance of ultrasonic. Then the solution up to the third order is,

$$u(x,t)=A_1\cos(kx-wt)-\frac{\beta}{8}k^2A_1^2x\cos 2(kx-wt)+\frac{\delta}{24}k^3A_1^3x[\cos 3(kx-wt)+3\cos(kx-wt)] \tag{9}$$

The amplitude of the second and third harmonic is $A_2=\frac{\beta}{8}k^2A_1^2x$ and $A_3=\frac{\delta}{24}k^3A_1^3x$ according to Eq. (9), then the expression of the second and third order nonlinear coefficient is

$$\beta=\frac{8A_2}{k^2xA_1^2} \tag{10}$$

$$\delta=\frac{24A_3}{k^3xA_1^3} \tag{11}$$

When the ultrasonic propagates in the isotropic and nonlinear elastic medium, supposing the value k and x are constant, the second and third order relative nonlinear coefficient is

$$\beta'=\frac{A_2}{A_1^2} \tag{12}$$

$$\delta'=\frac{A_3}{A_1^3} \tag{13}$$

When the metal material has fatigue damage, the variation of elastic constants can be occurred, the ultrasonic nonlinear coefficient β and δ would be changed when the ultrasonic propagates in the material. Therefore the ultrasonic nonlinear coefficient can be applied to characterize and evaluate the fatigue damage of material.

Experimental setup

The research object is the gear of sugarcane presser after three years service in sugar-making factory which is ready for repair. The material of gear is 45 steel, the tooth width is $b=500mm$, the tooth number is 16, and the physical map is shown in Fig. 1. The tooth root is carefully

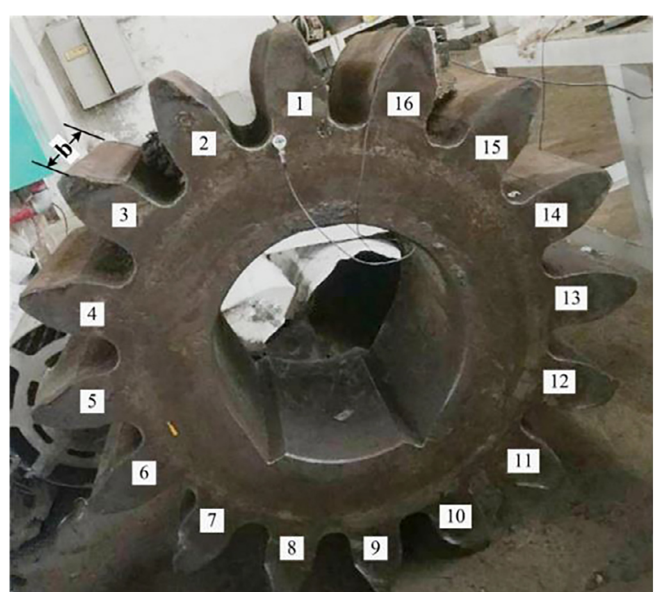

Fig. 1. The physical map of gear.