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Fatigue crack growth rate test using a frequency sweep method

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Abstract: Fatigue crack propagation characteristics of a diesel engine crankshaft are studied by measuring the fatigue crack growth rate using a frequency sweep method on a resonant fatigue test rig. Based on the phenomenon that the system frequency will change when the crack becomes large, this method can be directly applied to a complex component or structure. Finite element analyses (FEAs) are performed to calibrate the relation between the frequency change and the crack size, and to obtain the natural frequency of the test rig and the stress intensity factor (SIF) of growing cracks. The crack growth rate i.e. da/dN-ΔK of each crack size is obtained by combining the testing-time monitored data and FEA results. The results show that the crack growth rate of engine crankshaft, which is a component with complex geometry and special surface treatment, is quite different from that of a pure material. There is an apparent turning point in the Paris's crack partition. The cause of the fatigue crack growth is also discussed.

Key words: Crack growth rate, Residual stress, Frequency sweep method, Engine crankshaft, Reliability
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INTRODUCTION

For decades, fracture mechanics has been used to study the fatigue crack propagation of mechanical components. Great efforts have been made to investigate the growth rate and mechanism of the fatigue crack at different conditions (Lee and Song, 2000; Sadananda and Vasudevanb, 2005).

Many studies focused on establishing a method using a few proper parameters to describe the fatigue crack growth rate. The major issues involved include: (1) the initiation of fatigue cracks; (2) the determination of critical crack sizes beyond which the component may break into parts; (3) the growth behaviour of the crack before reaching its critical size; (4) the influence factors, such as geometrical parameters and residual stress. Tests on a great number of specimens have been performed and reported, by which understandings and conclusions, including the sensitivity of stress ratio (Zhao *et al.*, 2000), shot-peening treatment (Ochi *et al.*, 2001), and compressive stress (Silva, 2005) on the fatigue crack growth behaviour, have been obtained. However, very limited works have been done on the components with complex geometry structure and various surface treatments, such as engine crankshafts.

In the present work, a special test method based on frequency sweep was employed on a resonant bending fatigue test rig to obtain the fatigue crack growth rate of an engine crankshaft. The cause and governing rule of fatigue crack growth have been investigated.

DESCRIPTION OF THE TEST METHOD

The frequency sweep method is essentially based on the mechanical stiffness theory. It can be used to determine the resonant frequencies of a component. With the growing of a crack in a specimen loaded on a resonant bending fatigue test rig, the resonant frequency of the test rig drops. Therefore, the fatigue crack growth rate curve can be obtained by monitoring the rig's resonant frequency and correlating the

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relation between the frequency change and the crack size.

The resonant fatigue test rig has been widely used for engine crankshaft testing, as shown in Fig.1. Yu *et al.*(2004) and Chien *et al.*(2005) described its working principle in detail. Yu *et al.*(2004) studied, experimentally and numerically, the frequency drops of the notched specimen sections. In the study, notches with depth ranging from 1 to 5 mm machined by electrical-discharging machining system were introduced into the crankshaft sections at the fillet between the main crank pin and crank cheek. The resonant frequencies of the bending system with crankshaft sections of various notch depths were first obtained from the experiments. 3D finite element analysis (FEA) of the resonant bending system for various notch depths was then performed. The results showed that the resonant frequencies obtained from FEA were in good agreement with those from the experiments, which study has enabled to quantify the change of resonant frequency as a function of crack depth of the crankshaft specimens. This is critical to improving the test accuracy and designing a more automated resonant test system. Furthermore, we can obtain the fatigue crack growth rate by monitoring and recording the natural frequency of the test rig during the tests.

In order to monitor and record the natural frequency of the test rig online, frequency sweep was introduced into the main fatigue test flow. After the test was completed, a series of notched finite element models with the notches being similar to the actual cracks (position, shape and dimension) were observed. The natural frequency of the rig at each crack growth stage and the stress intensity factor (SIF) of each crack size were then calculated. Fig.2 shows the process for obtaining the fatigue crack growth rate of the specimen, based on the recorded frequency sweep data and the FEA results.

By the frequency sweep method, the time after time specimen demounting and remounting process can be avoided. Instead, what needed is just to excite the test rig by a series of sine wave vibration with frequencies (ω_i) ranging from about 80 rad/s to 250 rad/s, and to record the responses (α_i) for each frequency. The value of p stands for the natural frequency, and can be evaluated by fitting the data pairs $\{\omega_i, \alpha_i\}$ to the following function:

$$\alpha = (A + B\omega^2)/(1 - C\omega^2),$$

where A, B and C are the constants to be determined.

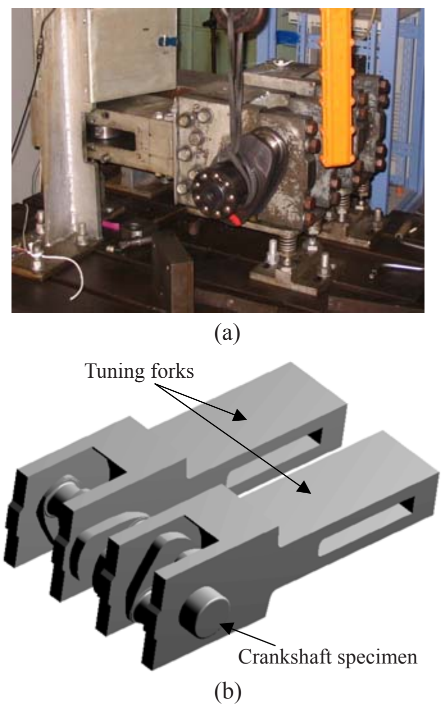

Fig.1 The resonant bending fatigue test rig for crankshafts
(a) The graph of the crankshaft test rig; (b) CAD model

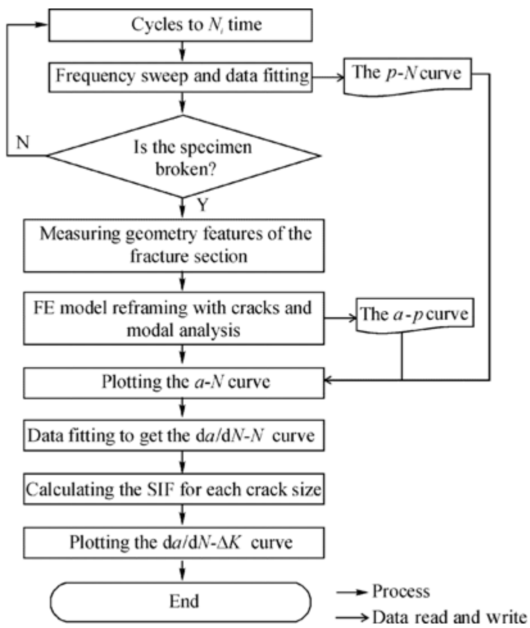

Fig.2 The test flow for crankshaft crack growth rate using frequency sweep method

The above function was derived according to the vibration model of the test rig and an error analysis on the data acquisition system. It can be used to compute the natural frequency as follows:

$$p = \sqrt{1/\hat{C}}.$$

By frequency sweep and data fitting at certain time intervals in fatigue tests, the relationship between the natural frequency p of the test rig and the loading cycle time N, i.e. the p-N curve, was established. After the fatigue test was completed and the specimen was broken, the fracture surface revealed the information of the crack growth, such as crack direction, dimension, shape and position. These details were then used to create the finite element models. According to the FEA, the relationship between the natural frequency of the test rig p and the crack depth a, i.e. the a-p curve, was established. The combination of the p-N and a-p curves leads to the a-N curve. Subsequently, the da/dN curve is derived from the a-N data using the seven-point incremental second-order polynomial method. Finally, the fatigue crack growth curve is obtained by plotting the da/dN data and the SIF range ΔK, which can be calculated using FEA of the notched models created previously.

On a resonant test rig, as shown in Fig.1, the cracks in specimens sometimes might not be seen due to the tuning forks, so it is difficult to measure them by an optical method. However, by the frequency sweep method, it is not necessary to know where the cracks are in fatigue tests, and what have to do is just to monitor and record the natural frequency of the test rig. All information about the position and size of the cracks were discovered after breaking the specimen.

EXPERIMENT

Test configuration

1. Test rig

A horizontal emplacement resonant fatigue test rig was employed in this study. The control software and hardware were developed specially for the test.

2. Crankshaft specimen

The fatigue crack growth rate test was conducted on the crankshaft of a 6-cylinder diesel engine. Two crankshafts were randomly selected from the finished product warehouse. The 2nd and 5th crankpins of each crankshaft were selected as experimental specimens, and numbered Nos. 1~4, respectively. The crankshafts are made of 42CrMo forging steel and were processed by the nitride hardening and shot-peening surface treatment. Table 1 gives some material and geometrical information of the crankshaft specimen.

Table 1 Material and geometrical information of the crankshaft specimen

Parameter	Value
Tensile strength (MPa)	880
Young's modulus (MPa)	2.08×10^5
Poisson's ratio	0.28
Crank journal diameter (mm)	100
Crankpin diameter (mm)	82
Crank body thickness (mm)	27

3. Test load

All specimens in resonance were tested under the same bending moment load. In order to determine the load level applied to the specimen in the resonant bending fatigue tests, a calibration test was carried out. It produces two calibration curves: one is the static calibration curve with strain gage reading results when the specimen is subjected to static bending; the other is a dynamic calibration curve with strain gage reading results when the specimen is loaded by resonant vibration of the test rig. By fitting the two calibration curves, a correct exciting frequency value can be calculated for a given bending moment magnitude.

When the engine was running under rated power, the nominal working moment of the crankshaft is about 2540 N·m. In the test, a load scaling factor of 1.7 was used to accelerate the test, so the specimens were subjected to a bending moment of

$$M_{-1} = 4318\ \mathrm{N \cdot m}.$$

Test results

In the fatigue test, frequency sweep was conducted once every 100000 cycles. When the specimen was close to fracturing, the specimen was demounted off the test rig. The specimen was then broken into parts on the cracking section in order to reveal and measure the crack propagation trail on the surface.

A crack usually initiates in the fillet web region of the crankshaft between the crank body and crankpin. The crack propagates along 45 degree angle to the axis of the crankpin. Fig.3 shows the fracturing surface. It can be seen that the crack shape looks like semi-elliptical or a cameo, and grows from a small one to a large one. Accurate dimension of the crack can be measured from the fracture surface graph.

As shown in Fig.4, the crack shape may be described by the depth *a* and the surface half-length *b*. The fracture section is represented by the hatched region, and the cracks are approximated with a group of partial ellipses. The crack geometries, including the depth and the half-length, were measured using a microscope. The geometry information was then used to create the finite element models that were analyzed to obtain the *a*-*p* curve. The *a*-*N* curve was derived from both the *a*-*p* and *p*-*N* curves, as described previously. Figs.5~7 show all *p*-*N* curves, *a*-*p* curves and *a*-*N* curves for Nos. 1~4 specimens, respectively. By using the seven-point increment second-order polynomial method, the d*a*/d*N*-*N* curves can be derived from the *a*-*N* data.

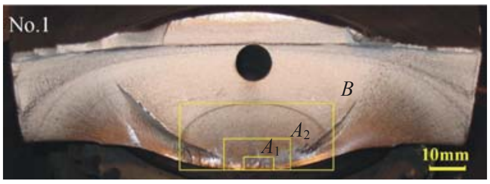

Fig.3 The fracture section graph of No. 1 specimen

For each cracked finite element model with the crack depth from 1 mm to about 20 mm, the SIF *K* at the crack depth point ($\varphi=\pi/2$) of the semi-elliptical crack was calculated using the 1/4-point displacement, which was proposed in (Lin and Smith, 1999; 2001). As the specimen is subjected to bending, the crack is considered as mode-I crack, so we have

$$K=K_{\mathrm{I}}.$$

The variation of SIF with crack depth obtained from the calculations is shown in Fig.8. For the alternating tensile stress due to the cyclic bending moment, the SIF range is

$$\Delta K_{\mathrm{I}}=2K_{\mathrm{I}}.$$

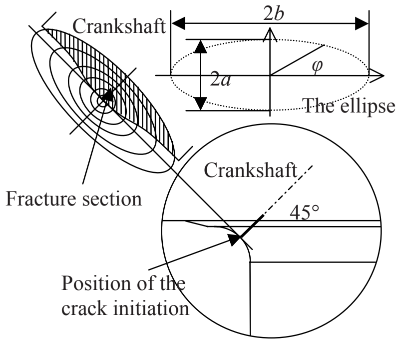

Fig.4 Geometry description of the crankshaft's crack

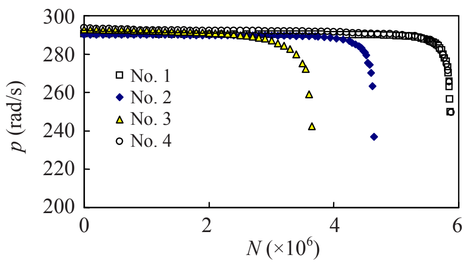

Fig.5 The *p*-*N* curves for Nos. 1~4 specimens by fitting frequency sweep data

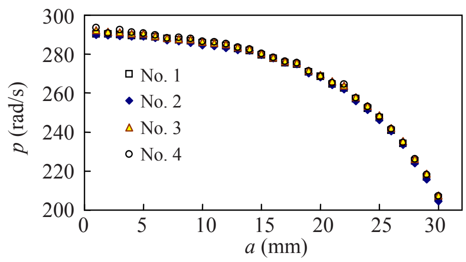

Fig.6 The *a*-*p* curves for Nos. 1~4 specimens derived from FEA

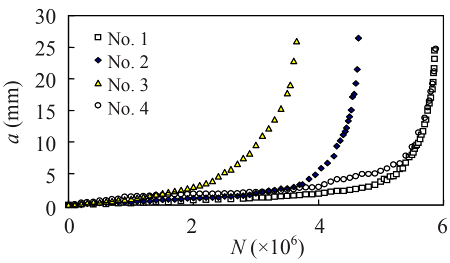

Fig.7 The *a*-*N* curves for Nos. 1~4 specimens by combining the *p*-*N* curves and the *a*-*p* curves

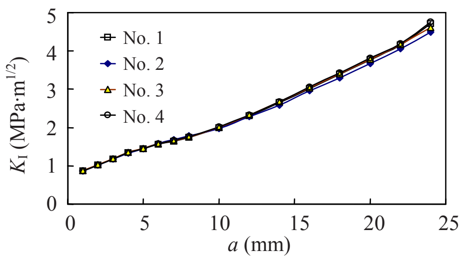

Fig.8 SIFs at the front of the crankshaft cracks with the depth ranging from 1 mm to about 20 mm

The da/dN-ΔK curves for all specimens are shown in Fig.9.

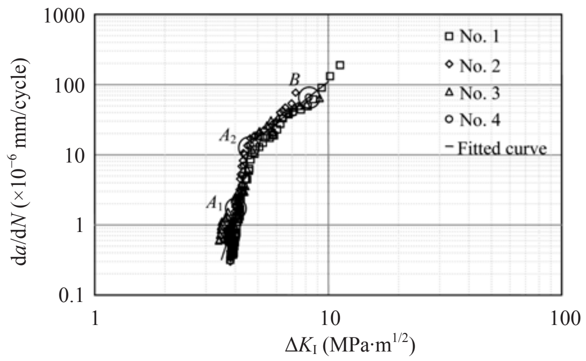

Fig.9 The crack growth rate for Nos. 1~4 specimens

Data analysis

Fig.9 shows a multi-linear curve fitting for the fatigue crack growth rate data. There are obvious slope transitions in the data, especially at the point A_2. For the A_1-A_2 and A_2-B regions, the following Paris type relations are obtained by the least square method,

$$\frac{\mathrm{d}a}{\mathrm{d}N}=\begin{cases}1.0054\times10^{-11}(\Delta K_\mathrm{I})^{18.32}, & 4.6<\Delta K_\mathrm{I}\le 4.7;\\ 0.2436(\Delta K_\mathrm{I})^{2.655}, & \Delta K_\mathrm{I}>4.7.\end{cases}$$

Empirically, for the 42CrMo forging steel, the exponent of the Paris relationship usually is in the range of 2 and 3. For the present case, only the exponent of the A_2-B region is within this range. However, this crack size beyond A_2 is larger than 10 mm. Divider lines between the mentioned regions for No. 1 specimen are also marked in Fig.3. It seems that the current fatigue crack growth relationship is a bit different from the empirical results. It may be caused by the residual compressive stress on the surface of the crankshaft.

CONCLUSION

A fatigue crack growth rate test method using frequency sweep was introduced. Based on the facts that the system frequency drops when the crack becomes larger, this method can be directly applied to a complex component or structure. By frequency sweep and data fitting at certain time intervals in fatigue tests, the p-N curves standing for the relationship between the natural frequency p of the test rig and the loading cycle time N were established. FEAs are performed to calibrate the relation of the frequency change and the crack size, i.e. the a-p curves, and to obtain the SIF range ΔK of growing cracks. The crack growth rate i.e. da/dN-ΔK of each crack size is obtained by combining the testing-time monitored data and FEA results.

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