Reliability-based Fatigue Life Prediction Method for Compressor Wheel Rub of Turbocharger for Vehicle Application

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Abstract The fatigue failure of compressor wheel rub is one of important failure modes of turbocharger for vehicle application. Because the operating state of turbocharger in the life cycle changes as the work condition of diesel engine changes, the compressor wheel rub of turbocharger is applied by the variable stress which can causes the fatigue failure. In this paper, the effect of centrifugal load, thermal load and aerodynamic load on the stress of compressor wheel rub is studied, and then the fatigue stress spectrum of compressor wheel rub is developed based on the endurance test profile of vehicle engine. In order to research the fatigue strength of compressor wheel rub, the fatigue specimen is designed and the relationship between the stress and fatigue life of compressor wheel rub is built. Then, utilizing the linear Miner cumulative damage rule and the first-order reliability method, the reliability model of compressor wheel rub with fatigue failure mode is derived, and the rule that the reliability of compressor wheel rub changes with life is studied. Based on the reliability model of compressor wheel rub with fatigue failure mode developed, the method for determining the reliable fatigue life of compressor rub of turbocharger is proposed. The result shows that with the method developed in this paper the fatigue life of compressor wheel rub for the given reliability can be predicted reasonably, and the reliability of compressor wheel rub can also be calculated for the given fatigue life.

Keywords Fatigue, Life prediction, Turbocharger, Compressor wheel, Reliability, Reliable life

1. Introduction

Turbocharger has been applied into all kinds of vehicle engines to improve the performance and reduce the emission in recent years [1-3]. The compressor wheel is one of the most key components of turbocharger, which can transform the mechanical energy recovered by the turbine to the energy of air and improve the intensity of inlet air of engine. For the turbochargers for vehicle application, because of the complex and variable operating section of vehicle engine, the running status of compressor wheel of turbocharger changes continuously and the compressor wheel is applied by the variable loading process, which can cause the fatigue failure of compressor wheel rub [4-5]. Once the fatigue failure happens in the compressor wheel, the turbocharger can not work normally. Thus, it is very important that analyze the reliability of compressor wheel rub with fatigue failure mode and predict its fatigue life scientifically.

Because the fatigue reliability and life of compressor wheel rub is related with the real operating profile of engine equipped with the turbocharger, it is very important that obtain the exact operating profile of engine in the process of analyzing the reliability and life of compressor wheel of turbocharger. However, in the development stage of turbocharger, it is hard to obtain the exact operating profile of engine or the turbocharger, especially for the engines for vehicle application, and in most cases it is very difficult to analyze the fatigue life and reliability of turbocharger compressor wheel.

In this paper, a new method for analyzing the fatigue reliability and predicting the life of compressor wheel rub of turbocharger is developed based on the endurance test profile of engine for vehicle application. The reliability model of compressor wheel rub with fatigue failure mode is derived, and the method for predicting the fatigue life of compressor wheel rub corresponding to the different given reliability is proposed.

2. Stress Analysis of Compressor Wheel Rub with Fatigue Failure Mode

The sketch of compressor wheel of turbocharger and its critical locations of fatigue failure (namely, the maximal stress appearing areas) are shown as Figure 1, and it can be seen that the maximal stress of compress wheel generally appears in the rub for the normal operating cases of turbocharger.

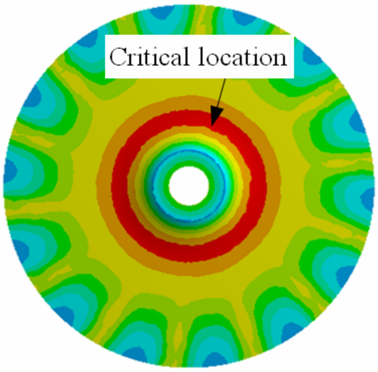

Figure 1. Critical locations of compressor wheel with fatigue failure mode

In the work process of turbocharger, the compressor wheel is applied by the centrifugal load, thermal load and aero dynamical load, simultaneously, and the stress value of compressor wheel rub is dependent on the running status parameters of compressor wheel of turbocharger, including the rotational speed, inlet and outlet temperature, inlet and outlet pressure, and so on.
Because in the development stage of turbocharger it is very hard to obtain the exact running status parameters of compressor wheel and the real operating profile of engine for vehicle application, in the following based on the endurance test profile of engine, the operating modes of engine which is composed of four main operating modes, is determined, and corresponding to different operating modes of engine the running status parameters of compressor wheel of turbocharger is studied. Further, according to the running status parameters of compressor wheel in different operating mode of engine, the stress of compressor wheel rub is calculated, shown as Table 1.

Table 1. Stress of compressor wheel rub corresponding to the operating modes of the endurance test profile of engine

Operating mode of engine	The running status parameters of compressor wheel of turbocharger						Stress of compressor wheel rub (MPa)
	Rotating Speed(r/min)	Inlet Temperature (K)	Outlet Temperature (K)	Inlet Pressure (Bar)	Outlet Pressure (Bar)	Flow (kg/s)	
1	104019	297	483	0.896	3.340	0.569	267
2	98735	297	479	0.894	3.216	0.548	223
3	95420	297	471	0.892	3.025	0.503	209
4	91984	297	468	0.891	2.873	0.476	195

According to the endurance test profile of engine and the stress of compressor wheel rub shown as Table. 1, the fatigue stress history of compressor wheel rub is built, shown as Figure 2.

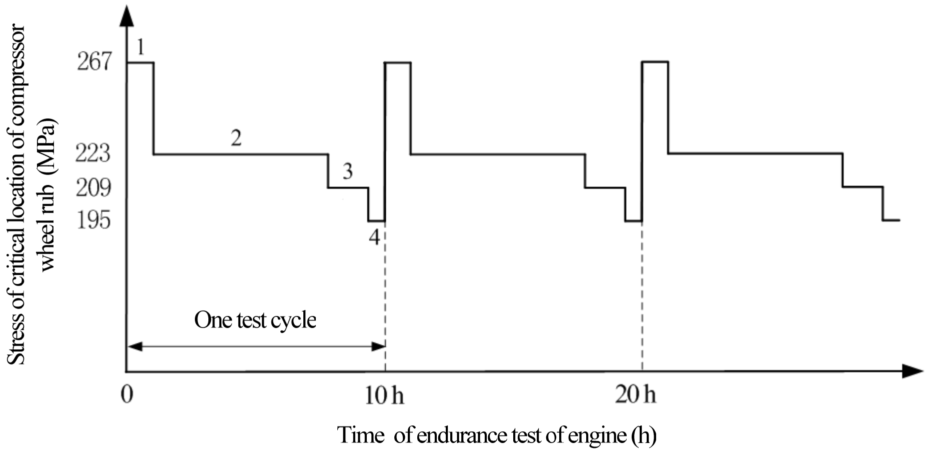

Figure 2. Fatigue stress history of compressor wheel rub corresponding to the endurance test profile of engine

3. Study on the strength of Compressor Wheel Rub with Fatigue Failure Mode

In order to study the fatigue strength of compressor wheel rub of turbocharger, the test specimen which can reflect the effect of structural characteristics and manufacturing process on the fatigue strength, is designed as Figure 3. Forty-five specimens of compressor wheel rub are manufactured and the fatigue test of these specimens is done at the fatigue-testing machine.

According to the results of fatigue test of compressor wheel rub specimen, the relationship between the fatigue life of compressor wheel rub and stress is subjected to the form of exponential function, namely,

$$Ne^{\alpha s} = C \tag{1}$$

And the relationship between the logarithm mean value $\mu_{\lg N}$ of fatigue life N of compressor wheel rub and stress s can be expressed as

$$\mu_{\lg N} + 0.02498\, s = 16.7535 \tag{2}$$

The relationship between the logarithm standard deviation value $\sigma_{\lg N}$ of fatigue life N of compressor wheel rub and stress s can be expressed as

$$\sigma_{\lg N} + 0.02522\, s = 13.5866 \tag{3}$$

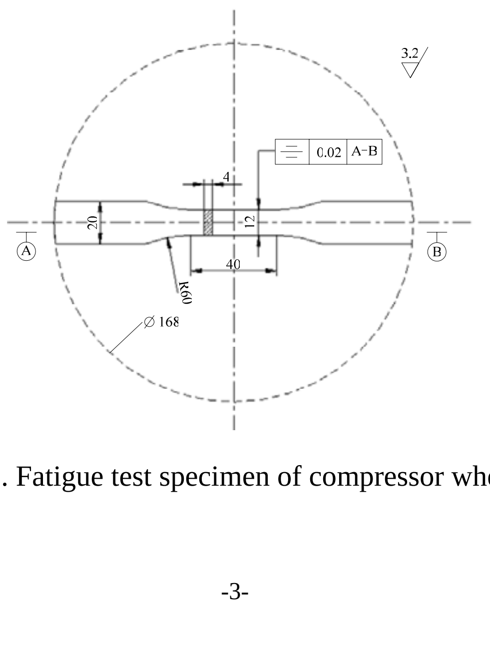

Figure 3. Fatigue test specimen of compressor wheel rub

4. Fatigue Reliability Modeling and Reliable Life Prediction of Compressor Wheel Rub

According to the linear Miner cumulative damage rule, the fatigue cumulative damage ΔD of compressor wheel rub corresponding to one cycle of endurance test of engine, can be expressed as

$$\Delta D = \frac{1}{N_1} + \frac{1}{N_2} + \frac{1}{N_3} + \frac{1}{N_4} = \sum_{i=1}^{4} \frac{1}{N_i} \tag{4}$$

Where, N_i is the fatigue life of compressor wheel rub corresponding to the stress s_i.

And the number of test cycles of engine endurance test to which the fatigue failure happened in the compressor wheel rub of turbocharger, can be derived as

$$n = \frac{1}{\Delta D} = \frac{1}{\sum_{i=1}^{4} \frac{1}{N_i}} \tag{5}$$

And the limit state function of compressor wheel rub with fatigue failure mode can be expressed as

$$Z = n\Delta D - 1 = n\sum_{i=1}^{4} \frac{1}{N_i} - 1 \tag{6}$$

When the fatigue life of compressor wheel rub is measured with the number of test cycles of endurance test of engine, the relationship between the fatigue reliability of compressor wheel rub of turbocharger and its life parameter can be developed as

$$R(n) = P\left(n\sum_{i=1}^{4} \frac{1}{N_i} - 1 < 0 \right) \tag{7}$$

Let $x_i = \log N_i$, and using the second moment method, the limit state function of compressor wheel rub with fatigue failure mode can be expressed as

$$\begin{aligned} Z &= n\sum_{i=1}^{4} 10^{-x_i} - 1 \\ &= n\sum_{i=1}^{4} 10^{-\mu_{x_i}} - 1 - n\ln 10 \sum_{i=1}^{4} 10^{-\mu_{x_i}} (x_i - \mu_{x_i}) \end{aligned} \tag{8}$$

And the mean value and standard deviation value of the limit state function of compressor wheel rub with fatigue failure mode can be expressed as

$$\mu_Z = n\sum_{i=1}^{4} 10^{-\mu_{x_i}} - 1 \tag{9}$$

$$\sigma_Z = n\ln 10 \sqrt{\sum_{i=1}^{4} \left(10^{-\mu_{x_i}} \sigma_{x_i}\right)^2} \tag{10}$$

With Eq. (2) and Eq. (3), the logarithm mean value and the logarithm standard deviation value of fatigue life of compressor wheel rub corresponding to the different stress shown as Tab. 1, can be calculated. and the result is substituted into Eq. (9) and Eq. (10), we have

$$\mu_Z = 9.0325 \times 10^{-11} n - 1 \tag{11}$$

$$\sigma_Z = 0.002772n \tag{12}$$

Further, according to Eq. (7), the reliability model of compressor wheel rub with fatigue failure mode can be developed as

$$R(n) = \Phi\left(-\frac{\mu_Z}{\sigma_Z} \right) = \Phi\left(\frac{1 - 9.0325 \times 10^{-11} n}{0.002772n} \right) \tag{13}$$

where， $\Phi(\cdot)$ denotes the cumulative distribution function of standard normal distribution.

The rule that the reliability of compressor wheel rub with fatigue failure mode changes as the number of test cycles of endurance test of engine can be obtained with Eq.(9), and it is shown as Figure 4.

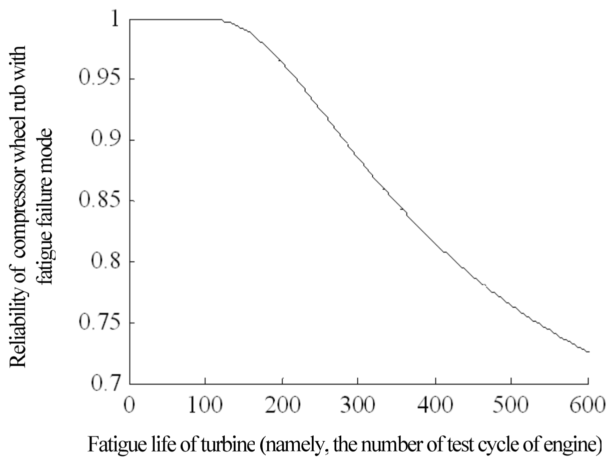

Figure 4. Reliability curve of compressor wheel rub with fatigue failure mode

From Figure 4, it can be concluded that the reliability of compressor wheel rub with fatigue failure mode decreases as the life parameter increases.

According to the relationship between the reliability of compressor wheel rub with fatigue failure mode and its life parameter, the reliable fatigue life of compressor wheel rub can be determined rationally. As shown in Fig. 5, when the reliability of compressor wheel rub with fatigue failure mode is 0.95, the reliable life $w_{0.95}$ is 220 cycles of endurance test of engine, and when the reliability is 0.9, the reliable life $w_{0.9}$ is 281 cycles of endurance test of engine.

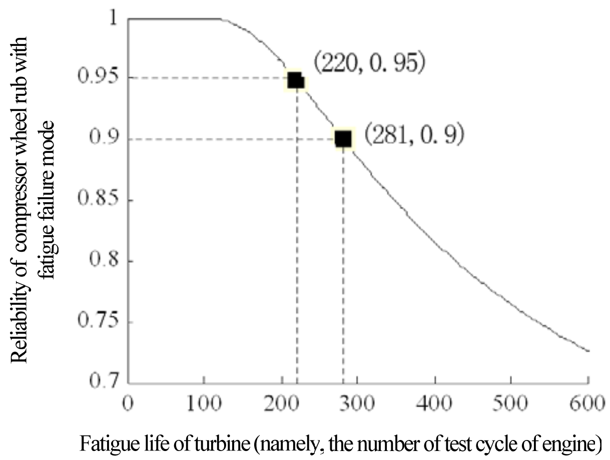

Figure 5. Reliable life of compressor wheel rub with fatigue failure mode corresponding to different reliability

5. Conclusions

The reliability and life of turbocharger compressor wheel rub with fatigue failure mode is studied in this paper. Based on the endurance test profile of vehicle engine, the running status of compressor wheel of turbocharger is analyzed when engine works in different operating modes, and the fatigue stress process of compressor wheel rub corresponding to the endurance test profile of engine is built. And the relationship between the fatigue life of compressor wheel rub and stress is developed through the fatigue test of fatigue specimen. The reliability model of compressor wheel rub with fatigue failure mode is derived, and then the method for determining the reliable fatigue life of compressor wheel rub is proposed. The result shows that as the life parameter increases, the reliability of compressor wheel rub with fatigue failure mode decreases. When the reliability is given, the reliable fatigue life of compressor wheel rub can be predicted with the method proposed rationally.

Acknowledgements

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