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Ultrasonic Fatigue Testing Machine Based on Resonance Principle

Yuhang WU*, Weifeng HE, Daihua LI*****
**National Key Lab of Aerospace Power System and Plasma Technology, Air Force Engineering University, Xi'an, People's Republic of China, E-mail: 2332577134@qq.com*
***National Key Lab of Aerospace Power System and Plasma Technology, Air Force Engineering University, Xi'an, People's Republic of China, E-mail: hehe_coco@163.com (Corresponding author)*
****National Key Lab of Aerospace Power System and Plasma Technology, Air Force Engineering University, Xi'an, People's Republic of China*

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1. Introduction

Fatigue failure is a key factor that limits the structural integrity and reliability of aviation equipment, especially for high-speed rotating structures such as compressors and turbines in aircraft engines, which experience alternating loads of up to 10^8 ~10^{10} times throughout their entire life cycle. With the continuous improvement of the requirements of modern aviation equipment for reliability and life indicators, the issue of ultra-high cycle fatigue of materials has become increasingly important. Due to the advantages of ultrasonic fatigue testing technology, such as time-saving, energy-saving, and suitability for the study of long-life fatigue of materials, the design of ultra-high cycle fatigue testing equipment and the evaluation of material life have become one of the research hotspots in the field of aviation equipment safety [1-2].

With the rapid advancement of design concepts and manufacturing processes, the fatigue failure of aviation engine blades has increasingly reduced and demonstrated the characteristics of ultra-long service life. Ultra-long life fatigue generally refers to the fatigue failure behavior with a cyclic load number higher than 10^7. In 2001, the US Air Force explicitly stated in its annual report on the "High Cycle Fatigue Program" that the fatigue design life of all military engine components should reach at least 10^9 cycles, and proposed the requirement to explore ultra-high cycle testing methods and means. In 2002, the US Military Structural Integrity Program (MIL-HDBK-1783B) was revised and issued, which comprehensively proposed the requirement for ultra-high cycle fatigue life design, that is, all engine parts should have a fatigue life of at least 10^9 cycles. The outline points out that this data is based on the fact that most materials do not have a fatigue limit, however, the outline does not provide clear test methods and means. At present, the strength and safety design of aviation engines in China still adopts the design concept based on the fatigue limit, and the design index is also limited to 10^7. Although the concept of ultra-long life design is mentioned in the design process, it has not yet affected the actual design due to the lack of relevant testing methods and equipment. For example, the AL31F turbofan engine used in China has a compressor speed of over 10000 rpm and a designed service life of over 1500 hours. Throughout the entire life cycle, components such as blades and discs are subjected to cyclic fatigue loads of up to 10^9 ~10^{10}, leading to increasingly common issues of ultra-long life fatigue failure. It can be foreseen that with the further improvement of design indicators and service life, aviation engines will face fewer problems of ultra-long life fatigue damage [4]. The research on ultra-high cycle fatigue in China faces a series of challenges, such as late start, lack of experimental methods, and inability to independently develop experimental equipment.

In recent years, the issue of ultra-long life fatigue failure has gradually attracted the wide attention of scientists from different countries, and various experimental methods have been explored to carry out ultra-long life fatigue experimental research [5-6]. Both the International Journal of Fatigue and Ultrasonic have published several articles on research on ultra-high cycle fatigue testing equipment and technology. This study focuses on the harsh load conditions and severe threat of ultra-high cycle fatigue damage faced by aerospace mechanical components, high-speed trains, and other equipment. The key technology research of ultra-high cycle fatigue experiments is carried out to improve the ability of anti-fatigue design, enhance the relevant technical reserves, and provide an important support foundation for the design and manufacture of major equipment in the future [7].

2. Research on Key Technologies of Ultrasonic Fatigue Experiment

As an emerging fatigue testing method, ultrasonic fatigue has the greatest advantage in utilizing high-frequency loading characteristics to achieve ultra-low crack propagation rates and ultra-long life fatigue performance. With 10^9 fatigue cycles, the ultrasonic fatigue test method takes only 13.9 hours, while traditional hydraulic servo and electromagnetic resonance require up to 1 year or even several years. From a time cost perspective, traditional fatigue experimental methods are no longer effective in conducting large-scale ultra-high cycle fatigue experimental research. This article focuses on the problem of ultra-high cycle fatigue fracture of aircraft engine compressor components, conducts research on the key technologies of ultrasonic fatigue experiments, and independently develops an ultrasonic fatigue experimental system.

2.1. Principles of ultrasonic fatigue experiment

The principle of ultrasonic fatigue testing is to convert electrical signals into weak high-frequency mechanical vibrations, and use vibration energy to focus and drive the sample to resonate to complete fatigue vibration. Ultrasonic fatigue testing is the process of converting electrical energy to high-frequency mechanical vibration energy and focusing energy. The control of ultrasonic electrical signals and the matching design between various components of the system are the key and difficult points for the smooth implementation of the ultrasonic fatigue experiment. At present, only Shimadzu Corporation of Japan and Branson Corporation of the United States have achieved commercial production of ultrasonic fatigue testing systems [8], as shown in Fig. 1.

Fig. 1 USF-2000 ultrasonic fatigue testing machine produced by Shimadzu Company

The ultrasonic fatigue experiment utilizes the piezoelectric effect of piezoelectric crystals to convert electrical and mechanical energy, and drive the resonance of the sample. It includes three processes: the generation and control of high-frequency excitation point signals, electrical force conversion, and focused amplification of mechanical energy. Specifically, the ultrasonic signal generator generates high-frequency electrical excitation signals and adjusts the signals based on the real-time resonance state to ensure that the system is always in a good resonance state. Under the action of high-frequency excitation electrical signals, piezoelectric crystals generate periodic mechanical stretching vibration, which has a very weak amplitude, usually not exceeding 10 μm. By focusing the vibration energy and amplifying the amplitude through a variable amplitude pole, the sample is driven to complete the forced vibration. When the frequency of the excitation electrical signal matches the natural vibration frequency of the mechanical system composed of the amplitude converter, transducer, and specimen, resonance occurs in the specimen. Fig. 2 shows a schematic diagram of the principle of the ultrasonic fatigue testing system.

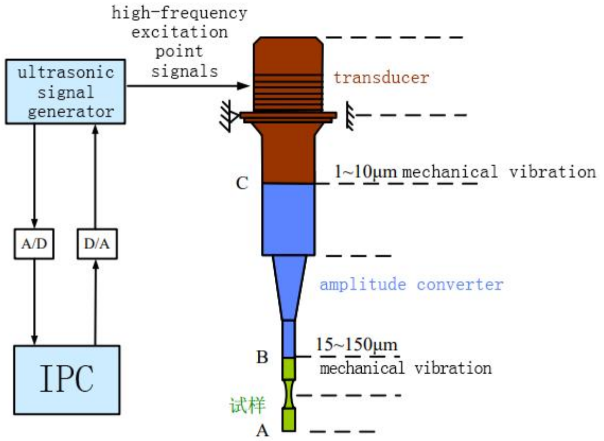


Fig. 2 Principle of ultrasonic fatigue experiment system

Its main components and functions are as follows:

1. Ultrasonic signal generator: It is mainly used to generate a 20kHz high-frequency excitation signal and dynamically adjust the signal to ensure that the test is always in good resonance condition.

2. Ultrasonic transducer: It is the main component of converting electrical energy into mechanical energy, which converts electrical signals into vibrational signals.

3. Ultrasonic horn: It amplifies the vibration displacement from the transducer.

2.2. Ultrasonic transducer

The transducer is the main component of the ultrasonic fatigue testing system to achieve energy conversion. Its function is to convert the high-frequency electrical signal output by the ultrasonic signal generator into high-frequency mechanical vibration. According to the principles used in the energy conversion process, ultrasonic transducers can be divided into magnetostrictive, piezoelectric, electromagnetic, and capacitive types [9-10]. Among them, piezoelectric and magnetostrictive types are widely used in longitudinal vibration modes, and the performance parameters of the two types of transducers are shown in Table 1. The loading frequency for ultrasonic fatigue experiments is generally 20 kHz. According to the performance indicators listed in Table 1, the sandwich piezoelectric ceramic transducer meets the frequency requirements for ultra-high cycle fatigue experiments and has high energy conversion efficiency. Therefore, this article selects the sandwich piezoelectric ceramic transducer for testing.

With a low resonance frequency and the ability to adjust the working frequency by adjusting the shape and counterweight of the front and rear metal cover plates. According to the different locking methods of piezoelectric crystals, sandwich piezoelectric transducers can be divided into single screw type, multi screw type, and expansion shell type. Among them, the single screw type uses pre-stressed bolts to lock the piezoelectric ceramic stack, with the simplest structure. Based on the structural characteristics of the ultrasonic fatigue testing system and the fixing method of the transducer in this article, the front cover plate is designed as a stepped transducer with chamfers, and the rear cover plate is a circular single-bolt sandwich transducer. The structural schematic diagram is shown in Figure 3. Due to the weak piezoelectric effect of a single piezoelectric ceramic sheet, it cannot meet the requirements of ultrasonic fatigue. Therefore, several piezoelectric ceramics are connected in series to increase the amplitude, and 0.2 mm thick copper sheets are used to isolate the piezoelectric crystals at all levels. The actual ultrasonic transducer prepared is shown in Fig. 3.

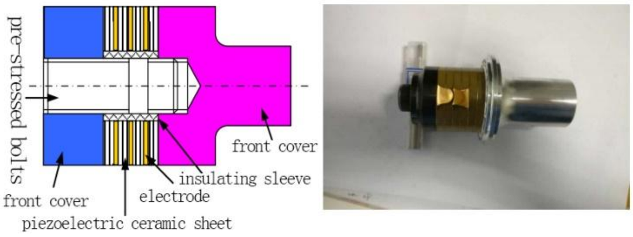


Fig. 3 Single screw sandwich piezoelectric ceramic transducer

Table 1

Comparison of the performance of piezoelectric and magnetostrictive transducers

Type of transducer	Piezoelectric transducer			Magnetostrictive transducer	
	Quartz	Piezoelectric ceramics (sheet shape)	Piezoelectric ceramics (sandwich type)	Nickel iron cobalt alloy	Ferrite
Operating frequency	1 MHz	200 kHz~1 kHz	10 kHz~100 kHz	below 50 kHz	above 100 kHz
Electroacoustic efficiency	~80%	~80%	70%~90%	20~50%	~80%

3. Ultrasonic Fatigue Experimental System

Based on the research on the basic principles and key technologies of ultrasonic fatigue experiments, theoretical analysis, hardware adaptation, and system construction were carried out, focusing on the two main components of the ultrasonic signal generator and ultrasonic transducer. It was determined whether the two designed components met the functional and performance requirements of the ultrasonic fatigue testing, and the stability of the ultrasonic fatigue test system was experimentally verified, to lay the foundation for subsequent ultra-high cycle fatigue experiments. Based on the analysis of the functional and performance requirements of the ultrasonic fatigue experimental system, the ultrasonic fatigue testing system was calibrated.

3.1. Construction of ultrasonic fatigue experimental system

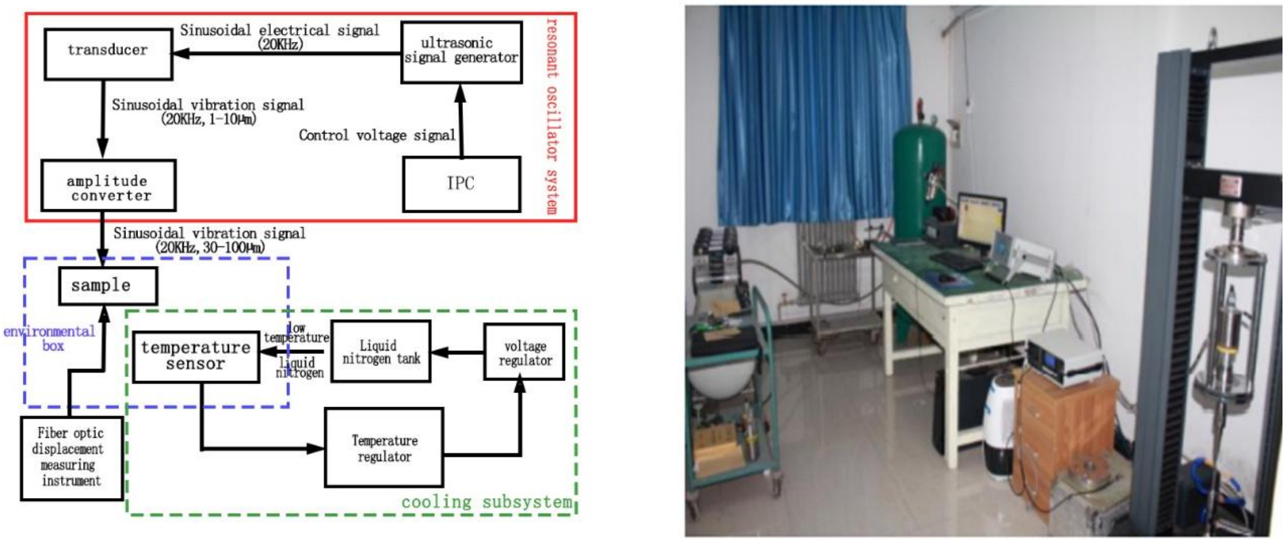
The ultrasonic fatigue testing system developed in this article mainly consists of a resonant oscillator system, a cooling subsystem, a measurement subsystem, and an environmental box, as shown in Fig. 4. The ultrasonic transducer and amplitude changing rod are fixed on the tensile testing machine through a partition frame, which facilitates subsequent high-cycle fatigue tests with variable stress ratio.

The harmonic oscillator system consists of an ultrasonic signal generator, a transducer, an amplitude transformer, and a sample. Two measures were taken to reduce the temperature of the sample: first, the continuous vibration loading was improved to intermittent loading, thereby reducing the accumulation of heat in the sample. The second is to cool the sample through an external cooling device. The external cooling device also includes two subsystems based on the different media used: low-temperature nitrogen cooling and low-temperature compressed air cooling. The low-temperature compressed air cooling subsystem consists of an air compressor, an air storage tank, a cold air gun, and an airflow nozzle.

3.2 Functional verification and performance calibration experiment

Two more tasks are required for the construction of the ultrasonic fatigue experimental system: first, verifying the performance of the ultrasonic signal generator. The second is to verify the stability and linearity of the ultrasonic fatigue experimental system. Firstly, a functional verification experiment was conducted on the ultrasonic signal generator. DEWESoft software was used to collect vibration displacement voltage signals measured by fiber optic sensors. The experimental conditions were set as frequency search, continuous loading, and intermittent loading. The intermittent loading program was set to load for 500 ms with an interval of 400 ms. The experimental results are shown in Figs. 5 to 6.

In ultrasonic fatigue experiments, a frequency search is performed on each specimen before starting the experiment, with the aim of finding the resonance frequency point of the system and serving as the frequency of the initial excitation signal of the ultrasonic transducer. It can be seen from Fig. 5 that with increasing frequency, the amplitude increases slowly at first, but suddenly increases at a certain frequency point. This frequency is the system resonance frequency, and the search process takes about 20 seconds.



a

b

Fig. 4 Fatigue experiment of ultrasonic system: a – schematic diagram of the principle structure, b – picture of the entire system

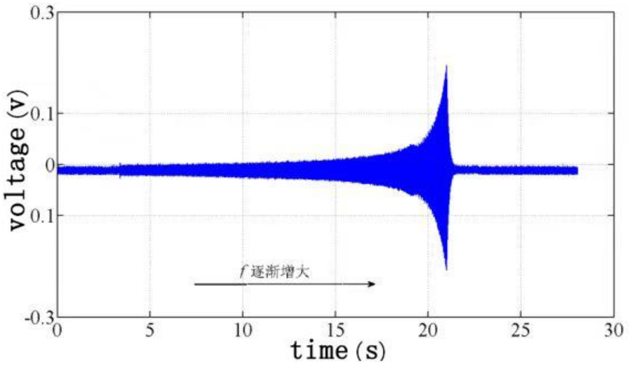


Fig. 5 Experimental results for the frequency search of ultrasonic signal generator

The continuous loading mode was set for the continuous loading experiment, with a time of 60 minutes. The corresponding experimental results are shown in Fig. 6. It can be seen that the ultrasonic signal generator can maintain stability during continuous operation, and the fluctuation value of the output signal is less than 3%, meeting the requirements of the ultrasonic fatigue experiment.

The experimental results of the discontinuous loading experiment are shown in Fig. 7. It can be seen that the ultrasonic signal generator realizes the intermittent output incentive signal. At the moment of loading, the output excitation signal has no obvious overshoot and the starting speed is fast, which has the conditions for the experimental investigation of ultrasonic fatigue through intermittent loading mode. The realization of the intermittent loading function prevents the continuous accumulation of the internal friction heat energy in the sample during the experiment, and reduces the need for continuous use of the external cooling system.

To ensure the accuracy and precision of the ultrasonic fatigue testing system, it must be calibrated. The objectives of calibration are: 1. To check the linearity of the ultrasonic fatigue test system, that is, the linear correlation between the control voltage and the output displacement of the experimental machine; 2. To calibrate the input stress value and the actual stress value of the ultrasonic fatigue test system. During the calibration process, the voltage is increased and decreased twice each time, and 7 voltage values are collected. The calibration results are shown in Table 2 and Fig. 8.

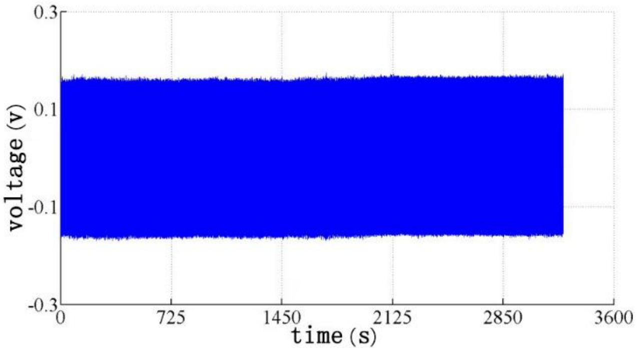


Fig. 6 Experimental results for continuous loading of the ultrasonic signal generator

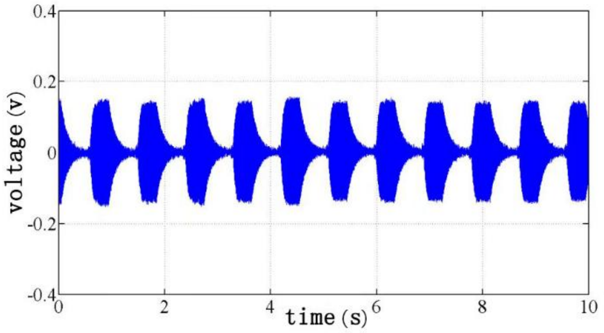


Fig. 7 Results of ultrasonic signal generator

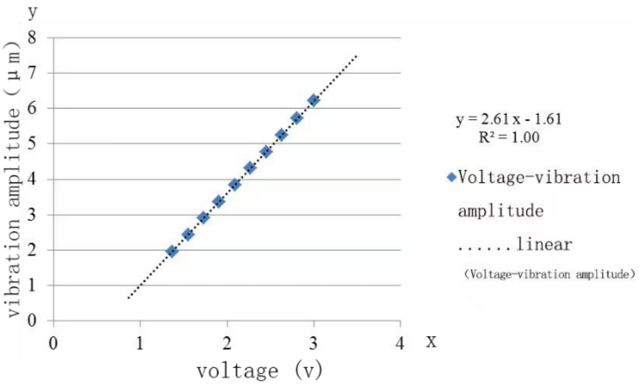


Fig. 8 Calibration of the control voltage and the output amplitude

As can be seen from Fig. 8, the output voltage of the industrial controller and the output amplitude of the transducer have a good linear relationship, and the correlation coefficient is 0.99. So, the ultrasonic fatigue test

Table 2

Calibration results of the ultrasonic fatigue system

voltage U, V	amplitude A, μm				average value
1.73	2.903	2.904	2.902	2.903	2.9030
1.91	3.373	3.371	3.374	3.374	3.3730
2.09	3.842	3.843	3.843	3.841	3.8422
2.27	4.311	4.313	4.312	4.310	4.3115
2.45	4.781	4.780	4.783	4.779	4.7807
2.63	5.251	5.253	5.249	5.240	5.2482
2.81	5.719	5.720	5.718	5.721	5.7195
3.00	6.215	6.214	6.216	6.215	6.2152
Fitting the transducer coefficient	a=2.6075 b=-1.6075				

system works well. It is also reliable; its output signal is stable and meets the requirements of ultrasonic fatigue testing

4. Conclusions

Based on the analysis of the functionality and performance of the ultrasonic fatigue testing system, key design index parameter ranges were proposed. We conducted research on structural design, characteristic analysis, parameter selection, and hardware adaptation for two main components of ultrasonic transducers and ultrasonic signal generators. Based on the research results, we integrated ultrasonic signal generators and ultrasonic transducers, established an ultrasonic fatigue testing system, and conducted verification and calibration experiments on the functionality and performance of the ultrasonic fatigue experimental system.

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Y. Wu, W. He, D. Li

ULTRASONIC FATIGUE TESTING MACHINE BASED ON RESONANCE PRINCIPLE

Summary

With the continuous improvement of reliability and life index of modern equipment, researchers and research institutions pay more and more attention to the problem of ultra-high cycle fatigue of metallic materials. Ultrasonic fatigue testing is the most effective and commonly used method to test ultra high cycle fatigue of metallic materials. It is an accelerated fatigue test method based on the principle of resonance. The typical test frequency is 20 kHz, which has an obvious time advantage and can greatly save the time cost and economic cost of fatigue testing. In this paper, based on the key technical requirements of the ultra-high cycle fatigue test, the design of the ultrasonic fatigue test machine is carried out by using the method of theoretical research and numerical simulation, focusing on key components such as ultrasonic transducer, signal generator, horn and so on. It can realize ultra-high cycle fatigue performance testing with low stress amplitude and high frequency, and complete the test in a short time.

Keywords: ultrasonic fatigue testing machine, ultrasonic transducer, high frequency, fatigue test, high cycle fatigue.

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