Dynamic Measurement Device of Aeroengine Pressure Probe

B Li¹, H Y Zhang¹, J Yang¹, Z J Zhang²

¹AVIC Changcheng Institute of Metrology& Measurement, Beijing, 100095, China
²CASC Beijing Institute of Precise Mechatronics and controls, Beijing 100076, China

libo@cimm.com.cn

Abstract. In order to improve the dynamic performance evaluating abilities of the pressure probe of the aeroengine, by loading sine pressure with variable static pressure and temperature and measuring the dynamic pressure process, the pressure probe is calibrated. The dynamic pressure device based on the electroacoustic transducer can produce (20~1000) Hz sinusoidal pressure within 1 MPa static pressure environment, and the sinusoidal pressure amplitude can reach 10 kPa. The temperature system is established by the convection heating mode to provide (20~400) °C temperature environment for the pressure probe. The dynamic measurement device of pressure probe with controllable static pressure and temperature is established. The performance of the device is tested, and the test results are stable and reliable. The device is used for dynamic measurement of traditional pressure sensor and pressure probe. The device can simulate the work environment of the tested object and could be widely used in dynamic characteristics tests and evaluation of the pressure probe and other pressure system with transmission pipe.

1. Introduction

The pressure parameters of aeroengine are mainly measured by all kinds of pressure sensors with transmission pipe in front end, which are called pressure probe in engineering. Pressure probe usually is installed inside the engine and works under high temperature and high pressure draught[1-4]. The development of aeroengine design puts new requirements for the measurement of aeroengine. First of all, in terms of pressure probe design, fast dynamic response, high accuracy and adaptation to high temperature, pressure environment and other severe environment[5-7]. Secondly, both exclusive or general sensors and pressure measurement in use are constrained by the traceability of value. Reliability of equipment use and accuracy of test data demand the establishment of measurement method and device[8]. The level of pressure testing equipment and related metrology and measurement technology also reflect the development of aeroengine.

Dynamic measurement of pressure probe has been carried out for many years, foreign institutions and companies such as NASA, LMT and Dassault aircraft company, etc devote to the mechanism analysis and modeling of pressure probe of aeroengine[9,10]. Relevant exclusive facilities are also made for measurement and metrology. The research on the measurement of pressure probe with different media under various temperatures and multi-physical field coupling is developed. A large number of theoretical and experimental studies have also been carried out on the dynamic characteristics of pressure probes in China[11-17]. However, a lack of special measurement equipment in complex environments leads to failure to assess accuracy of pressure probe measurements, which limits the manufacturing of aeroengine.
To solve the problem of accuracy of pressure probe measurement, a dynamic measurement device which can simulate the actual usage is designed. This device can be used for the dynamic test of pressure measurement system with transmission pipe, such as pressure probe, under high temperature and pressure. The device can create a coupled environment where static pressure ranges from 0 to 1 MPa, temperature from 20 °C to 400 °C and sinusoidal gas pressure from 1 kPa to 10 kPa. The device can also effectively simulate the multi-physical field coupling phenomenon in the actual use of the pressure probe, provide reference for the measurement results of the pressure probe and technical support for the design of the pressure probe and the compensation and correction of the dynamic characteristics of the pressure probe.

2. System composition

In order to realize the accurate dynamic measurement of pressure probe, the actual test environment such as high temperature environment, static pressure changing environment is supposed to be simulated as much as possible. The designed dynamic measurement device for pressure sensing area can generate sinusoidal pressure under a specific temperature and static pressure by sinusoidal excitation, which mainly contains static pressure system, dynamic pressure system, temperature system and DAQ system. The device is shown in Figure 1.

![Figure 1. Structure diagram of pressure probe measuring device](image)

Static pressure system mainly consists of gas source, pressure controller, cavity, vibration isolation base, pipe valves and so on. Gas source supplies high pressure gas medium, which is input into the pressure cavity after steady pressure regulation by the pressure controller, generating a (0–1) MPa static pressure environment.

Dynamic pressure system contains signal generator, power amplifier and electroacoustic transducer. Sinusoidal signal from 20 Hz to 1000 Hz created by signal generator is amplified and adjusted by power amplifier. Then the output is sent to the electroacoustic transducer which produces a sinusoidal vibration to help generate sinusoidal pressure wave in the sealed cavity. By changing sinusoidal signal voltage of the signal generator and the gain coefficient of the power amplifier, the sinusoidal pressure amplitude can reach 10 kPa.

Temperature system includes temperature controller, heating device and so on. The resistance furnace is a hollow open-hole structure so that a pressure probe can be installed. The electric heating wire in the resistance furnace is used to heat the pressure probe to produce a (20–400) °C temperature condition.

DAQ system is able to control the key parameter of static pressure, dynamic pressure, temperature and frequency and acquire output signal, finishing the analysis to test and data processing.

3. Main function realization and performance

3.1. Static pressure system

Pressure cavity shown in figure 2 is the key structure of static pressure system which cooperates with pressure controller, electroacoustic transducer and pressure probe. Pressure cavity aims to fix and
support the electroacoustic transducer so that a steady static pressure environment can be provided and pass dynamic pressure to pressure probe.

![Figure 2. Structure of pressure cavity.]

Static pressure in pressure cavity mainly depends on abilities of pressure controller. Using pressure controller with high precision can control the static pressure with 1 MPa and keep the relative error no more than 0.05%.

Pressure cavity material chooses 06Cr19Ni10. Cavity thickness can be calculated according to ASME VIII-1. Internal diameter of cavity is supposed to be decided by the outside diameter of electroacoustic transducer. Considering the high temperature environment, cavity height is supposed to be as small as possible to decrease the effects to the frequency response characteristics of electroacoustic transducer caused by cavity resonance.

In order to create a sinusoidal pressure at 400 °C and 1 MPa, it is necessary to decide special structural parameter and check safety of pressure cavity. The whole structure needs to be considered and designed comprehensively. When the pressure cavity simulation structure is established, the strength should be checked.

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![Figure 3. Pressure cavity structure stress analysis]

By the analysis in figure 3, the maximum stress 51 MPa of the pressure tolerance cavity is less than the allowable stress level, which meets the requirements of use under high temperature and pressure conditions.

3.2. Dynamic pressure system
Dynamic excitation in pressure probe measurement device is realized by dynamic system whose important part is electroacoustic transducer shown in figure 4. Dynamic pressure device is mainly used to generate a sinusoidal vibration in the sealed cavity by electroacoustic transducer to get a sinusoidal pressure wave supplying excitation for the measurements. As sinusoidal signal has single frequency component, and any complex signal can be decomposed into many sinusoidal signals with different amplitude and different frequency by frequency domain transformation. Therefore, sinusoidal pressure wave generated by electroacoustic transducer is steady and easy to adjust. Meanwhile, sinusoidal signal is a representative excitation.

Using exclusive electroacoustic transducer to generate sinusoidal pressure wave are supposed to take two things into account. For one thing, working frequency at least ranges from 20 Hz to 1000 Hz. For another, it is required to work at 1 MPa. Due to the limit of manufacturing technology and element capabilities, electroacoustic transducer has its own frequency response characteristics and outputs different amplitudes at different frequency. The cone paper of the electroacoustic transducer can be regarded as a rigid body when working at low frequency. However, with increase of working frequency, cone paper is no more than thought as a rigid body and segmentation vibration will appear. Besides, when vibrating, cone paper and surround will interact. Because of all above reasons, when input different frequency signals to electroacoustic transducer, although signal voltage remains constant, amplitude of sinusoidal pressure wave of electroacoustic transducer changes with the frequency of signal.

To obtain flat frequency response characteristics from 20 Hz to 1000 Hz and work under 1 MPa, the cone paper material of electroacoustic transducer is honeycomb sandwich composite, which is a special type of composite material and consists of three basic materials. The chosen carbon fibre panel - aluminium honeycomb sandwich has light weight, high rigidity, high strength, good fatigue resistance, smooth surface, helping generate ideal sinusoidal signal. The amplitude-frequency characteristics measured by B&K3144 sensor are shown in figure 5. The sensor is along the reference axis of electroacoustic transducer with a distance of 1m to the voice coil.

Figure 4. Structure of electroacoustic transducer

Figure 5. Amplitude-frequency characteristics
The results show that the electroacoustic transducer has good uniformity from 20 Hz to 1000 Hz, and the electroacoustic transducer can produce 10 kPa pressure amplitude in the pressure cavity through the calculation of sound pressure level.

Test the output signals at different frequency points under the same voltage, select the frequency points of 20 Hz, 300 Hz, 600 Hz and 1000 Hz as shown in figure 6.

![Graphs of different frequency outputs](image_url)

**Figure 6.** Output at different frequency points

The results show that the electroacoustic transducer has some distortion at 20 Hz and 1000 Hz where the amplitude output is smaller at the same voltage. The output of sinusoidal waveform is better and the consistency is higher at the other frequency points.

Keep voltage constant and do frequency sweep experiment seven times. The step of experiment is 1 Hz. Then repeatability of electroacoustic transducer from 20 Hz to 1000 Hz can be obtained and shown in figure 7.

![Graph of RSD vs Frequency](image_url)

**Figure 7.** Dynamic pressure system output repeatability
According to figure 7, the maximum relative standard deviation of the dynamic pressure device from 20 Hz to 1000 Hz is less than 1.8%. The output of the system at each frequency point is stable and has good repeatability, which can provide a stable sinusoidal excitation for the pressure probe.

3.3. Temperature system

The temperature system of pressure probe measurement device serves stable high temperature environment. Usually pressure probe is made of metal or composite materials, thus, resistance furnace is used to heat. Resistance furnace has the characteristics of small heat loss, simple heating mode, uniform distribution of temperature field, suitable for most materials heating. The resistance furnace adopts the convection heating method, and the pressure probe is heated by heating air. The designed resistance furnace adopts the open structure, the upper and lower position is adjustable, which is beneficial to place the pressure probe and adjust the heating position and stabilize the temperature in the furnace to the set temperature value within a predetermined time. Three K type thermocouples are set at top, middle and base to measure the temperature of pressure probe. Moreover, PID controller makes the furnace temperature more precise and stable. The device structure is shown in figure 8.

![Figure 8. Resistance furnace device](image)

By setting different temperature points selected between 20 ℃ to 400 ℃, the performance of resistance furnace device is tested and shown in table 1.

| Temperature (℃) | Average value of measured temperature (℃) | Maximum deviation (%) |
|----------------|------------------------------------------|-----------------------|
| 20             | 20.1, 20.1                               | 0.50                  |
| 60             | 60.4, 60.1                               | 0.67                  |
| 80             | 80.2, 80.2                               | 0.50                  |
| 100            | 100.2, 100.2                             | 0.20                  |
| 200            | 200.3, 200.2                             | 0.15                  |
| 300            | 299.8, 300.3                             | 0.10                  |
| 400            | 400.2, 400.3                             | 0.08                  |

Results show that temperature system can provide stable temperature environment from 20 to 400℃ for pressure probe.

4. Measurement methods

The relative method is used to measure the pressure probe. Install pressure probe and reference sensor at the same plane and make them as close as possible. In that case, they are thought to measure the pressure of one point. Wind heating wires on pressure probe so that the measurement can be carried on at the set temperature. Measuring principle of pressure probe is shown in figure 9.
Pressure peak value $p_p$ is generated by electroacoustic transducer which is a complex electromechanical coupling system. Therefore, $p_p$ cannot be obtained by theoretical calculation and can only be measured by reference pressure sensor. The pressure value at the $p_1$ and $p_2$ of the pressure point is equal in theory. The pressure distribution deviation of pressure point 1 and pressure point 2 at normal temperature from 20 Hz to 1000 Hz is measured. The results in figure 10 shows that measurement deviation of two points is less than 1.0%. It is considered that $p_p \approx p_1 \approx p_2$.

**Figure 9.** Measuring principle of pressure probe

Dynamic pressure amplitude of sealed pressure cavity can be calculated according to the following formula.

$$p_p = \frac{U_1}{S_1}$$  \hspace{1cm} (1)

$U_1$ is the peak output voltage of the reference sensor, $S_1$ is the sensitivity of the reference sensor. Amplitude sensitivity of calibrated pressure probe can be calculated by next formula.

$$S = \frac{U_2}{p_p} = \frac{U_2}{U_1}S_1 = kS_1$$  \hspace{1cm} (2)

**Figure 10.** Pressure distribution deviation
is the output peak value of pressure probe at pressure point 2, \( U_1 \) is the output peak value of reference sensor at pressure point 2, \( k \) is amplification coefficient.

According to formula (2), amplitude ratio of pressure probe signal and reference signal is regarded as the ratio of output and input, thus the amplitude frequency characteristics of pressure probe can be got. Theoretically, the pressure probe can amplify the signal in some frequency bands. Amplification coefficient \( k \) is related to structure of pressure probe, pressure medium, environment conditions and so on.

Above all, \( k \) can be used to describe the dynamic sensitivity and amplitude frequency characteristics.

5. Measurement methods

This device can also carry on the experiment test of traditional pressure sensor. The device is shown in figure 11.

5.1. Traditional pressure sensor test

Using this device to carry out dynamic measurement of traditional pressure sensors. Two verified PCB pressure sensors are selected, one of which is the reference sensor(RS) and the other is the device under test(DUT). The technical parameters of the two sensors are shown in table 2

| Type  | Serial number | Sensitivity (mv/kPa) | Natural frequency (kHz) |
|-------|---------------|----------------------|-------------------------|
| RS    | 112A22-38767  | 14.65                | ≥250                    |
| DUT   | 112A22-38768  | 14.56                | ≥250                    |

The sweep frequency experiment with 1 Hz step from 20 Hz to 1000 Hz at 0.2 MPa and 20 °C is made to measure the sensitivity of DUT. The dynamic sensitivity shown in figure 12 is calculated based on formula (2). Results at 500 Hz is presented in figure 13.

![Figure 11. Pressure probe measuring device](image)

![Figure 12. Dynamic sensitivity of DUT.](image)

![Figure 13. Measurement results at 500 Hz](image)
Above results show that this device can realize the dynamic measurement of sensitivity in a certain frequency band. A deviation between the dynamic sensitivity and the given static sensitivity is within 4%. The results show that the dynamic sensitivity of the sensor fluctuate is little and the dynamic characteristics are good, which is basically consistent with the verification results.

5.2. Pressure probe test
When using this device to carry out dynamic measurement of pressure probe, the reference remains and pressure probe as the measured object. Keep the measurement environment same and the amplitude frequency characteristics of pressure probe at different temperatures appears in figure 14. Output of 500Hz at different temperatures is shown in figure 15.

![Figure 14. Amplitude frequency characteristics of pressure probe](image1)

![Figure 15. Measurement results of different temperature at 500Hz](image2)

As pressure probe has cavity structure, at special frequency the signal has resonance amplification. The same conclusion can also be obtained from above experiment results. Dynamic characteristics of pressure probe at different temperatures varies, in other words, with the increase of temperature, the amplitude-frequency characteristics of the pressure probe shift to the right and the amplification decreases. When measuring at a single temperature, the increase of temperature causes increase of amplitude and the shift of phase. Shift of phase means the delay in time domain. Measurement results at different temperatures provide support for the use of pressure probe.

6. Main function realization and performance
In this paper, the dynamic measurement device of pressure probe is established, and the related performance test and dynamic measurement of sensor are carried out, the main conclusions are as follows:
1) Dynamic pressure system of device based on electroacoustic transducer can generate effective sinusoidal excitation which is adjustable. The convection heating method provides a suitable environment, realizing the measurement of pressure probe under multi-physical field coupling.
2) The application of relative method for dynamic pressure measurement meets the measurement requirements of the pressure probe, which can be applied to the evaluation of dynamic characteristics of the pressure probe.
3) The measuring device formed in this study has provided the measurement service for the dynamic performance evaluation of the pressure measurement system with transmission pipe, for example, pressure probe, and the technology formed can be used for dynamic pressure measurement.

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