GPPS-BJ-2019-0001

Study on thermal-acoustic-structural performance of Aeroengine Combustor based on Coupled-Field Technology

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ABSTRACT

A typical combustion chamber model is established to study the thermal-acoustic-structural performance of Aeroengine Combustor. Fluid and structure interaction (FSI) technology is used to simulate the ignition process of combustion chamber with different air-fuel ratio and vibration of combustion chamber. The calculated data is exchanged between fluid and solid interface by two-way coupled FSI. The results show that by varying the air-fuel ratio from 0.6 to 1.4, the average temperature and acoustic pressure are increased by 15% and 64.8%, respectively. The stress waves of the combustion chamber are consisted with three main frequencies of waves, which are one, two, and three doubling frequency, respectively. The studied structural vibrations are mainly caused by the one and three doubling frequency. The structural deformation caused by acoustic pressure accounts for 3.3%-4.9% larger than that of thermal expansion.

INTRODUCTION

A combustion is an important component of aircraft engine, which is used to provide a space for fuel to burn and convert into mechanical energy in turbo machineries. Unsteady burning of in the combustion usually causes fluctuations in temperature and pressure, and lead to structural fatigue damages. It's important to study the internal gas field and structural performances of the combustion chamber, to give a helpful analysing of fatigue failure mechanism of combustion chambers.

At present, lots of studies have been carried out to show the influence of flame model on combustion acoustics field and structure vibration characteristics. Sattelma [1] studied the gas field of a swirl stabilized premixed burner in an annular and a single burner combustion chamber, the effect of different gas field on combustion heat release rate was analysed. Prakash [2] studied the dynamic performances of

chamber flame at different gas equivalent ratios, and the interaction between acoustic pressure and flame was analysed. Artur [3] analysed the heat-acoustic instability, and the interaction between temperature field and acoustic pressure field was studied. Huls [4] studied the vibration in combustion chambers basing on acoustic-elastic finite element model and sound vibration test. Shu [5-6] carried out the combustion chamber pressure wave under a single point and excitation conditions by applying visual high-speed photography technology. Most of the studies focus on the interaction between air and structural fields. However, the acoustic field and structural vibration are all strongly affected by the temperature field, the study without temperature is one-sided.

A simulation modal of both combustion chamber and gas field is established to study the effect of temperature filed on the gas acoustic and structural vibration. The aim of this paper is to show the combined effect of thermoacoustic load on the wall of combustion chamber. The sound wave transmission process is simulated by CFD method. The vibration equation of plane noise is derived and solved to verify the accuracy of CFD method. Under different air-fuel conditions, the acoustic pressure, fluctuation, and combustion chamber vibration are all simulated to analyse the influence of gas acoustic on vibration of the combustion chamber. The results of the simulation is to provide a reference to the design of aero-engine combustors.

1 NUMERICAL ANALYSIS METHOD

1.1 Numerical simulation process

In the physical process of the combustion, the heat transfer speed of the temperature in solid field is much lower than that of gas. Therefore, the steady state temperature results are used as initial conditions of chamber domain. The adiabatic condition is used in the numerical simulation process. Transient structural analysis of ANSYS software is

used to analyse the structural deformation of the combustion chamber. The gas field performances are analysed by SST turbulence model of CFX software. Double cycle iterative method is used to simulate strong coupling phenomenon in the interactive boundary between combustion chamber and gas. The initial pressure and initial velocity of each node in the gas according to the given initial boundary condition are solved by CFX at the first [7]. The total time is 0.5s and the simulation process is divided to 1000 steps. The principle of the simulation method is shown in Fig. 1. At the beginning of each step, the structural deformations results and the gas data solved by previous step are used as initial condition. After the calculations of the gas domain have been converged, the parameters on gas interactive boundaries are sent to the structure boundaries by the grid interpolation calculation technology. Then the combustion chamber structure transient dynamic responses are solved by finite element calculation. After the structure calculation is converged, the parameters on solid boundaries are sent back to gas domain to solve the next calculation step.

Fig. 1 The principle diagram of the bidirectional coupling

1.2 Combustion chamber structure model

The combustion chamber structure is shown in Fig. 2. The overall length of the combustion chamber is 2000 mm, the wall thickness is 4mm, and the side length of the square channel is 150mm. The inlet of the combustion chamber includes air and fuel. The diameter of air inlet is 47mm compared with 12mm of fuel inlet. To balance the running time and accuracy, the length of the studied combustion chamber section is 400mm. The mass gas rate of the fuel is 8.1g/s and air-fuel ratio Φ_0 is changing from 0.6 to 1.4. In order to produce combustion noise, the fuel inlet is set as pulse entry. In a real combustion chamber the sound waves are synthesized with variety frequencies which is hard to analyse. Thus sound wave in this paper is assumed to only have one kind of frequency.

The structured grid with 34 000 nodes and unstructured grid with 52 000 nodes are used for combustion chamber and gas domain, respectively [8]. The total number of nodes are 86 000. As the temperature simulation results have little change (less than 1%) by enlarging the number of grid nodes so the node number of 86 000 is used in the following analysis.

Fig. 2 Structure diagram

In order to verify the accuracy of finite element calculation and the number reasonableness of the structured grid, an actual combustion chamber modal test using hammering model method is carried out. The experimental device is shown in Fig. 3. The test equipment includes a hammer, a torque wrench, LMS acquisition system, and a computer. The LMS acquisition system uses a third-generation test system and is equipped with TestLab software which is used for modal post processing analysis. The modal analysis is solved by ANSYS software. The solid 186 element type is used in both of modal analysis and bidirectional coupling analysis.

Fig. 3 The test device of the modal test

The comparison of simulation results and test data is shown in table 1. The calculated results of the natural frequencies are in good agreement with the test results. The results of the test partly prove the reliability of the finite element method (FEM).

Table. 1 Comparison of first six order inherent modal frequencies

Order	Calculation results	Experimental results
1	195.00Hz	179.630Hz
2	280.96 Hz	279.858 Hz
3	281.12 Hz	309.583 Hz
4	283.60 Hz	312.176 Hz
5	354.24 Hz	338.354 Hz
6	354.44 Hz	362.402 Hz

1.3 Boundary conditions

Fig. 4 shows the boundary conditions of bidirectional coupling calculations, and the detailed parameters are shown in Table 2. The fluid domain inlet is set to the speed inlet, and the fuel is methane [9].

Fig. 4 The boundary conditions of schematic diagram

Table. 2 Status parameters of combustion chamber

parameter	Value
inlet air speed	20m/s
inlet gas speed	100m/s
inlet air temperature	300K
inlet gas temperature	300K
outlet relative pressure	0Pa

The frequency of the pulse gas inlet is 50Hz [10] and the air-fuel ratio is controlled by the oxygen content of gas. The three-dimensional finite-volume method is used to solve the turbulent closure is SST model. The interface is set as a movable boundary condition in the bidirectional coupling analysis.

2 Theoretical discussion of sound waves

The acoustic pressure fluctuation in the combustion chamber is mainly caused by combustion instability. The combustion area is considered as a sound source, when the flame thickness is much lower than acoustic wavelengths, the flame may be assumed as an acoustic source distributed on the zero-thickness flame surface. Thus the acoustic pressure waves in the combustion chamber are similar to plane waves, as shown in Fig. 5.

Suppose that the reflection in the propagation process of sound waves in the combustion chamber is weaker than the main stream and most of the waves are absorbed into the chamber boundaries. Then the sound waves are assumed to propagate only in the X direction.

Fig. 5. Sound wave diagram

Under this assumption, the acoustic equation can be used for the description of non-viscid harmonic acoustic wave propagation. For a long prismatic tube with rigid walls, the acoustic equation can be reduced to one-dimensional form as follows:

$$p(x, t) = A_1 e^{j(\omega t - kx)} + A_2 e^{j(\omega t + kx)} \quad (1)$$

Where A_1 and A_2 are the (complex) amplitudes of the acoustic pressure waves traveling with the mean speed of sound c_0 in the negative and positive x -direction, respectively. The wave number k ($k = \omega/c_0 = 2\pi/\lambda$) is defined as a ratio between angular frequency and speed of sound, respectively. Where ω is the angular velocity, λ is wavelength. A_1 and A_2 are determined by boundary

conditions and vibration conditions. Because there is no reflection in the propagation process of sound waves, $A_2=0$.

The Eq. (1) transforms to:

$$p(x, t) = p_m e^{j(\omega t - kx)} \quad (2)$$

Where P_m is the sound pressure amplitude. Subsequently, the linearized momentum equation can be used to obtain the velocity perturbation from the pressure perturbation $p(x, t)$ as:

$$u(x, t) = -(\rho_0 c_0)^{-1} A_1 e^{j(\omega t - kx)} \quad (3)$$

Where ρ_0 is the mean density of gas.

In this paper, the pressure fluctuations caused by combustion instability are considered as the sound pressure fluctuations. ANSYS CFX 16.0. software is applied to simulate the acoustic transmission process. An excitation is given at the entrance of the combustion chamber and the fluid domain is ideal gas. The comparison of analytical solution and CFD results is shown in Fig. 6. The point sound wave results located at 0m, 1m and 2m away from the inlet of combustion chamber from x direction are compared with the CFD results.

Fig. 6 Theoretical result and simulated result of sound wave

It is shown that the theoretical results of acoustic propagation are agree well with the CFD results. The results prove that it is feasible to analyse the acoustic wave by CFD method.

3. Result and discussion

3.1 Simulation results of gas field

The temperature field in the combustion chamber and the temperature distribution on the axis of the gas field is shown in Fig. 7 and Fig. 8.

Fig. 7 Temperature field

Because the maximum and minimum temperature of different given air-fuel ratio is varied, a dimensionless temperature T_d , $T_d=(T-T_{\max})/(T_{\min}-T)$ is used to express temperature distribution in Fig. 7. Where $T_{\max}$ and $T_{\min}$ are the highest and lowest temperature of different curves as shown in Fig. 8, respectively.

Fig. 8 Temperature distribution on the central axis

The combustion heat release rate increases with the air-fuel ratio, and the flame shape changes with the air-fuel ratio, as shown in Fig. 7 and Fig. 8. The average temperature in the combustion chamber increases by 15%. The high temperature region is located at the end of the combustion chamber, and the temperature distribution in the high temperature region is evenly distributed. The flame core is the source of sound. The change of the combustion gas field also cause the internal pressure fluctuation at the gas field, the pressure-time curve at the ignition point of the combustion chamber is shown in Fig. 9.

Fig. 9 The entrance pressure

A large fluctuation at the beginning of the flame is caused by ignition. Then, the pressure amplitude tends to be stable, and the sound pressure frequency is stable as well. The increase of air-fuel ratio makes the burning of fuel becomes more fully, and more energy is released in the process. The gas temperature increases, and the acoustic field is affected too. The frequency of sound pressure waves are related to the frequency of inlet given pulse.

3.2 Simulation results of combustion chamber

The von-Mises stress is used to evaluate strength of combustion chamber, and it is related to the principal stresses by the equation:

$$\sigma = \left[\frac{(\sigma_x - \sigma_y)^2 + (\sigma_x - \sigma_z)^2 + (\sigma_y - \sigma_z)^2}{2} \right]^{1/2} \quad (4)$$

Where, σ represents the equivalent stress. σ_x , σ_y , and σ_z represent the stress in x, y, and z direction, respectively. A dimensionless equivalent stress σ_d , $\sigma_d=(\sigma-\sigma_{\min})/(\sigma_{\max}-\sigma)$ is used to express stress distribution. The distribution of

dimensionless equivalent stress caused by the sound pressure under different air-fuel ratio conditions is shown in Fig. 10.

Fig. 10 stress of the structure section caused by acoustic pressure

As it shown in Fig. 10, the variation law of stresses in the combustion chamber structure is consistent with the sound pressure. With the increase of sound pressure, the stresses are increasing and the stress concentrations at the edge are obvious. These stress concentration could lead to the initiation and expansion of fatigue cracks. It will endanger the safe operation of aero-engine and gas turbine [11]. Two points on the combustion chamber, A and B are selected as shown in Fig. 10. The stress-time diagram of the two points under four conditions is shown in Fig. 11 and Fig. 12.

Fig. 11 Stress of point A

Fig. 12 Stress of point B

As it shown in Fig. 11 and Fig. 12. Similar to the sound pressure, the equivalent stress fluctuation amplitude is large at first, then dropped and stabilized. The stress fluctuation frequency is also affected by the sound pressure frequency.

The stress-time curve with air-fuel ratio of 0.9 is subjected to Fourier transform, as shown in fig. 13.

Fig. 13 Frequency-domain characteristics of equivalent stress

The combustion chamber stress waves are mainly made up by 1, 2 and 3 times frequency of acoustic wave in the combustion chamber. The second kind of the wave has smaller coherence with stress wave compared with the others, as it shown in Fig. 13. The equivalent stress of point A is shown in Fig. 14.

Fig. 14 The equivalent stress of point A

The stress has a high value and fluctuates violently at the initial time, then it drop down and keep stable. By comparing the sound pressures with the thermal stresses, the sound pressures have bigger relative amplitude than the thermal stresses, and the sound pressures alternate stress leading to structural resonance. Fig. 15 shows the stresses and displacements effect by temperature when the stress trends to be stable.

(a) $\phi_0=0.6$

(b) $\phi_0=1.0$

(c) $\phi_0=1.4$

Fig. 15 Equivalent Stress and Deformation caused by temperature field

The average displacements caused by the thermal stresses under different air-fuel ratio conditions are shown in Fig. 16.

(a) $\phi_0=0.6$

(b) $\phi_0=1.0$

(c) $\phi_0=1.4$

Fig. 16 Displacement under different working conditions caused by the thermal stress

As it shown in Fig. 16 the displacement caused by sound trends to be stable. With the increase of air-fuel ratio, the grid deformation of the combustor chamber increases gradually. It shows the influence of temperature on the deformation is much larger than that of gas noise. However, the noise causes periodic vibration of the stable thermal deformation, which is also the main reason for the ultimate failure of the structure.

4. Conclusion

Based on the bidirectional coupling technology, the thermal-acoustic-structural performance of aeroengine combustor is studied. The main conclusions are as follows:

(1) The Acoustic wave theory and the modal test are agree well with the CFD and FEM, respectively. The average temperature in the combustion chamber increases 15% and the acoustic pressure increases 64.8% by increasing the air-fuel ratio from 0.6 to 1.4, and the frequency of acoustic pressure wave is constant.

(2) By the effect of thermoacoustic coupling, the sound pressures distribution in different positions of combustion chamber are non-uniform, and the sound pressure amplitude decreases significantly by 75% near the outlet of the chamber.

(3) The stress concentrations at the edge of the combustion chamber are obvious, and the stress waves are almost made up by three kinds of waves. The frequencies of stress waves are 1, 2 and 3 times than that of acoustic waves. The average of thermal stress accounts for 3.3 to 4.9 percent of the sound pressure.

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Nomenclature

P	acoustic pressure (Pa)
c_0	mean speed of sound (m/s)
k	ratio between angular frequency and speed of sound
ω	angular velocity (rad/s)
λ	wavelength of sound (m)
P_m	amplitude pressure of sound (Pa)
ρ_0	mean density of gas (kg/m ³)
T	temperature (K)
T_d	dimensionless temperature
$T_{\max}$	highest temperature (K)
$T_{\min}$	lowest temperature (K)
σ_d	dimensionless equivalent stress
σ	equivalent stress (MPa)

ACKNOWLEDGMENTS

This work was sponsored by the National Natural Science Foundation of China (Grant No. 51406124).