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Investigation on Coupling Physical Mechanism between Acoustic and Structural Vibration of Elastic Cavities at Supersonic Speed

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Abstract. The coupling of cavity noise and the structural vibration caused by the flow around the cavity at high speed will adversely affect the structure of the aircraft and threaten flight safety. Through the synchronous test method of noise and structural response, the test of acoustic/vibration coupling characteristics of the elastic cavity at supersonic condition in a wind tunnel was carried out, and the elastic cavity noise, structural vibration response characteristics and the coupling law were studied. The results show that the intracavity noise load mainly affects the low-order modal response of the cavity structure. Compared with the rigid cavity, the maximum position of the intracavity noise affected by the radiated sound wave is near the elastic boundary with strong vibration characteristics, and the noise peak frequency component is particularly affected.

1. Introduction

The cavity structure is a typical structural form in the aerospace field, such as aircraft landing gear bays, buried weapon bays, combustion chambers, aircraft component joints, etc[1]. At supersonic speed, the high-intensity noise load induced by the flow around the cavity can easily cause the random vibration of the cavity structure and accelerate the crack formation, which leads to material fatigue failure and seriously threatens the structural safety of the aircraft[2]. It is of great practical significance to carry out research on the coupling characteristics of cavity acoustic and vibration. Aiming at the problem of unsteady flow and flow-induced noise in rigid boundary conditions, domestic and foreign scholars carried out a lot of research, and significant progress was made in these areas, such as the mechanism of cavity flow oscillation, and in-cavity acoustic modes coupling resonance characteristics, cavity noise/flow control mechanism[3-4]. However, in practical engineering applications, the cavity structure cannot guarantee complete rigidity and there will be elastic boundaries. Under the condition of high-speed inflow, the acoustic-vibration coupling problem of cavity with elastic boundary is complicated in numerical and theoretical research due to the coupling of structural vibration and cavity noise[5]. At present, there are a few related studies. Wagner and others[6-7] fixed a missile model in the cavity, and simultaneously measured the noise load in the cavity and the vibration acceleration of the model in three directions of space, studied the influence of the existence of the model on the sound field environment in the cavity, and the coupling law between the noise field and the model vibration. There is no perfect theoretical model for the vibration response of the elastic cavity wall under the excitation of high frequency pulsating pressure and the acoustic radiation generated by that[8].

Xiansheng Wang[2] conducted preliminary research with wind tunnel tests. The results show that the vibration of the cavity structure is closely related to its natural frequency. When the vibration intensity is weak, the structural vibration has little effect on the noise inside the cavity.

By analyzing the research status of the elastic cavity noise and structural vibration coupling characteristics, it is found that there are still some shortcomings in this field: less research on that at supersonic speed; second, and there is still a lack of understanding of the coupling mechanism of noise and the thin-walled structure vibration inside the cavity. Therefore, based on wind tunnel test, this paper studied the acoustic-vibration coupling characteristics of elastic cavity at supersonic speed inflow conditions, and focused on the interaction law between high-intensity noise and elastic cavity wall structure vibration, and further analyzed the coupled resonance characteristics of the cavity noise and the natural mode of the cavity wall structure.

2. Experiment Method

Aiming at the coupling characteristics of acoustic and vibration inside cavity under supersonic flow conditions, an elastic cavity test model was established, and the model was verified by simulation tools and ground experiments. Through the high-speed wind tunnel test, the high-time-resolution dynamic pressure and structural vibration response test system was used to measure the noise and structural response of the rigid (basic state) and elastic boundary under supersonic inflow conditions.

2.1. Measuring Equipment

The test wind tunnel is the wind tunnel of the China Aerodynamics Research and Development Center. The Mach number of the wind tunnel is from 0.4 to 4.0, and the cross-sectional area of the test section is 0.6×0.6 m, and the length is 2.5 m. The noise load on the cavity surface was measured using a Kulite's model XCQ-062 piezoresistive pulsating pressure sensor with a range of 15 PSI and a natural frequency of 200 kHz. The elastic boundary vibration acceleration was measured using Entran's model EGAX-100-C20005 acceleration sensor. The test data was collected and stored in real time by DEWETRON-2601. The sampling frequency is 50 kHz and the sampling time is 10 s.

2.2. Test Model

The test model was installed on the side wall of the wind tunnel (see Figure 1). The cavity length L, width W and depth D were 540 mm, 180 mm, and 90 mm, respectively. For the basic state test, the sidewalls of the cavity and the bottom plate were each selected from a steel plate having a thickness of 25 mm to simulate an absolute rigid boundary. The elastic model of the 2.65 mm thick wall (the material is 30CrMnSiA) was used to simulate the elastic boundary state of the cavity.

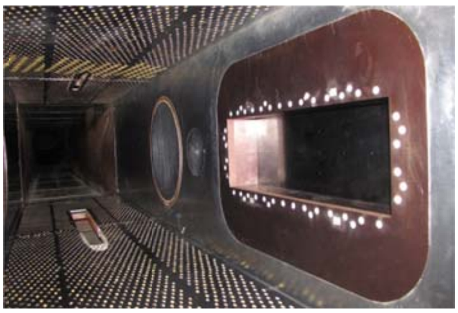

Figure 1. The experimental model in wind tunnel.

The modal simulation analysis of the elastic cavity was carried out by using finite element software. The first eight natural frequencies and mode shapes of the structure were obtained (see Figure 2), and the acceleration sensor is arranged according to the mode shape. Figure 3 is a schematic diagram of the location of the noise wall of the cavity wall and the location of the acceleration point, wherein the blue dot represents the noise load measurement point, and the green rectangular point represents the acceleration measurement point. In the actual wind tunnel test, the natural frequency of the elastic floor of the cavity was measured by the hammer method, and compared with the numerical simulation results, the relative error of the first five natural frequencies is within 3%, as shown in Table 1.

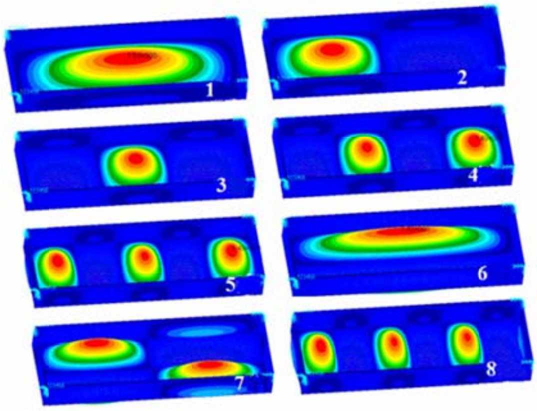

Figure 2. Structural modal shape of elastic cavity floor.

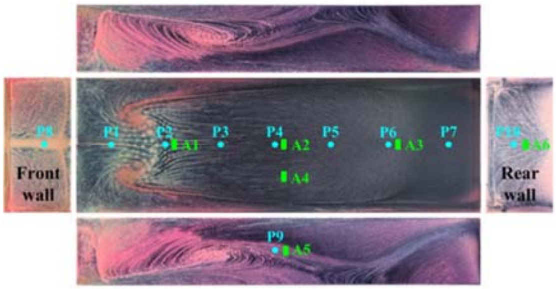

Figure 3. Schematic diagram of installation positions of noise and acceleration sensors.

Table 1. Comparison of structural natural frequencies between simulation and experiment for elastic floor.

Modes/Hz	1st	2nd	3rd	4th	5th
Simulation	356	411	510	655	845
Experiment	348	409	513	653	847
Relative error	2.2%	0.5%	0.6%	0.3%	0.2%

3. Data Processing Method

The noise load and structural vibration response in the cavity are stationary random signals, 11-point necessary to analyze the power spectral density with statistical characteristics[9]. Based on the classical power spectral density estimation method, Welch method is used to estimate the noise load and vibration acceleration power spectral density. In order to reduce the energy leakage caused by signal truncation, Hanning windows were added in the data processing process., and the data blocks are not overlapping[10]. For the noise load, the root mean square value p_{rms} and the total sound pressure level OASPL are usually used to measure its strength. The distribution of the noise energy in the frequency domain can be described by the power spectral density function $P(f)$ and the sound pressure power spectrum function SPFS. For vibration acceleration signals, the root mean square value and power spectral density are usually used to describe their time domain statistical characteristics and their energy distribution in frequency. The function expression of each parameter is as follows[2]:

$$p_{\mathrm{rms}} = \lim_{\mathrm{T}\to 0}\sqrt{\frac{1}{\mathrm{T}}\int_0^{\mathrm{T}} p^2(t)dt} \tag{1}$$

$$\mathrm{OASPL} = 20\log\frac{p_{\mathrm{rms}}}{p_{\mathrm{ref}}} \tag{2}$$

$$P(f) = \lim_{\Delta f\to 0}\frac{1}{\Delta f}\left[\lim_{\mathrm{T}\to\infty}\frac{1}{\mathrm{T}}\int_0^{\mathrm{T}} |\tilde{p}|^2\left(t, f, \Delta f\right)dt\right] \tag{3}$$

$$\mathrm{SPFS}{=}10\lg\frac{P(f)}{P_{\mathrm{ref}}^2} \tag{4}$$

Where T is the sampling time, P_{ref} is the reference sound pressure of $2\times 10^{-5}Pa$, and $\tilde{p}$ is the windowed amplitude spectrum of the noise load.

4. Vibration Response Characteristics of Elastic Cavity Structure

Table 2 records the root mean square value of the structural vibration response at different acceleration points of the elastic cavity under Ma1.5 conditions. From the data in the table, the root mean square value of the vibration response at the acceleration measurement points of the cavity bottom plates A1, A2 and A3 is relatively close. The vibration response strength of the cavity bottom plate is much larger than that of the side wall and the rear wall.

Table 2. Root mean square value of structural vibration response at different acceleration points of elastic cavity (g).

Ma1.5	cavity bottom plates				cavity side wall	cavity rear wall
	Point A1	Point A2	Point A3	Point A4	Point A5	Point A6
	129.7	131.5	123.6	96.2	44.4	59.5

Figure 4 shows the vibration response power spectrum of the elastic cavity structure under Ma1.5 condition. Comparing the vibration response spectrum curves of different acceleration points, it is found that the peak of the vibration response spectrum of the elastic cavity wall occurs in the natural frequency of the structure and the peak frequency of the noise, and it is mainly concentrated below 1000 Hz. As the elastic structure modal test results recorded in Table 1, it can be seen that the fifth-order natural frequency of the elastic cavity is 847 Hz, which indicates that the intracavity noise mainly affects the low-order modal response of the structure and has little influence on the high-order modal response. It can be seen from Fig. 2 that the low-order mode shape of the cavity is mainly embodied on the bottom plate of the cavity, and the modal displacement of the side wall and the back wall is small. The high-order mode shape is more obvious on the side wall and the back wall, but the higher-order modes contribute less to the structural vibration response. Therefore, during the actual vibration process, the vibration strength of the cavity floor is the largest, and the vibration of the side wall and the front and rear walls is relatively weak, which is consistent with the results in Table 2.

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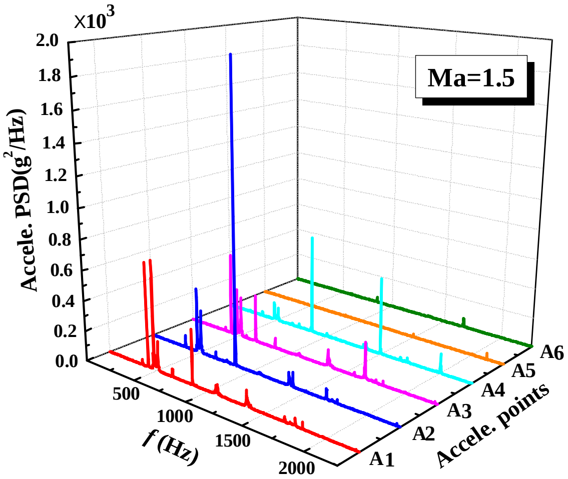

Figure 4. Vibration response power spectrum curve of elastic cavity structure under Ma=1.5 condition.

5. Elastic Cavity Noise Characteristics

Figure 5 and Figure 6 are the results of the sound pressure power spectrum comparison between the elastic cavity and rigid cavity, which was measured at the leading edge of the bottom plate and at the center point of the rear wall. The comparison shows that for the elastic cavity, the peak height of the main frequency of the cavity is lower than that of the rigid cavity under the condition of Ma1.5, indicating that the existence of the elastic boundary reduces the intensity of the intracavity noise at the main frequency position. However, as can be seen from the results of Figure 5, the sound pressure power spectrum curve of the elastic cavity noise load shows peaks not found in the sound pressure power spectrum curve of the rigid cavity noise load at some frequency positions, further indicating the influence of the elastic boundary. Whether the cavity noise intensity is enhanced or weakened is related to the phase of the structured radiated sound wave and the phase of the noise generated by the cavity flow oscillation.

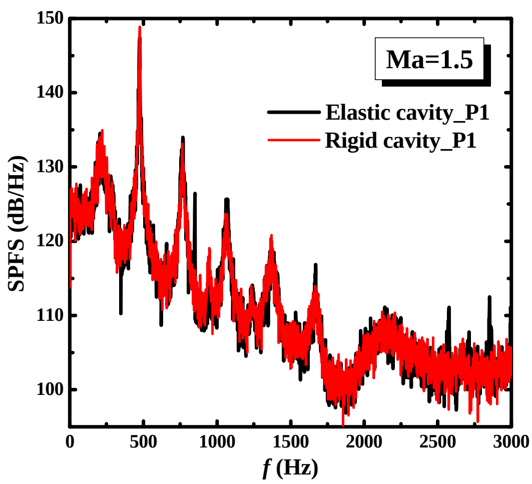

Figure 5. Comparison curve of sound pressure power spectrum of noise load at the leading edge of elastic cavity and rigid cavity bottom plate at Ma=1.5.

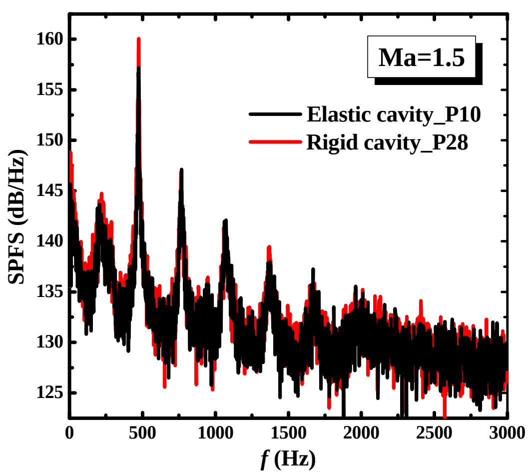

Figure 6. Comparison curve of sound pressure power spectrum of noise load at the center point of elastic cavity and rigid cavity at Ma=1.5.

6. Conclusion

Aiming at the vibration response characteristics and cavity noise characteristics of the elastic cavity structure at supersonic speed, the coupling effect analysis of cavity noise and structural vibration response was carried out by means of wind tunnel test and cross-correlation analysis. The results show that under the condition of supersonic flow, the structural vibration and noise load are most likely to couple at the main frequency position of the noise, which can cause the structure to have strong vibration at the frequency, however the vibration of the elastic boundary will reduce the intensity of the main frequency of the noise to a certain extent.

The vibration response of the elastic cavity structure is mainly concentrated on the bottom plate of the cavity, and the vibration response of the side wall and the front and rear walls is relatively small; due to the elastic boundary, whether the cavity noise intensity is increased or weakened relative to the rigid cavity is related to the phase of the radiated acoustic wave of the structure and the phase of the noise generated by the flow oscillation.

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