DOI: 10.13009/EUCASS2019-246

Effects of Cavities on Pressure Fluctuation Characteristics of Hypersonic Vehicle Wall Plate

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Abstract

In this paper, It takes the hypersonic vehicle as the background, uses the simplified model of a typical vehicle wall plate with cavities as the research object, and conducts the research on these cavities on the pressure fluctuation of vehicle wall plate. The test was carried out in a conventional hypersonic wind tunnel (FD-07) at China Academy of Aerospace Aerodynamics. Miniature, high frequency transducers were arranged at the bottom of the cavities. The different the depth of sinking of the transducer and the different opening diameter formed different cavities, the cavities had significant influence on the power spectrum density(PSD).

1. Introduction

Complex flow phenomena on the surface of the hypersonic vehicle induce a random dynamic pressure which is called pressure fluctuation. The strength and frequency of the pressure fluctuation are important basis for the structural design, aerodynamic loads and acoustic vibration characteristics of morden hypersonic vehicle. At present, wind tunnel test is still the main means of study on pressure fluctuation of a flight vehicle. Since the early 1960s, tests of measurement of pressure fluctuation, data analysis and engineering research had been carried out [1]. A.A.Ezra, HC et al. measured the pressure fluctuation of the launch vehicle surface in the wind tunnel, and obtained the power spectral density function of the typical flow field, which guided the structural dynamics of the launch vehicle [2]. Katya M. Casper's pressure fluctuation of the test on 70-cone model at the Sandia National Laboratory Hypersonic Wind Tunnel and Purdue University's hypersonic wind tunnel improved the accuracy of predicting hypersonic pressure fluctuation [3]. Researchers in China also carried out pressure fluctuation tests, such as the study of the back vortex structure and the pressure fluctuation characteristics of the slender body at high angle of attack in the NF3 low-speed wind tunnel [4] and studied the pressure fluctuation of the body in the FD-06 transonic wind tunnel [5].

In recent years, with the rapid development of flight tests, advanced test techniques are required, , especially flight tests have become the top priority in judging the surface flow characteristics of the target vehicle. Taking the hypersonic vehicle as the background, taking into account the simplified model of a typical aircraft wall plate with cavities, we conducted the theoretical and experimental study on the pressure fluctuation characteristics of the laminar boundary layer for the typical flow under

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various condition. The results might provide theoretical support for the layout, mechanism design, and new methods for acoustic and vibration control of modern space vehicles.

2. The wind tunnel、Measurement Instrumentation and Model

2.1 The hypersonic wind tunnel

The pressure fluctuation test was carried out in the conventional hypersonic wind tunnel (FD-07) at China Academy of Aerospace Aerodynamics. The wind tunnel is an intermittent, blow-down, ejection driven and semi-opening free jet configuration with the nozzle diameter of 500mm, as shown in Figure 1. Its test-section with closed chamber has a size of 1880 mm × 1400 mm × 1130 mm, with air as the test gas. The Mach number ranges are from 4 to 8. The nozzle diameter is 400mm at Mach 4, 500mm at other Mach numbers. The nozzles with a Mach number of 6 or higher are equipped with a water cooling device to prevent the nozzle structure from being deformed by the hot throat. There is an optical glass window with a diameter of 520×320 mm on the both sides of the test section, which are used for the observation and taking photos of the flow field during tests.

Figure 1: The FD-07 hypersonic wind tunnel

2.2 measurement instrumentation

The measurement instrumentations include transducers and other data acquisition device. The Kulite XCL-100 B-screen absolute pressure transducers were used to measure the pressure fluctuation characteristics of hypersonic vehicle wall plate. This type of transducers use the four-wire wiring principle and a silicon diaphragm as the basic sensitive component. The diaphragm consists of a

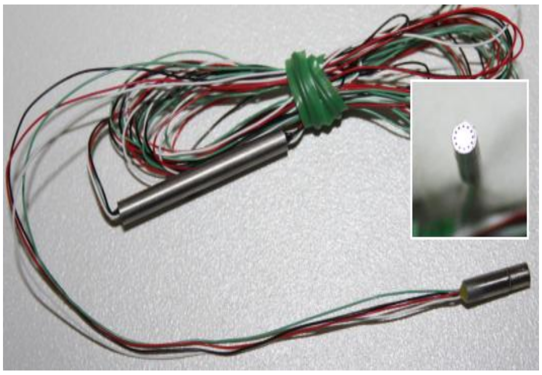

Figure 2: Kulite XCL-100 pressure transducer

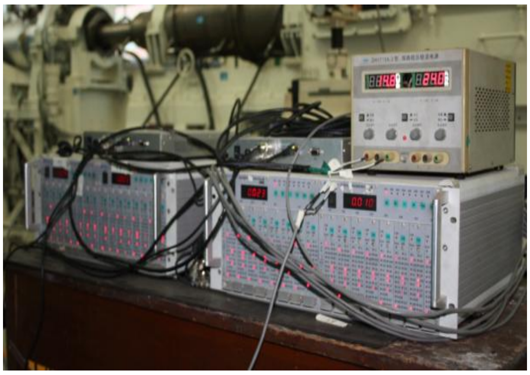

Figure 3: Data acquisition devices

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four-arm Wheatstone bridge. There is a protective screen above the diaphragm to prevent damage to the transducers, shown in Figure 2. The diameter of the transducer is 2.5mm, the length is 9.5mm; the typically resonant frequency of the diaphragm is 240kHz, the maximum effective measurement pressure is 1.7Bar, the temperature range is 250C--800C, zero drift ±5mv, sensitivity error and linearity error are less than ±0.1% FS BFSL; it satisfy the requirement for our test.
The LXI-5402 high-speed acquisition system was used during the test., It has 16 parallel channels, A/D resolution of 16Bit and bandwidth of DC 0～50KHz. Its sampling rate is 500K, The data spectrum analysis plus Hanning window, the analysis frequency upper limit is 30KHz. Figure 3 shows the data acquisition system.

2.3 model

The simplified model of a typical hypersonic vehicle wall plate with cavities was taken as the research object, as shown in Figure 4. The model was made of No.45 steel with the dimension of 400mm in length and 300mm in width. There are six holes in the model for transducers installation, which were arranged two rows and three in a row. The three holes in a row were aligned, they were located 80mm from the leading edge of the model in the span-wise direction and other three were 100mm, giving enough distance for the boundary layer to be established. Two holes were arranged along the center line in the span-wise direction and 20mm distances on both sides. The opening diameter of the holes is 4mm, and the leading edge of the model had a bluntness of 0.5mm, which was chamfered to a wedge angle of 20o. The transducers flush mounted or sunken in these holes.

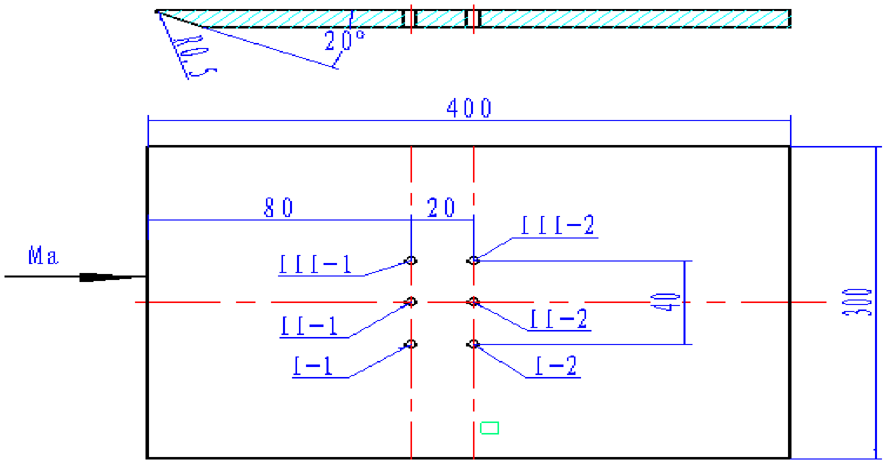

Figure 4: the simplified model of a typical hypersonic vehicle wall plate (not scaled)

3. Test Conditions and Data Processing

The present experimental work was conducted at Mach number of Ma=6.The Wind tunnel operated with an initial total pressure P0 of 6MPa and an initial total temperature T0 of 504 K, corresponding to a freestream unit Reynolds number of Re_unit=5.16×107m^{-1}.
For each test, nearly 42 seconds of data were collected. The sampling rate was 100 K/s. Figure.5 shows the sample points for a given measurement point. The pressure fluctuation signals were collected to analyze and process, which existed in the steady section of the flow field and the noise was relatively

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lower. In this paper, the Welch method was used, the Hanning window samples has 640 data points, and each piece of data was repeated 50%. Find the power spectral density (PSD).Figure 5 shows the sample points for a given measurement point.

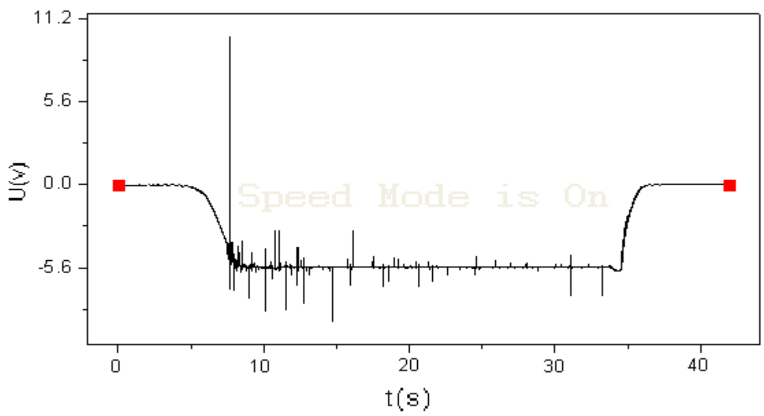

Figure 5: the sample points for the some measurement point

4. Test Results and Analysis

The measuring points I-1, II-1, III-1 are equal to the distance from the leading edge of the model and the working conditions are the same. Due to the uniformity of the flow field, the aerodynamic characteristics of the three measuring points are the same under the same condition. According to the relevant tests, it can be concluded that the six measuring points on the model are in the laminar flow zone. Figure 6 shows the installation of the pressure sensor on these measuring points.

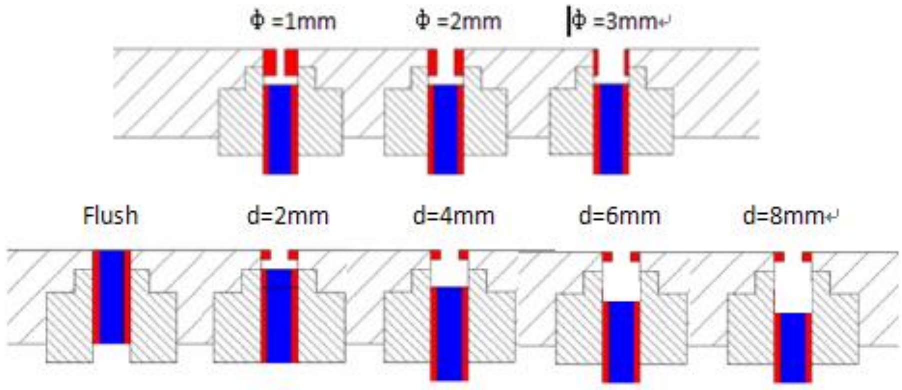

Figure 6: Schematic diagram of pressure transducer installation

4.1 The effects of different sinking heights

According to the power spectrum analysis results of Figure 7 and Figure 8. Before the frequency is 10 kHz, the PSD shows a good regularity with the difference of the sinking depth, from flush mounting to different sinking depths. the sinking depth is d=2mm,4mm,6mm and 8mm.Installation, the energy is starting to decline, and after reaching a trough, it begins to rise again, and the energy returns to around the initial value at about 10KHz. This may be due to the fact that the sensor head forms a cavity on the surface of the plate, the depth of sinking is different, and the flow of gas in the cavity is different. When the flow in the cavity tends to be stable, the energy returns to the initial state. The greater the

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depth of sinking, the larger the trough value, which may also be due to the different flow states in the cavity. All of the energy of the PSD for the measurement locations is decreasing when the frequency is over 10KHz, and the value of d is larger, The energy drops faster.

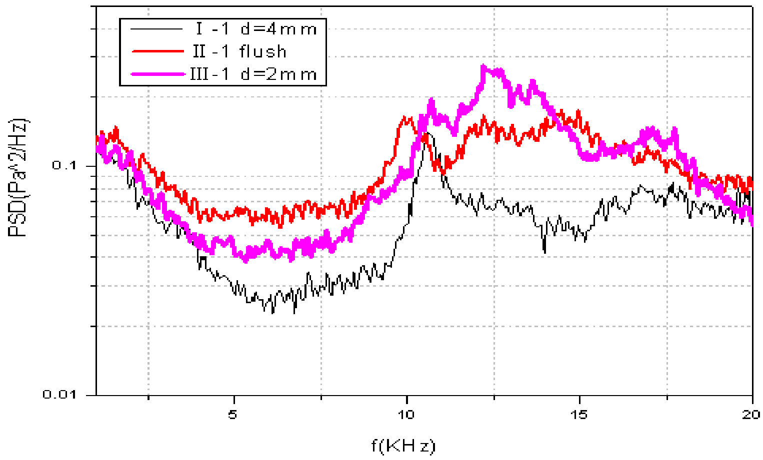

Figure 7: Power spectrum density of pressure fluctuation for different sinking depth

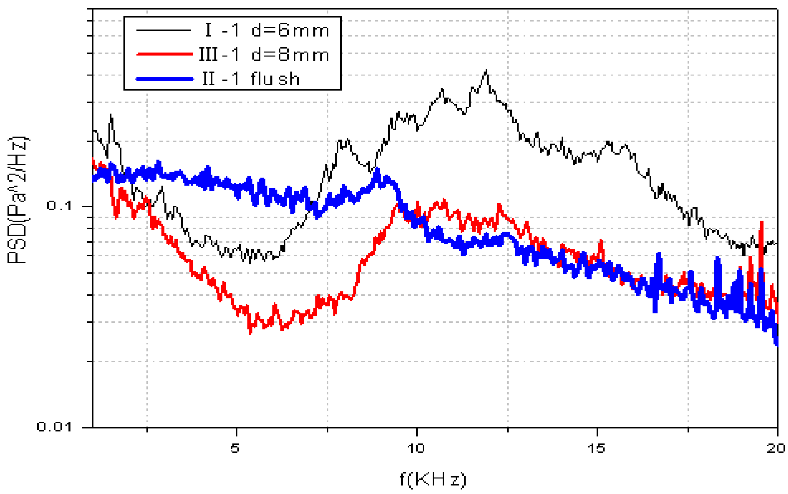

Figure 8: Power spectrum density of pressure fluctuation for different sinking depth

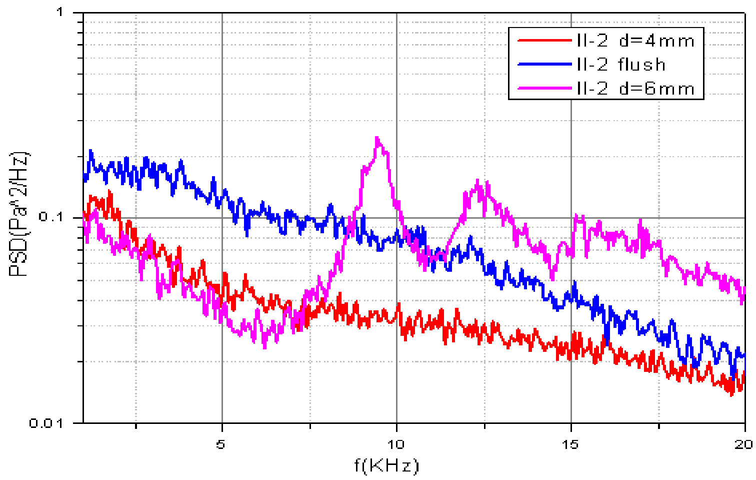

Figure 9: Power spectrum density of pressure fluctuation for different sinking depth

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Under the condition that the measuring point I-2 is flush, Figure 9 shows the power spectrum analysis results of the measuring point II-2 under different sinking conditions. The low-frequency part shows the same analysis results as above, and the other shows inconsistency, the difference may be caused the variation of installation of the measuring points I-1 and III-3, and will not be described again.

4.2 The effects of different opening diameter on plug

When a transducer was sunk mounted, it formed cavity. The diameter of the cavity is changed by inserting plugs which has different opening diameters, and the height of the plug is also different. The opening diameter of plug is φ = 1mm, 2mm, 3mm,3.5mm and 4mm, and the plug height is h = 3mm,3.5mm and 4mm. When the plug inserted into the cavity, a small cavity is formed between the transducer and the surface of the model. Because of different opening diameters and the height of the plug, these cavities volume are different. When d=4mm, Figure 10, Figure 11 and Figure 12 show the PSD is directly related to the volume of the cavity. In Figure10, Figure 11 and Figure 12, it also can be seen that the flow mechanism of the air in the cavity is uniform.

In this test, with the same sinking height and different opening diameter of plug conditions, the test is divided into two cases: one is that there is no cavity between the bottom of plug and the transducer (h=d), as shown in Figure 10; the other is that has cavity.

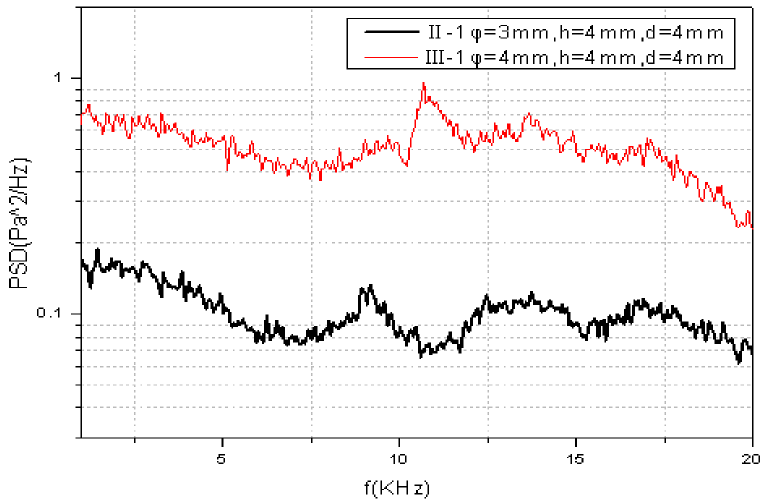

Figure 10: Power spectrum density of pressure fluctuation for different opening diameter

When there was no cavity, Figure10 shows that smaller the opening diameter of a plug, smaller the energy of the PSD, but there is no obvious peak, which may be due to the small volume of the cavity and the less inflow of air.

When there is a small cavity between the bottom of plug and the transducer (h≠d), as shown in Figure 11 and Figure 12, at this time, clear peaks appear in the PSD of pressure fluctuation. In figure 12 when φ=1mm, h=3.5 mm and d=4mm, cavity volume is the smallest. It can be found that the peak energy is the largest, and the frequency of the peak is higher than the frequency of other peaks. It appears near 8KHz. Figure 11 and figure 12 also present that the energy of the PSD begins to decay, when the frequency is greater than 12KHz.The larger the opening diameter of plug is larger, the energy attenuation is faster.

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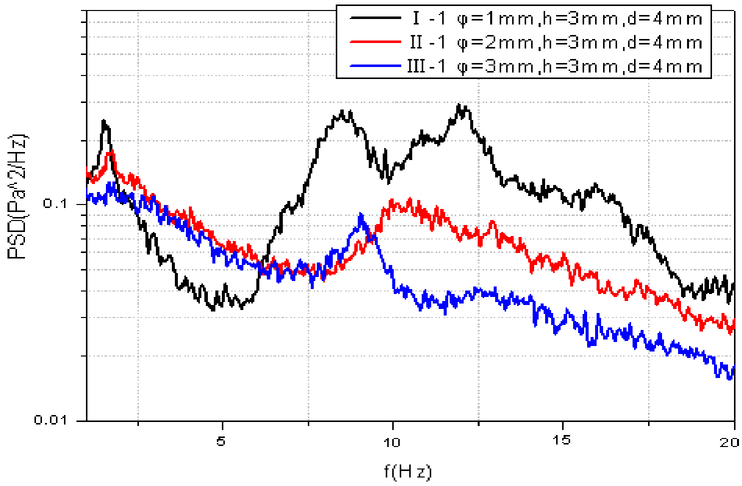

Figure 11: Power spectrum density of pressure fluctuation for different opening diameter

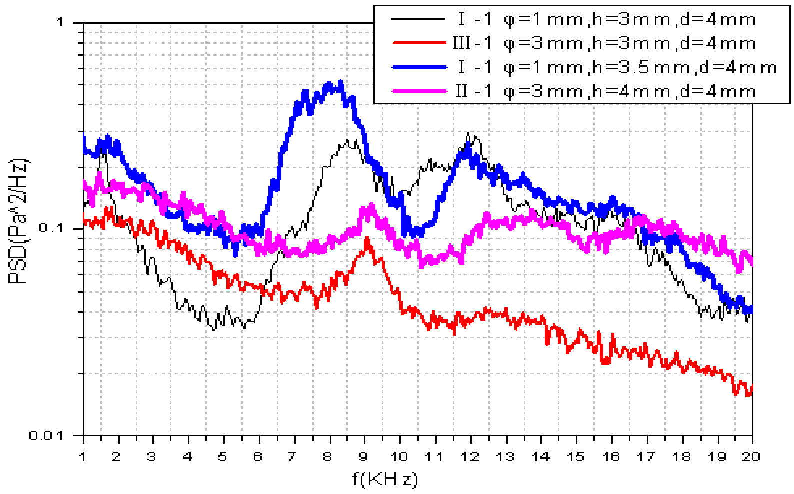

Figure 12: Power spectrum density of pressure fluctuation for different opening diameter

4.3 Uncertainty analysis

Uncertainty quantification is critical to the design and execution of the pressure fluctuation test. There are many possible sources of measurement uncertainty, which include the flow field quality of the Wind Tunnel and the model imperfection effects, other possible sources of measurement uncertainty include sensor and acquisition equipments, sensor bias error, spatial resolution and frequency response, and electrical noise. In particular, the uncertainty source of the instrument including the uncertainty source of the transducer, the data acquisition device and flow field calibration of wind tunnel play a major role in the uncertainty of the test results.

A complete uncertainty of test result was conducted using Taylor Series Expansion (TSE) approach.

The frequency response width of the pressure transducer used in this test greater is over 100 kHz, and the sensitivity error and linear error are less than 5 ‰; the signal modulation collector nonlinearity is less than 0.05% of full scale, and the accuracy error is less than 0.5%. Using TSE approach, the hardware error of the pressure transducer is less than 1%.

Figure 13(a) and Figure 13(b) show that the repeatability of PSD is very good in condition of the same test state at the same position during different tests. It can conclude that the repeatability of the wind

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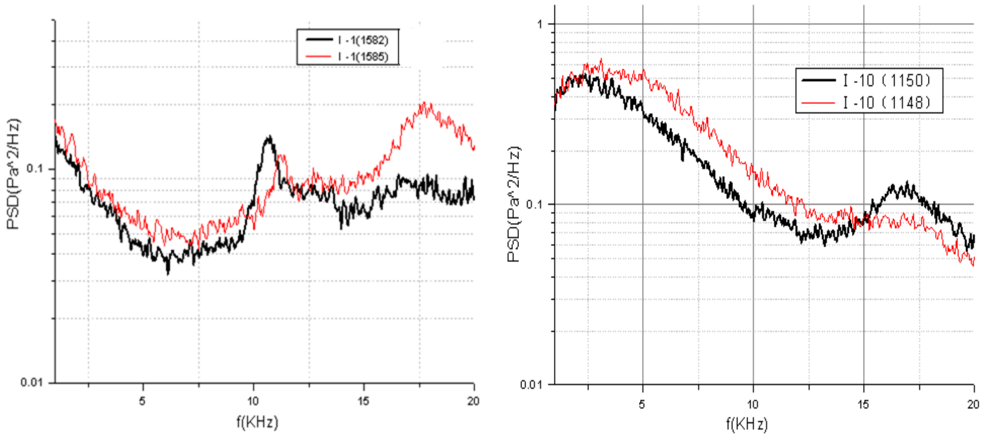
tunnel test is very well, hence there is no uncertainties in different tests to effect the repeatability of the test results.



(a) (b)

Figure 13: Power spectrum density of pressure fluctuation in condition of the same test state, the same position and different test trains

Flow field calibration of wind tunnel was accomplished under the current test condition. $|\triangle M_{max}|/M_{cp}$is less than 1%,which satisfy the test requirements. $|\triangle M_{max}|$ is the maximum variation of the March number in calibration and M_{cp} is the corresponding root mean square value.

The source of the comprehensive test uncertainty, the test accuracy error at the typical test point of this test meets the test requirements.

In particular, we point out that previous study demonstrated that the cavity flow exhibits different flow characteristics at different positions of the cavity, and the present measurement results are the general reflection of all the flow structures inside the cavity.

5. Conclusions

Through the experimental study of the model of Hypersonic Vehicle Wall Plate, the following conclusions can be drawn:

1. Considering only the different sinking depths of the transducer, when the frequency is less than 10KH, the energy first drops and then rises back to the initial level. When the frequency is over 10KHz, the energy is simultaneously attenuated, the larger the transducer installation sinking amount, the larger the energy attenuation gradient.

2. When the depth of sinking of the transducer installation is the same, changing the opening diameter of the surface of the model, and a small cavity is formed between the transducer and the plug. When there is no cavity , the smaller the opening diameter, the smaller the power spectrum energy is overall and the peak does not occur. When the small cavity is present, a peak appears in its spectrum. When the volume of the small cavity is smaller, the peak of energy is larger, but the frequency where the peak is generated is smaller.

3. The source of the comprehensive test uncertainty, the test accuracy error at the typical test point of this test meets the test requirements.

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