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Study on Stability Analysis of Cavity Flow Using PIV and PSP

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Abstract

Cavity flows can generate a number of complex flow field characteristics including boundary layer separation, shear layer instabilities, self-sustained pressure oscillations and acoustic noise. The open cavity was widely used for its uniform distribution and low resistance. With the development of experimental techniques and facilities, more visualization methods were applied on the flow diagnoses, notably, particle image velocimetry (PIV) and pressure sensitive paint (PSP).In this paper, PIV and PSP measurement was applied to investigate the flow phenomena on the bottom and above the cavity at a L/D=6 cavity. The experiment was conducted in FD-03 wind tunnel in China Academy of Aerospace Aerodynamics (CAAA). This wind tunnel is transient, and blow down free jet one whose nozzle outlet diameter is 170mm x 170mm. The flow phenomena above the cavity were shown by PIV and schlieren. The original particle images and speed fields of PIV results gave a strong confirmation for the thought. Hence, the quantitative evaluation of pressure distribution on the bottom was obtained by PSP measurement. A detailed pressure distribution pattern of complex flow phenomena including shockwave/boundary layer interactions could be clearly measured with PSP.

1 Introduction

Flow past rectangular cavity has been the subject of many studies since the 1950s. The applications of cavity flow are in aircraft weapon bays, wheel wells and device of scramjet for flame holding. Cavity flows can generate a number of complex flow field characteristics including boundary layer separation, shear layer instabilities, self-sustained pressure oscillations and acoustic noise. Researchers have used theoretical, experimental, and computational investigations to examine and understand the flow physics that occur inside the cavity at various length to depth ratios (L/D), Mach, and Reynolds numbers. Cavities are typically defined as open, transitional and closed types based on the L/D. However, the open cavity was widely used for its uniform distribution and low resistance. Krishnamutry was the first to obtain the cavity configuration through experiments. Rossiter produced a theoretical model from experimental data for the cavity geometry. Zhuang and Moon used the high-speed shadowgragh and schlieren systems to describe five different waves that present in the flow. With the development of experimental techniques and facilities, more visualization methods were applied on the flow diagnoses, notably, particle image velocimetry (PIV) and pressure sensitive paint (PSP). Ukeiley and Murray, Dudley, Koschatzky have shown the velocity contours within the cavity and in the shear layer using PIV in the flow field at low speed. Olivier used the PSP system to visualize the pressure distribution on the bottom of cavity in the Ma 2 flow. Flaherty, et al. was the first to calculate the full side wall pressure spectra and analyze cavity passive flow control using fast response PSP at Ma 0.7 and 1.5.

Pressure-sensitive paint （PSP） is a relatively new measurement technique for global surface pressure measurements in aerodynamic testing. Many aerodynamic phenomena and test facilities are inherently unsteady, requiring a fast response pressure measurement system. Facilities such as short-duration wind tunnels and shock tubes require a paint formulation that will reach a steady-state indicated value within the duration of the test. Similarly, unsteady pressure phenomena in aerodynamic, acoustic and turbo machinery testing require fast response instrumentation. Thus, the conventional paint formulation was insufficient for many of these tests. This deficiency has motivated the development of PSP for unsteady testing. Compared with a conventional unsteady pressure transducer, data accuracy of unsteady PSP measurement needs to be improved, however, it has advantage about high-spatial resolution due to the large number of pixels of a high-speed camera. A high-speed camera is progressing year after year, its pixel size, maximum frame rate, and photo-sensitivity are increased rapidly.
In this paper, PIV and PSP measurement was applied to investigate the flow phenomena on both the bottom and the side wall of the cavity configuration. The complex flow phenomena were examined at a Mach 5 L/D=6 cavity. Hence, the quantitative evaluation of pressure distribution on the bottom was obtained by steady PSP measurement. And unsteady flow phenomena on the side wall were shown as time-series images. Steady PSP was measured on the bottom of the cavity. Quantitative evaluation of unsteady PSP measurement compared with pressure sensors was conducted. The results of schlieren above the cavity were also discussed.

2 Wind Tunnel and Instruments

The experiment was conducted in FD-03 wind tunnel in China Academy of Aerospace Aerodynamics (CAAA). This wind tunnel is transient, and blow down free jet one whose nozzle outlet diameter is 170mm x 170mm. The mach number extends from 5 to 10, every mach number has a corresponding nozzle that can be changed to change the Mach numbers. Besides the oil flow and Schlieren visualization, FD-03 provides abundant non-intrusive diagnostic techniques such as high-speed schlieren, PIV, PSP/TSP, and Oil film. The calibration Mach number of test section is 4.98, and the standard deviation is 0.020. There is one round optical window above test section, and two Rectangular windows on both sides of test section. The total pressure of freestream was in the range 1.167–1.33MPa, the total temperature of freestream was in the range 280.85–287.65K, the unit Reynolds of freestream was in the range 0.503–0.576×10^6 /m. The test model was designed according to the size of test section, and installed in test section. The attack angle of model can be set by mechanical fitting between support arm and dowel hole of pedestal.

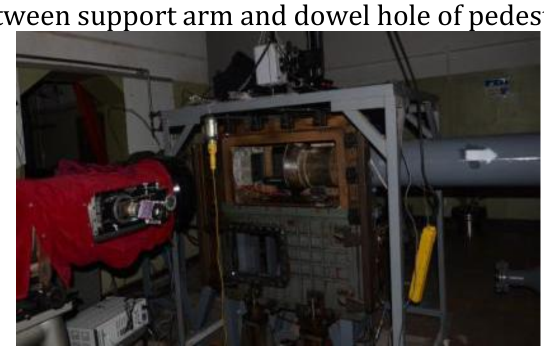


Figure 1：Measurement system installed at FD-03 wind tunnel

The cavity model was designed and assembled from references and examples of previous work. However, a trailing end was replaceable so that both passive and active flow control are easy to insert without replacing the model. The cavity dimensions are: length 120 mm, depth 20 mm and width 70 mm, the standard L/D is 6 and adjustable from 4 to 6.5. The model is 100 mm wide with a 60 mm long fore body. The fore body has a height of 25 mm above the nozzle outlet to ensure the cavity was in the laminar boundary layer. The standard model was a L/D=6 cavity without any flow control. The typical configuration of a open cavity flow field was shown, consisted of internal and external regions separated by the shear layer along the cavity. The internal region contains a large recirculating flow.

PIV is English abbreviation of particle image velocimetry, has broken through limitation of traditional single point test technique and flow visualization, can accurately measure velocity distribution of 2-D flow field section and reflect flow condition of measurement area. The PIV system contains image acquisition subsystem, laser light source subsystem, synchronization control subsystem and image processing subsystem. A YAG double exposure laser with maximum pulse energy of 350mJ at 532nm and 6ns pulse duration at 10 Hz is used as laser light source subsystem. The image acquisition subsystem is composed of frame straddle CCD camera with 2048×2048 resolution, image acquisition board and computer. A delay signal generator exporting 6-channel standard TTL format delay signal with 0.25ns delay accuracy is used as synchronization control subsystem to control the synchronous operation of YAG laser and CCD camera through software. The image processing subsystem is compiled by international popular algorithm of DPIV.

Figure 2： DPIV system

The requirements for tracer particle in hypersonic DPIV experiment are: Moderate tracer particle concentration should be distributed in air flow to obtain continuous time and space information; Tracer particle should possess a list of excellent physical properties such as following features, tiny diameter and density close to fluid density; The chemical properties of Tracer particle should be safe and stable such as non-toxic, non-corrosion and non-abrasion; Sufficient light scattered from tracer particle should ensure detector can obtain particle image with high signal to noise Ratio. This experiment adopted solid powder as tracer particle with size of 40nm, 60nm and 90nm. Through three seeding joints welded on air inlet pipe, tracer particles were injected into and mixed with main air flow by high pressure air.

Figure 3： injection of tracer particle

Figure 4： Nano tracer particle generator

Particle generator is an important equipment of DPIV experiment, relying on which tracer particles could be produced to obtain particle images and extract motion information of flow field. the particle generator for this experiment was equipped with four slot nozzles, from which high pressure air spray out and bring surrounding Nano-particles to run out from three exits.

Figure 5 is experiment arrangement sketch. Laser and CCD cameras were arranged on both sides of the wind tunnel test section. Laser light sheet was guided to the top of wind tunnel test section by the light guide arm and then was projected into wind tunnel to illuminate flow field experiment area mixed with non-particles through optical window. CCD camera was synchronized with laser light sheet pulse to record particle images. In wind tunnel test section, Laser light sheet was overlapped with the vertical symmetry plane of model. Before experiment, a calibration plate was placed on experimental area, and recorded with a CCD camera to determine the actual measurement area size and the ratio between CCD camera pixel and calibration plate size. According to total temperature and experiment Mach number, approximate flow velocity of test section could be calculated. So laser pulse exposure interval can be estimated by proposed displacement pixel number and pixel size. Before experiment, tracer particles should be put into drying oven for 12 hours. When experiment, the particle generator was switched on in advance, then the wind tunnel started running, at the same time the CCD camera began recording. In order to eliminate the influence of reflected light from the model, fluorescent dye was smeared on models and a narrow-band light filter (532±5nm) was fixed on CCD camera. The exposure interval of CCD camera was 300ns, and the lens was Nikkon200mm/F4D. The size of recording area was 54mm, and the thickness of light sheet was 1mm.

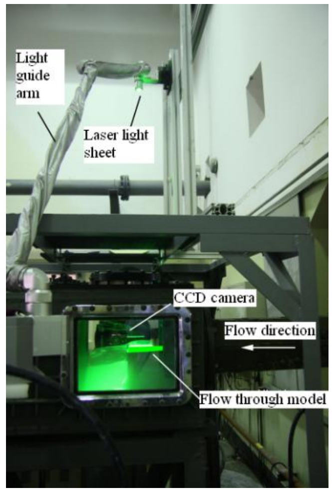


Figure 5： Experiment arrangement sketch

A number of researchers have studied passive and active flow control methods, and focued on the state of the approaching boundary layer prior to separation and the separated turbulent shear layer. Typically, the front edge, such as Baffle, Sawtooth and Cylinder, are intended for the thickening of the separated shear layer. Hence, The trailing edges include different shape of step are used to deflect the shear layer and acoustic wave .

Figure 6：PSP measurement of cavity in the wind tunnel

3 Results

Schlieren and PIV were used to examine the influence of flow control devices above the cavity . The leading edge shock wave can be seen on the schlieren image. The fore body was covered by the boundary layer. The original particle images of PIV provided a clear show of the development of the turbulent boundary layer. These two methods provide the information of the flow field above the cavity. Sequences of the experiment are: S1 for the case without flow control, S2 for the baffle front edge case, S3 for the sawtooth front edge case, S4 for the Cylinder front edge case, S5 for the combination of Cylinder front edge and 45°slope trailing edge case.

Compared to the baseline S1, the baffle front edge acted to lift the separating boundary layer, reduced the impingement on the rear wall, and impacted the cavity wave. However, the sawtooth front edge was designed to induce or enhance vortex into the shear layer along the flow direction. The horizontal cylinder front edge play a role to generate vortex shedding from the cylinder and break up the integral structure of cavity shear layer. The original particle images and speed fields of PIV results gave a strong confirmation for the thought in Figure8 and Figure9.

Figure 7： Schlieren image of cavity flow without flow control

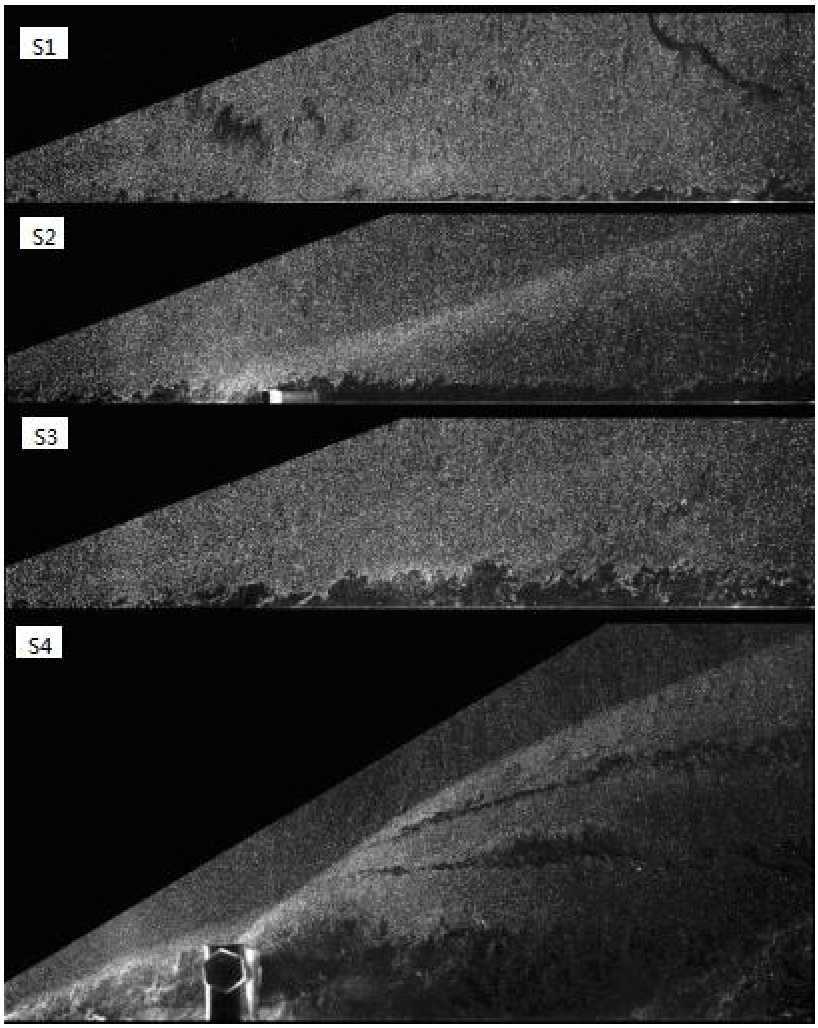
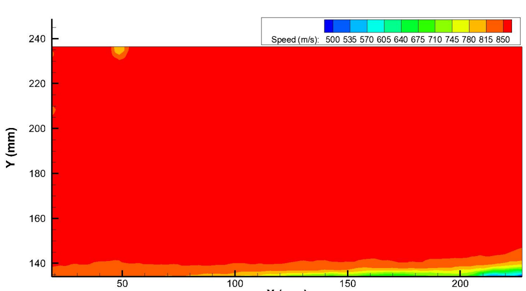
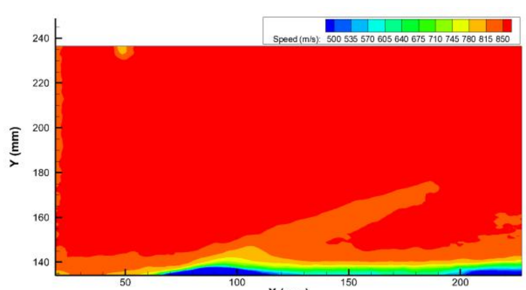


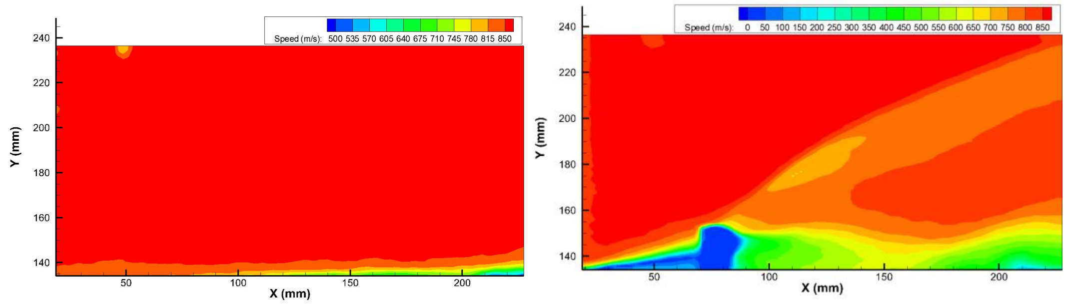
Figure 8： Particle image of cavity flow using different flow control devices



(1)S1



(2)S2



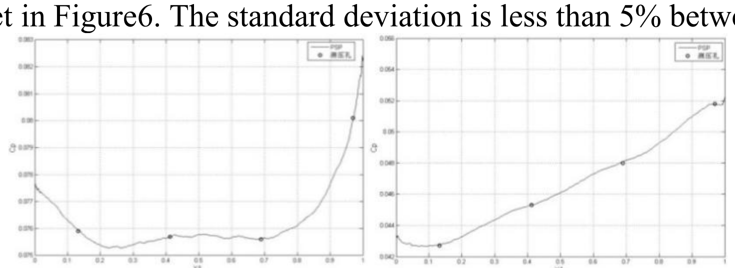
(3)S3 (4)S4

Figure 9： Speed field above the cavity using different flow control devices

The PSP results show that the connection between low pressure region in the front and high pressure region in the rear, led to even pressure distributions, however, an inevitable high pressure area before the trailing wall. The flow direction was from left to right on image. The front edge has a more important impact on the flow structure, and a relatively weaker impact on the bottom pressure distribution of the cavity. For trailing edge or combined flow control device, the pressure distribution inside the cavity bottom became gentle after the front edge and uneven with the enlargement of pressure gradient.

A detailed pressure distribution pattern of complex flow phenomena including shockwave/boundary layer interactions could be clearly measured with PSP. It was confirmed that pressure sensitive paint could be used for quantitative pressure distribution measurements in hypersonic unsteady flows.

Via the transformation relations about pressure-intensity, data processing and in-situ calibration method, The comparison of quantitative pressure data between PSP data and pressure taps on the centre line can be get in Figure6. The standard deviation is less than 5% between two methods.

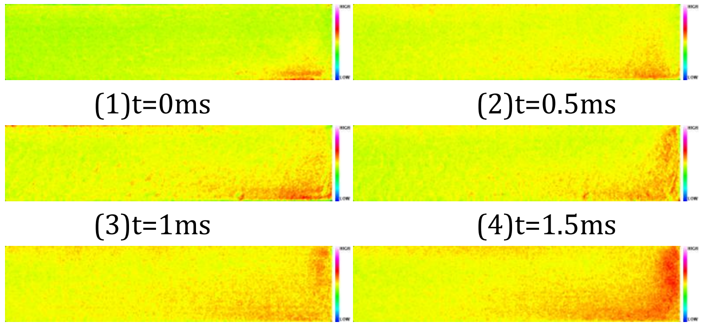


(1)S1 (2)S5

Figure 10： Comparison of pressure on the Center section of the bottom wall

The comparison on the side wall give another validation of four typical flow control methods. The horizontal cylinder front edge combined with the trailing edge flow control method can effectively reduce the cavity pressure and result in a increase in pressure gradient, which is conducive for mixing enhancement and flame holding.

The quantitative pressure value was calculated in this study. The pressure distribution results are shown every 0.5ms. Pressure step caused by boundary layer separation, shear layer instabilities and vortices can be seen clearly. Unsteady flow behavior was caused by the shockwave/boundary layer/vortices interaction. At the same time, the average of all the time-series wind-on images was used as the reference image in order to show the motion of vortex and the pressure fluctuations. However, the arrangement was according to the development of vortices rather than the chronological order, due to the relatively low frequency of PSP for hypersonic flow field. The results were shown in Figure11.



(1)t=0ms (2)t=0.5ms

(3)t=1ms (4)t=1.5ms

(5)t=2ms (6)t=2.5ms

Figure 11： Unsteady pressure behavior and fluctuation (S1)

4 Conclusion

PIV and PSP were used to examine and validate the open cavity flow field characteristics in hypersonic wind tunnel and typical passive flow control methods. These two methods provide the information of the flow field above the cavity. Time-series pressure images were acquired from the PSP data measured by a high-speed camera involving pressure transducer data. Quantitative and time-series images gave global pressure distribution and time series behavior of the unsteady flow field on the side wall configuration. PIV and PSP measurement was confirmed as a powerful tool to investigate unsteady flow field.

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