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Unsteady PSP Measurement in Shock Tube

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Abstract

An experimental study on shock past a cylinder was carried out by fast-response pressure-sensitive paint. A PtTFPP&Acrylic-TiO_2 fast-response PSP is sprayed on the wall near the end of driven section where a double-screw bolt is fixed in. The paint's response frequency is lower than the frame rate of camera. This PSP system captures a blurred leading edge of the shock wave, and successfully shows unsteady wake oscillations.

1 Introduction

PSP techniques are widely used in wind tunnel experiments (Merienne et al. (2004), Liu et al. (2005), Xiang et al. (2013)) with the advantage of high spatial resolution. In order to analyze unsteady flow field, it is necessary to apply fast-response pressure-sensitive paints. AA-PSP and PC-PSP are the most common forms of fast-response PSPs. Usually, AA-PSP have better time-response performance, which can be shorter than 10μs (Kameda et al (2004), Gregory et al. (2007)). However, most models used in transonic and supersonic wind tunnels are made of steel, which can't be anodized. Thus, PC-PSPs are still widely used in high frequency wind tunnel experiments.

PSP system with AA-PSP paint is capable of capturing ultrahigh-frequency phenomena in flow field (Yang et.al,(2012), Fujii et al. (2013)). When it comes to PC-PSP with lower frequency-response, it will not be able to follow pressure changes completely. Shock tube is a useful device to determine step response characteristics of PSP paints (Sakaue et al. (2012), Gregory et al. (2014), Pandey et al. (2015)). In order to test a self-made PC-PSP, and to determine whether it is capable of using in ultrahigh-frequency systems, several experiments in shock wave tube are performed.

2 Preparation

PC-PSP paint used in this experiment consists of two parts: screen layer and sensitive layer. Screen layer is made of acrylic emulsion and TiO_2 powder. Sensitive layer contains only PtTFPP solution. Paint is spread onto the wall near the end of driven section. A Φ6mm, height 8mm screw bolt is fixed onto the wall, in the center of the paint area.

When pressure difference between driver and driven section reaches 300kPa, the thin film will break, and a shockwave is generated. A Photron® SA-X camera is used to capture fluorescent images at a frame rate of 100kHz, resolution 256×256, then binning 2×2 (128×128 output) to enhance signal-noise ratio. Four 405nm LED exciters are kept constantly lighted. DG645 captures the rising pressure signal from a sensor upstream, and converts it to a standard TTL signal, which is used to trigger the camera.

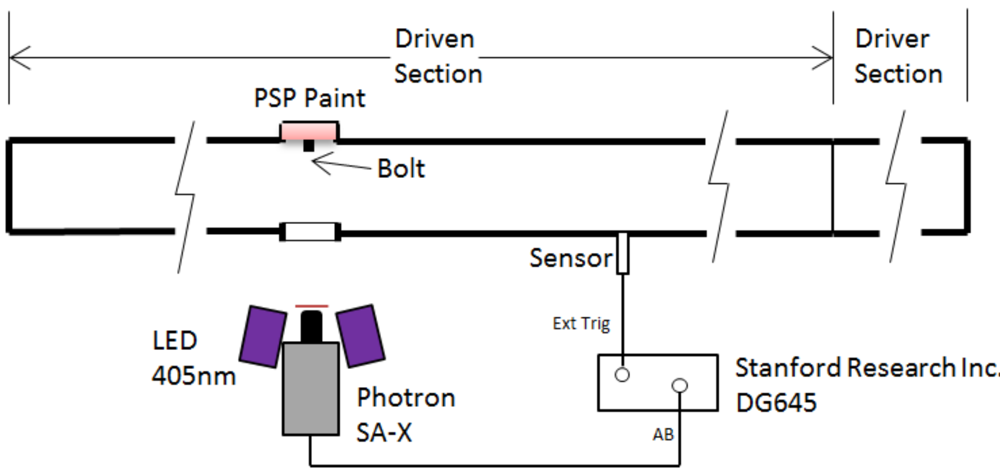

Figure1 A sketch of system arrangement

3 PSP Results

Figure2 shows some images when shock wave crashes the bolt. Timer starts when shock wave passes the sensor upstream. Relative intensity (Ir) is calculated based on the pressure of driven section before the experiment starts. The leading edge of shock wave is blurred and here are some vortices after the bolt.

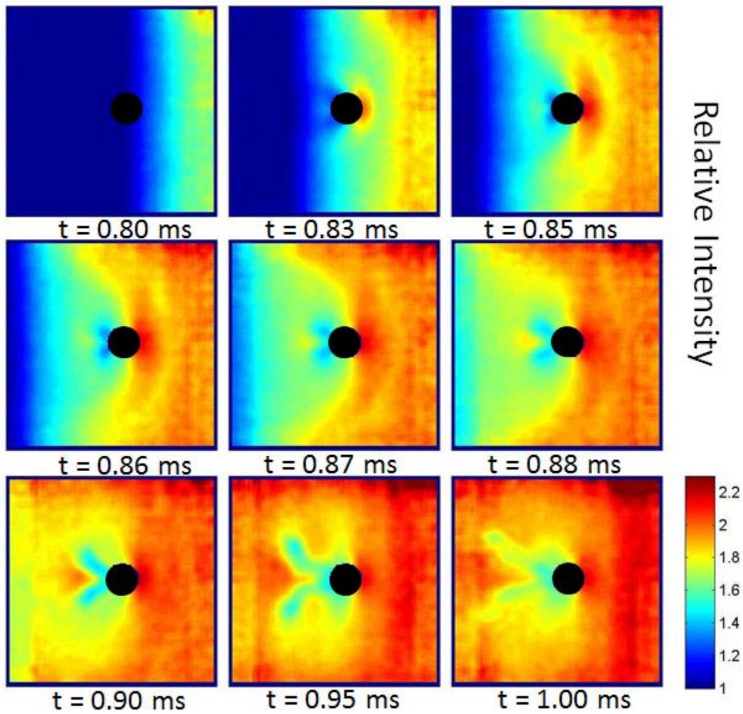

Figure2 PSP results when shock wave crashes the bolt

Figure3 contains four Ir curves of different points in PSP area. Shock wave moves at a speed of about 380m/s, means 12 pixels between each frame. Pressure at point 3 shows some periodic characteristics due to the vortices.

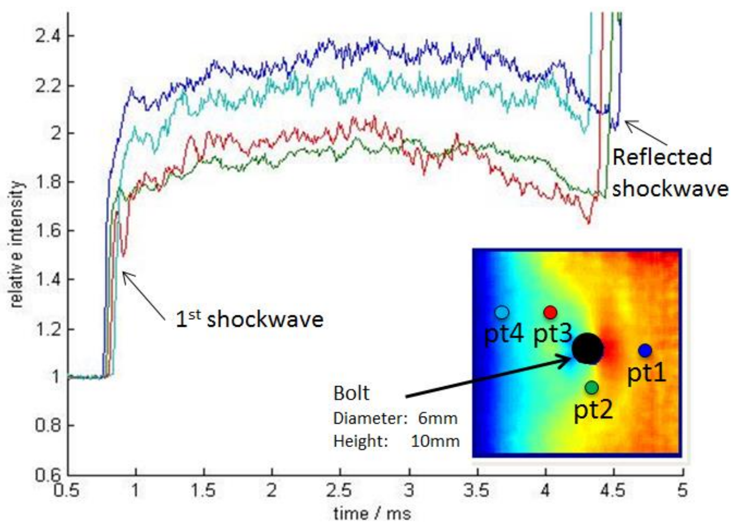

Figure3 Relative intensity curves of 4 points in PSP area

3 Blurring of PSP results

In order to evaluate the time response characteristics of this paint, a high frequency shock wave test is performed in this shock tube. A Thorlabs® APD110A phototube and a 405nm laser are used in this experiment, instead of CMOS camera and LEDs. This system can capture intensity changes of single point at frequency of 1MHz.

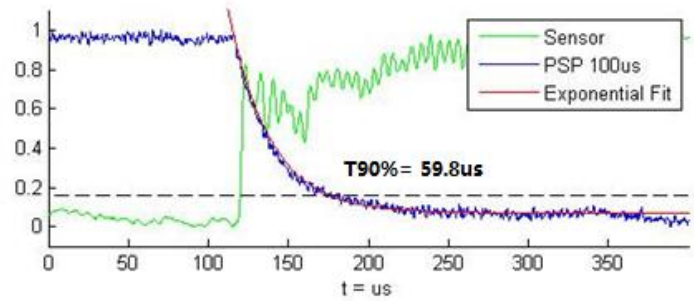

Figure4 Relative intensity (Ir^{-1}) curve of PSP paint

Usually the intensity decline can be described with exponential model below. I_0 means intensity before shock wave arrives. I_∞ represents intensity after shock wave passes. t_0 is the moment when PSP intensity starts to decay. τ is time coefficient, which is calculated by curve fitting.

$$I(\mathrm{t}) = (I_0 - I_\infty)e^{-\frac{t-t_0}{\tau}} + I_\infty \tag{1}$$

Response time of 90% intensity rise to a step change of pressure can be calculated with equation below:

$$t_{90\%} = -\ln(1 - 90\%) \times \tau = 2.30\tau \tag{2}$$

The paint has a $t_{90\%}$ of 60μs, and it is expected to response 34% pressure change in 10μs. In the shock wave & bolt experiment, this paint is definitely “over-rated”.

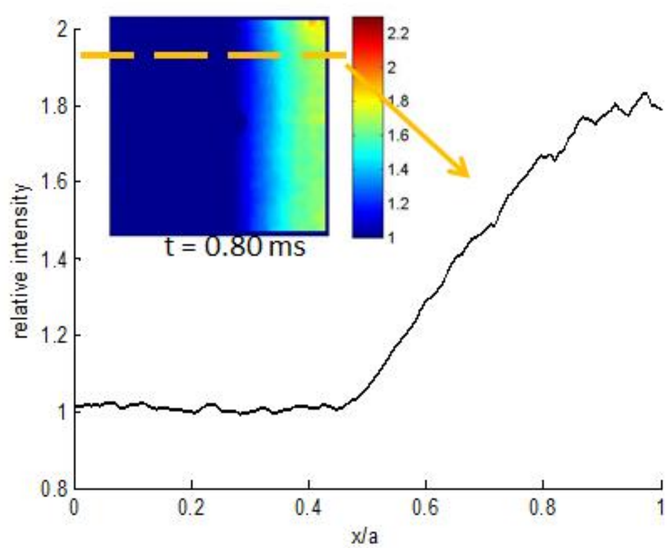

Figure5 Leading edge of shock wave at t = 0.80ms

The blurred shock wave leading edge in PSP images consists of two parts: shock wave motion combined with camera integration and PSP response characteristics. If the paint is ideal (immediately pressure response), then shock wave motion will lead to a linear rising edge of PSP. The width is predicted to be 12 pixels, which equals about 10% PSP area width. Considering PSP response time (60μs), the blurred rising edge will be expanded to at least 60% PSP area. It is impossible to locate accurate shock wave position with this paint.

Even though this paint is impossible to follow shock wave motion, qualitative measurements can still be performed. PSP system can't provide accurate pressure value at frequency of 100 kHz, but its average value is acceptable and it can show us the trend of flow field.

4 Vortices after shock wave

PSP system captures some vortices after shock wave passes the bolt. Even though the response of the paint is slow to follow the measurement, it can still be a powerful tool to observe the flow phenomenon.

The upper 6 images in figure 6 show a sequence of PSP relative intensity fluctuation (Ir_{fl}) after shock wave has passed. Ir_{fl} is calculated based on equation below. Ir_{avg} means the average relative intensity image of 100 samples from 1.04ms to 2.04ms. $A(img)$ means the average value of all valid pixels in this image.

$$Ir_{fl} = Ir - Ir_{avg} \times \frac{A(Ir)}{A(Ir_{avg})} \tag{3}$$

Due to the high noise level of CMOS camera, it's hard to distinguish vortices from noise pattern. The 7th image in figure6 shows the standard deviation map of 100 samples from 1.04ms to 2.04ms, which clearly tells us the pattern of unsteady wake oscillations.

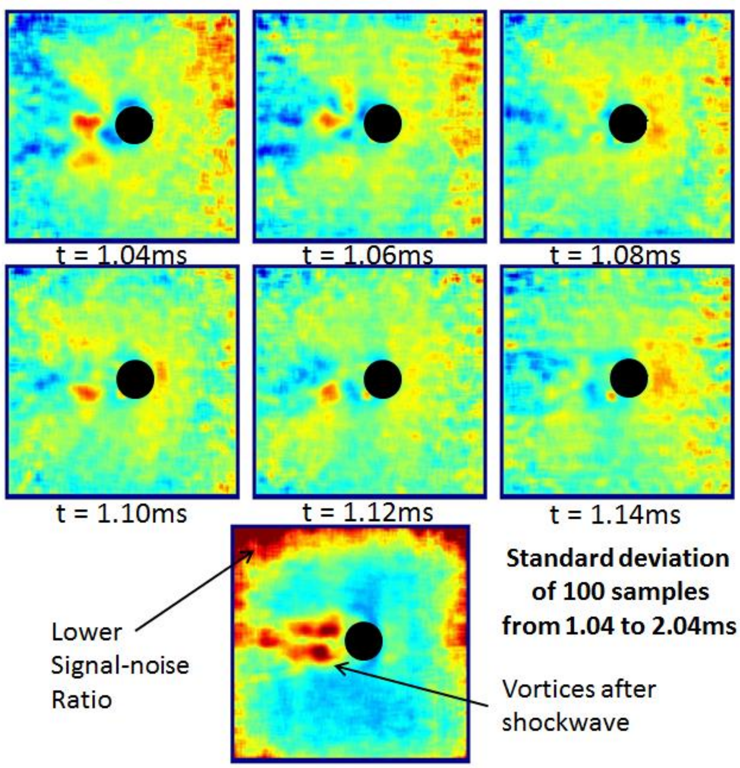

Figure6 Relative intensity fluctuation of PSP and standard deviation of 100 samples

Figure7 mainly shows the FFT plot of a point downstream the flow. Pressure (Ir) at that point has the highest standard deviation in figure6. The wakes after the bolt oscillate at frequency of 9.4 kHz, approaching the limit of this PSP paint. Then correlation coefficients of pressure changing are calculated between this single point (t ~ [1.28ms, 1.58ms]) and whole PSP area (full time sequence), the highest coefficients and phase distribution are also plotted in figure7. Coefficients map is similar with deviation map, and phase distribution map tells us the mode of wake oscillations.

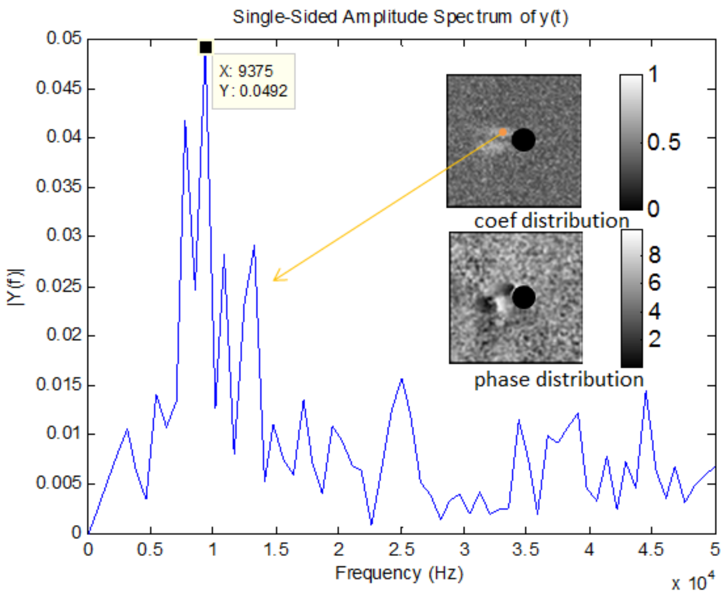

Figure7 FFT plot of single point, correlation and phase distribution

5 Conclusion

This PSP system is capable of capturing the phenomena of shock wave impacting the screw bolt and the unsteady wake oscillations. Due to the low time response characteristics of this PC-PSP paint, the leading edge of shock wave is blurred and it's impossible to tell the accurate location of the shock wave. However, the blurring is predictable and the paint can still show some high frequency phenomena such as wake oscillations in the flow field qualitatively or half quantitatively.

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