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Investigation of transonic buffet using high speed PIV

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Abstract

Transonic buffet of a supercritical airfoil (OAT15A) is investigated by means of schlieren visualization and high speed PIV. The buffet conditions were observed to be strongest at M = 0.7 and $\alpha = 3.5^{o}$ at a frequency of 160 Hz. By means of conditional averaging according to the shock location and movement, the typical buffet cycle is illustrated, confirming observations from literature. In addition, proper orthogonal decomposition is used to further characterize the unsteadiness and it was found that the first 3 modes contain the bulk (> 80%) of the fluctuating energy. Furthermore, through spectral analysis it was found that the typical frequency connected to these modes is equal to the buffet frequency. For mode 4 and higher no peak in the power spectrum is found at the buffet frequency.

1 Introduction

Buffet is an unsteady oscillatory periodic phenomenon characterized by a low-frequency high-amplitude movement of a shock wave over the surface of an airfoil for a specific range of aerodynamic parameters as Mach number, angle of incidence or Reynolds number. The phenomenon induces a complex unsteady coupling of different flow features that normally includes turbulent boundary layer separation and reattachment at the shock foot. This phenomenon is purely aerodynamic and not coupled with any structural behavior. Since buffet was first observed the main issue of most experimental, theoretical and numerical studies has been to understand the physics that define this phenomenon, see for example Lee (2001). Great progress has been made on this issue (Deck (2005) and Hartmann et al (2013)), however, the actual mechanisms that trigger buffet and that make possible the self-sustained motion are only partially understood.

2 Experimental setup

The unsteady transonic flow field is investigated for the supercritical OAT15A airfoil (Jacquin et al, 2009). In addition also measurements were performed on a NACA0012 airfoil but these will not be discussed in the present paper. The OAT15A airfoil has a 10 cm chord and spans the complete test section (27 cm) of the TST-27 blowdown wind tunnel. Experiments were performed at Mach numbers ranging from 0.6 to 0.78 at 0, 2 and 3.5 degrees angle of attack. The total pressure and total temperature were respectively 2 bar and 283 K resulting in a chord-based Reynolds number of approximately 2.6×10^{6}. For the OAT15A airfoil the boundary layer was tripped at 7% using a 2 mm wide carborundum 500 strip.

Measurements were performed using schlieren and high speed PIV. A standard z-shaped optical layout was used with a continuous light source and a pinhole diameter of 2 mm. The images were recorded by an Imager Pro HS 4M high speed camera. The active sensor size was 864 × 864 pixels and the maximum used framerate was 8 kHz with an exposure time of 10 μs.

The high speed PIV system used two Photron FastCAM SA-1 cameras in 2C mode in order to increase the spatial resolution. The cameras (active sensor size 768 × 480 pixels) were equipped with 105 mm Nikkor objectives set at f# = 8. The first camera observed the flow field from x/c = 0.30 to 0.70 while the field of view from the second camera was from x/c = 0.65 to 1.05. During post-processing both fields of view were combined. For illumination a Quantronix Darwin Duo Nd:YLF high speed laser was used operating in dual pulse mode at 8 kHz. Finally solid Titanium Dioxide particles were used as seeding material.

3 Unsteady flow field

A schlieren image is shown in Figure 1 (left) for the typical buffet conditions. Near the nose of the airfoil two oblique shockwaves are observed which originate from the trip strip indicating that the flow is supersonic at that location. Further downstream a normal shockwave terminates the supersonic region. Downstream of the shock the boundary layer separates and in the flow above a number of waves can be seen in the flow field. On the right side of Figure 1 a typical PIV snapshot is shown for an upstream movement of the shock in the buffet cycle. It is clearly observed that the boundary layer separates due to the presence of the shock.

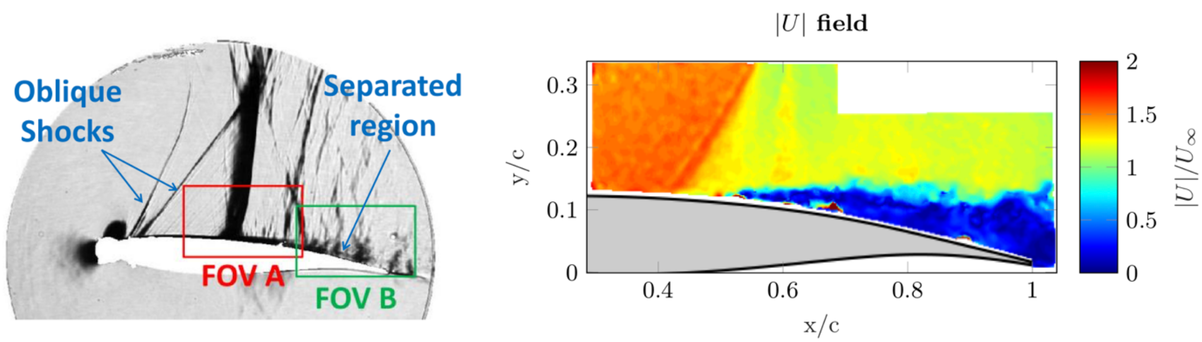

Figure 1: Schlieren visualization (left) and instantaneous PIV snapshot (right), M = 0.7 and $\alpha = 3.5^o$.

In order to identify the buffet conditions the free stream Mach number and angle of attack was varied. For each condition a high speed schlieren was recorded and from the sequence the shockwave location versus time was extracted. From this signal the power-spectrum was computed, see Figure 2. For M = 0.7 a distinct peak emerges at 160 Hz, which corresponds to the buffet frequency. Then at larger Mach numbers this peak disappears and a peak is observed around 410 Hz. This peak is believed to be associated to facility noise and requires further research. Based on these results M = 0.7 and $\alpha = 3.5^o$ were selected as typical buffet conditions.

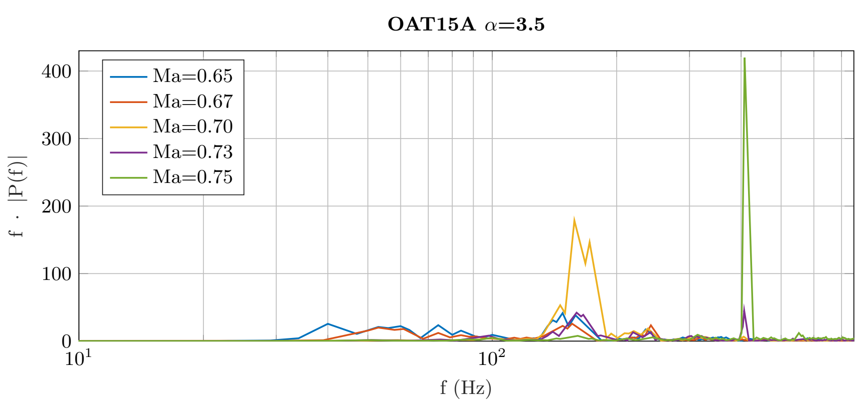

Figure 2: Pre-multiplied powerspectrum of the shock movement in time

The high speed PIV results are conditionally averaged based on the shock location and movement. The velocity snapshots are categorized in 8 bins: bin 1 contains the images where the shock is at the most downstream location, bin 3 corresponds to the mean shock location and moving upstream, bin 5 corresponds to the most upstream shock location and bin 7 corresponds to the mean location and moving downstream, bins 2,4,6,8 are the bins in between. The resulting averages are reported in figure 3, and from the images it is apparent that boundary layer separation is most pronounced when the shockwave moves upstream. This can be ascribed to the fact that the relative velocity and thus also the local shock Mach number is higher in that case. This corresponds to what is reported in literature. Furthermore it can be seen that the shock is oblique when moving upstream while it is more normal when moving downstream. Also this can be related to the fact that separation is more pronounced in the part of the cycle where the shock moves upstream.

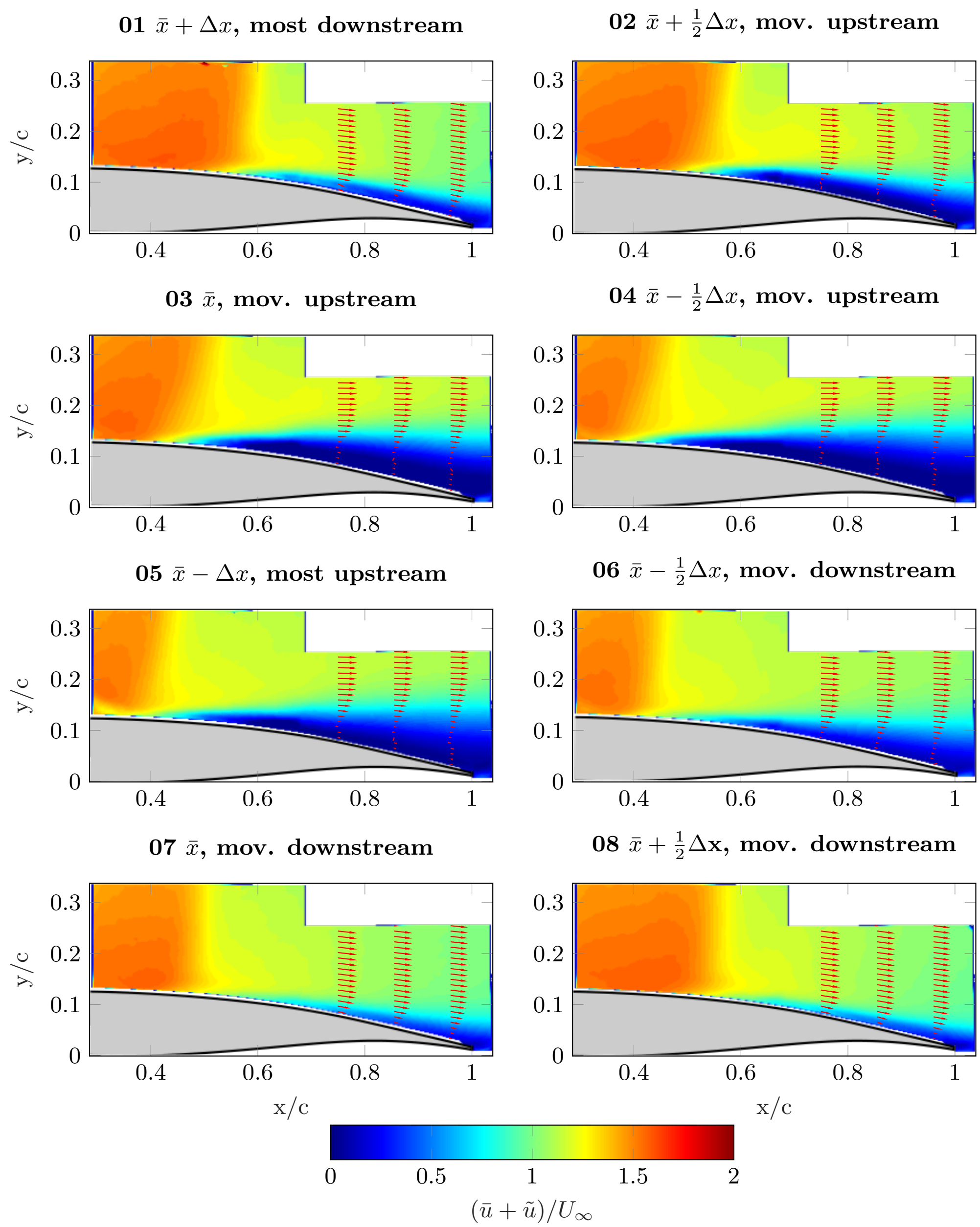

Figure 3: Phase averaged horizontal velocity component illustrating the complete buffet cycle. x represents the mean shock location while Δx indicates the shock oscillation amplitude around its mean

4 POD analysis

In order to further investigate the unsteady organization of the flow in more detail a proper orthogonal decomposition (POD) was performed on the (mean subtracted) fluctuating velocity field. Figure 4 shows the POD spectrum and it can be seen that the first 3 modes are dominant in describing the unsteadiness as they represent more than 80% of the total fluctuating energy.

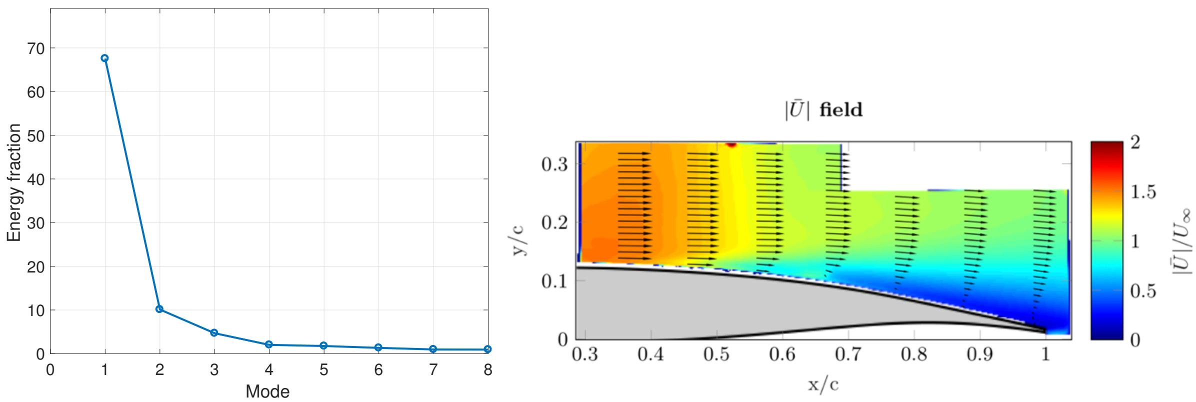

Figure 3: POD spectrum (left) and average flow field (right)

The first three modes are shown in Figure 4, mode 1 basically represents the up and downstream displacement of the shock position and the corresponding growing and shrinking of the separated region, while modes 2 and 3 represent the temporal asymmetry in the flow field due to the upstream and downstream motion of the shockwave.

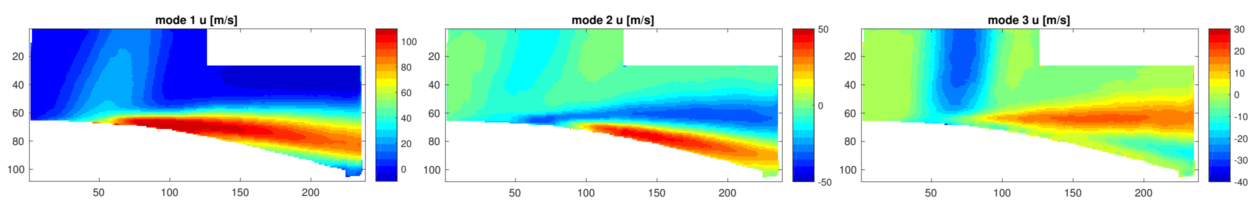

Figure 4: POD mode 1 (left), 2 (middle) and 3 (right)

The contribution of the modes to the dynamics of the flow field is further investigated by computing the power-spectrum of the POD time-coefficients, see figure 5. From the spectrum is can be seen that the first 3 modes have a strong peak at 160 Hz which exactly corresponds to the buffet frequency extracted from the high speed schlieren measurements. For modes 4 and higher this peak is absent.

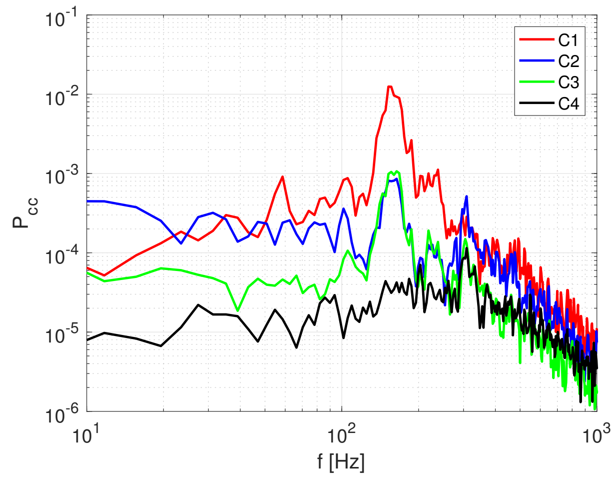

Figure 5: Power-spectrum of the POD time-coefficients

It has already been established that mode 1 is most important since it describes the growing and shrinking of the separated region downstream of the shockwave. In order to further investigate the relation between mode 1 and modes 2 and 3, the joint PDF has been computed, see Figure 6. Both PDFs feature an arc-like shape either curving downward (figure 6-left) or upward (figure 6-right) which quite nicely illustrates their contribution to the temporal asymmetry of the system (i.e. the difference in the flow field when the shock moves downstream or upstream).

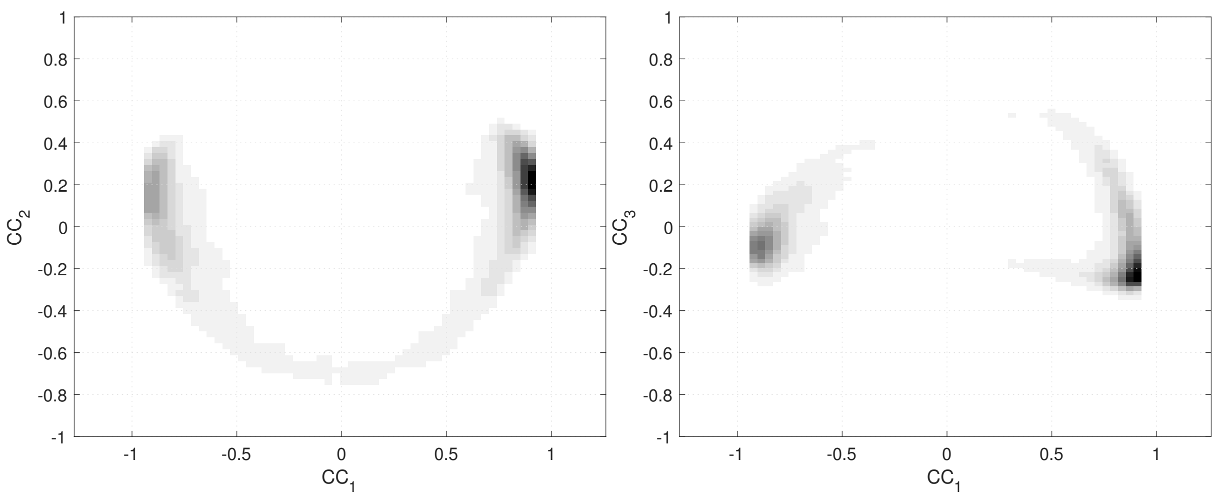

Figure 6: Joint PDF of the first and second (left) and first and third (right) POD time coefficients.

4 Conclusion

In the present paper the conditions for transonic buffet of a supercritical airfoil (OAT15A) are established using schlieren visualization and the unsteady flow field is characterized by means of high speed PIV. Conditional averaging based on the shock location and movement direction allows to obtain a quantitative overview of the flow field during the buffet cycle. In addition a POD analysis was performed and it was found that 3 modes contained the bulk of the fluctuating energy and frequencies associated to buffet. In the analysis of the buffet cycle important aspects are the separated shear layer stability and upstream travelling waves. Especially the latter have been regarded as one of the driving factors for the loop-back mechanism.

From the POD analysis, these aspect cannot be captured. However POD can be used to isolate these flow features. Furthermore additional analysis will be done for conditions where buffet is not fully developed and for the NACA 0012 airfoil.

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