Transonic base-flow buffeting: characterisation of the large scale flow unsteadiness using POD

F. Schrijer, A. Sciacchitano and F. Scarano
Delft University of Technology, The Netherlands

Introduction

During its ascent an orbital launcher encounters different flow regimes from subsonic to hypersonic. The design and optimization of a launch vehicle must therefore be based on a multitude of criteria, ranging from efficiency to safety and predictability. One of the most important aspects of the launcher is its propulsion system. For an optimal design, the structure must be as light as possible while still being able to withstand the large thermal and pressure loads coming from the exhaust. However, the outer flow that passes over the nozzle also introduces loads on the structure. In the separated region over the nozzle a multitude of flow scales can be observed that vary from scales related to the size of the mixing layer to structures that scale with the size of the separated region itself. typically these are intermittent phenomena that have a very broad band spectrum. However for axis-symmetric geometries a certain coherence in these flow structures is observed which leads to unsteady loads on the nozzle (Depres et al, 2004; Deck and Thorigny, 2007). This is especially pertinent in the transonic regime where it is referred to as transonic buffeting.

In this paper the phenomena of transonic buffeting is investigated and the focus is directed toward the description of the large scale flow unsteadiness which is associated to the buffeting phenomenon. Two experimental data-sets are used in the investigation: a double cylinder model (see Fig. 1, Schrijer et al, 2013) that was tested at Mach 0.7 and measurements performed on a 1:60 scale Ariane V at Mach 0.5 and 0.8 (Hannemann et al, 2011). In both cases the velocity field was measured using high speed PIV and for the Ariane V measurements also unsteady pressure measurements were performed. In both cases proper orthogonal decomposition is used to investigate the large scale flow unsteadiness. In order to extract the large scale fluctuations from the measurements, proper orthogonal decomposition (POD) is performed on the data (Berkootz et al, 1993).

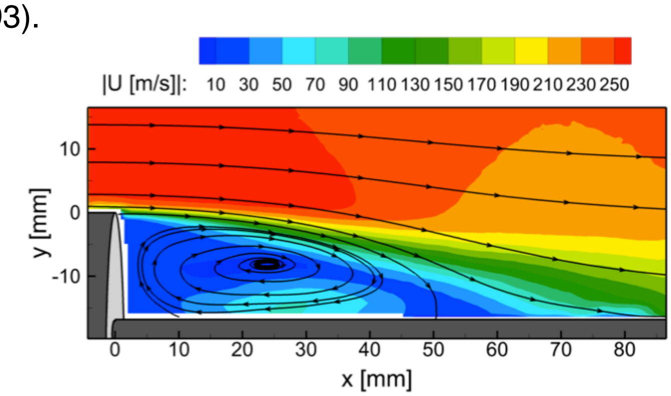

Fig 1 - Average velocity field over the double cylinder model

Double cylinder geometry

In figure 2 the first two POD mode shapes are shown that represent the most energetic flow fluctuations, respectively 16% and 9% of the total fluctuating turbulent kinetic energy. From the spatial distribution of the first mode, it can be observed that the velocity fluctuations associated to this mode represents the growing and shrinking of the separation bubble, see figure 3-top.

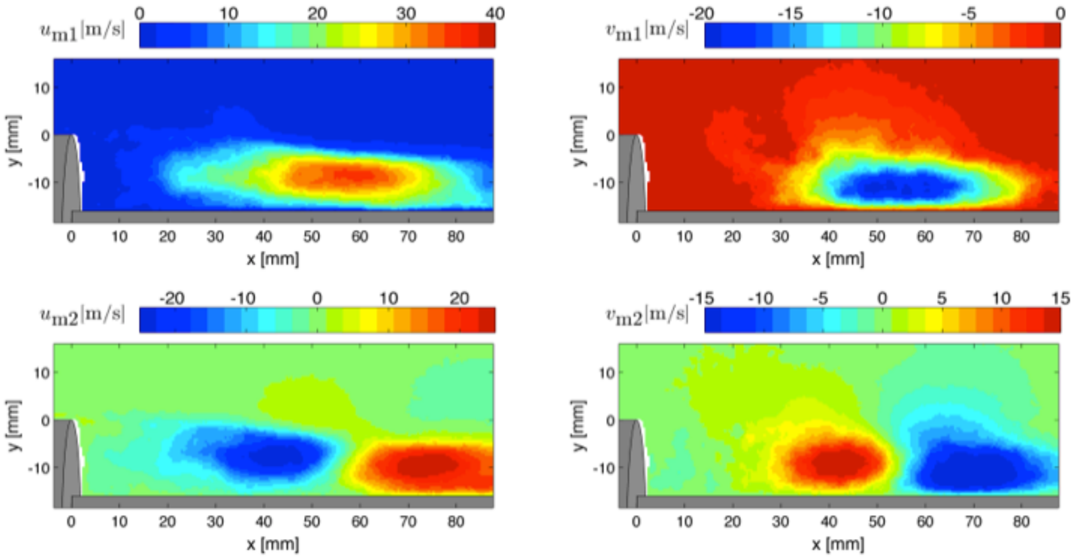

Fig 2 - Shape of the 1st POD mode (top - row) and 2nd POD mode (bottom - row); u (left) and v (right) component.

For the second mode it can be observed that the associated velocity fluctuations represent an undulating motion of the shear layer (figure 3-bottom).

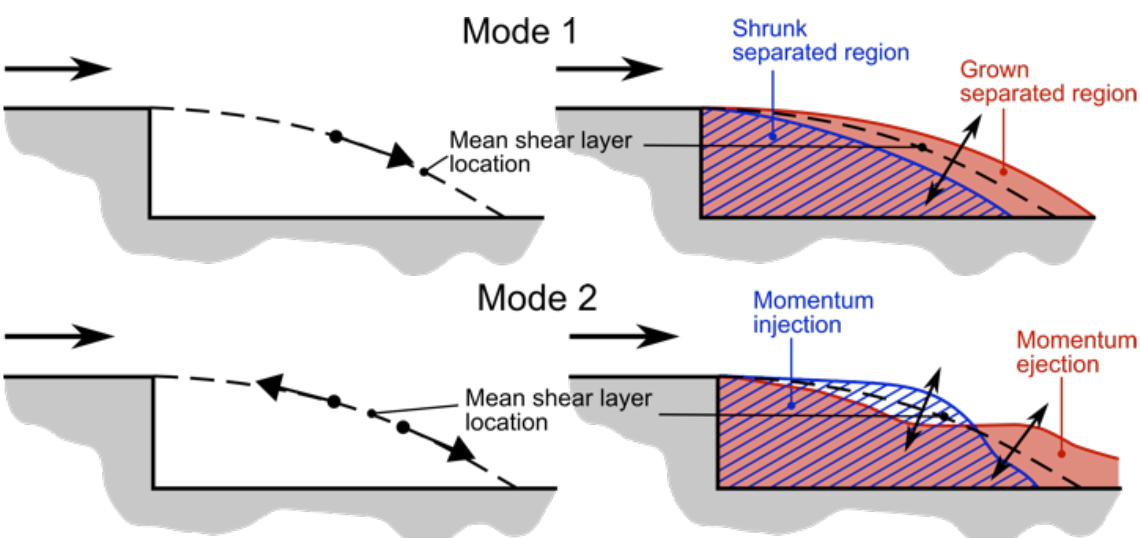

Fig 3 - Contribution of mode 1 (top - row) and 2 (bottom - row) to the flow field (left) and the effect on the shear layer position (right).

1:60 Ariane V model

A similar analysis was applied to the measurements that were performed on the Ariane V configuration. Figure 4 shows a typical result of the average velocity field over the geometry (left) clearly indicating the separated region and the turbulence intensity on the right showing the unsteadiness of the flow.

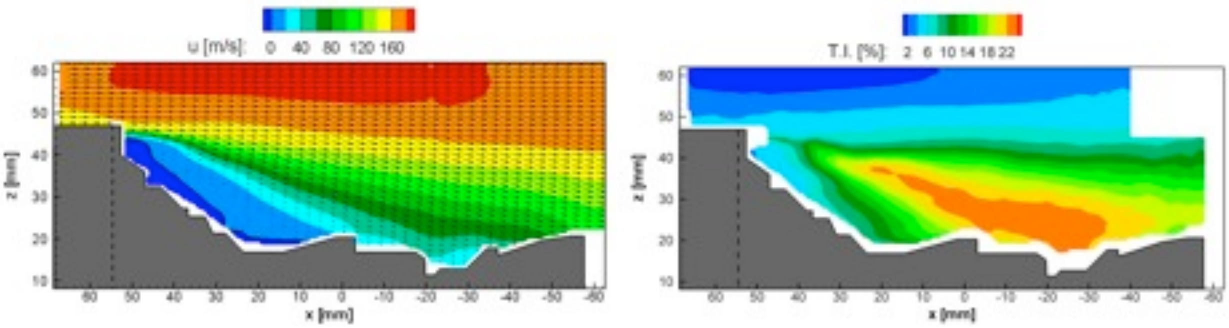

Fig 4 - Average velocity field (left) and turbulence intensity (right) for the Ariane V configuration

The POD mode shapes for this configuration are shown in figure 5 and they look strikingly similar to the results for the double cylinder geometry. Mode 1 again represents the growing and shrinking of the separated region while mode 2 represents the undulating motion of the shear layer. For the current geometry it can be observed that the flapping motion starts to become statistically significant at approximately x = 20 mm.

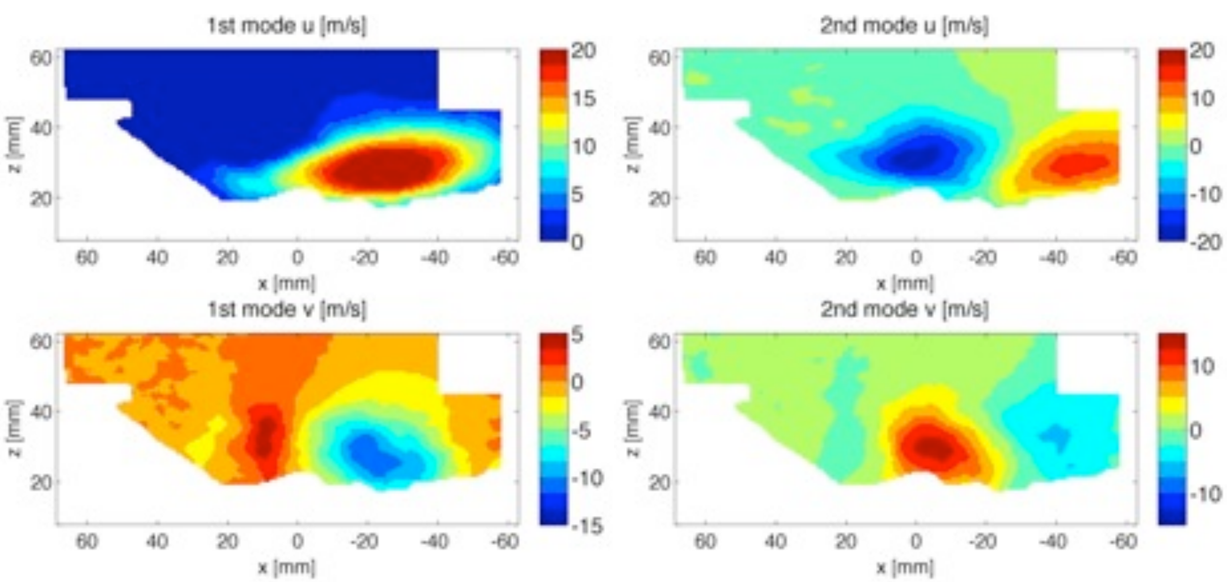

Fig 5 - Shape of the 1st POD mode (left - row) and 2nd POD mode (right - row); u (top) and v (bottom) component for the Ariane V configuration

In addition to the velocity measurements, a POD analysis is made also of the unsteady pressure measurements. Figure 6 shows the result of the first two POD mode shapes. It is found that when mode 1 is integrated over the azimuth, an effective force results in the direction of the 0° - 180° axis. For mode 2 no effective force results since it is point-symmetric. Therefore it seems that mode 1 can be related to the unsteady load on the nozzle, while mode 2 represents the so-called 'ovalization'-mode.

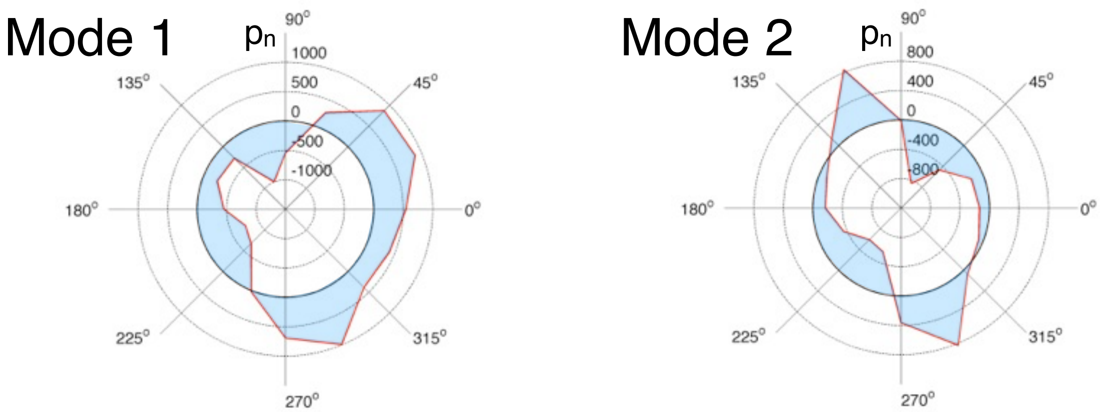

Fig 6 - 1st and 2nd POD mode shape as obtained from the unsteady pressure measurements

Finally the spectra related to the POD pressure modes is shown in figure 7. For mode 1 a very clear peak is observed near the well know value (Depres et al, 2004; Deck and Thorigny, 2007) of $St_D = 0.2$.

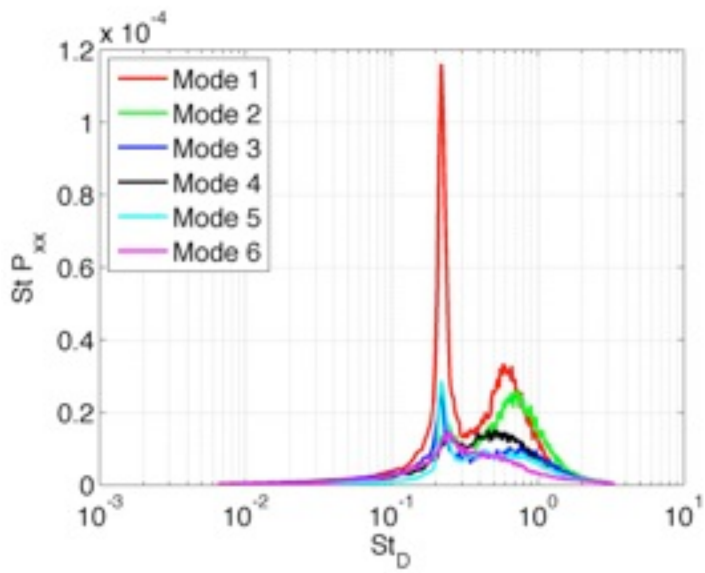

Fig 7 - Power spectra related to the first 6 POD modes

Outlook for the full paper

In addition to the above the full paper will also cover the following topics:

- Additional details on the POD analysis of the double cylinder geometry including the relation between the mode shapes and the shear layer/separation region dynamics.
- The experimental database of the Ariane V measurements contains 4 geometrical configurations, the POD analysis is used to study more in detail the effect of the geometry variations on the dynamics of the separated region.

References

G. Berkooz, P. Holmes and J. L. Lumley (1993), The proper orthogonal decomposition in the analysis of turbulent flows, Annu. Rev. Fluid Mech. 25: 539-75

S. Deck and P. Thorigny (2007) Unsteadiness of an axisymmetric separating-reattachning flow: Numerical investigation, Physics of Fluid, Vol. 19 065103

D. Deprés, P. Reijasse and J. Dussauge (2004) Analysis of unsteadiness in afterbofy transonic flows, AIAA journal, Vol. 42, No. 12

K. Hannemann, J. Pallegoix, M. Frey, S. Deck, H. Maseland, F. Schrijer, H. Lambare and R. Schwane (2011), Launch vehicle base buffeting – recent experimental and numerical investigation, Proceeding of the 7th European Symposium on Aerothermodynamics for Space Vehicles, 9th – 12th May 2011, Bruges, Belgium

F. Schrijer, A. Sciacchitano and F. Scarano (2013) Spatio-temporal and modal analysis of unsteady fluctuations in the transonic base flow, to be published