TRIPLE DECOMPOSITION OF A FLUCTUATING VELOCITY FIELD IN A MULTISCALE FLOW

Pawel Baj[1], Paul J.K. Bruce[1] & Oliver R.H. Buxton[1]
[1]*Department of Aeronautics, Imperial College London, UK*

Abstract A method for the triple decomposition of fluctuating velocity in a multiscale flow, suitable for a spatiotemporal data set, is presented. It is applied to experimental data gathered by means of particle image velocimetry (PIV). The basic properties of the decomposed parts are shown. The presented method is then used to perform a conditional study on the residual transverse velocity fluctuations. It was found that phase locking occurs between the stochastic fluctuations embedded in the wakes of different bars, appearing after the wakes have merged.

THE TRIPLE DECOMPOSITION GENERALIZATION

The Reynolds decomposition is commonly used in studies on turbulence to extract fluctuations of a given quantity. However, if those due to coherent structures present in a flow have a significant share in the overall energy, the triple decomposition, as introduced by [2], is more suitable because it makes the distinction between stochastic and coherent fluctuations. Although this decomposition has already been adopted by numerous authors (e.g. [2, 1, 4]), it has thus for only been applied to single scale flows (e.g. a flow past cylinder). This study expands the triple decomposition into multiscale flow cases in such a way that coherent structures belonging to each of the length scales introduced into the flow are treated separately. The method is based on the novel optimal mode decomposition technique (OMD), [5], that aims to approximate the flow with a linear dynamical system of an arbitrary rank in an optimal way. The flow modes produced by OMD can by linked to different coherent structures easily, making this technique suitable for our purpose. The proposed method is snapshot based, just like proper orthogonal decomposition (POD).

RESULTS AND ONGOING WORK

The near wake of a multiscale bar array (see figure 1) has been used as a test case for the proposed method. The velocity fields at two locations downstream of the obstacles have been captured by means of PIV. First, OMD has been used to extract coherent structure mode shapes associated with the shedding of each bar (see figure 2). Next, the proposed method has been utilized to recover the coherent fluctuations based on the OMD modes. The essential proof of the method's effectiveness is provided by the power spectral density (PSD) of the stochastic velocity fluctuations. These are revealed after subtracting the previously established coherent fluctuations from the original data, which are washed out of the coherence peaks (see figure 3) without artificially suppressing the frequencies corresponding to coherent events. Probability density functions (PDF) of the stochastic fluctuations form another promising result. The original PDFs are M shaped, which is characteristic for PDFs evaluated in a shedding area. The PDFs of the extracted stochastic fluctuations, however, approach a sub Gaussian shape (see figure 4) which rather resembles that for developed turbulence. Both PSD and PDF results indicate that the presented method enables the effective triple decomposition.

The method can be utilized to conduct various conditional analyses that can provide a significant insight into the nature of multiscale generated turbulence; the space scale unfolding mechanism (SSU, the concept introduced by [3] as an explanation for the enhanced mixing behind fractal objects) can be investigated with the developed technique in particular. Two novel results regarding that issue are presented here. The first one is a study of the transverse integral length scale. It has been calculated conditioned on the phase angle of the small bar shedding using the extracted stochastic fluctuations at two distinctive downstream positions: before and after the small and the medium wakes are merged (see figure 5). In the first case there is a bulk of laminar flow, characterized by the large value of integral scale, separating the small and the medium wakes and there are no signs of dependance of the medium wake's length scale on the small bar shedding angle. In the second case there is some kind of phase locking, i.e. the sinusoidal pattern appears within the medium wake's area. The second result is a finding of an additional organized motion within the wake of the small bar downstream of the intersection point. The isosurfaces of the bin averaged residual transverse fluctuation, presented in figure 6, shows that the motion depends on the phase angles of both sheddings. This phenomenon is not observed before the wakes are merged. It might be linked to a shift of the shedding frequency of the small bar which also appears downstream of the intersection point (see figure 3). The physics behind these results are not yet clear but their understanding forms our ongoing work. It seems though that the results are consistent with the SSU idea in the sense that transverse properties of the stochastic fluctuations are strongly altered downstream of the intersection point. This might, therefore, be an Eulerian manifestation of the SSU mechanism, which was originally described in terms of Lagrangian variables. Additional insight is going to be brought by a scalar concentration measurement to come since it will allow us to investigate turbulent scalar transport which is directly linked to SSU. A careful treatment of the scalar data will also enable us to estimate some Lagrangian statistics through tracking procedures and confirm or reject the hypothesis stated above. Both results will be included in the final paper.

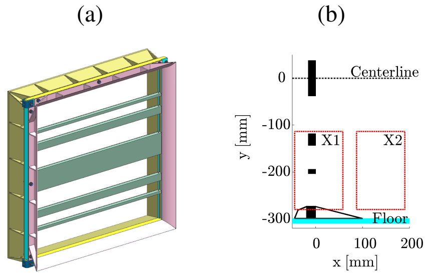

Figure 1: a) The multiscale bar array used in the experiment, b) The field of view covered in the experiment

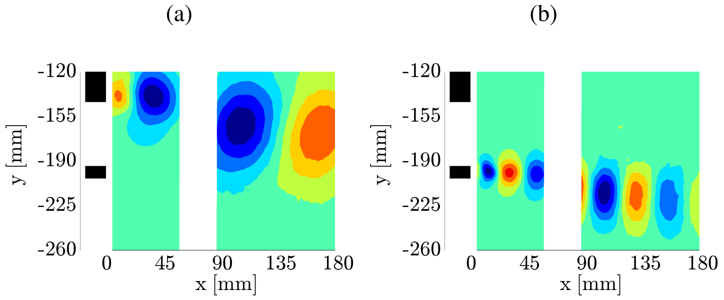

Figure 2: Coherent structures of transverse velocity fluctuation revealed by the means of OMD associated with: a) the medium bar, b) the small bar

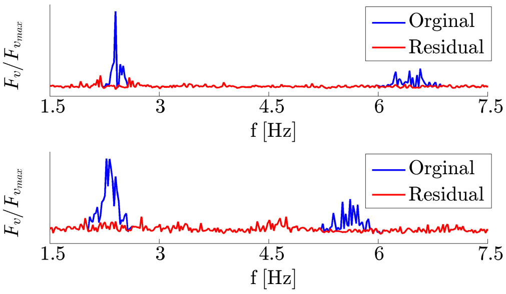

Figure 3: PSDs of the stochastic part (residual) and the total (original) transverse velocity fluctuation before and after the intersection point (plots below and above respectively)

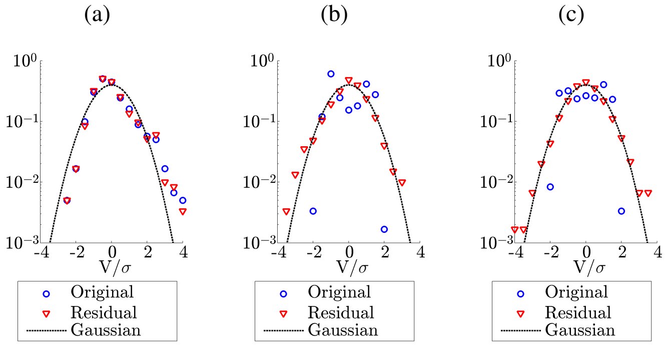

Figure 4: PDFs of the stochastic part (residual) and the total (original) transverse velocity fluctuation evaluated in points: a) outside the wakes, b) inside the wake of the small bar, c) inside the wake of the medium bar

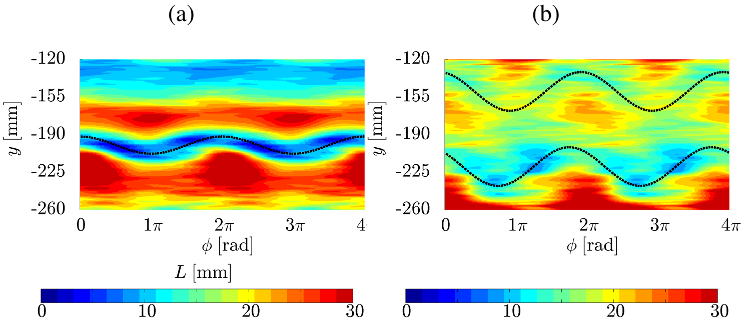

Figure 5: Transverse integral length scale conditioned on the small bar shedding phase angle evaluated: a) upstream of the intersection point, b) downstream of the intersection point

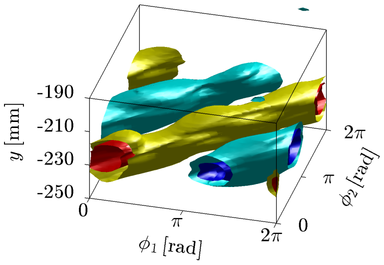

Figure 6: Isosurfaces of a phase averaged residual transverse velocity fluctuation downstream of the intersection point (ϕ_1 and ϕ_2 are phase angles of the small and the medium bar shedding respectively)

References

[1] GJ Brereton and A Kodal. A frequency-domain filtering technique for triple decomposition of unsteady turbulent flow. *Journal of fluids engineering*, **114**(1):45–51, 1992.

[2] Abul Khair Muhammad Fazle Hussain and William C Reynolds. The mechanics of an organized wave in turbulent shear flow. *Journal of Fluid Mechanics*, **41**(02):241–258, 1970.

[3] S Laizet and JC Vassilicos. Fractal space-scale unfolding mechanism for energy-efficient turbulent mixing. *Physical Review E*, **86**(4):046302, 2012.

[4] Rodolphe Perrin, Marianna Braza, Emmanuel Cid, Sebastien Cazin, Franck Moradei, Arnaud Barthet, Alain Sevrain, and Yannick Hoarau. Near-wake turbulence properties in the high Reynolds number incompressible flow around a circular cylinder measured by two-and three-component PIV. *Flow, turbulence and combustion*, **77**(1-4):185–204, 2006.

[5] A Wynn, DS Pearson, B Ganapathisubramani, and PJ Goulart. Optimal mode decomposition for unsteady flows. *Journal of Fluid Mechanics*, **733**:473–503, 2013.