On dynamics of the flow in gap between two buildings in tandem configuration

Václav Uruba[1, 2*], *Pavel* Procházka[1], *Václav* Svoboda[3], and *Renata* Gnatowska[4]

[1]Department of Fluid Dynamics, Institute of Thermomechanics of the Czech Academy of Sciences, Dolejškova 5, 182 00 Prague 8, Czech Republic

[2]Department of Power System Engineering, Faculty of Mechanical Engineering, University of West Bohemia, Universitní 8, 306 14 Plzeň, Czech Republic

[3]Faculty of Nuclear Sciences and Physical Engineering, CTU in Prague, Břehová 78/7, 115 19 Prague 1, Czech Republic

[4]Czestochowa University of Technology, Faculty of Mechanical Engineering and Computer Science, 21 Armii Krajowej Av, 42-200 Czestochowa, Poland

Abstract. Two buildings differing in height in tandem configuration are subjected to a turbulent boundary layer flow. The physical modelling in a wind tunnel has been performed, Particle Image Velocimetry in horizontal planes has been applied. The time-mean flow-field is dominated by the contrarotating vortex pair in the near-wake of the upstream building forming strong back-flow in this wake. Dynamical activity is located close to the bigger downstream building below the level of the smaller building roof. The dynamical structures in the space between them are studied using advanced analytical methods, Oscillation Pattern Decomposition (OPD). The 3 important OPD modes were detected differing by topology and frequency. The 2 OPD modes are characterized by vortical structures formed within the wake of the smaller upstream building and moving downstream towards the bigger building. The last OPD mode shows strong pulsation transversal flow in front of the bigger building. Typical frequency of the cyclo-stationary behaviour could be characterized by the Strouhal number in the range from 0.09 up to 0.15.

1 Introduction

With increasing urbanization and density of population, the understanding of the problem of flow fields in urban environments, so called micrometeorological situation, becomes more important. Increased interest in has been observed over the past few decades. The results of such studies could be applied in the design process of new buildings as well as reconstruction and optimization of the existing urban areas and city centres. This issue plays an important role in environmental protection, defining so-called wind comfort around and between buildings, the life quality in urban areas as well as specific economic aspects of utilization of the defined zones. The studies of the wind environment around buildings are generally performed as wind tunnel experiments since it is the most well-established way to simulate a natural wind. The Reynolds number of wind tunnel modelling is several orders of magnitudes lower than this in the real situation, however its value is supercritical, turbulence in wakes is well developed and thus the results on turbulent diffusion are relevant, however the relevance is limited, see the discussion e.g. in [1,2].

Wind-tunnel measurements are performed using classical point techniques such as hot-wire or hot-film anemometry very often, see e.g. [1-5]. Recently, the Particle Image Velocimetry (PIV) technique is used, [6,7], as it provides much more information about the flow topology than the point methods.

The objective of this paper is to provide a detailed experimental analysis of the flow interactions of buildings models situated one after another in a so-called tandem arrangement. This configuration is rather common in practice. The main aim is to clarify the flow field between the buildings with help of advanced experimental technique, as the time-resolved PIV technique in several measuring planes to capture both spatial and dynamical features.

The preceding study [8] was performed on the same geometry, however vertical flow around the buildings has been studied within the vertical plane of symmetry. Dominant vortical structures have been detected both in time-mean and velocity fluctuation fields. The dynamical analysis has been performed using Proper Orthogonal Decomposition (POD) method based on turbulence kinetic energy assessment.

The presented paper is concentrated on flow in horizontal planes in gap between the buildings.

2 Experimental setup

The existing blown-down facility located in Shear Flows and Turbulence laboratory of the IT AS Prague was used for the experiments.

* Corresponding author: uruba@it.cas.cz

2.1 Physical model

The model of the buildings in tandem configuration is placed to the flow in the test-section inlet of the blown-down facility. The cross-section of the closed test-section is 250 x 250 mm^2 and 4.5 m long.

The model of buildings is placed in the test-section axis, 4 m from the inlet and it is shown in Figure 1, where positions of the planes of measurement are shown in green.

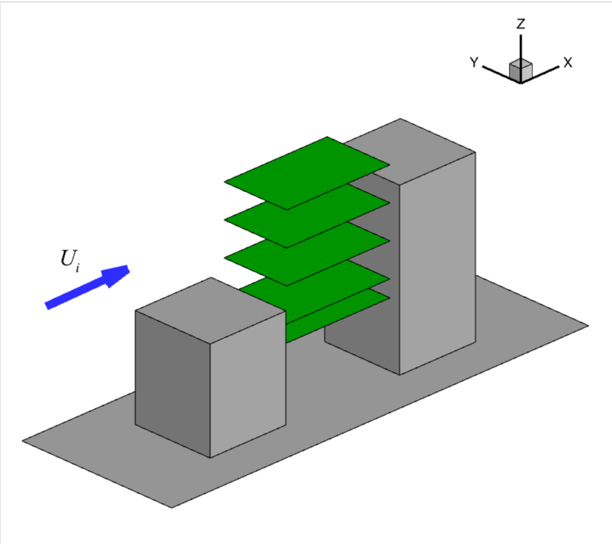

Fig. 1. The three-dimensional image of the experiment setup, planes of measurement are in green.

The two buildings with the same square ground plane with side d = 25 mm and heights 1.2d and 2d are shown, respectively. The smaller building is placed upstream, the flow is along the building's axis. The gap between the buildings is 1.5d is the streamwise direction.

The coordinate system is shown in Figure 2, where the view from above towards the model in -z direction is shown. The coordinates are dimensionless, indicating multiples of the building ground plane side d.

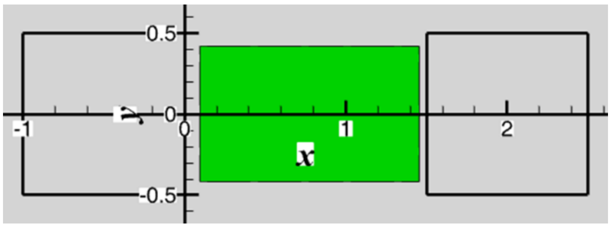

Fig. 2. The Cartesian coordinate system, view from above.

The mean velocity profile in the edge of the upstream, smaller building (position x = -1) is shown in Figure 3. The heights of the smaller (1.2d) and bigger (2d) buildings are shown only for comparison. The velocity profile is well-developed turbulent boundary layer velocity profile, conventional thickness is about 2d. In z direction the profile is constant in the central region z = +-3d. The velocity U is dimensionless, indicating multiples of the incoming velocity U_i = 10 m/s outside the boundary layer.

The mean velocity profile was measured using PIV and HW measuring techniques, see [9].

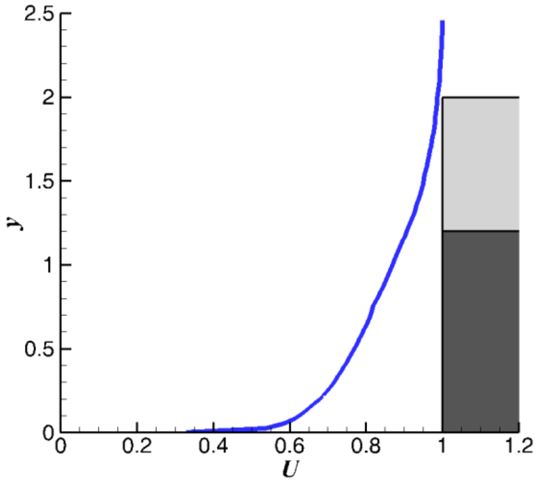

Fig. 3. Mean velocity profile on the model inlet.

The Reynolds number based on the velocity U_i and buildings side d was about 16 thousands.

2.2 Experimental technique

For evaluation of velocity distributions within the measuring planes (see Figure 1) the Particle Image Velocimetry technique was applied, hereinafter PIV.

The velocity vector field was measured using time-resolved PIV method. The measurement apparatus consists of laser and CMOS camera by Dantec. The laser is New Wave Pegasus, Nd:YLF double head with wavelength of 527 nm, maximal frequency 10 kHz, shot energy is 10 mJ (for 1 kHz) and corresponding power is 10 W per one head. The camera Phantom V611 with resolution of 1 280 x 800 pixels is able to acquire double-snaps with frequency up to 3 kHz (full resolution) and it uses internal memory 8 GB. The data were acquired and post-processed in Dynamic Studio software. The evaluated velocity fields consisting of 159 x 99 vectors were acquired in frequency 2 kHz, one record contained 4 000 double-snapshots representing 2 s in real time. The SAFEX particles, oil droplets 1 μm in diameter, have been used.

2.3 Methods of analysis

Besides the classical statistical data analysis based on averaging, the advanced methods were applied.

The Oscillation Pattern Decomposition method (hereinafter OPD) is used to study the dynamical properties of the flow-field. The OPD method yields series of OPD modes. Each OPD mode is characterized by its topology in complex form (consisting of real and imaginary parts), frequency f and attenuation of the pseudo-periodic (oscillating) behaviour. Attenuation or amplitude decay is described by so called e-folding time τ_e representing the mean time period of the mode amplitude decay by factor "*e*". The other decay characteristic is dimensionless "periodicity" p which expresses the e-folding time in multiples of periods of the OPD mode defined by its frequency.

$$p = \tau_e \cdot f \tag{1}$$

The frequencies are expressed in dimensionless form as Strouhal numbers *Sh*, defined as follows:

$$Sh = \frac{f \cdot d}{U_i} \tag{2}$$

The details on OPD method could be found in [9,10].

3 Results

All results are to be presented in dimensionless form. For this purpose, the model dimension d and inlet velocity U_i were used.

First, the statistical data, mean values and variances, are to be shown. Then, the results of advanced dynamical analysis OPD will be presented.

3.1. Time-mean patterns

The method of averaging was applied on velocity vector field series. The results are to be shown as vector fields with vector-lines added arbitrarily (blue lines).

Two typical results in the lanes $z = 0.8$ and 1 are shown in Figures 4 and 5, respectively.

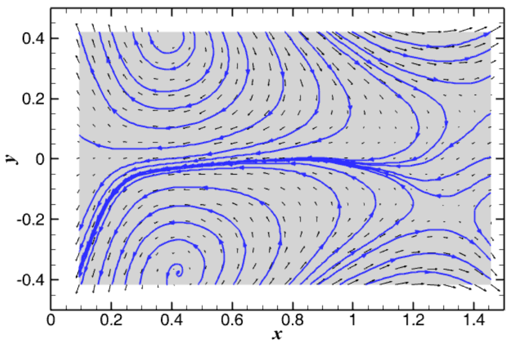

Fig. 4. The mean velocity field in the plane $z = 0.8$.

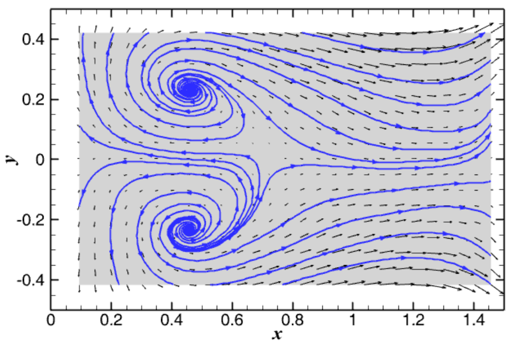

Fig. 5. The mean velocity field in the plane $z = 1$.

The measuring planes bellow the smaller building roof are strongly affected by the buildings presence. The plane $z = 0.8$ shows the contra-rotating vortices located at $(x;y)$ positions (0.4;+-0.4) generating strong back-flow on the axis – see Figure 4. Close to the downstream building, the saddle point is detected at $x \approx 1.3$.

The vortices are well pronounced in the plane $z = 1$, they are closer to each other, again generating back-flow just behind the upstream building. The vortices centres are located at positions (0.4;+-0.25), see Figure 5.

The higher measuring planes ($z > 1.2$) show nearly unperturbed flow above the upstream building. In Figure 6, there is the flow-field in the plane $z = 1.4$, the flow declination could be detected close to the higher building, for $x > 1.1$

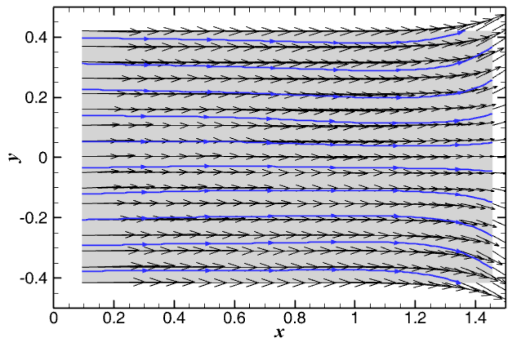

Fig. 6. The mean velocity field in the plane $z = 1.4$.

The measuring planes for higher z exhibit even smaller perturbations of the mean flow.

The Turbulent Kinetic Energy (*TKE*) is a measure of local dynamical activity of the flow-field, which plays an important role in diffusion processes. The *TKE* is defined using all 3 velocity components fluctuations as half of sum of velocity components variances in a given point in space. As we have at our disposal only 2 velocity components in the plane of measurement (the out-of-plane component is not detected) we have used the following definition of the *TKE*:

$$TKE = 3/4\left(\overline{u^2} + \overline{v^2}\right), \tag{3}$$

here u and v are fluctuations of streamwise and spanwise velocity components, respectively. Then, $\overline{u^2}$ is the streamwise velocity component variance. Dimensionless velocity is considered. This definition of *TKE* presumes the variance of the third, unresolved velocity component to be average of the two resolved.

The distribution of the *TKE* in the plane $z = 1$, is shown in Figure 7. The near wake behind the upstream building is relatively calm, maximal fluctuation activity is detected just in front of the higher building in the position $x = 1.2$.

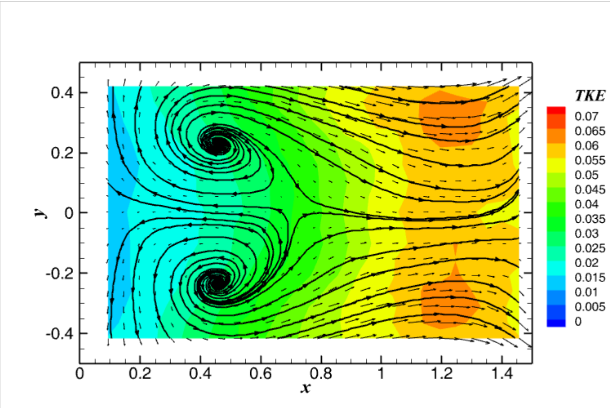

Fig. 7. Turbulence Kinetic Energy in the plane $z = 1$.

The distribution of TKE in the whole measured domain is shown in Figure 8, where the iso-surfaces of TKE are drawn.

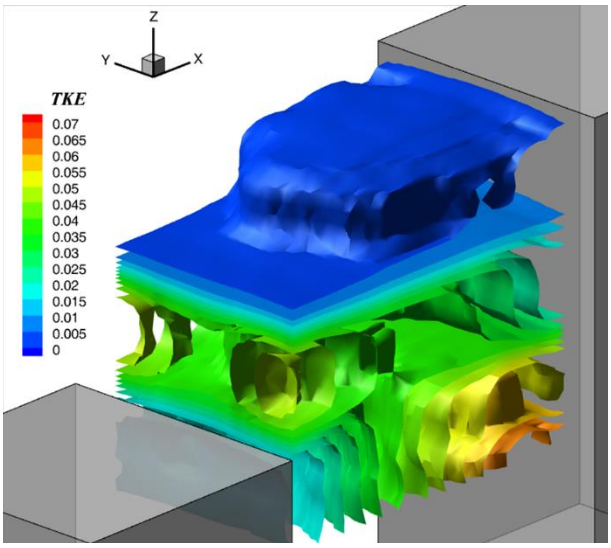

Fig. 8. Isosurfaces of Turbulent Kinetic Energy in the whole measurement domain.

Indeed, maximal fluctuation activity could be detected just in front of the higher building and bellow of the smaller building roof level. Above the smaller building roof, the *TKE* is decreasing considerably, slightly below the higher building level, the *TKE* is approaching zero.

The dynamical analysis will be performed for the level $z = 1$.

3.2. Dynamical patterns

The flow-field in the position $z = 1$ has been subjected to detailed dynamical analysis using the OPD method.

The 16 OPD modes have been evaluated, in Figure 9 the modes are represented in the plane *Sh*-*p*, definitions see (1) and (2).

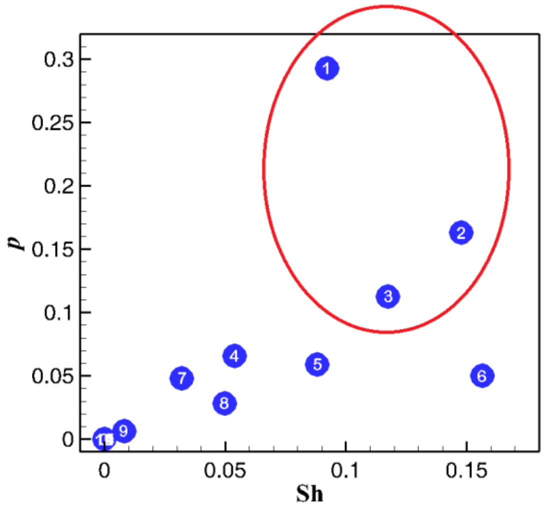

Fig. 9. OPD spectrum.

The periodicity bellow 0.1 indicates rapid decay of a an OPD mode in question, such modes are dominated by random behaviour, and as such they play minor role in the flow dynamics. So, we decided to analyse only 3 OPD modes with the *p* above 0.1, within the red zone in Figure 9.

The first OPD mode topology, the most stable one, is depicted in Figure 10, the real and imaginary parts, respectively. It consists of the fluctuation velocity vector-field, the vector-lines are added arbitrarily for better clarity.

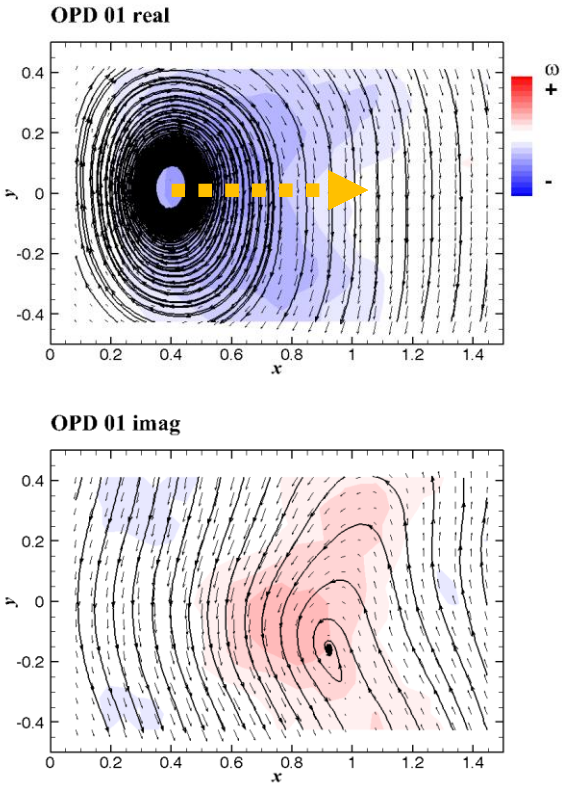

Fig. 10. Topology of the 1st OPD mode, real and imaginary parts.

In representations of the OPD modes topologies, the vorticity component perpendicular to the plane of measurement is added for better clarity, indicating positive (in red) and negative (in blue) orientations, however in arbitrary units. The real and imaginary parts of an OPD mode represent phase 0 and $\pi/2$ of the cyclostationary process, respectively. More information of OPD modes interpretation could be find e.g. in [9,10].

The mode OPD 1 is dominated by a vortex moving along the *x* axis. It originates within the near wake of the smaller building as a strong vortex and moving towards the bigger building, weaken and changing orientation of rotation in the same time. The yellow broken arrow indicates the vortex trajectory. The frequency corresponds to the Strouhal number about 0.092.

The OPD mode 2, in Figure 11, is characterized by a pair of contrarotating vortices. Their dynamics is similar to the mode OPD 1, they raise just behind the smaller building and moving in the streamwise direction towards the bigger one. Unlike the mode OPD 1, the vortices strengthen approaching the bigger building and tend to its sides. The Strouhal number is about 0.15.

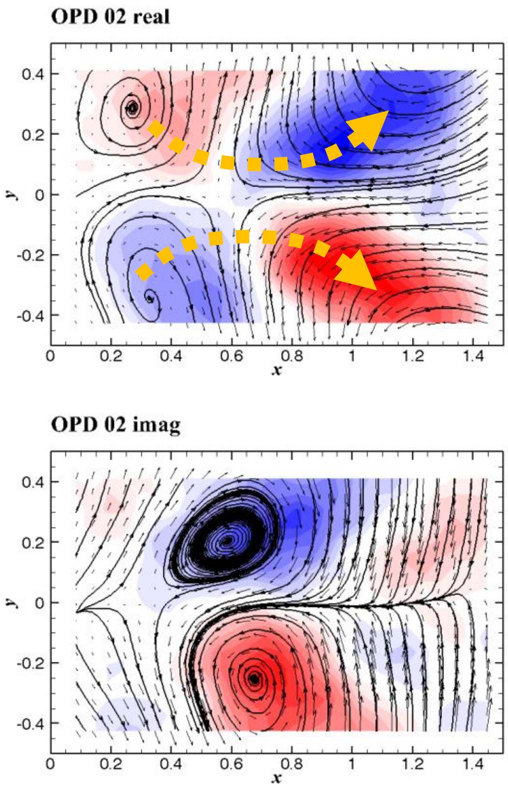

Fig. 11. Topology of the 2nd OPD mode, real and imaginary parts.

The OPD mode 3 topology is depicted in Figure 12. This mode is dominated by strong spanwise flow in front of bigger building. The direction is changing from positive to negative *y* axis orientation. The Strouhal number is about 0.12.

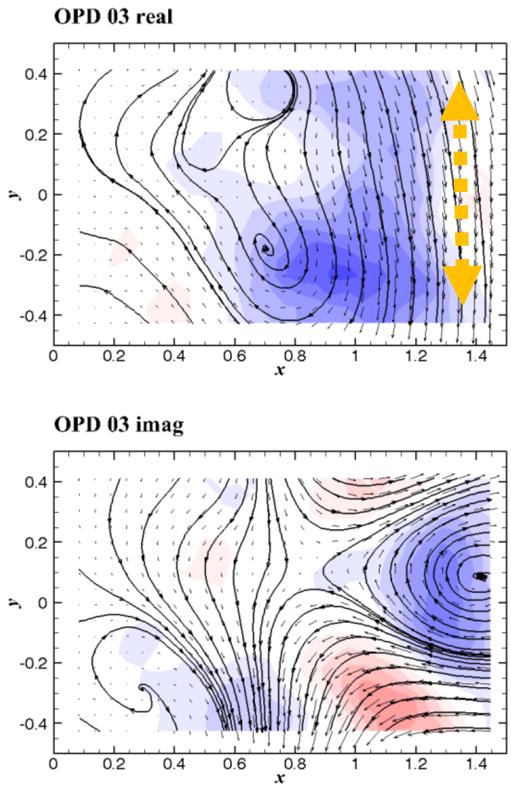

Fig. 12. Topology of the 3rd OPD mode, real and imaginary parts.

The higher order OPD modes are characterized by periodicity lower than 0.1 or even 0. This means that the damping of the mode is very quick in terms of period of cyclo-stationary behaviour. The real part of topology simply appears on random basis in time and then disappear gradually.

4 Conclusions

The presented paper shows some aspect of flow in the gap between two buildings in tandem configuration. Both mean velocity field and flow dynamics are addressed with emphasis to the region just below the smaller building roof level.

The time-mean flow-field is dominated by the contrarotating vortex pair sitting in the near-wake of the upstream building forming strong back-flow in this wake. Dynamical activity is located close to the bigger downstream building bellow the level of the smaller building roof. Above this level, the turbulence activity decay very quickly and it is very weak on the higher building roof level.

The pseudo-periodical or cyclo-stationary flow dynamics contains 3 important modes differing by topology and frequency. The vortical structures are formed within the near wake of the smaller upstream building and they are moving downstream towards the bigger building. In the 1st OPD mode the single vortex travels from the upstream wake to the downstream building. The 2nd OPD mode shows the vortex contrarotating pair moving from the wake around the sides of the bigger building. The 3rd mode exhibits strong transversal pulsations just in front of the bigger building.

The typical frequency of cyclo-stationary behaviour could be characterized by the Strouhal number in the range $\mathrm{Sh} \in (0.09; 0.15)$

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