

Structure of conical vortex on and behind a cube in smooth and turbulent flows

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ABSTRACT: The structure of the conical vortices on and behind the cube in uniform smooth flow and turbulent boundary layer flow when flow attacks normal to the diagonal line is investigated by synchronous measurements of 3D-SPIV and multi pressure sensor systems. The conical vortex at one side is always stronger than that at the other side. The conical vortices at the both sides sway in a body on the cube, and the strength of vortices changes all the time. The side at the stronger vortex changes occasionally in relatively long interval. An arch-type vortex is formed behind the cube in any times of which shape is reentrant at the center and inclines to the side of the stronger conical vortex. When the conical vortex at one side is stronger, the vortex at the other side is drawn into the one side of the arch-type vortex.

KEYWORDS: Cube, 3D-SPIV, Conical vortex, Arch-type vortex, Switching phenomenon, Flow interaction

1 INTRODUCTION

When flow attacks to a flat roof from an oblique angle, a pair of conical vortices is formed on the roof. The vortices induce strong suction on the roof along the windward edges. Roof tiles are often scattered by the local strong peak negative pressure induced by the conical vortices [1],[2],[3],[4],[5],[6].

The vortex at one side of the roof is always stronger than that at the other side. The stronger vortex switches side by side occasionally in smooth flow. This phenomenon is known as the switching of flow pattern [6],[7]. On the other hands, a very strong conical vortex is formed on one side in turbulent flow when a strong gust attacks to the eave in a particular angle of attack of around 25 degree, and the pulse like extremely large negative pressure is induced [6].

In order to investigate how the switching is induced and what causes the switching, Nishimura et al. measured pressure on the flat roof in smooth flow with and without a splitter plate in the wake [8]. According to the experimental results, they have mentioned that the switching is induced by flow instability related with an interaction between the conical vortex and the separated shear layer from the side of the model in the wake. This remark is deduced from the simultaneous measurement of pressure fluctuations on the roof and the base floor.

This research has been planned to make clear the mechanism of the switching and the interaction between the conical vortices and the separated shear layer in the wake.

2 EXPERIMENTAL DESCRIPTION

In order to achieve the objectives of the research, the three dimensional stereoscopic PIV system (3D-SPIV) is used to measure three components of velocity vector on and behind a cube synchronized with pressure measurement on the cube. The experiments were carried out at the boundary layer wind tunnel of Building Research Institute in Japan with the test section of 3m x

2.5m. In order to avoid the effect of naturally developing boundary layer on the tunnel floor, a horizontal flat plate was set at 30cm above the tunnel floor shown in Figure 1. In the experiments, two kinds of approaching flow are used. One is a nearly smooth uniform flow (USF) and the other is turbulent boundary layer flow (TBL). Figure 2 shows profiles of mean wind

speed and turbulence intensity in stream wise direction in the both flow at the position of the cube. According to the profile of USF shown as red circles, the flow is influenced by boundary layer developed on a flat plate up to 40mm from the plate and blue circles show TBL. The flow is uniform and the turbulence intensity is below 1% beyond 40mm. TBL was produced by roughness blocks and spires. The turbulence intensity is 13% to 20% up to 100mm in TBL.

A cube of which side is 80mm is used for the experiment in USF, and a cube of which side is 50mm is used for the experiment in TBL. The cube was set at 957mm downstream from the windward

edge of the flat plate to the center of the cube normal to the diagonal line in USF. In TBL, the cube was set at 825mm. The reference wind speed, U , was set at 5m/sec at 100mm above the plate. The coordinate is defined as x in stream wise direction, y in cross flow direction and z in vertical direction. The characteristic length is the length of diagonal line of the cube, which is defined as D , so the Reynolds number based on D and U are 24960 and 15600 respectively in USF and TBL.

Figure 1 shows the experimental set up for 3D-SPIV in USF which can measure three components of velocity vector on a plane based on two pairs of shots taken by two high speed cameras. The measurements in USF were carried out in 7 perpendicular planes (y - z plane) on the cube and in the wake behind the cube at $x/D = -0.5, -0.25, 0, 0.25, 0.5, 1.0, 1.5$. In the measurements, instantaneous velocity vectors at 77×63 points on each plane of which resolution is 4.26mm, were calculated from a pair of shots, which are taken by high-speed video cameras with intervals of 0.05msec. In each run 2727 pairs of the shot were taken at 250Hz rate. On the other hands, the measurements in TBL were carried out in 16 perpendicular planes from $x/D = -0.25$ to

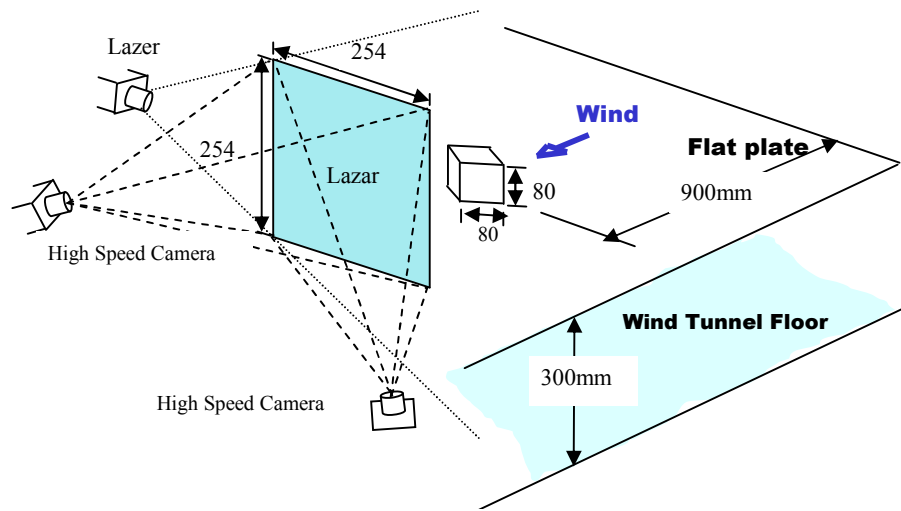


Figure 1 Experimental set up for 3D-SPIV in USF

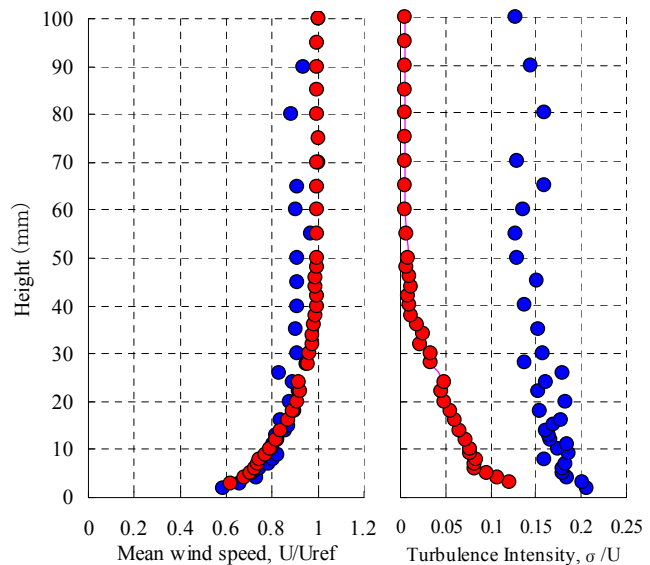


Figure 2 Profiles of mean velocity and turbulence intensity

3.0 with intervals of 0.25D. In the measurements, instantaneous velocity vectors at 63 x 63 points on each plane of which resolution is 4.11mm, were calculated from a pair of shots, which are taken by high-speed video cameras with intervals of 0.05msec. In each run 2727 pairs of the shot were taken at 500Hz rate. See the detail of the 3D-SPIV in Kawai et al. [9].

3 EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1 Flow structure on and behind the cube in USF

Figure 3 shows the velocity vectors and the stream-wise component of the vorticity as the isogram in the five perpendicular planes (y-z plane). Red zone shows anti-clockwise vorticity and blue zone shows clockwise vorticity. The large vorticity zone produced by the conical vortex enlarges towards the downstream until $x=1D$. The zone is almost disappear at $x=1.5D$, which means the conical vortices are drawn into an arch type vortex in the wake as discussed later in detail. Figure 4 shows the velocity vectors and the stream-wise component of the vorticity at $x=1D$. It is shown in Figure 4 that strong downwash is induced by the conical vortices and the vortex at the left hand side is drawn towards the right hand side.

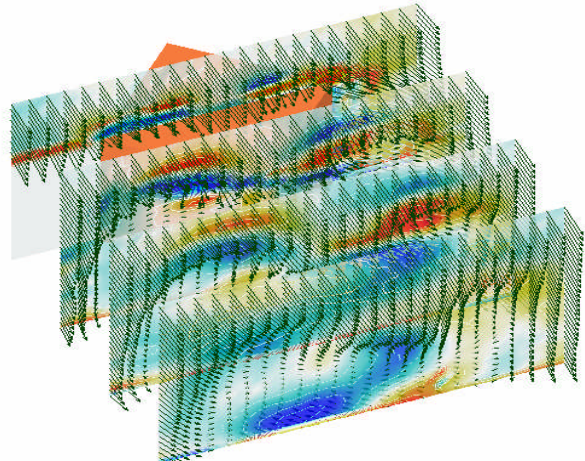


Figure 3 Velocity vectors and stream-wise vorticity on and behind the cube in USF

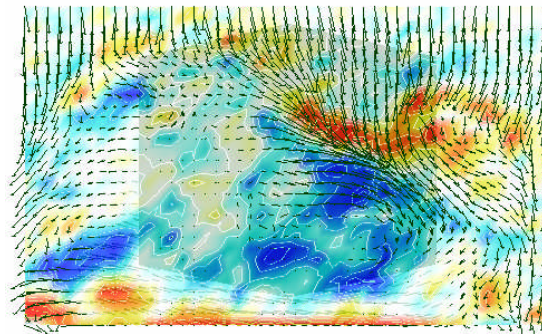
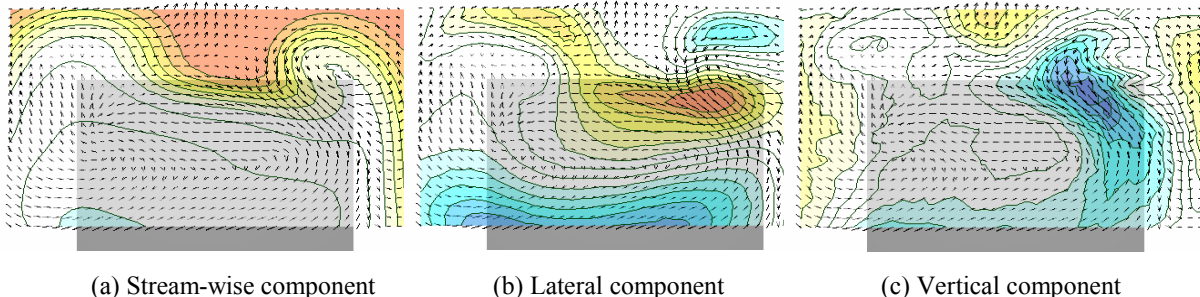


Figure 4 Velocity vectors and stream-wise vorticity at $x=1.0D$ in USF

3.2 POD analysis of velocity fluctuation behind the cube in USF

In order to make clear the structure of the wake behind the cube and the draw of the conical vortex, POD analysis is carried out for the velocity fluctuations. Figure 5 shows the first modes for the three components at $x=1D$ together with the velocity vector in the first mode. (a), the stream wise component of the velocity fluctuation, shows that an center of the separated shear layer is depressed and the layer moves and inclines to the right side. (b), the lateral component of the velocity fluctuation, shows that the draw of the left side conical vortex to the right side is shown as



(a) Stream-wise component (b) Lateral component (c) Vertical component

Figure 5 First mode of POD of three components of velocity fluctuation in USF

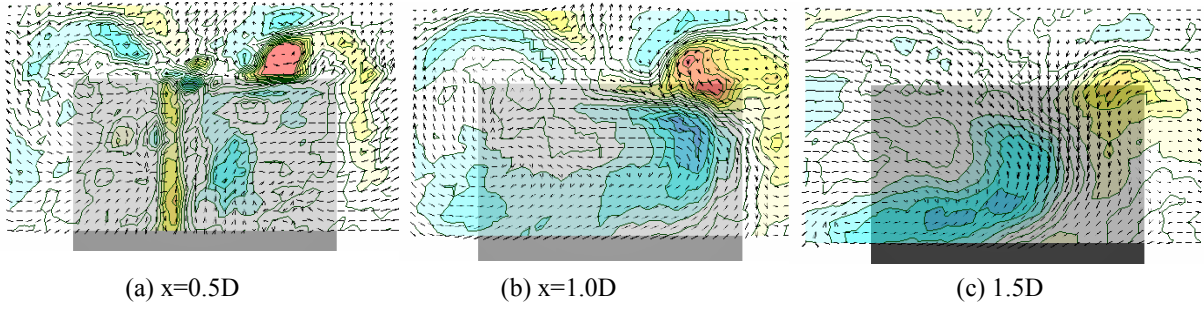


Figure 6 First mode of POD of stream-wise vorticity fluctuation in USF.

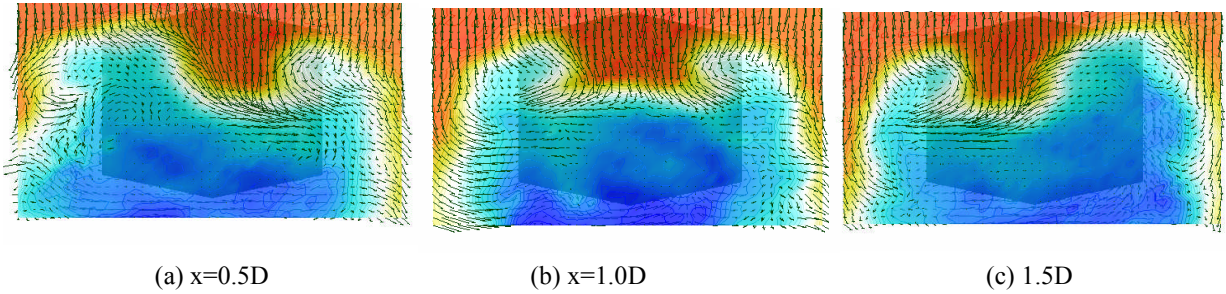


Figure 7 Sway of the conical vortex and switching phenomenon of the flow in USF.

wake at $x=1.5D$. On the other hands the conical vortex at the right hand side stays at the same position at $x=0.5D$, $1D$ and $1.5D$ though its vorticity becomes weaker as x increase.

3.3 Sway of the conical vortex and switching phenomenon of the flow in USF

As discussed in the former section, the flow is unsymmetrical and the conical vortex at one side is always stronger than that at the other side. However, the stronger vortex side changes occasionally in relatively long interval. This phenomenon is known as the switching of the flow pattern. The phenomenon is discussed in this section.

Figure 7 shows the velocity vectors and the stream-wise component of the velocity at $x=1D$ when the switching phenomenon occurs. Red zone shows positive and blue zone shows negative. White zone shows when the velocity is 0, and it corresponds with the center of the shear layer. (a) shows that the vortex at the left hand side is stronger, (b) shows that the vortex at the right hand side is stronger and (c) is the instant of the switching from (a) to (b).

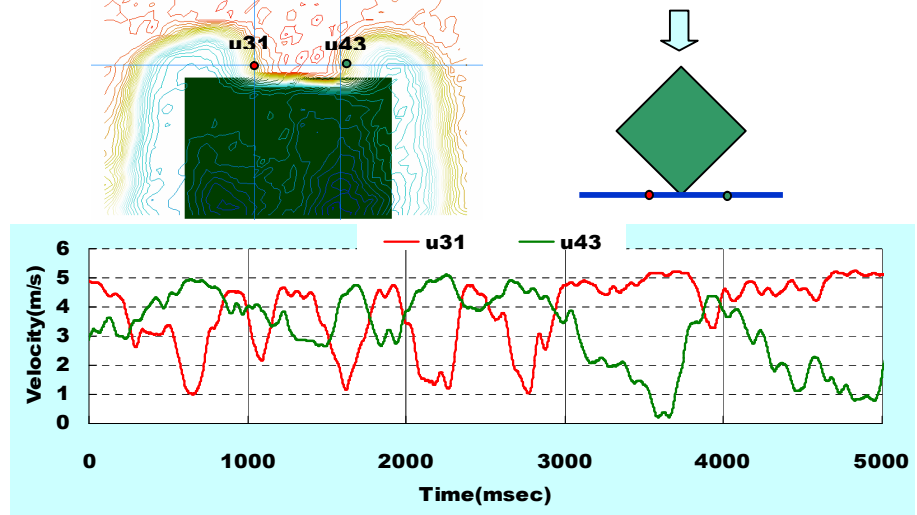


Figure 8 Velocity fluctuations at the edge of the shear layer.

The conical vortex sways all the time even when the vortex at one side is stronger Figure 8 shows time history of stream wise velocity component just out side of the shear layer behind a cube in USF when the vortex at the right hand side is stronger than that at the left hand side. The green line shows the velocity fluctuation at the right hand side, u43 and the red line shows that at the left hand side, u31. The velocities both at u43

and u31 fluctuate nearly regularly in the period of 0.4sec to 0.6sec until 3 second, and then the velocity at u43 decreases after the switching of the flow pattern occurs. The velocities at the both sides fluctuate out of phase. This means that the conical vortices sway quasi-periodically in a body suggested by Kawai et. [4]. The moment of switching corresponds when the pair of the vortices moves to the left.

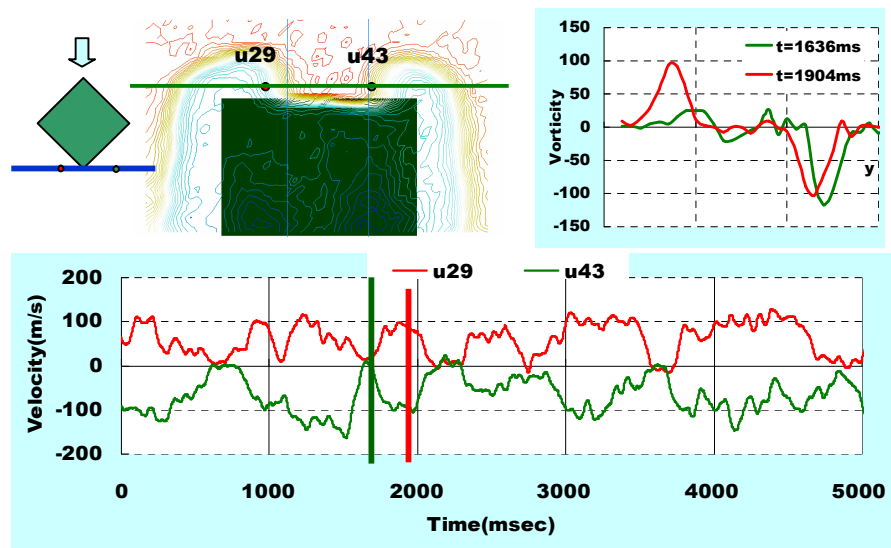


Figure 9 shows time history of stream wise component of vorticity at u29 and u43 in USF when the vortex at the right hand side is stronger than that at the left hand side. The vorticity fluctuates in the same period of the velocity fluctuation shown in Figure 8. Figure .9b shows the profiles of the vorticity along the green line at the instant of 1636msec and 1904msec. When the vorticity at u43 is nearly 0 at 1636msec, the velocity at u43 reaches the peak and the peak value of the vorticity at the right hand side reaches the maximum. This corresponds that the conical vortex reaches to the most right side. In this instant, the vortex at the left hand side becomes weak as shown by a green line in Figure 9b. When the vortex moves to the left, the vorticity at u43 increases and then takes the peak at 1904msec. In this instant, the strength of the vortices at both sides is almost same as shown by a red line in Figure 9b. The switching occurs when the vortex at the left hand side is stronger a little than that at the right hand side at the instant of 3000msec.

3.4 Structure of flow in the wake and pressure on the cube in TBL

The general feature of the flow on and behind the cube does not so change from USF to TBL except that the sway of the conical vortex is not so regular but random and the switching is affected by the approaching turbulence.

In order to investigate the interaction between the conical vortex and the separated shear layer from the side, the three components of the vorticity are calculated at $x=0.75D$ and shown in Figure 10 with the velocity vector. (a) is the stream wise component, (b) the lateral component and (c) is the vertical component of the vorticity. The large positive stream wise vorticity zone (clock-wise vorticity) shown as blue region in Figure 10a spreads under the negative vorticity zone (anti-clock-wise vorticity) at the right hand side. The pattern of the isogram is similar to that

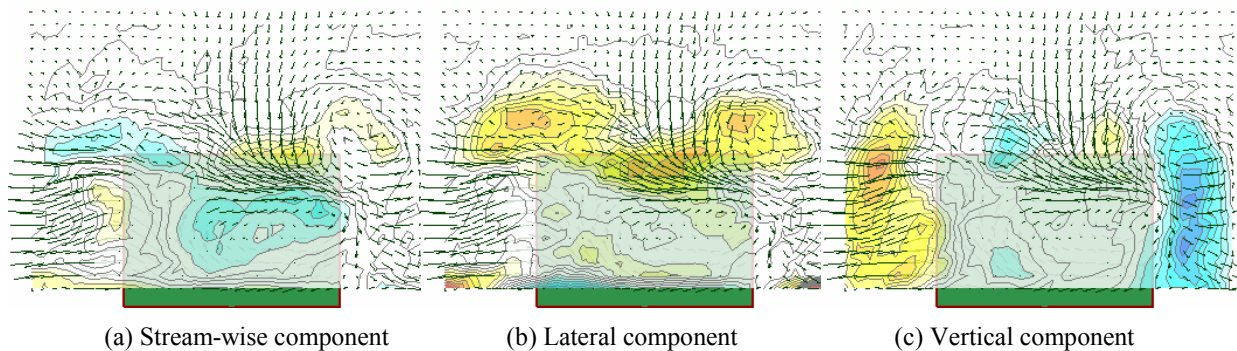


Figure 10 Three components of vorticity in TBL

of Figure 6b in USF. The lateral component of the vorticity shown in Figure 10b shows again the draw of the vortex from the left to the right. The large positive and negative zones of the vertical component of the vorticity locate at the outside of the cube which is induced by the separated shear layer from the side. Moreover, the small zones of negative and the positive vertical vorticity are seen near the center of the cube which is induced by the reentrant arch-type vortex behind the cube.

Figure 11 shows the pressure distribution on the cube when the strength to the conical vortex at the right hand side becomes the maximum. Blue zone shows negative and red zone shows positive. When the conical vortex at the right hand side becomes much stronger than that at the left hand side, the negative pressure on the upper surface at the right hand side becomes larger and the large negative peak pressure is induced near the windward corner. The negative pressure on the right leeward side increases at the same time. Particularly, the large negative peak pressure acts on the leeward corner at the right hand side.

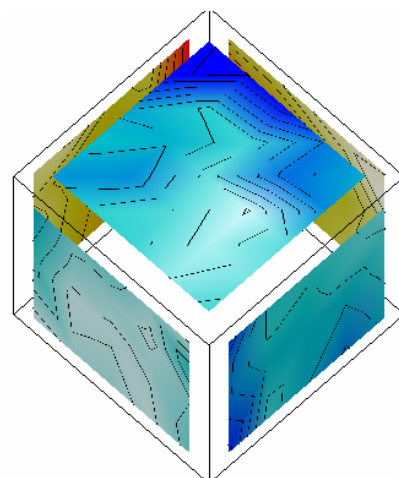


Figure 11 Pressure distribution the cube in TBL when the strength of the conical vortex at the right hand side reaches to peak.

3.5 Structure of vortex behind the cube

Figure 12 shows the three dimensional stream lines behind the cube in TBL. The stream lines are drawn from $x=0.75D$. According to Figure 12, the roll up of the separated shear layer from the side seems to connect to the roll up of the shear layer over the cube and to form an arch-type vortex. When the conical vortex at the right hand side is stronger than that at the left hand side, the conical vortex at left hand side is drawn into the wake to bring the large clockwise circulation in the wake. The arch-type vortex inclines greatly to the right side by the interaction between the conical vortex and the separated shear layer. When the strength of the pair of vortices is same, the very clear arch-type vortex can be seen in the move.

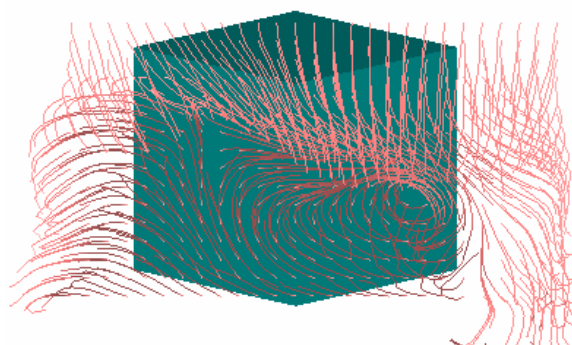


Figure 12 3D stream lines behind the cube in TBL
Starting points are on the perpendicular plane (y-z plane) at $x=0.75D$.

According to the above results, the schematic picture of the vortex in the wake behind the cube is shown in Figure 13 when the conical vortex at the right hand side is stronger than that at the left side. The shape of the arch-type vortex is reentrant at the center by the down wash induced by the pair of the conical vortices and inclines to the right. When the conical vortex at the left hand side is drawn to the right, the sign of the vorticity of the conical vortex and the arch-type vortex is opposite each other and the conical vortex is drawn into the wake over the arch-type vortex. On the other hand, the vorticity of the conical vortex at the right hand side has the same sign of that of the arch-type vortex, so the conical vortex makes to increase the vorticity of the arch-type vortex.

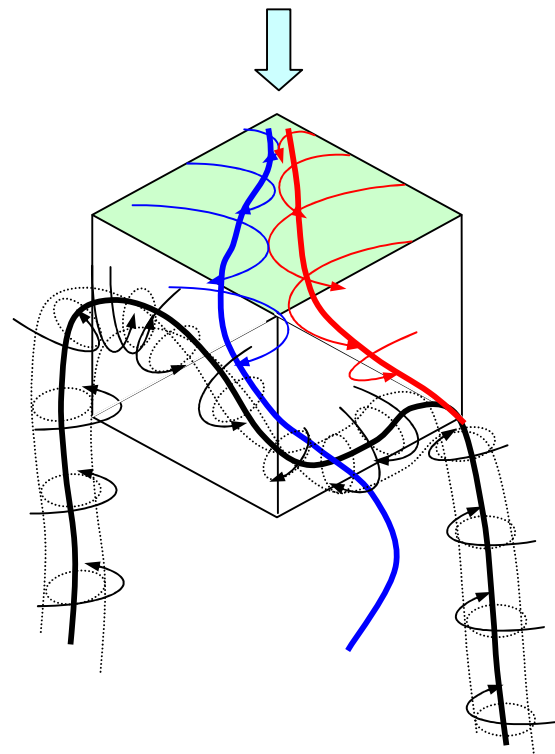


Figure 13 Schematic model of the interaction between the conical vortices and arch-type vortex behind the cube.

4 SUMMARY AND CONCLUSIONS

The structure of the conical vortices on and behind the cube in USF and TBL when flow attacks normal to the diagonal line is investigated by synchronous measurements of 3D-SPIV and multi pressure sensor systems. According to the measurement, the following results are found.

- (1) The conical vortex at one side is always stronger than that at the other side. The side at the stronger vortex changes occasionally in relatively long interval. By this change the flow pattern switches to the reflected pattern.
- (2) The conical vortices at the both sides sway quasi-periodically in a body on the cube in USF, and the strength of vortices changes all the time. When the strength of the vortex at one side increases, the strength at the other side decreases.
- (3) The trigger of the switching is brought by the sway of the conical vortex. When the order of the strength of the conical vortices changes at both sides by the sway, the flow pattern is switched to the reflected pattern.
- (4) An arch-type vortex is formed behind the cube in any times of which shape is reentrant at the center and inclines to the side of the stronger conical vortex. When the conical vortex at one side is stronger, the vortex at the other side is drawn into the one side of the arch-type vortex. The structure of the flow in TBL is similar generally to that in USF.

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Assessment of design wind speeds for metro cities of India

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ABSTRACT: Prediction of site specific wind speed plays a key role in the determination of wind-induced response of structures. The wind speed value is typically taken from the local code of practice, which is IS:875 - Part 3 [1] in India. Considering that this code hasn't been updated for the last 25 years, a revisit of the wind speed including the last three decades of data is warranted. In this paper, the design wind speeds for the metro cities of India have been assessed based on the local airport data.

KEYWORDS: Design wind speed, India.

1 INTRODUCTION

India is witnessing an unprecedented amount of construction in the tall building area to meet up with the ever increasing demand for housing in the Indian metros (Mumbai, Delhi, Kolkata, and Chennai – see Figure 1). Significant growth in tall building sector is connected to the growing economy, and this is expected to persist for long time.

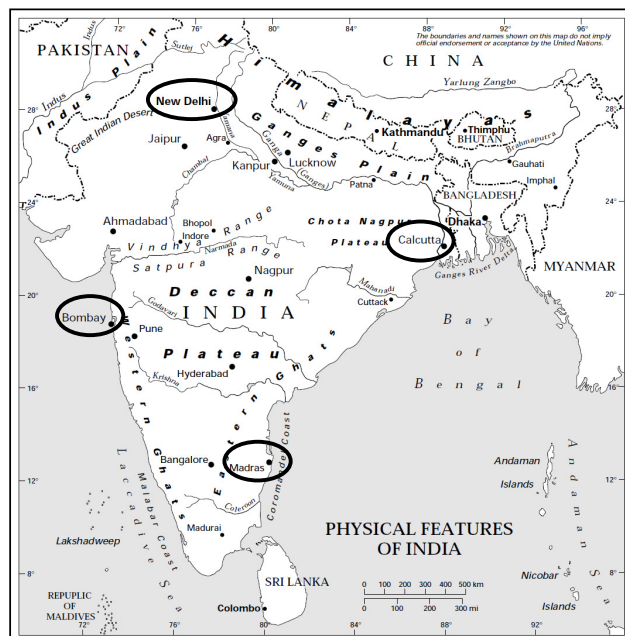


Figure 1. Map of India showing metros.