COMPILATION OF VORTEX FILAMENT OF ARCH VORTEX IN WAKE OF COOLING TOWER MODEL

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Abstract

This paper deals with flow around a bluff body of hyperboloid shape. It consists of results gathered in the course of research by means of Particle Image Velocimetry (PIV) and Hot-Wire Anemometry (HWA). The experiments were carried out in a range of Reynolds numbers from 42000 to 52000. A model was measured in a wind tunnel with a modelled atmospheric boundary layer. The model was tested in a subcritical range of Reynolds number and various planes in a wake of the model were captured with the intention of getting a picture of an arch vortex, moreover the HWA system was used to get the frequencies of the vortex shedding.

Keywords: mechanics of fluids, arch vortex, Particle Image Velocimetry, Hot Wire Anemometry

1. Introduction

In this contribution, research in the mechanics of fluids that developed from experimental testing of a model for civil engineering will be presented. Originally one of the often-investigated problems of civil engineering, wind loading on cooling towers, had been investigated. However, this paper is not going to deal with the cooling towers as civil engineers usually do.

The original civil-engineering problem was solved in a classical way - wind loadings on the cooling towers were measured and evaluated. Thereafter structures around the model began to be investigated. This is how the civil engineering investigation turned into a pure mechanics of fluids problem. Results were already presented in a few papers (Eg. [1] and [2]). This contribution goes into more detail. An arch vortex appeared in pictures presented in [2]. Therefore for this paper a more detailed measurement was done, in a wake of the model, in order to get the coordinates of an arch vortex filament. During the measurement, interesting parts were revealed in the results, which lead to Hot Wire Anemometry and the calculating of Strouhal numbers.

To get some knowledge about the fluid flow around such an object, one can gain some inspiration from classical literature. For instance, Zdravkovich in [3] illustrates the cooling towers problem can be remotely compared to a circular cylinder problem. To get an approximate picture of the flow, it is therefore possible to come out of the mean flow topology of the cylinder, as depicted in Pattenden, Tunock & Zhang [4] for instance (see Fig. 1).

In the flow around the hyperboloid object we can expect various structures, depending on the model geometry. A detailed and thoroughly processed summary of these structures and under which conditions they appear, with many references to the relevant papers and literature was given by Heseltine [5].

It might seem that this problem is already well described. However, there are many difficulties when it comes to the model differing from the simple geometry of regular and symmetric cylinders. The main difference is that there is an object with a variable diameter, meaning the Reynolds number of the experiment varies from 42000 to 52000. To further complicate the problem, the model is submerged in a tunnel boundary layer, which is to be explained later together with experimental facilities, so the velocity of incoming flow changes as the altitude of the model changes. This means that the boundary layer thickness developed on the model will vary as well. In addition to this, as the measurements show, the separation line is bent many times. (These results will not be part of the paper though.) Additionally the model remained covered by small grains, therefore our last piece of known theory might fall. Such a rough surface forces the transition in the boundary layer on the model to occur at higher Reynolds numbers. On the other hand, the high rate of turbulence of incoming flow has the opposite effect. The
surface roughness as the influencing parameter can be studied in Zdravkovich [6] and Merrick & Bitsuamlak [7].

This phenomenon together with quite a large tunnel blockage by the model, and the low aspect ratio of it ensures the measurement is filled with results different from the classic circular cylinder knowledge.

There is another separate object of discussion. According to Sakamoto & Arie [8], the shedding of vortices changes from an asymmetric type to a symmetric arch type at a geometrical aspect ratio of an object (cylinder) of 2.5. As the aspect ratio of our measured hyperboloid object varies from 1.3 to 2.54, the narrowest area of the model – called simply the throat - could be measured with respect to this fact. Some other background of the aspect ratios of the cylinders can be found in Sumner & Heseltine [9].

Generally, vortices and vortex structures in flow fields are topical problems of fluid mechanics so far. The authors attempt to describe geometry parameters and the effects of a complex vortex behind a hyperboloid-shaped model. The purpose of this paper is to present experimental data and to achieve results, contributing knowledge on the effects of flow past bodies.

![Schematic diagram of the time-averaged flow around the circular cylinder from Pattenden, Tumock & Zhang [4] (left). Detail of the arch vortex (right).](image)

2. Experimental Facility

The tunnel used for the measurement was the Boundary Layer Wind Tunnel (BLWT) for simulating atmospheric boundary layer. The main purpose of this tunnel is to serve the civil engineering measurements. It is equipped with a special surface helping the development of the boundary layer of certain characteristics according to standards [10]. Detailed characteristics of this particular turbulent boundary layer, its development, the tunnel itself and the atmospheric boundary layer modelling can be found in report by Jirsák [11]. A velocity profile of this boundary layer can be seen in Fig. 2. It should be mentioned here, that the turbulence intensity of the boundary layer falls from $Tu = 30\%$ close to ground to $5\%$ at 900 mm altitude above the ground.

The wind tunnel boundary layer strongly influences the wake area. It was already presented in [12], how significant the influence is. It is due to relatively high level of turbulence in the boundary layer in the wind tunnel flow. The comparison of measurements provided by PIV done in two types of wind tunnels was shortly discussed in the contribution. The two types of the wind tunnels were: Boundary Layer Wind Tunnel described in this paper and Low Speed Wind Tunnel of Eiffel Type with low rate of turbulence ($Tu = 1\%$). Coordinates of the vortex filament in x-y plane for an altitude $z/L=0.625$ for both wind tunnels can be seen in Fig. 4. Further research of this problem is prepared and more detailed study of the turbulence influence on the vortex structures will be presented in future.

To complete the description of BLWT, it has to be said that dimensions of the rectangular measurement area are 1.8 x 1.5 meters. The experimental part was provided by means of 2D Particle Image Velocimetry (PIV). The measurement was provided at Reynolds numbers $Re = 42000$ to 52 000 (Fig. 3) with free stream velocity $v_\infty = 5$ m/s measured independently on PIV by Prandtl probe.

The model was printed using a 3D printer as a 320 mm tall plastic object. The bottom part of the model consists of pillars, so called vented-base and is penetrable for the flow. The model is hollow as well. The ratio of the height of the model to the thickness of the modelled boundary layer in the BLWT is 1/3. The model blocking of the tunnel is 2.2%.

The PIV experiment was provided in a classical way - the measurement area was seeded with olive oil droplets produced by Laskin nozzles and a green laser light was used to illuminate the area. Nd:YAG laser offers only low frequency (15 Hz) of the pulses. All image processing, and later calculations of
Particle movements in two consecutive images were provided with the help of Dynamic Studio software. Usually, the vector statistics representing averaged velocity field and streamlines were calculated. For evaluation, a method called adaptive correlation was used with these parameters: final interrogation area was 64 x 64 pixels, which represented several tens of square millimetres of real area (exact area depended on the altitude of the measured plane above the ground). This detailed PIV measurement was later accompanied by Hot Wire Anemometry measurement system (HWA), because from 15 Hz frequency PIV measurement one cannot prepare decomposition and thus the frequency spectrum. While the HWA was set to 9 kHz frequency. The frequency spectrum was measured at the same altitudes above the ground as the PIV measurement was. The one-wire probe was used for this type of measurement. From each HWA measurement, the frequency spectrum was evaluated by means of Fast Fourier Transformation and then a peak was found with the main frequency – the shedding frequency. Then Strouhal number was evaluated. The example of the frequency spectrum with the peak can be seen on Fig. 5.

3. Results

It was already explained, that the picture of the flow around the hyperboloid-shaped model is being hunted. This contribution focuses on compilation of vortex filament of the arch vortex, most probable structure caught in past by PIV measurement and introduced in [2]. For this purpose, sixteen planes parallel to the surface were measured by PIV, which covered sufficiently the vertical part of the filament [Fig. 1 b)]. Four of the streamline pictures calculated from averaged velocity fields are shown [see Fig. 6 a) and b) and Fig. 7 a) and b)]. So far, it is not possible to catch that part, where the structure bends. The limitation consists in lack of space for the appropriate positioning of the camera in the wind tunnel (located just under a tunnel roof).
Figure 6: The streamlines of the wake behind the model in the plane at a) 0.13 and b) 0.19 dimensionless altitude above the surface.

Figure 7: The streamlines of the wake behind the model in the plane at a) 0.63 and b) 0.69 of dimensionless altitude above the surface.

Figure 8: Strouhal numbers for varying altitude (plot a) and against the Reynolds number (plot b).
As the second task for this contribution the searching for vortices separation frequencies was chosen. This measurement was provided by 1-wire probe in the wake of the model at each altitude above the surface where the PIV was done. Evaluated Strouhal numbers are enlisted in plots [see Fig. 8 a) and b)].

From the PIV plane measurements described above the coordinates of the arch vortex were evaluated and the comprehensive picture was compiled (Fig. 9).

4. Conclusion

The hyperboloid-shaped model was measured in a Boundary-Layer Wind Tunnel with a modelled atmospheric boundary layer. The main aim of the measurement was to prepare a compilation of arch vortex filaments (Fig. 9). For this purpose, Particle Image Velocimetry was chosen as the suitable method. In relatively short time duration one could gain data from an area of approximately 0.06 m² and quickly evaluate, finding the desired centre of rotation where vortex filaments points could appear.

It has to be considered, that the PIV measurement revealed vanishing regularity at the bottom part of the wake (between the dimensionless altitudes 0.13 and 0.19 above the surface, Fig. 6). The typical pattern of the wake seen at higher altitudes vanishes closer to the bottom as a consequence of interactions (the vented base has its strong influence close to the ground and one could consider the boundary layer of the tunnel to be responsible as well). It could be emphasized here, that this vented base area seems to have a very strong influence on the flow around the model, and will be one of the reasons why the model of such a set-up cannot be easily compared to the flow around the circular cylinder. Going up the vortex filament, there is another area of special attention at the throat area.

The PIV results described above initiated Hot Wire Anemometry measurement. The Strouhal number was expected to be around 0.15 to 0.2, but some areas surprisingly showed a wider range of it and the Re – Sh plot reminds one of a ray [Fig. 8 b)]. Some peaks from evaluated turbulent spectrums (an example on Fig. 5) were too weak to clearly show the shedding frequency, mainly in the throat area. The PIV measurement of this area shows irregularities at the dimensionless altitude of 0.63 on the surface in comparison with other areas [see Fig. 7 a) and b)]. But as the throat could be the area of an argument between asymmetric vortex shedding and symmetric vortex shedding due to the geometrical aspect ratio, one might expect this could be a challenge for more detailed research too.

As the main result, an approximate vortex filament picture was compiled (Fig. 9). The x-z plane shows slight differences between the left and right branch of the filament coordinates, growing at the altitude z/L = 0.3. The y-z plane filament coordinates copy the shape of the model, but many influences (already described above) cause this filament shape to appear irregular.

It is apparent, that the combination of the geometry parameters of a hyperboloid-shaped model and the special flow conditions create a complicated mixture for research. The authors tried to partially describe the 3D structure called the arch vortex, although a need for more research has arisen (the throat area, the bottom part). With this paper the authors hope to contribute with a tiny piece to the knowledge of flow past bodies.
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