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DETERMINATION OF VORTEX CONVECTION VELOCITY WITH APPLICATION OF FLOW VISUALIZATION AND IMAGE PROCESSING

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Abstract − The paper is related to von Karman vortex shedding phenomenon being the basis of the vortex flow meter design. The vortex convection velocity belongs to the problems rather rarely touched on in papers and articles. But its recognition can improve our knowledge concerned the applied phenomenon and finally help in its better understanding. Due to the flow visualization supported by the image processing, tracking of the vortices is feasible. Finally, the convection velocity can be calculated and its changeability along the pipe axis can be evaluated.

Keywords: von Karman vortex street, vortex shedding, stagnation region

1. INTRODUCTION

The vortex flow meter is based on the well-known von Karman vortex street phenomenon [1]. It is obvious, that each succesful meter design is determined by comprehensive understanding of applied physical phenomena. Von Karman vortex street phenomenon is very complex and sensitive on numerous physical factors. Hence the necessity of investigations with application of miscellaneous methods. Determination of the vortex convection velocity – being the subject of the paper – is aimed at the deeper understanding of the phenomena.

2. PROBLEM DESCRIPTION

The problem of the convection velocity of vortices is very interesting, although almost never was present in the papers and articles related to the vortex meter. The first approach to von Karman vortex street description – known from the literature – is based on supposition, that vortices are transported by the flowing fluid and their velocity is equal to the fluid velocity. Only results of simulation of the analytical model [2,3] performed by Pankanin et al. show, that the velocity is not stable, but – on the contrary – its considerable changes in the closest neighbourhood of the bluff body are observed. The model concerns the vortex development vs. distance from its origin. The idea of the model is shown in Fig.1.

The concept of the model is based on the existence of the "low motion" area in the close neighborhood downstream the bluff body. This area called later the "stagnation region" has been suggested by Birkhoff [4-6] as a factor being conducive to vortex generation. It is worth to mention, that the existence of the stagnation region has been confirmed by the laboratory investigations [7]. In the model, eddies arise on the bluff body surface in the area of boundary layer separation. Then they grow-up rolling downstream on the surface of the stagnation region. Succeeding layers are added to the vortex, hence its diameter and energy increase.

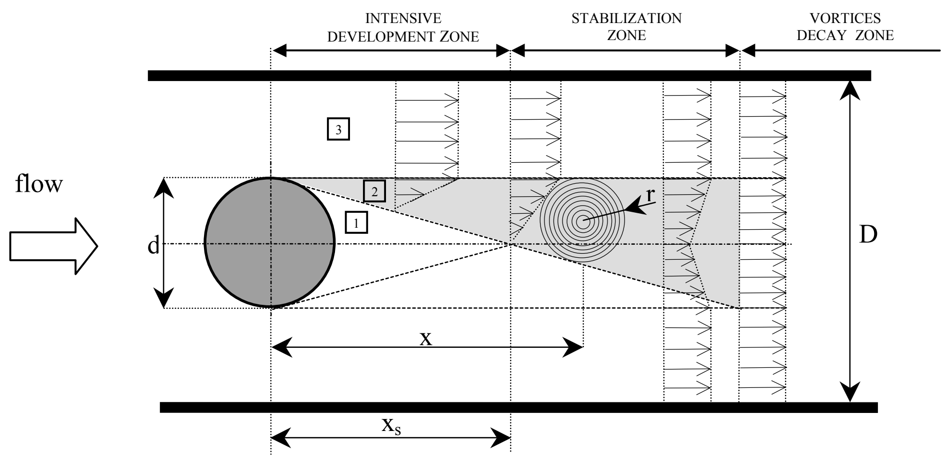

Fig1. Vortex development downstream the bluff body (1 – stagnation region, 2 – region of vortices development, 3 – region of steady velocity profile).

Due to simulation of the phenomenon using the model, the changeability of the vortex convection velocity has been discovered (Fig.2.).

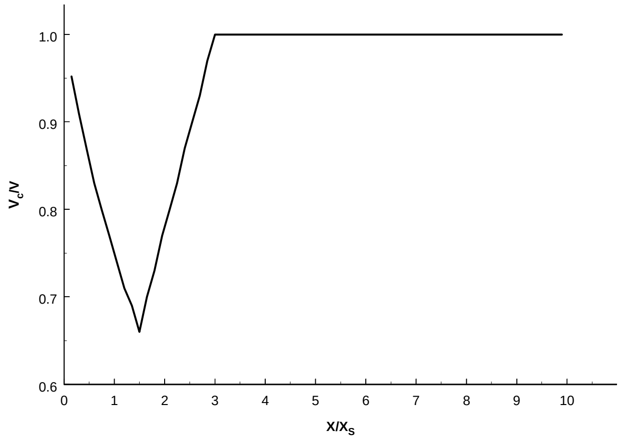

Fig. 2. Relative convection velocity vs. relative distance from the bluff body – results of simulation (v_c – convection velocity, v – velocity upstream bluff body, x – distance from bluff body axis, x_s – stagnation region length).

As it is seen, the convection velocity of vortices decreases at the beginning and then increases to the stable value equal to the axial velocity of the flowing fluid. It should be mentioned here, that this model has been performed for circular cylinder as the bluff body.

In the assumed model (Fig.1.) – described in detail in [2] – the convection velocity decrease results from the stagnation region appearance just downstream the bluff body. Such area, where the mobility of fluid particles is limited, can be observed – among other things – also on the flow visualization pictures (Fig.3.).

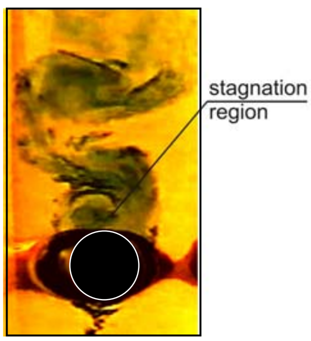

Fig. 3. Stagnation region on flow visualization picture.

In the case of the other bluff body shapes: circular cylinder with the slit, rectangular cylinder, rectangular cylinder with the slit – the stagnation region is considerably limited (it can be also observed on the flow visualization pictures). Hence the question: what about the convection velocity changes? The attempt to answer this question is the purpose of this paper.

3. METHODS

3.1. Flow visualization

It is worth to notice, that the most important discoveries in the fluid mechanics strongly were supported by the flow visualization. Particularly, the flow visualization often was used in von Karman vortex street investigations. Leonardo da Vinci in XV century draw stream profiles and vortices formation downstream of the pilings of warfs [8]. Later Hiemenz as well as von Karman used flow visualization as supported research method. Due to the flow visualization application, certain hypotheses have been confirmed and discovery of accompanying phenomena was feasible [9,10]. Also other researchers like Igarashi [11-13], Bentley [14-16], Turner and Popiel [17-19] and the author of this work [7,20] successfully used the flow visualization and valuable results have been attained.

Due to the flow visualization, the observation of the whole area of the vortices appearance is feasible. The flow visualization experiments were carried out with the application of the direct injection tracer method. Two various tracers (red and blue) were injected into the flowing fluid through small holes drilled in the bluff body. The outlets of these holes are located near the vortices origin on both sides of the body. This way the vortices generated on the upper edge of the bluff body are red coloured, but the vortices originated on the bottom are blue coloured (Fig.3.). Due to application of two colours, the further image processing of the pictures is easier and enables obtaining more reliable results.

Applied fast camera ensures making of series of 8 pictures with chosen intervals. Series of von Karman vortex street generated on various shapes of the bluff body are presented in Fig.4.-Fig.7.

As it is clearly seen, the pictures differ from each other. In the case of the circular cylinder, the stagnation region just downstream the bluff body is clearly observed. It is also remarkable, that dimensions of this region depend on the flow rate. For lower values the stagnation region is considerably bigger than in the case of the grater flow rates. But in the case of the bluff bodies with slit (circular and rectangular cylinders) the stagnation region practically is not visible. The vortices development appears just on the surface of the bluff body. Also the process of the vortices decay can be analysed on the basis of the flow visualization. The vortices generated on the rectangular cylinder with the slit earlier are subjected to the dissipation than in the case of circular cylinder with the slit.

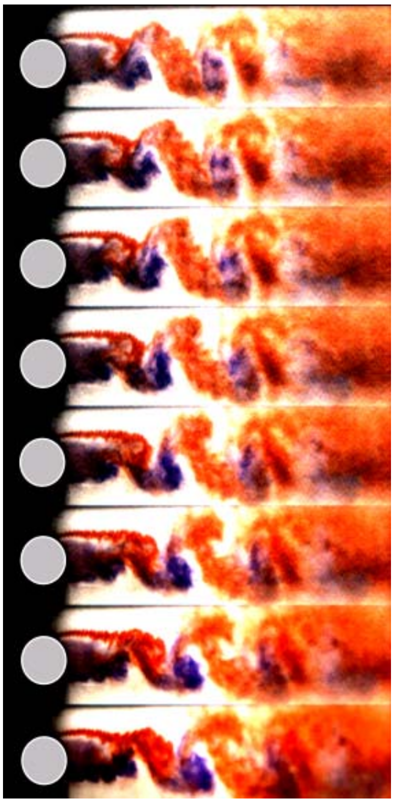

Fig.4. Von Karman vortex street generated on circular cylinder $\phi 13$ ($Q=0{,}72\ m^3/h\ \ \Delta t=20{,}16$ ms).

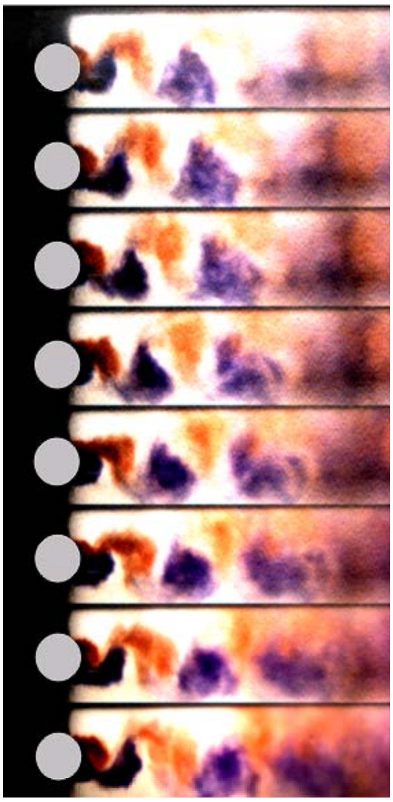

Fig.5. Von Karman vortex street generated on circular cylinder $\phi 13$ ($Q=6{,}6\ m^3/h\ \ \Delta t=5{,}04$ ms).

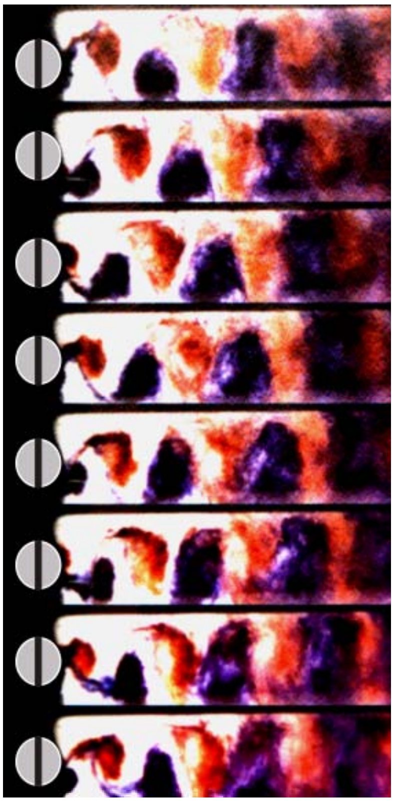

Fig.6. Von Karman vortex street generated on circular cylinder $\phi 13$ with slit ($Q=2{,}5\ m^3/h\ \ \Delta t=20{,}16$ ms).

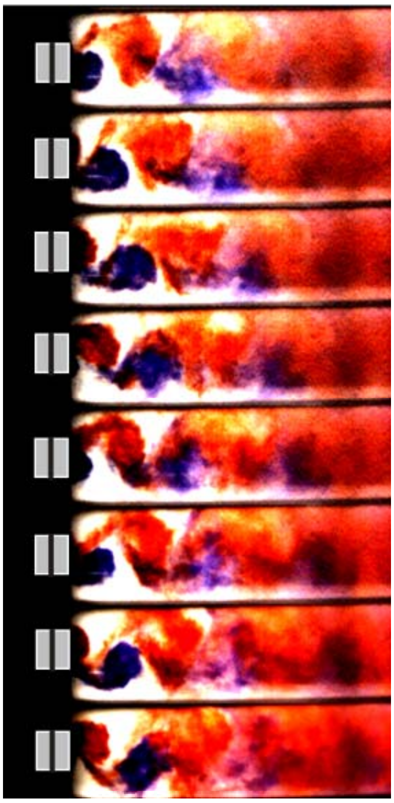

Fig.7. Von Karman vortex street generated on rectangular cylinder 13x8,5 mm with slit ($Q=0{,}78\ m^3/h\ \Delta t=20{,}16$ ms).

3.2. Image processing

Digital image processing seems to be the natural continuation of the flow visualization. It enables gaining the quantitative information from the pure qualitative source (flow visualization pictures). In the case of von Karman vortex street it means the determination of the distance between consecutive vortices, their convection velocity and trajectory of movement.

The fundamental problem is such image processing which enables isolation of vortices as the separate objects. It requires special techniques application leading to the quality improvement of the pictures. Various methods of improving picture quality are known:

- methods of histogram modification,
- spatial methods,
- frequency methods,
- morphological methods.

Morphology – based operations prove to be the most important image processing techniques. They have prevalence over the spatial and frequency methods. A specific operation is undertaken only when defined circumstances are fulfilled. Hence very precise picture processing is feasible.

Analysis of pictures of von Karman vortex street is rather difficult because of hydrodynamic phenomena nature and used flow visualization method. Consecutive vortices combine each other and the marker dissipation intensively proceeds. Hence the analysis should be supported by the individual invention and experience of the programmer.

4. RESULTS

Exemplary results of the analysis of the flow visualization pictures are presented in Fig.8.-Fig.10. The von Karman vortex street pictures have been processed using two-colour algorithm of image processing. After founding of images of vortices as the separate objects, the centres of gravity for each of them have been determined. Next, on the basis of known vortex centre of gravity displacement, the convection velocity has been calculated (the time interval between two consecutive pictures was known).

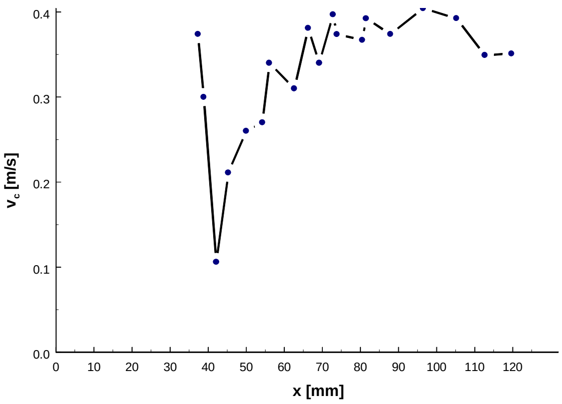

Fig.8. Convection velocity of vortices generated on circular cylinder (Q=1,18 m^3/h) v_c – convection velocity, x – distance from bluff body axis.

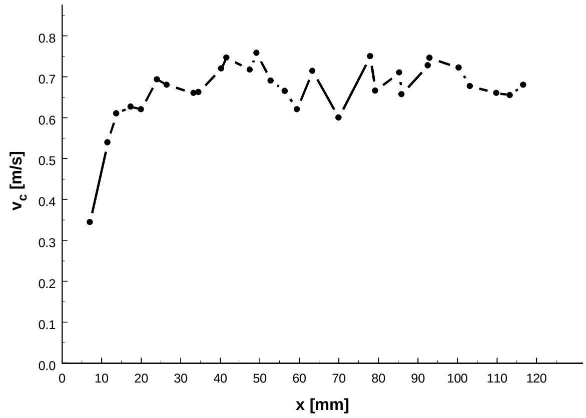

Fig.9. Convection velocity of vortices generated on circular cylinder with slit (Q=2,47 m^3/h) v_c – convection velocity, x – distance from bluff body axis.

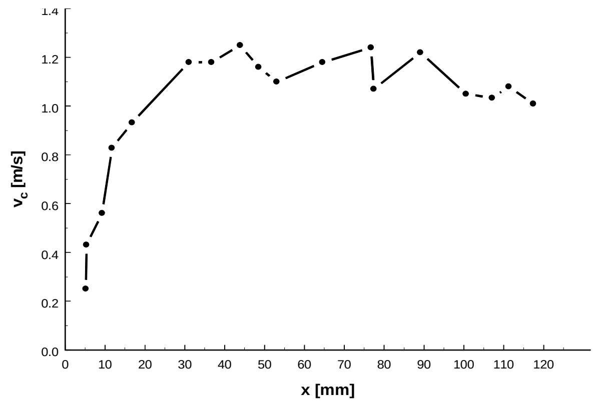

Fig.10. Convection velocity of vortices generated on rectangular cylinder with slit (Q=4 m^3/h) v_c – convection velocity, x – distance from bluff body axis.

It is worth to find that these graphs strongly correspond to results of simulation of the phenomenological model (Fig.2.). Especially typical is the convection velocity decrease in the certain distance downstream the bluff body. Particularly it is visible in Fig.8. (for the circular cylinder as the bluff body). In the case of the cylinders with slits (Fig.9. and Fig.10) the local convection velocity decrease is much more close to the bluff body. As it has been mentioned earlier, the convection velocity changes result from the stagnation region existence (see analytical model [2]). Hence the differences in graphs presented are related to the differences in stagnation region length. But the results also prove, that in the case of each tested bluff body the stagnation region exists – even when it is not clearly visible on the flow visualization pictures.

5. CONCLUSIONS

Flow visualization supported by the image processing appears as very useful couple of methods for von Karman vortex street investigations. Due to the flow visualization the observation of the whole flow area at that very moment is feasible. Hence such important phenomena like the occurrence of the stagnation region can be evaluated. On the basis of the pictures it can be concluded, that in the case of the circular cylinder as the bluff body, the stagnation region has considerable size and it depends on the flow rate value. But in the case of the bluff bodies with the slit (circular and rectangular cylinder) the stagnation region is meaningfully limited and is not visible in the pictures. It means, that the slit in the bluff body takes a part of the stagnation region as an information medium of generated vortices (information concerned the vortex generated on one side of the bluff body must be relayed to its other side).

Quantitative information concerned visualized phenomena is feasible due to the digital image processing of obtained pictures. Identification of vortices as separate objects enables determination of the distance between consecutive vortices. Hence, vortices convection velocity has been determined. Obtained results confirmed the findings of the analytical model simulation [3]. The most important conclusion is that the convection velocity is not steady, but it varies in the close neighbourhood of vortices origin. The phenomenon is strongly dependent on the bluff body geometry.

ACKNOWLEDGMENTS

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