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DYNAMICS OF SWIRLING FLOWS IN INDUSTRIAL APPLICATIONS

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Abstract: *Many industrial devices positively utilize the action of centrifugal forces induced by highly swirling flows (e.g. hydrocyclones, swirl burners). On the other hand swirling flow causes significant problems in operation of turbines or aircraft. Presented paper is going to review the current state of knowledge about swirling flows (stability of swirling flows, vortex breakdown phenomenon, helical precessing vortex core) and outline possible approaches leading to better understanding of these phenomena. Inevitably it is a mixture of analytical techniques, computational simulations and advanced experiments. It also proves efficient to employ some of the methods for spatio-temporal description of dynamical systems like proper orthogonal decomposition (POD).*

Keywords: Swirling flow, Stability, Vortex rope, Proper orthogonal decomposition.

1. Introduction

Strongly swirling flows are quite common in lots of industrial applications. Resulting centrifugal forces are exploited in many devices especially in chemical and processing industries, furnaces and combustion chambers, HVAC, etc. The reason is that centrifugal forces are much more effective than only the action of gravity. Positive effect of swirl is utilized for solid particles separation and classification (cyclones, hydrocyclones), flame stabilization (swirl burners), cooling/heating of air (vortex tubes), in fluidic devices (swirl valves), measurement devices (vortex flowmeters). Most of these devices are mechanically very simple, very often with no moving parts. The only two problems, which are connected with their operation are:

- increased hydraulic losses,
- limit on the operation is imposed by stability of the swirling flow.

Whereas the first issue is not very severe and devices achieving same function with different design or using different principle would have similar energy consumption or much higher manufacturing costs, the latter issue poses a serious problem, because it restricts further intensification of the swirling apparatus processes. The limit point is so called vortex breakdown.

Swirling flows are also typical in turbomachinery, where vortical structures are tackled as undesirable features. Highly swirling flow leaves the runner of hydraulic, steam or combustion turbines. The rear diffuser of these machines is an appropriate place, where vortex breakdown occurs resulting in precessing helical vortex, which induces pressure pulsations, vibrations and noise. Instability of swirling flow also appears on wing tips, where it leads to stream disturbances, which limit air traffic.

Rather common are instabilities of the vortex breakdown type also in nature. The best known example is tornado or waterspout.

2. Swirling Flows and Coherent Structures

Swirling flows are very susceptible to instabilities. Instability of particular interest in industrial applications is vortex breakdown. This phenomenon is characterized by axial velocity decrease along the axis of the swirl, eventually internal stagnation point or even backflow, and by formation of bubble, which later transforms, with increased swirl intensity, into helical vortical tube. Precessing helical core

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satisfies definition of the coherent structure, i.e. flow structure, which persists for a relatively long time or the flow structure which remains after subtracting the noise from the flow field.

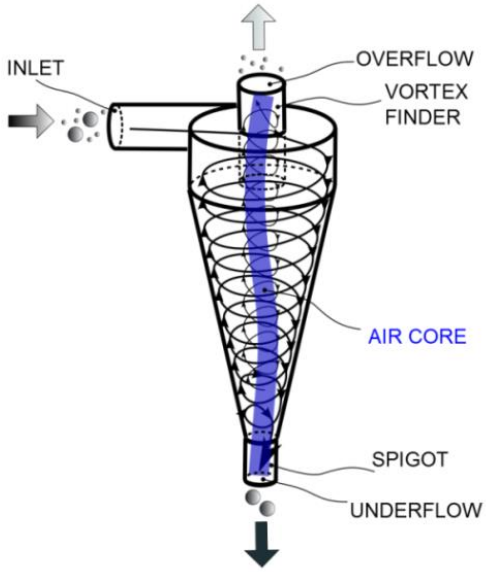


Fig. 1: Hydrocyclone (Rudolf, 2013).

Fig. 2: Vortex rope in hydraulic turbine draft tube (Ciocan et al, 2007).

While vortex breakdown bubble can only be observed for low Reynolds numbers and relatively low swirl numbers (see Figs. 3, 4), the helical precessing core (see Fig. 2) forms a very compact vortical structure, which is associated with high Reynolds numbers and broad range of swirl numbers *Sr*.

$$Sr = \frac{1}{R} \frac{\iint_S v_{ax} v_t r dr}{v_{ax}^2 dr} \tag{1}$$

Helical precessing core starts to appear for higher swirl rates in the aft of the vortex breakdown bubble. Further increase of swirl leads to disappearance of the bubble and helical precessing vortex core dominates the flow. It was hydraulic machinery, where this helical vortical structure, known also as vortex rope, was experimentally observed and studied for the first time. Characteristic frequency of the vortex rope rotation is 20-30% of the runner speed. Therefore it is a typical source of low frequency pressure pulsations in hydraulic turbines.

Fig. 3: Bubble vortex breakdown in cylinder with rotating top lid (laminar flow), exp.: left side (Escudier, 1984) comp.: right side (Rudolf, 2008).

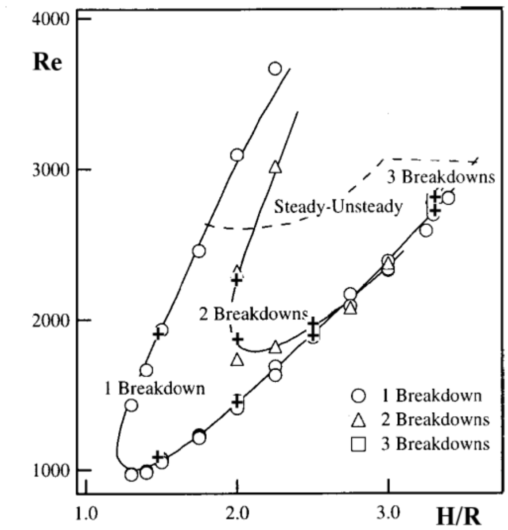


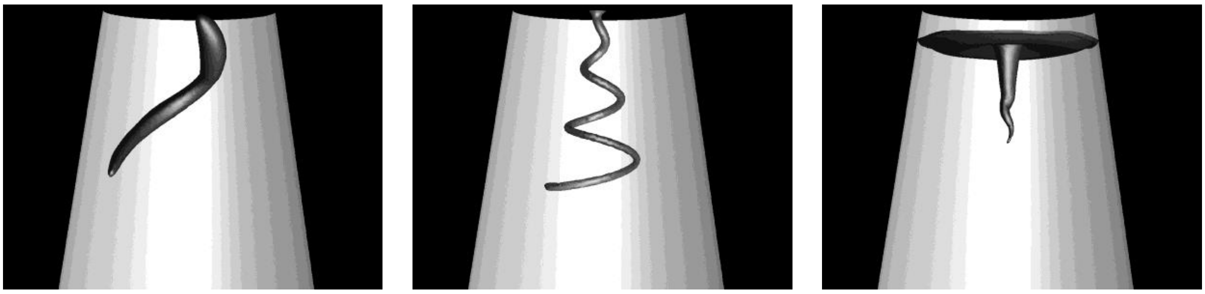
Fig. 4: VB map for cylinder with rotating lid, (Escudier, 1984), crosses: CFD simulation (Rudolf, 2008).

3. Stability of Swirling Flow

Theoretical analysis of the swirling flow stability is dating back to sixties, but systematic analysis of the vortex breakdown, including its spiral form, was initiated by Gupta et al (1984). Investigation carried out with Euler equations for inviscid flow by Pochylý et al (2009a) and Pochylý et al (2009b) revealed that the swirling flow is extremely sensitive to boundary conditions. Conclusion is that proper distribution of not only velocity components at the domain inlet, but especially their derivatives is decisive for the inception of the unstable behavior.

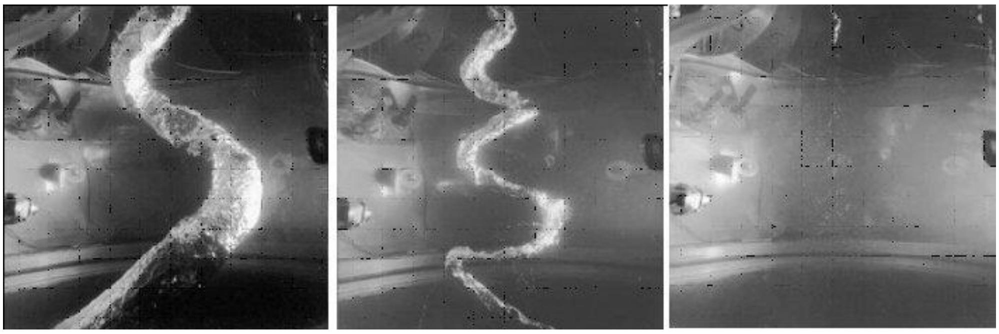
4. Computational Modeling of Swirling Flow

Development of computational methods in fluid mechanics enabled new possibilities in study of the swirling flows. While laminar flow computations are managed without difficulties, turbulent flows still pose problem due to the uncertainty in turbulence model choice. It was noted by Skoták and Rudolf (2001) that Reynolds stress model offers the minimum complexity level for correct capturing of the vortex rope in the hydraulic turbine draft tube. Yet higher level of detail, but at substantially higher computational costs, is offered by large eddy simulations and different crossovers between RANS and LES approaches (e.g. detached eddy simulation). However it still remains serious problem and obtaining reliable vortex breakdown map in turbulent regime for broad range of swirl numbers is not feasible. Computational complexity can be further increased by presence of vapour phase in case of cavitating vortex rope or by combination of phases (water - air - solid particles) in case of hydrocyclone (Rudolf, 2013).



a) 70% of BEP discharge *b) 90% of BEP discharge* *c) 100% of BEP discharge*

Fig. 5: Vortex rope visualized by contour of constant pressure (CFD simulation) (Rudolf, 2009).



a) 70% of BEP discharge *b) 90% of BEP discharge* *c)100% of BEP discharge*

Fig. 6: Vortex ropes experimentally visualized by cavitation (Jacob, 1993).

5. Decomposition of Swirling Flows

Promising results in analysis of swirling flows are offered by application of proper orthogonal decomposition (POD). This technique was introduced by Lumley in 1967 (cited in Berkooz et al, 1993) for the spatio-temporal description of coherent structures in turbulent flow. Rudolf and Jízdný (2011) successfully applied POD for swirling flow in hydraulic turbine draft tubes. POD enables to decompose the flowfield into a set of spatial eigenmodes, which can be viewed as basic cornerstones of the flow.

Next step is development of low order dynamical model, which enables to model the spatio-temporal behavior of the swirling flow with only the most dominant eigenmodes.

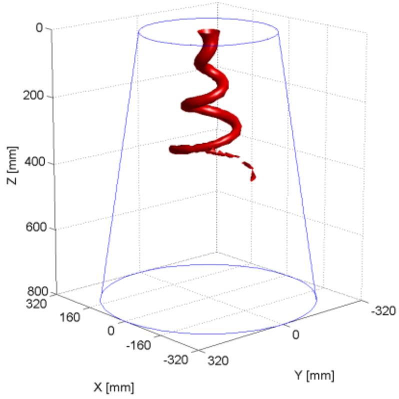


Fig. 7: Instantaneous snapshot of the vortex rope.

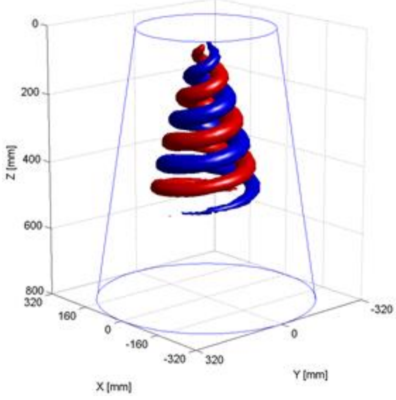


Fig. 8: First eigenmode of the pressure field.

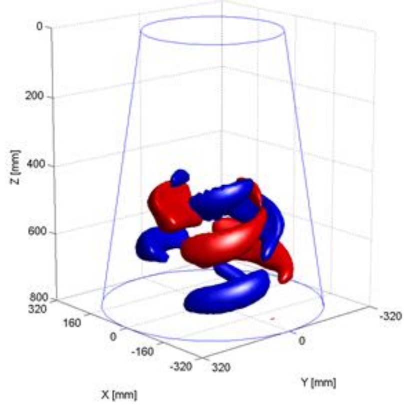


Fig. 9: Fifth eigenmode of the pressure field.

6. Conclusions

Present extended abstract provides a very rough overview of the swirling flows in industrial applications and methods for their analysis. Importance of swirling flow in technology, where it plays both positive and negative roles, is stressed and need for better analytical description is underlined. While computational and experimental methods offer much more complex view than in past, we still lack the fundamental understanding of the instability process leading to vortex breakdown.

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