THE BEHAVIOUR OF VORTEX STRUCTURES NEAR SOLID OBSTACLES

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Summary This lecture will address the problem of a dipolar vortex approaching solid objects like a cylinder, a row of closely positioned cylinders, or a sharp-edged plate. Just like in the case of an infinite flat wall, the vorticity generated at the no-slip surface of the obstacle is advected away from the wall and quickly starts to interact with the primary vortex structure. This may lead to very complicated behaviour, like partial rebound of the primary dipole.
Laboratory experiments have been performed in a rotating fluid tank, the background rotation being introduced in order to make the relative flow approximately two-dimensional. The flow evolution has been visualized by adding dye, while quantitative information about the vorticity distribution was obtained by PIV measurements. In addition to numerical flow simulations, some analytical studies have been carried out, which provide important information about the vortex-wall interaction.
This lecture will report on recent joint work with Prof. Slava Meleshko, who died tragically on 14 November 2011.

INTRODUCTION

The behaviour of a vortex dipole colliding normally against an infinite flat, solid wall is well understood since the numerical study of Orlandi (1990). This study revealed the crucial role played the boundary-layers at the wall, containing vorticity oppositely-signed to that of the primary vortex structures. After being advected away from the wall, these secondary vorticity patches pair with the primary vortex patches, resulting in the splitting of the primary dipole and the formation of two asymmetric dipoles that move away from the wall along curved paths. A similar behaviour was observed for the case of a vortex dipole moving towards a solid cylindrical obstacle, as reported by Verzicco *et al.* (1995). A crucial question is: what happens when the vortex dipole approaches obstacles of more complicated shapes? For example, what is the effect of a sharp edge of the obstacle on the vortex behaviour? How does the vortex dipole behave when approaching an opening in a flat plate, so when two sharp edges are present? What is the dipole behaviour when approaching a row of solid cylinders?
We have carried a systematic study of some generic obstacle shapes and configurations, both through experiments and numerical flow simulations. In this lecture we will focus on the cases of a vortex dipole colliding against a row of cylinders and a dipole moving close to the sharp edge of a thin plate.

LABORATORY ARRANGEMENT AN NUMERICAL SIMULATIONS

Laboratory experiments on dipolar vortex structures have been carried out in a rotating fluid tank. The background rotation is employed in order to generate vortex flows that are in good approximation two-dimensional, owing to the Taylor-Proudman theorem. Different methods are available for generating vortices in a rotating fluid, see van Heijst & Clercx (2009). Dipolar vortices are conveniently produced by moving a thin-walled open cylinder horizontally through the rotating fluid, while gradually lifting it vertically out of the fluid. For a certain translation speed, after withdrawal the wake flow behind the cylinder organises itself into a columnar dipole vortex that has the characteristics of a Lamb-Chaplygin dipole (see Meleshko & van Heijst, 1994). The parabolic shape of the rotating fluid may have a topographic effect on the vortex flow; this undesirable effect may be eliminated by using a parabolic bottom of the proper shape (for a certain specified rotation speed of the turntable). When the appropriate measures are taken, one is thus able to produce symmetric columnar vortex dipole structures that move along a straight line, which may hence be directed at any object mounted in the fluid container.
In the present study, the dipoles thus generated are characterised by a Reynolds number $Re = UD/\nu$ (based on the dipole's speed U and size D, and kinematic viscosity ν) of typically 1000. Dye visualisation has been used in order to get important information about the general flow evolution, and additional Particle Image Velocimetry (PIV) measurements have provided essential quantitative information of the flow, in terms of velocity fields and vorticity distributions. Numerical flow simulations have been carried out with a finite-volume code.

RESULTS

A systematic study has been performed of vortices colliding against solid objects of different shapes and configurations. The case of a vortex dipole colliding against a row of cylinders will be discussed in detail. Attention will also be given to work that has been performed in collaboration with Prof. Slava Meleshko, *viz.* on the dipolar vortex moving against or around a semi-infinite thin plate with a sharp edge.

Vortex dipole colliding against a row of cylinders

The problem of a vortex dipole colliding against an infinite solid wall has been investigated in detail by Orlandi (1990). His numerical simulations have revealed the crucial role played by the solid wall: boundary layers are formed with vorticity of sign opposite to that of the primary vortices. This secondary vorticity is advected away from the wall by the approaching dipole structure, which also widens when getting closer to the wall. These primary vorticity patches pair with the secondary wall-vorticity patches, leading to the formation of two new, asymmetric dipoles which subsequently move away from the wall along curved trajectories.
The same behaviour is observed when a dipole collides against a solid cylinder of a size comparable to that of the vortex dipole, as revealed by the experiments and numerical simulations by Verzicco *et al.* (1995). In a systematic study, we have recently found that the rebound-behaviour of the primary dipole becomes more complicated when the cylinder diameter d is much smaller than the dipole diameter D.
In order to better understand the behaviour of a dipole colliding against a porous wall, we have investigated the case of a dipole colliding against a row of equally-spaced cylinders. Apart from the Reynolds number Re based on the dipole's size and translation speed, the relevant parameters are the ratios d/D and d/L, with L the spacing distance of the cylinders. By systematically varying these parameters, we have been able to construct a regime diagram, classifying the dipole behaviour. We have restricted our attention to the case of the dipole colliding centrally against one of the cylinders in the row. For $d/D \geq 1$, the dipole behaves as in the case of a collision against a single cylinder. Completely different behaviour may be observed when $d/D < 1$, now also crucially depending on the spacing parameter d/L.
Figure 1 shows the flow evolution for the case $d/D = 0.3$, $d/L = 1$: the dipole rebounds as in the case of an impermeable flat wall. For somewhat larger d/L-values the dipole was found to penetrate through the row of obstacles, but for $d/L \geq 4$ the dipole is again deflected completely.

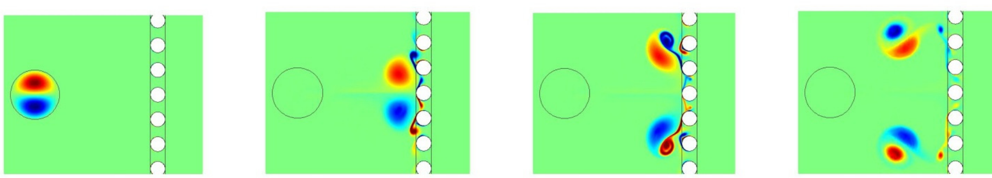

Figure 1. Snapshots of the vorticity distribution in four stages of the vortex dipole collision against the row of cylinders for $d/D = 0.3$ and $d/L = 1$. Numerical flow simulation for Re = 1000.

Vortex dipole near a sharp-edged plate

As in the case of an infinite flat wall, the no-slip condition at the plate surface implies the occurrence of boundary layers containing vorticity opposite to that of the approaching vortices. Besides, the sharp edge plays an important role in the shedding of a vorticity sheet, which rolls up into one or more secondary vortices. Restricting ourselves to a dipole approaching in a direction perpendicular to the plate surface, we have varied the off-set distance δ of the initial dipole axis and the sharp plate edge. Depending on this distance δ, one may observe different behaviour: for larger off-set values δ the dipole moves along the edge without being affected significantly by the plate. For smaller δ-values, the original dipole interacts with the vortices arising at the wall and near the plate edge, resulting in complicated behaviour like 'exchange scattering'. For $\delta < 0$ the dipole behaves more or less like in the case of an infinite solid wall.

CONCLUDING REMARKS

The lecture will focus on a few cases of dipole structures approaching solid objects with different shapes and in different configurations. In general, the laboratory experiments show very good agreement with the numerical flow simulations.
The work reported here was partly carried out in close collaboration with Professor Slava Meleshko. His great interest in vortex dynamics and his profound knowledge of this topic have been an important source of inspiration and have been the essential basis for our very fruitful collaboration for many years. Slava's expertise and his warm friendship are sorely missed.

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