The Behaviour of Vortex Structures Near Solid Obstacles

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Abstract

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. Vorticity generated at the no-slip surface of the obstacle or due to flow separation at sharp edges is advected away from the wall and may thus interact with the primary vortex structure. This may lead to very complicated behaviour, like splitting and partial rebound of the primary dipole.

Laboratory experiments have been performed in a rotating fluid tank, the background rotation providing a mechanism for making 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.

Introduction

When a vortex structure approaches a solid obstacle, it may become quite affected by the vorticity generated at this object. The no-slip condition imposed by a solid wall implies the presence of a boundary layer containing oppositely-signed vorticity. Also, sharp edges may result in flow separation and hence generate vorticity that may affect the behaviour of the vortex. In the lecture we will focus the attention on a self-propelling vortex structure, namely the vortex dipole.

The behaviour of a vortex dipole colliding normally against an infinite flat, solid wall is well understood since the numerical study of Orlandi [4]. 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. Depending on the initial flow conditions, these secondary vortex structures may collide and exchange partners, so that two new couples are formed: while one of these moves back towards the wall (likely to undergo a new collision), the other moves away from the solid wall. A similar behaviour was observed for the case of a vortex dipole moving towards a solid cylindrical obstacle, as reported by Verzicco et al. [5]. When the cylinder diameter is comparable or larger than the dipole size, the wall curvature is not a major factor, and the dipole behaves as when colliding against a flat solid wall.

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?

A systematic study of some generic obstacle shapes and configurations has been performed, 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, a dipolar vortex moving towards a gap in a solid wall, and a dipole moving close to the sharp edge of a thin plate.

Laboratory arrangement and numerical flow simulations

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 [1]. 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 in good approximation the characteristics of a Lamb-Chaplygin dipole [2]. 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 translation speed U and size D, and the kinematic viscosity ν of the fluid) of typically 1000. Dye visualisation has been used in order to obtain 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.
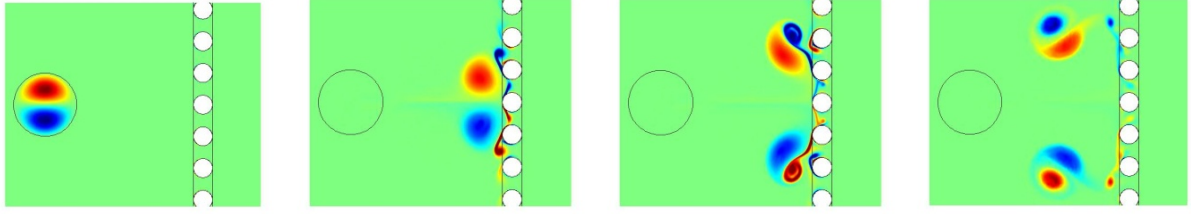
Figure 1. Snapshots of the vorticity distribution in four stages of the vortex dipole collision against the row of cylinders for $d/D = 0.3$ and $d/L = 0.6$. Numerical flow simulation for $Re = 1000$.
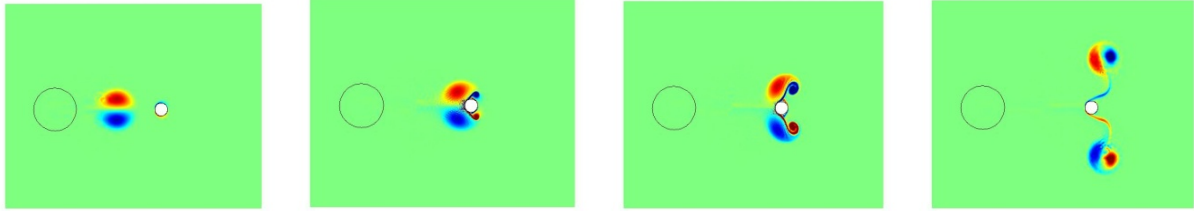

Figure 2. As in Figure 1, but now for a single cylinder with $d/D = 0.3$.

Additionally, 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.

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 [4]. 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. [5]. 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 (measured between their centres). 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 $d/D = 1$, the dipole behaves as in the case of a collision against a single cylinder. 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 $d/D = 0.3$, $d/L = 0.6$: the dipole rebounds as in the case of an impermeable flat wall. For somewhat smaller d/L-values the dipole is found to penetrate through the row of obstacles, but for $d/L \leq 0.15$ the dipole is again deflected completely. In the latter case, the rather isolated, relatively thin cylinder generates a substantial amount of high-amplitude vorticity that leads to splitting and effective rebound, as illustrated in Figure 2.

Vortex dipole near the opening in a wall

The effects of curvature of a solid wall become even more pronounced in the case of a vortex dipole approaching the gap in a solid wall. For ease of modeling, the edges of the gap are not taken very sharp, but rounded. In fact, the wall is given a finite thickness, with the gap edges having a finite radius of curvature (being half the wall thickness). The relevant geometrical parameters are the scaled gap width B ($= b/D$) and the scaled curvature radius of the edges $C = d/D$, with b the gap width and d the wall thickness. In numerical simulations these parameters were systematically varied, and for Reynolds number values up to 6000 three different types of behaviour have been observed. Although the values of Re and C have been varied, their effect on the dipole behavior turned out to be limited. For a relatively small opening ($0 \leq B \leq 0.8$) the dipole completely rebounds, as if colliding against a solid wall, while for relatively large gap widths ($B \geq 1.3$) the dipolar vortex passes through the opening almost without any distortion. In the intermediate regime ($0.8 \leq B \leq 1.3$), however, the vortex dipole partially rebounces, partially passes through the opening. This remarkable behaviour is illustrated by Figure 3. At the first approach of the dipole, it is too big to pass through the gap, and it rebounds as in the case of the row of cylinders shown in Figure 1. The rebounding secondary dipolar structures meet and collide at some distance from the wall, and two new dipoles are formed: one going back towards the opening in the wall, while the other travels in the opposite direction, away from the wall. This is the situation shown in the first panel of Figure 3, where one can clearly see the second attempt (now of one of the secondary dipoles, which is substantially smaller than the original dipole) to travel through the opening in the wall. This time the attempt is successful: although some vorticity is created near the edges, the dipole passes through almost unaffected.

The dipole behavior observed in these three regimes has been confirmed by dye visualization experiments.
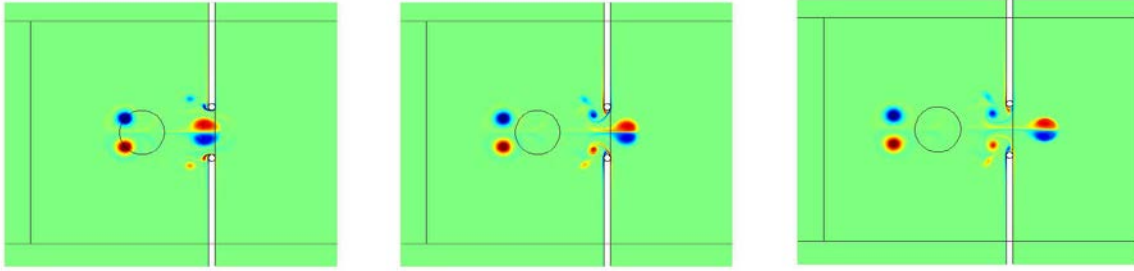
Figure 3. Snapshots of the vorticity distribution in three stages of the dipolar vortex colliding against a gap in a solid wall as observed in the intermediate regime. The first panel shows the situation after the first rebound of the dipole, just after the partner-exchange collision of the secondary dipoles. Numerical simulation for $B = 0.9$, $C = 0.4$, $Re = 1500$.
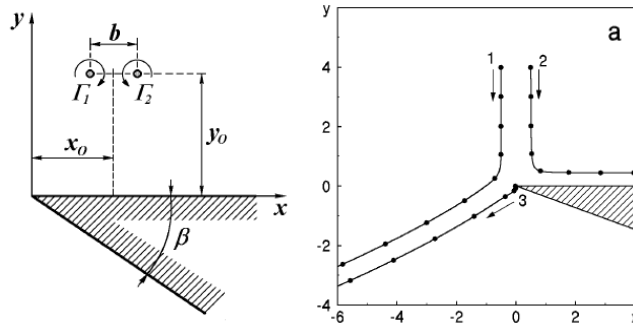

Figure 4. Definition sketch (left) and calculated point-vortex trajectories (right) for the vortex dipole approaching a sharp edge. In the analytical approach, a Kutta vortex was added and later released near the sharp edge in order to remove the singularity. Details will be discussed in [3].

Vortex dipole near a sharp-edged plate

In a separate study of the effect of a sharp edge of a solid obstacle, we have carried out an analysis of the vorticity generated at this edge, both analytically and experimentally [3]. 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. In the analytical approach, this problem was tackled by an appropriate conformal mapping and the addition of a so-called 'Kutta vortex' near the sharp edge, in order to satisfy the Kutta condition at the edge (i.e. by continuously adjusting the vortex strength so as to remove the singularity). Once the strength of this Kutta vortex has exceeded a certain set threshold value, it is released and travels freely with the other vortices. This technique has been incorporated in an algorithm in the numerical point-vortex model that was used to describe the behaviour of the original vortex structure (thus ignoring any effects of the no-slip condition at the solid wall).

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 δ < 0 the dipole behaves more or less like in the case of an infinite solid wall. Figure 4 shows the problem configuration and an

illustration of the calculated trajectory of the point vortices of the original dipole and the Kutta vortex formed and later released at the sharp edge for the off-set value δ = 0. It is clearly observed how the original vortex dipole splits into two, with one point vortex moving parallel to the wall (due to its image) away from the edge, while the other point vortex pairs with the Kutta vortex and forms a slightly asymmetric new dipole that moves under a certain angle away from the edge. More detailed results will be discussed in Meleshko et al. [3].

Concluding remarks

A few cases of dipole structures approaching solid objects with different shapes and in different configurations have been considered. In general, the laboratory experiments show very good agreement with the numerical flow simulations. The material presented here mainly serves to illustrate the rich phenomenology that is encountered. More detailed results will be presented in a forthcoming publication.

References

[1] van Heijst, G.J.F. & Clercx, H.J.H., Laboratory modeling of geophysical vortices, *Ann. Rev. Fluid Mech*., **41**, 2009, 143-164.

[2] Meleshko, V.V. & van Heijst, G.J.F., On Chaplygin's investigations of two-dimensional vortex structures in an inviscid fluid, *J. Fluid Mech.,* **272**, 1994, 157-182.

[3] Meleshko, V.V., Gourjii, A.A., Zannetti, L. & van Heijst, G.J.F., Behaviour of a two-dimensional vortex pair approaching a solid wedge (*paper in preparation*).

[4] Orlandi, P., Vortex dipole rebound from a wall, *Phys. Fluids,* **A2**, 1990,1429-1436.

[5] Verzicco, R., Flór, J.B., van Heijst, G.J.F. & Orlandi, P., Numerical and experimental study of the interaction between a vortex dipole and a circular cylinder, *Exp. Fluids*, **18**, 1995, 153-163.