Active Control of Flows with Trapped Vortices

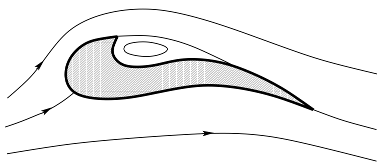
Ruslan M. Kerimbekov, Owen R. Tutty

AFM Research Group, School of Engineering Sciences, University of Southampton, Southampton, SO17 1BJ, United Kingdom, r.kerimbekov@soton.ac.uk

Abstract. An approach to developing active control strategies for high Reynolds number flows with trapped vortices is presented. The particular problem considered is the stabilisation of the vortex in a special cavity on the airfoil, using suction as an actuator. The flow dynamics are modelled by the parallel discrete vortex method capable of handling wall irregularities, arbitrary boundary conditions, and turbulence. System identification is performed based on the open-loop analysis with the constant flow rate suction. Feedback control results show that a properly designed linear PI controller prevents the large-scale vortex shedding from the cavity region and considerably reduces flow unsteadiness in the downstream boundary layer.

Key words: trapped vortex, discrete vortex method, feedback control design.

1 Introduction



Large vortices forming in separated flows over bluff bodies tend to be shed downstream, with new vortices arising in their stead. This results in the increased drag, unsteady loads on the body, and produces an unsteady wake. An alternative flow pattern involves 'trapped' vortices which are permanently kept near the body surface. Vortices can be trapped in vortex cells that are special cavities on the airfoil, as shown in the picture. In essence, a trapped vortex reproduces the effect of a moving wall, resulting in the postponing or even eliminating flow separation.

The idea of trapping a vortex was first suggested (and implemented in flight experiments) by Witold Kasper in the early sixties. However, soon it became obvious that a proper flow control is required to ensure that the vortex remains stably trapped. For example, in the aircraft EKIP designed by Lev Schukin in 1980–1996, vortices were stabilised with the help of central bodies in the cells and a constant flow rate suction (see website *http://www.ekip-aviation-concern.com*). A more reliable and significantly less power consuming system involving active feedback control was recently proposed by Iollo & Zannetti (2001). Somewhat earlier, Anderson *et al.* (2000) showed that a simple linear PI controller and backside suction as an actuator can be used in order to stabilise the vortices behind a flat plate oriented perpendicular to the free-stream velocity.

This paper is aimed at designing a feedback control system for stabilising real flows with trapped vortices. The flow geometry has been chosen according to the experimental setup provided by the Centro Italiano Ricerche Aerospaziali (Donelli 2007). We shall consider an airfoil with a cavity mounted on the lower wall of a

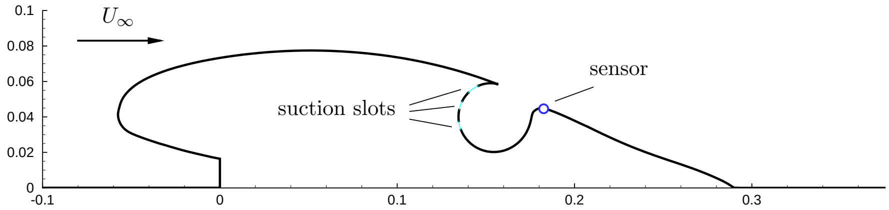


Figure 1: Flow geometry and control arrangements.

straight channel, as shown in figure 1. The shape of the cavity has been computed at the Politecnico di Torino by Zannetti (2007). The actuator comprises three suction slots on the upstream cavity wall, and the suction velocity is assumed uniform and normal to the body surface. The flow state is monitored by a sensor situated on the airfoil near the cavity exit (see figure 1).

The paper is organised as follows. In Section 2 the parallel discrete vortex method (DVM) is introduced as a numerical tool for modelling the flow dynamics. Section 3 performs system identification and explains the procedure for designing a linear PI controller. The results of our work are summarised in Section 4.

2 Numerical Method

In order to calculate the flow past an airfoil with a cavity, the two-dimensional discrete vortex method is employed. According to the DVM approach, the Navier–Stokes equations are written in the vorticity/stream function form. The flow field is partitioned into a large number of blobs having a Gaussian distribution of vorticity. The solution is discretised in time, and for each time step the convection and diffusion processes are treated independently. Such an operator-splitting technique was first introduced by Chorin (1973) and is commonly used in the viscous discrete vortex methods. The convection step is governed by the kinematic relation $\dot{\mathbf{x}}_j = \mathbf{u}\,[\,\mathbf{x}_j(t), t\,]$, where $\mathbf{x}_j$ is the position vector of the j-th vortex, t is time and $\mathbf{u}$ is the velocity field calculated from the known vorticity field using the Biot–Savart law. The diffusive part of the Navier–Stokes equations is solved for each vortex by computing the fraction of vorticity to be distributed amongst neighbouring vortices (for details, see Shankar & Van Dommelen 1996).

In our DVM code, the boundary conditions on the body surface are satisfied approximately with the aid of novel vortex-source panel method, in which the vortex and source panels are located just outside and just underneath the wall, respectively. This approach allows us to account for eventual suction and/or blowing through the solid walls. The panel elements are taken in the form of curved segments with a linear distribution of vorticity. Previously, Clarke & Tutty (1994) showed that such elements can significantly reduce the boundary leakage as compared to the standard textbook panels. Upon completing each time step, the vortex panels are transformed into vortex blobs and released in the flow, thus imitating the effect of vorticity diffusion in the boundary layer. It is worth noting that the blob radius has the same order of magnitude as the panel length. Thus, for an adequate resolution of the boundary layer, the number of panels must be kept proportional to the square root of the Reynolds number.

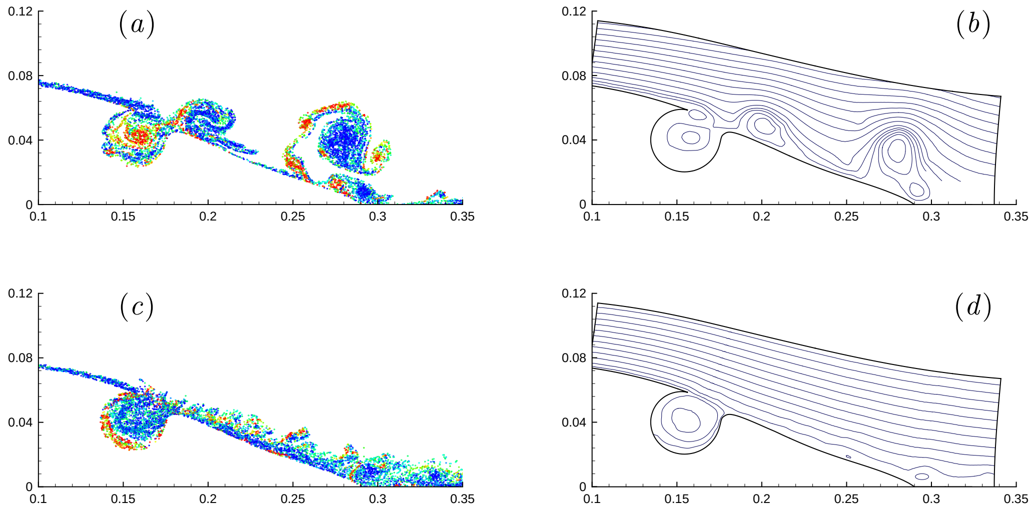


Figure 2: Instantaneous vorticity fields and streamline patterns for flow past the test-bed airfoil; (a)–(b) no control, (c)–(d) open-loop control with constant suction $S_0 = 0.04$.

As panel methods normally break down near the sharp corners, we find it convenient to transform physical coordinates in such a way that in the new variables the flow domain turns into a straight channel of unit width. The mapping is based on the generalised Schwarz–Christoffel formula for channels with curved walls (Davis 1979, Sridhar & Davis 1985). It is provided in the form of grid-to-grid transformation with a bilinear interpolation between the mesh lines. Taking into account that the Navier–Stokes equations are invariant under conformal mappings, the flow field can be computed by supplying the Jacobian of the transformation to the standard DVM solver and mapping the results back to the physical plane when the calculation is complete. A special care is still required though for the vortices that come close to the cusp point, where the mapping is singular. This problem is handled by imposing a lower boundary on the value of the Jacobian.

The DVM code has been validated against various published results on laminar and turbulent flows past a circular cylinder and a flat plate at zero incidence. In particular, a good agreement has been observed in predicting the drag crisis for a cylinder flow and the structure of the flat-plate boundary layer up to the Reynolds number of 10^7. On average, the number of vortices used in our calculations was 5×10^5, with the number of vortex panels being 1200. For further details of the discrete vortex method, see Kerimbekov & Tutty (2006).

3 Feedback Control Design

The numerical results presented in this section are obtained for a channel flow past the test-bed airfoil of figure 1, with the Reynolds number being $Re = 2.1 \times 10^6$ per unit length. As shown in figures 2(a) and (b), the uncontrolled flow is characterised by the large-scale vortex shedding from the cavity region, which results in the increased unsteady drag force. The control objective is to reduce this drag force by trapping the vortex in the cavity using suction as an actuator. The non-dimensional

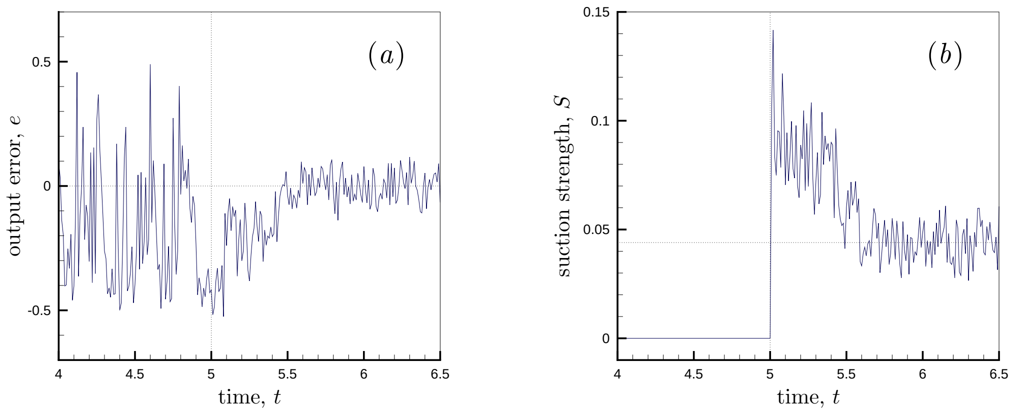


Figure 3: Time histories of (a) output error e, and (b) suction strength S. The PI controller is activated at $t = 5$.

rate of creation of vorticity λ at the sensor point may conveniently be used as an output parameter for monitoring the flow state.

In the open-loop tests with constant suction, we discovered that the vortex remains stably trapped if the suction velocity (non-dimensionalised by the inlet velocity U_∞) reaches the level $S_0 = 0.04$. In this case, the time average value of the output signal becomes $\langle\lambda\rangle = 0.038$, and a sharp drop in the variance of λ is observed. The instantaneous vorticity field and streamline pattern for such flow are displayed in figures 2(c) and (d). However, in practice the amount of suction required to capture the vortex is not known *a priori*, therefore the feedback control strategy capable of computing the appropriate suction is desired.

Although the system dynamics proves to be highly nonlinear, we have found that the linear PI controller can be used to stabilise the vortex. The control law in this case is given by the equation

$$S(t) = K_p e(t) + K_i \int_0^t e(\tau)\,\mathrm{d}\tau,$$

where $e(t) = \lambda_0 - \lambda(t)$ is the output error, K_p and K_i are the proportional and integral gains respectively. These may be determined with the help of Ziegler–Nichols method as $K_p = -0.3$ and $K_i = -0.2$. The target output, $\lambda_0 = 0.038$ is chosen according to the open-loop results described above.

In figures 3(a) and (b) the flow is uncontrolled for $t < 5$, and at $t = 5$ the PI controller is activated. As a consequence, the mean output error rapidly tends to zero, and the suction strength fluctuates about $S = 0.44$ after some overshoot. Thus, the linear PI controller is able to achieve the target output measurement and to inhibit the vortex shedding process, but the required average suction is approximately 10% higher than the value of S_0 obtained in the open-loop analysis.

4 Conclusions

The paper develops an active control strategy for stabilising high Reynolds number flows with trapped vortices, using suction as an actuator. The flow dynamics are modelled by the parallel discrete vortex method capable of handling wall irregularities, arbitrary boundary conditions, and turbulence. We find it convenient to accept the rate of creation of vorticity at the wall near the cavity exit as an input control parameter, since it can easily be linked to the values observable in experiments (e.g. pressure, wall shear stress). The open-loop analysis with constant suction reveals a strongly nonlinear behaviour of the system and determines the level of the actuation required for stabilising the flow. Feedback control results show that a properly designed linear PI controller prevents the large-scale vortex shedding from the cavity region and considerably reduces flow unsteadiness in the downstream boundary layer.

Acknowledgements

This work has been completed as an integral part of the research project *Fundamentals of Actively Controlled Flows with Trapped Vortices*, funded by the European Commission within its FP6 Program, Contract No: AST4-CT-2005-012139. The project particulars can be found on the website *http://www.vortexcell2050.org.*

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