Optimization of cylinder flow control via zero net mass flux actuators

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A direct search method in combination with a DNS/LES numerical approach is applied to optimize the control of the flow around a circular cylinder. The objective is the minimization of the drag coefficient and control is achieved via zero net mass flux actuators. The optimization process has been first evaluated and validated at Reynolds number 500 and then the more demanding flow at Reynolds number 3900 has been considered. The search of the optimum has been carried out in 2D simulations, and a 3D simulation indicating similar drag reduction, has been performed using the parameters of the 2D optimization.

1. Introduction

Flow control has the potential of manipulating flow fields in order to achieve transition delay/advancement, separation prevention/provocation, and turbulence suppression/enhancement. The modifications of these flow properties can lead to large benefits in the aeronautical applications such as increased aerodynamic efficiency, reduced structural weight, reduced operating costs and reduced emissions. In addition flow control techniques are employed to improve the aerodynamic capabilities of wings at off-design conditions, and to maintain performance throughout the flight envelope of vehicles whose design is driven by mission requirements (i.e. unmanned, stealth) and not by aerodynamic considerations.

Flow control methods can be classified as passive or active. Passive control devices, such as riblets, vortex generators, and boundary-layer trips, have been shown to be quite effective in delaying flow separation, but cannot adapt to changes of the incoming flow, and introduce a drag penalty if the flow does not separate. The active control approaches, such as external and internal acoustic excitation, vibrating ribbons or flaps, and steady and unsteady blowing and suction, couple the control input to the flow instabilities and can operate in a broad range of conditions. However, so far, the active flow control methods have relied on sophisticated and complicated support systems that require their own power supply devices.

A novel concept for active flow control is the use of Micro Electronic Mechanical Systems (MEMS). The MEMS couple sensors, control and logic electronics, and actuators into a single low-weight compact device. Several low power MEMS such as microflaps, surface heating elements and synthetic jets are been used for flow control. Synthetic jets (Glezer & Amitay 2002) are zero net mass flux active control devices that do not require internal fluid supply lines. They consist of an oscillating membrane located at the bottom of a cavity having small orifices in the face opposite to the membrane. When the

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membrane moves upwards fluid is expelled through the orifice, and a shear layer is formed at the orifice edge. The shear layer rolls up to form a vortex ring that moves away from the orifice under its own momentum. When the membrane moves downwards fluid enters into the cavity. The entrainment process is not affected by the vortex ring supposed to be sufficiently far from the cavity. Over one period of oscillation of the membrane the net mass flux is zero.

The actuators based on the synthetic jet techniques have been shown to be very effective for several applications of aerodynamic flow control. The modification of the global forces on a circular cylinder induced by applying synthetic jets has been investigated experimentally at Reynolds numbers of up to 1.3×10^5 by Amitay et al. (1997) and Amitay, Smith & Glezer (1998). They found that the interaction between the jet and the main flow induces a local separation bubble that acts as a virtual surface and displaces the streamlines outside the undisturbed boundary layer. Drag increase and decrease can be achieved depending on the azimuthal location of the actuators. The control of the separated flow over an unconventional airfoil (cylindrical leading edge + the aft portion of a NACA 4 digits series) at Reynolds number 3×10^5 has been investigated experimentally by Smith et al. (1998) and Amitay et al. (1999, 2001). The airfoil without control stalls at $\alpha = 5°$, while with control fully attached flow was achieved at α of up to 15°, and partial reattachment and recovery of lift were found for α of up to 25°.

In the present work, the synthetic jet is numerically modeled as time periodic blowing and suction of fluid at the cylinder surface. The peak velocity, operating frequency, and location are the defining parameters of a synthetic jet actuator. The objective is to explore the use of a direct search technique, namely the response surface method (Grigoriu 1982, Rackwitz 1982), to optimize the synthetic jet parameters. To this end, two-dimensional, unsteady laminar flows are first considered, with the expectation of future extension to high Reynolds number turbulent flows such as those in the experiment of Amitay, Smith & Glezer (1998). The drag coefficient of the flow at Reynolds numbers 500 and 3900 has been chosen as cost function. The optimization process has been carried out in 2D, and a 3D simulation using the 2D "optimum" actuator parameters has been performed for comparison.

2. Optimization techniques and numerical set-up

We implement a response surface technique (Grigoriu 1982, Rackwitz 1982) in order to identify the optimal parameters for the control actuators. The response surface method belongs to a class of optimization techniques called direct techniques as they do not use gradient information for the function minimization. Key advantages of such methods include their portability and robustness and their capability of escaping local minima. Disadvantages include relatively slow convergence rates when compared with gradient based techniques and its inefficiency in large dimensional spaces.

The response surface technique relies on the iterative reconstruction of the initially unknown cost-function using the values acquired during the optimization. A surface is fitted to a set of function values obtained from an initially chosen set of parameters and the minimum of this surface is found using analytical or gradient based methods. The surface constitutes a model of the "true" cost function and the minimum found serves as the next candidate point for the iterative procedure. An extensive description of the method can be found in Booker et al. (1998).

The response surface method in combination with a LES/DNS numerical approach has been applied to find the minimum drag coefficient of the circular cylinder subject to control via synthetic jets. The optimization process has been first evaluated at Reynolds number 500 and then the flow at Reynolds number 3900 has been considered. The search of the optimum has been limited to the 2D flow, although a 3D simulation using the 2D optimal control parameters has also been carried out to investigate if the cost function reduction still exists.

An energy conserving Navier-Stokes flow solver (Choi 1993) of hybrid finite difference/spectral type using C meshes (Mittal & Moin 1997) has been employed in the numerical simulations. The equations are advanced in time using the fractional step approach, in combination with the Crank-Nicholson method for viscous terms and the third order Runge-Kutta algorithm for the convective terms. The continuity constraint is imposed at each Runge-Kutta substep by solving a pressure Poisson equation employing a multigrid iterative method. The dynamic procedure (Germano et al. 1991) together with a least-square contraction and spanwise averaging (Lilly 1992) is used to model the subgrid scale stress tensor. The numerical simulations have been performed in 3D using LES, and in 2D with the subgrid model switched off.

The actuator is modeled by imposing a velocity normal to the surface as

$$\frac{V_j}{V_\infty} = g(\theta_j) V_{jA} sin\Big(2\pi f_j \frac{V_\infty t}{D}\Big) \tag{2.1}$$

where V_∞ is the free-stream velocity, θ_j is the jet location, and D is the cylinder diameter. The frequency is made proportional to the natural shedding frequency of the flow

$$f_j = k_j f_s \tag{2.2}$$

and $g(\theta_j)$ is assumed to be a top hat function (Rizzetta et al. 1998).

The momentum transferred by the jet to the main flow is measured by the following coefficient defined as

$$C_\mu = \frac{2\rho_j V_{jA}^2 b}{\rho_\infty V_\infty^2 D} \tag{2.3}$$

with ρ_j the density of the jet and b the width of the jet orifice.

The parameters that define the synthetic jet model are the amplitude, the frequency, and the location. The objective of this work is to apply a direct search method to find the values of V_{jA}, k_j, and θ_j that minimize the drag coefficient C_D of a circular cylinder.

3. Results

3.1. *Flow at Reynolds number* 500

First two simulations without control, on meshes of 201×60 points and 401×80 points, have been performed to compute the reference value of the drag coefficient. The resulting C_{D0} was 1.390 on the coarse mesh with a variation of only 0.5% on the fine mesh, suggesting that the coarse one is sufficient for the optimization iterations. The computed flow exhibits vortex shedding with a Strouhal number of about 0.2 and with the flow separating on the rear part of the cylinder at about $\theta = 105°$.

A first search for the minimum drag coefficient has been performed keeping the amplitude V_{jA} constant with a momentum coefficient of 6.5×10^{-3} and varying the jet location and the frequency. The surface $C_D = f(\theta_j, k_j)$ has been computed by means of a series of 2D simulations. To initialize the optimization process, four additional points in the (θ_j, k_j) parameter space are obtained. The optimization process has been carried

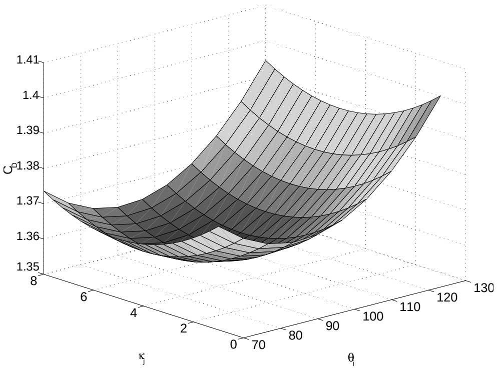

FIGURE 1. Approximate surface $C_D = f(\theta_j, k_j)$ at $Re = 500$, at the last iteration.

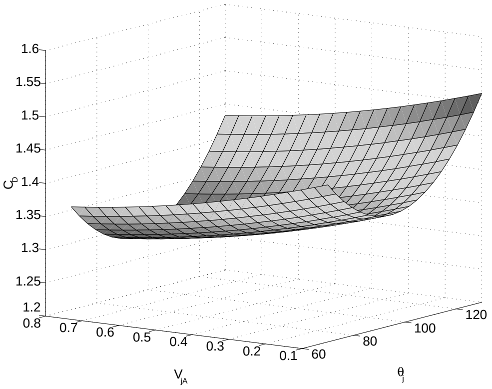

FIGURE 2. Approximate surface $C_D = f(\theta_j, V_{jA})$ at $Re = 500$, at the last iteration.

out iteratively evaluating at each iteration the minimum of the response surface. The convergence has been reached in 6 steps and the response surface at the final iteration is shown in Figure 1. The optimum values found for θ_j and k_j and the resulting reduction in drag coefficient with respect to the unforced flow

$$\Delta C_D = \frac{C_{D0} - C_D}{C_{D0}} \tag{3.1}$$

are reported in the first row of table 1.

From figure 1, it can be seen that the drag coefficient depends more strongly on θ_j than on k_j. Hence, another search with the frequency constant and θ_j and V_{jA} variable has been performed. The final response surface is shown in figure 2, and the optimum parameters found are reported in the second row of the table 1. A decrease of about 6% for the C_D has been achieved.

To check if the reduction in C_D persists when the flow is three-dimensional, a 3D LES using the optimum parameters (second row of table 1) found in 2D is performed. A mesh of $401 \times 120 \times 49$ points with a spanwise domain size of four times the cylinder diameter is used. The simulation has been advanced for about 300 time units (based on D/V_∞) and the value obtained for the mean C_D is 1.104. This is about 8% lower than the experimental value of the unforced flow (in Zdravkovich 1997).

In an attempt to further reduce the drag coefficient, a spanwise variation of the jet amplitude has been introduced. The jet is modeled as

$$\frac{V_j}{V_\infty} = g(\theta_j) V_{jA} sin\Big(2\pi k_z z\Big) sin\Big(2\pi f_j \frac{V_\infty t}{D}\Big) \tag{3.2}$$

where $k_z = 0.5$, and V_{jA}, k_j and θ_j are the values reported in table 1 (second row). The C_D obtained was 1.130, lower than the experimental unforced value but higher than the drag coefficient found with a jet with constant V_{jA}. However an optimization using also k_z as a parameter has not been performed.

The flow at this Reynolds number has shown to be fairly insensitive to the control applied, and the decrease obtained for the cost function has been quite small. In order to achieve a larger reduction of the cost function and to further validate the methodology used, two jets located symmetrically with respect to the streamwise direction and

Table 1. Optimum synthetic jet parameters at $Re = 500$

	V_{JA}	θ_j	k_j	ϕ	$\Delta C_D\%$
One jet	0.14	89.8°	4.4	-	4
One jet	0.59	93.9°	5.0	-	6
Two jets	0.62	93.9°	4.18	132°	12

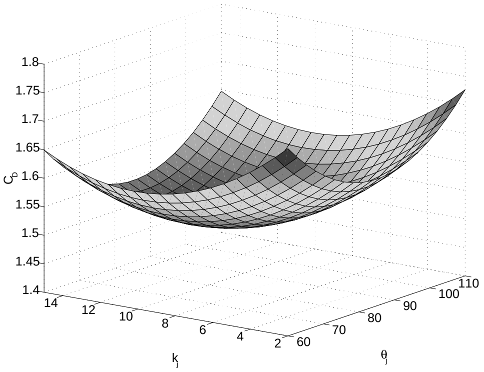

Figure 3. Approximate surface $C_D = f(\theta_j, k_j)$ at $Re = 3900$ at the last iteration.

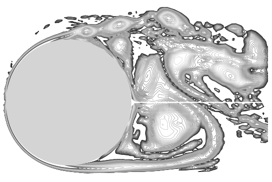

Figure 4. 2D Flow at $Re = 3900$ forced by a synthetic jet located at $\theta = 85.12°$ with $C_\mu = 6.5 \times 10^{-3}$. 50 contours (levels from 1 to 50 with exponential distribution) of the instantaneous vorticity magnitude are plotted.

with different phase ϕ have been considered. The amplitude and the location are kept fixed, while the frequency and the phase are chosen as the parameters to optimize. The reduction in C_D is 12% and the optimal k_j and ϕ are reported in the third row of table 1.

3.2. *Flow at Reynolds number* 3900

The drag coefficient of the unforced flow has been obtained by employing a mesh of 401×120 points. Its value of 1.719 compares well with the C_D computed by Beaudan and Moin (1994). The mean flow exhibits two symmetrical recirculation bubbles from about $\theta = 105°$ to $\theta = 120°$, and coherent vortex shedding with a Strouhal number of about 0.22.

The search of the minimum drag coefficient has been performed considering the location and the frequency as parameters to optimize while keeping the amplitude fixed with a momentum coefficient of 6.5×10^{-3}. The response surface at the last iteration is shown in figure 3 and the optimum values found are reported in table 2. The reduction in drag coefficient is about 13%. The instantaneous vorticity field of the 2D flow forced by a synthetic jet using the optimum values is presented in figure 4. The small-scale vortices due to the interaction of the jet with the boundary layer are clearly visible.

A 3D LES, with the optimum jet parameters found in 2D, has also been performed. The mesh used has $401 \times 120 \times 49$ points and the spanwise length of the computational domain

TABLE 2. Optimum synthetic jet parameters at $Re = 3900$

V_{JA}	θ_j	k_j	$\Delta C_D\%$
0.14	85.12°	9.21	13

is πD. The simulation has been advanced for about 270 time units and the resulting mean C_D is 1.01. The unforced flow around a circular cylinder at $Re = 3900$ has been investigated numerically using LES by Beaudan and Moin (1994), who found a mean drag coefficient of 1.00. The unforced experimental value (Norberg 1987) is 0.98 ± 0.05.

Evidently, the optimized jet parameters found from the (admittedly artificial) 2D simulation does not work for the 3D turbulent flow. This is not unexpected since the flow structures are different. In particular, the points of boundary layer separation, which affects the optimal location of the actuator, are more advanced in the 3d case than in 2D. It has not been possible, due to lack of time, to carry out the optimization using 3D simulations during the summer program. However this remains our longer-term objective.

4. Concluding Remarks

A response surface method in combination with a LES/DNS numerical approach has been applied to minimize the drag coefficient of the flow over a circular cylinder controlled via synthetic jet actuators. The optimization process has been evaluated and validated in 2D model problems at Reynolds numbers of 500 and 3900. 3D simulations using optimal parameters obtained from 2D have also been performed.

The process has been successful, although the flow is shown to be quite insensitive to the controls applied, and the decrease in cost function is quite small at Reynolds number 500. At Reynolds number 3900, the drag coefficient reduction is more significant in 2D, which is however not reproduced in 3D with the same set of control parameters. Overall, we have demonstrated the robustness of the technique for this type of control problems. Optimization using 3D simulations at higher Reynolds number will be of longer-term interest beyond the summer program.

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