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FEEDBACK CONTROL OF VORTEX SHEDDING IN A SEPARATED DIFFUSER

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Summary We propose closed-loop control for vortex shedding in a separated diffuser. Pulses of zero-net-mass injection (consecutive blowing and suction) are issued based on estimates of the circulation of a vortex in the separated region, and a model that suggests an optimal vortex spacing that minimizes stagnation pressure loss. The circulation is estimated using the wall pressure at a limited number of observer points. The closed-loop algorithm improves the robustness of open-loop control when external disturbances are added.

INTRODUCTION

Traditional separation control has relied on steady boundary layer energization (e.g. vortex generators, suction). Recently unsteady zero and positive-net mass injection have been shown to effectively increase lift-to-drag ratio (airfoils) or pressure recovery (diffusers) based on a different principle: spanwise vorticity near the separation point is modulated to produce a more favourable distribution of vorticity [e.g. 1]. In a variety of external and internal flows, it appears to be optimal to oscillate or pulse the injection at roughly twice the frequency of natural vortex shedding [e.g. 2,3,4 for results pertaining to diffusers]. Recently, we proposed a simple model to relate vorticity distribution and performance metrics (e.g.\ airfoil lift/drag or diffuser pressure recovery) [4]. The model allows us to develop a simple, yet effective, feedback control strategy.

Most previous work has focussed on open-loop control, but feedback (on the timescale of the vortex shedding) has the potential to enhance performance and decrease sensitivity to uncertainties and disturbances. Application of feedback requires three elements: effective actuation, sensors that permit identification of key flow events, and a control law that dictates how sensor information is used to modulate the actuation. The past decade has seen rapid advancements to actuator and sensor design, but owing to the complexity of predicting unsteady fluid motion, flow identification and control law development, especially in a form suitable for practical application, have lagged. Techniques currently under development are based on Direct Numerical Simulation [e.g. 5], reduced-order-modeling such as with Proper Orthogonal Decomposition (POD) [e.g. 6], and structure-identification using stochastic estimation [e.g. 7,8]. All of these methods generally require extensive experimental or numerical simulation data as input in their development.

CLOSED-LOOP CONTROL STRATEGY

We present a closed-loop control strategy (see Figure 1) for vortex shedding in a separated diffuser that is based on a much simpler model of the timescale for vortex shedding and its relation to the overall stagnation pressure loss [4]. The model consists of two parts--a vortex pinch-off criterion that yields an estimate for the (natural) vortex shedding frequency of the diffuser, and a control-volume analysis that connects the overall loss in stagnation pressure to the properties of the vortex shedding. The model identifies several parameters that are important in reducing stagnation pressure loss. The most important parameter is the size (or circulation) of the pinched-off vortex near the separation point; other parameters, such as the amount of circulation absorbed at the wall and the convection speed of the shed vortex, are strongly correlated with the size of the pinched-off vortex. We also show that the effects of unsteady mass injection can be understood by their impact on the size of the pinched-off vortex. This leads to the present control strategy: use feedback to pinch-off optimally sized vortices.

In order to exploit the connection between actuation, the size of the shed vortex, and the stagnation pressure loss, we need to be able to estimate the location and circulation of the vortex that is developing near the separation point. For this we introduce an inverse vortex imaging method [9] that detects the position and circulation of a vortex (or vortices) from pressure histories at a limited number of points. The algorithm minimizes a cost function that represents the difference between an inviscid, potential (point) vortex propagating in a diffuser and the measured, time-dependent pressure signal at the wall. In the present study, we use 12 sensors located just downstream of the separation point (see Figure 1). The detection algorithm is implemented using an estimator-corrector approach that averages the measured and predicted vortex trajectories in order to suppress random errors associated with the detection process. Results from a typical detection process are shown in Figure 1. A variety of related implementation issues are discussed in refs. [9] and [10].

To close the loop, we issue a pulse of zero-net mass injection whenever the estimated circulation reaches a pre-defined threshold value. The threshold is defined by varying (in open-loop) the (constant) frequency of pulse injection—the frequency that gives the minimum stagnation pressure loss defines the optimal vortex size and, in turn, the threshold circulation. As noted previously this frequency is approximately twice the natural (no actuation) shedding frequency.

RESULTS FROM NUMERICAL SIMULATIONS

We have designed and implemented the control strategy in a simplified flow using numerical simulation. We solve the Navier-Stokes equations for a laminar, two dimensional (smooth) diffuser with an area ratio of $h_2 / h_1=2$ (see Figure 1). The incoming flow is uniform across the inlet with a laminar boundary layer whose thickness is 10% of the inlet width, h_1. The Reynolds number (based on h_1) is 4000. A synthetic jet actuator is modeled by a distributed source of mass, momentum, and energy in the boundary layer just upstream of separation. Details of the numerical modelling and justifications for the simplified actuator model are given in ref [4]. Without actuation, the laminar boundary layer separates at a stationary location (see Figure 1) and quasi-periodic vortex shedding occurs on a timescale (and with a resulting stagnation pressure loss) that are in good agreement with the aforementioned model. A time history of stagnation pressure at the diffuser exit is given in Figure 2.

Under open-loop operation (but without any external disturbances), periodic pulse injection with sufficient amplitude (results below used a fixed momentum coefficient, $C\mu=1.3\times10^{-3}$) stabilizes vortex shedding over a range of frequencies (i.e induces frequency locking), and leads to the identification of the optimal frequency where the stagnation pressure loss is minimized. This is used to set the threshold circulation ($\Gamma/Uh_1 = 1.26$) at which closed-loop injection should start as noted above.

We investigate both open and closed-loop performance in the presence of inflow disturbances. Disturbances are added by placing a small acoustic source upstream of the separation point. Figure 2 shows significant deterioration in the open-loop performance caused by the disturbances (in this case harmonic disturbances with a frequency five times the natural frequency). The disturbances apparently break the frequency locking and cause vortices of different (non-optimal) sizes to be shed. When closed-loop control is activated, frequency locking is nearly recovered, and stagnation pressure loss is substantially improved (see Table 1). Time-averaged stagnation pressure losses across the diffuser for the different cases are indicated in Figure 2.

DISCUSSION AND FUTURE WORK

We have demonstrated feedback separation control in a simplified two-dimensional diffuser flow. For brevity, we have shown only a few representative results--in the final presentation, additional results, including variation of the temporal waveform of actuation, the addition of random (white noise) disturbances, and further improvements to the vortex detection algorithm, will be given. The control strategy is based on a simple representation of the vortex pinch-off process, and the recognition that optimal performance is obtained (in open loop) at a frequency roughly twice the natural shedding frequency, and when the vortices are shed with nearly equal size and spacing (i.e. when frequency locking occurs). Closing the loop allows this optimal shedding to occur even in the presence of disturbances that significantly deteriorate the open-loop performance. The control law is sufficiently simple and the number of sensors sufficiently small that we expect it could be implemented in real-time in experiments that we hope to complete in future.

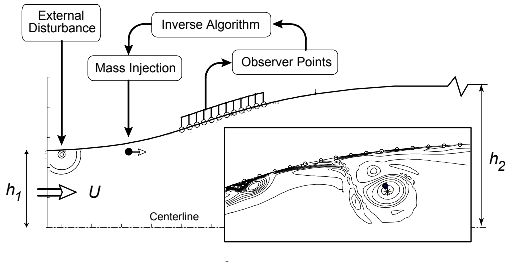

Figure 1. Schematic of control scheme. Inset: contours of vorticity from DNS illustrating the vortex detection algorithm. (*) vorticity maximum from DNS, (●) detected vortex center

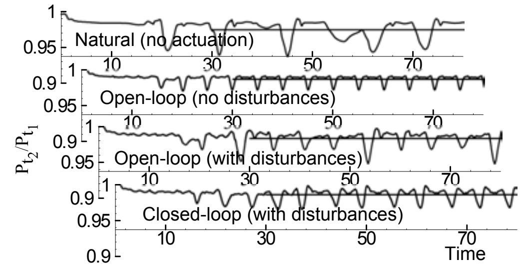

Figure 2. Stagnation pressure ratio across diffuser for different cases. The straight lines are the time averaged values over the period indicated. The average stagnation pressure losses are 2.50,1.23,1.67, and 1.37% (from top to bottom).

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