Reactive Control of an Unsteady Separating Flow

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Introduction

EXPERIMENTS[1] were carried out to attempt the real-time, reactive control of a model unsteady separating flow that was dominated by the evolution and movement of a strong vortex. The results described in this Note underscore the fact that measurements of pressure at *a single location* can be used to sense the flow condition, as well to activate a flow controller to modify the extent of the separated region. The unsteady separation was introduced in the flow over a flat plate by a spanwise flap moving into the flow. The wall pressure at a chosen control location was monitored during the deployment of the flap to determine when flow reversal associated with the unsteady separation occurred. When the prescribed criterion was met, a pulsed-jet flow controller was activated to modify the separated region by reducing its mean reattachment length.

Description of a Model Experiment

The arrangement to obtain a controlled unsteady flow is described in detail by Ramiz.[2] An unsteady separation was generated in the flow over a flat plate, 60 cm wide and 3.1 m long, by raising a flap, 4 cm high and 60 cm in span, into the flow (Fig. 1a). The flap, located 137 cm from the leading edge of the plate, could be driven in a variety of motions, including single pitch-up, single pitch-down, or multiple pitch-up and pitch-down motion segments. A two-dimensional, pulsed-jet manifold was located directly beneath the flap (Fig. 1b), such that either a steady or pulsed jet could be directed into the region downstream of the flap when the flap was raised. The jet was activated by operating a solenoid valve under computer control. To obtain a pulsed jet, the solenoid valve could be opened and closed at rates up to 10 Hz, depending on the desired frequency of pulsing. The flow rate of the jet was controlled by setting a second valve.

In the unsteady experiments, the wall static pressure was monitored at a chosen location during the deployment of the separation generator, and a flow-state identification criterion was applied to the data in real time to determine when flow reversal associated with the unsteady separation or reattachment occurred at the monitoring location. The criterion used[2] was to compare the wall static pressure at that location to a preset threshold level corresponding to a pressure coefficient $c_p = -0.15$ for both unsteady separation resulting from a flap rise and unsteady reattachment caused by a flap drop. When the threshold was crossed, a command signal activated the flow-control jet at the set frequency. The pressure signal was monitored continuously and the solenoid valve was either deactivated or reactivated, in the event that the threshold was crossed in either direction. The control strategy or goal in these experiments was to obtain a reduction in the reattachment length of the separated region formed behind the flap. Details of the experiment can be found in Ref. 1.

Results of Control Experiments

The results presented in this Note are for a flow velocity of 5.1 m/s, corresponding to a Reynolds number of 4.5×10^5 based on the distance from the leading edge to the flap location. The jet was set at an angle of 45 deg, and the blowing coefficient was 0.24. Figure 2 compares the time-averaged wall static pressure distribution, with the pulsed jet operating continuously at 4 Hz, to that with no control jet, for a steady flap at an angle of 45 deg. The pressure recovers to its asymptotic value at an earlier streamwise location, indicating that the pulsed jet produces a reduction in the mean reattachment length of the separated region. Similar results were obtained for other flap angles. Based on an examination of these pressure distributions, the static pressure at a single location seven flap heights downstream of the flap was chosen to monitor the flow state in the unsteady experiments. The increase in the mean pressure level at this location resulting from the pulsed-jet control is seen in Fig. 2.

Figure 3 demonstrates reactive control of the separated region under unsteady conditions for a single, constant-velocity ramp-up of the flap from 0 to 90 deg in 0.2 s. The control jet was turned off initially and activated at 4 Hz at the instant during the flap motion that the separation inception criterion was satisfied. The figure shows the variation of both the control pressure and the jet actuation command signal, recorded simultaneously during the rise of the flap. The beginning and end of the flap motion are marked on the figure. Also shown by dashed lines are the mean pressure levels measured at the control location for a steady flap at 90 deg, with and without the application of pulsed-jet control to modify the separated

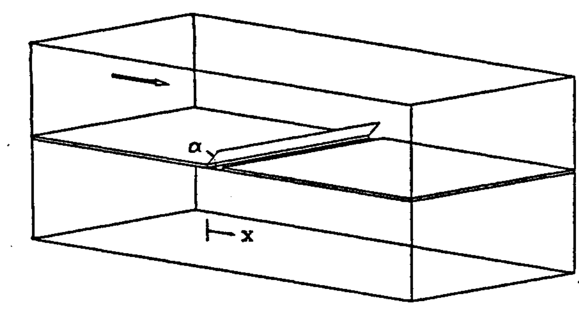

Fig. 1a Schematic of experimental arrangement.

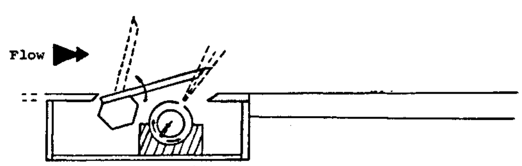

Fig. 1b Detail of arrangement showing position of pulsed-jet controller.

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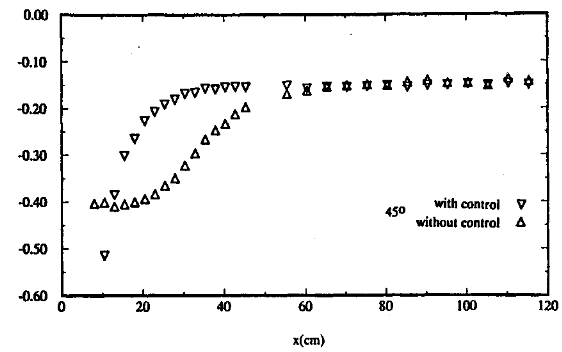

Fig. 2 Static pressure distributions with and without pulsed-jet control for flap angle of 45 deg.

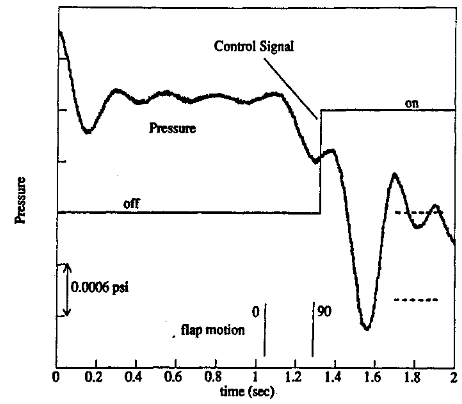

Fig. 3 Reactive control for a single pitch-up motion of the flap; mean pressure levels are indicated by dashed lines.

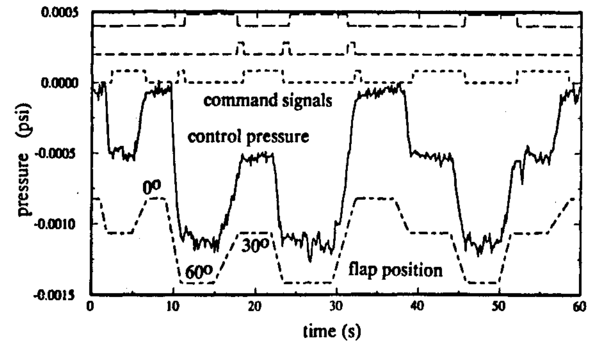

Fig. 4 Response of reactive-control system to random preprogrammed flap motions.

region (the higher level is with control). The control pressure dipped lower momentarily, shortly after activation of the pulsed jet, but returned quickly thereafter to the higher level indicative of a modified separated region. This result was found to be very repeatable. The cause of the initial dip has not been established with certainty, but is known to be connected with the initial unsteadiness caused by activation of the jet. Experiments[2] showed that, when the control jet was not activated during a flap rise event, the control pressure dropped to the level indicated by the lower dashed line in Fig. 3.

Experiments were conducted to examine the possibility of using an optimized pulsed-jet control to modify the unsteady separated region resulting from random movement of the flap. The flap motion was made up of a series of preprogrammed, but random, rise and drop segments, in which the initial and final angles, the time of motion, and the hold time at the end of a motion segment were varied. Different separation region heights were obtained by moving the flap to angles of 0, 30, 45, and 60 deg. The optimum frequency of forcing is known to scale with the height of the separated region.[3,4] Based on such a scaling, values for the jet pulsing frequency of 7, 5.5, and 4 Hz were selected to control the separation when the flap was at angles below 30 deg, between 30 and 45 deg, and between 45 and 60 deg, respectively. The control pressure was compared with three different threshold levels, defined for each of these ranges of flap positions. The command signal was altered to change the pulsation frequency by switching in one of three different drivers for the solenoid valve. The results of one such experiment are shown in Fig. 4. The position signal of the flap, the control pressure signal, and the on-off status signals of all three drivers were acquired simultaneously for a flap random-motion sequence lasting 60 s. In this sequence, the flap made motions between 0, 30, and 60 deg in a preprogrammed but arbitrary fashion. The control jet was off when the flap was embedded in the plate, the jet turned on when the flap rose into the flow, the frequency of the pulsed jet adjusted to the angle of the flap (i.e., to height of the separated region), and the mean-pressure levels at the control location corresponded to those for a modified separated region for the appropriate flap angle. Anomalous behavior did occur. For example, in two instances the flap passed through an angle of 45 deg without the middle frequency being triggered. In other cases examined, the level of fluctuation in the control pressure signal was of the order of the change to be sensed in the mean level, resulting in either an incorrect actuation of the controller or no actuation at all when such actuation was warranted. This was corrected by low-pass filtering the control pressure signal.

Conclusions

These experiments demonstrate the feasibility of real-time, reactive control of a model unsteady separating flow using simple but effective techniques. Although some questions still need to be addressed, the basic approach is viable. A significant feature of this model flow is that the unsteady separation process is dominated by the evolution and movement of a strong vortex. A similar approach, which uses the signature of wall pressure at appropriate locations to detect some characteristic feature of the flow, should work for other unsteady separating flows, which are similarly characterized by the appearance and movement of a strong vortex.

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