Detection of Flow State in an Unsteady Separating Flow

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A model experiment that exhibits some of the characteristics of the leading-edge separation over unsteady airfoils was conducted, and a simple, nonintrusive technique for detection of flow reversal was developed. The unsteady separation introduced in a turbulent boundary layer, by the motion of a spanwise flap into the flow, was investigated for a range of Reynolds number and flap angular velocities. Smoke-wire flow visualization, measurements of the time-varying flow direction at various locations behind the flap, and wall pressure data were used to characterize and document the steady as well as unsteady separation. Ensemble-averaged static-pressure data measured for a representative set of parameters were used to formulate different criteria to identify a change in flow direction at different streamwise locations. These criteria were tested by playing back time-series data of the wall pressure covering a range of Reynolds numbers and flap-rise times. Phase-conditioned flow-direction measurements were used as the reference to evaluate the performance of these criteria. Flap-drop experiments representing unsteady flow reattachment, as well as combined flap motions, were also examined. Two of the criteria formulated in this study show good promise for use as flow-state identifiers in the active control of unsteady separated flows.

Nomenclature

c_p = nondimensional pressure coefficient
h = flap height
p = static pressure
Re_{x_0} = Reynolds number, $U_0 x_0/\nu$
T_0 = flap-rise (or flap-drop) time
t = time
t_a = time of first flow reversal
t_d = detection time of flow reversal
U_0 = freestream velocity
x = streamwise distance from flap
x_0 = distance from leading edge to flap
y = transverse distance from wall
α = flap angle
$\alpha_{i,f}$ = initial and final flap angles

I. Introduction and Background

A PRINCIPAL goal of separated flow management is to minimize the presence of separation and the associated undesirable effects. Several recent reviews, including those by Reynolds and Carr,[1] Gad-el-Hak,[2] and Ericsson and Reding,[3] provide an assessment of our current understanding of unsteady separated flows. The production, accumulation, and transport of vorticity are central to the evolution of such flows and must be altered or influenced by any procedure that is to be successful as a flow control technique. Many techniques have been used to combat separation[4-8] including the use of suction, blowing, unsteady forcing, slats, vortex generators, and compliant walls. However, these techniques invariably have been applied to what might be described as well-defined separated flows, in which the location and extent of the separated region are well known. In such cases, the techniques just described can be tailored to yield optimum results.

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We need to develop the ability to manage flow separation in more general situations, where conditions are either unknown a priori or change with time, such as those that might occur during the pitch-up motion of an airfoil. In such situations, one must be able to monitor the flow to detect the presence of separation, or better yet, incipient separation, at any location along the surface; use a command signal to activate a control mechanism that provides the appropriate corrective response; continue to monitor the flow state; and turn off the controller when a need for control no longer exists.

Our approach to this problem has been to conduct model experiments that would allow an examination of the important mechanisms and provide guidance for the development of tools for management and control of unsteady separated flows in general. The flow behind a rising, two-dimensional flap was one of the cases chosen for this investigation since an unsteady separation could be generated in a controlled manner, with a defined location for the separation line. The goal of the present study was to develop the capability to identify the flow state in a simple and reliable manner in an unsteady separated flow, using nonintrusive techniques, and to develop a set of criteria that could be used to initiate a control sequence using a combination of sensor inputs. Results of this nature can be used together with a flow-control device, for example, unsteady forcing or suction, in a flow-management system.

II. Experiments

The experimental setup, wind tunnel, instrumentation, etc., are described briefly. The reader is referred to Ramiz[9] for details.

A. Experimental Arrangement

The experimental arrangement is shown schematically in Fig. 1a. A two-dimensional boundary layer was generated on a test plate of width 60 cm and length 3.1 m. The leading edge of this plate was formed by a 4:1 half-ellipse, and the first 50 cm of the plate was covered with number 24 roughness sandpaper. Forty-six static pressure ports were located along the plate to enable measurements of the wall pressure.

An unsteady separation was generated in this boundary layer by raising a 4-cm-high, two-dimensional flap into the flow. The flap was located 137 cm from the leading edge of the plate. The boundary layer at this point could be either laminar or turbulent, and the streamwise pressure gradient was nominally zero. The flap motion was derived from a low-

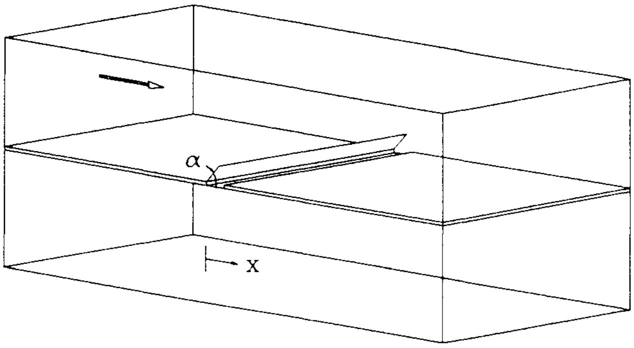

Fig. 1a Schematic of experiment.

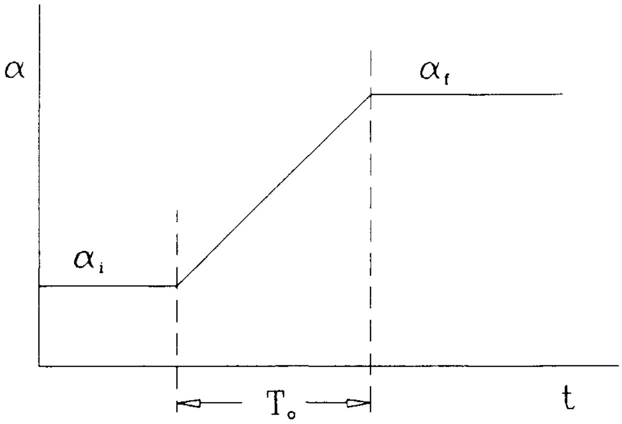

Fig. 1b Flap motion.

inertia, high-torque, printed-circuit dc motor operated under computer control. The time-motion history of the flap for these flap-rise experiments was described by a ramp function (Fig. 1b). The flap rose from an initial angle α_i (typically 0 deg when it was embedded in the flat plate) to a final angle α_f over a rise time T_0 and then stayed at this final position. The undisturbed boundary-layer thickness at the flap location was of the order of the flap height for the Reynolds number range investigated. Flap-drop experiments were also carried out to study the process of unsteady reattachment. In these, the flap motion was described by an inverse ramp with a final angle of 0 deg. Additional experiments with a combination of rising and falling flap motions were also conducted. It must be emphasized that the flap was used as a generator of unsteady separated flow in these experiments, rather than as a flow-control device.

B. Wind Tunnel

The experiments were conducted in the Andrew Fejer Unsteady Flow Wind Tunnel, a closed-circuit, low-speed facility with a test section 0.6 × 0.6 m in cross section and 3.1 m in length. The test plate was installed in the horizontal midplane of the test section. Flow velocities up to 40 m/s could be obtained with a corresponding freestream turbulence intensity of 0.03%. Special features of the wind tunnel include the ability to introduce a controlled oscillation in the flow using a computer-controlled shutter mechanism mounted at the downstream end of the test section and provisions to impart a prescribed motion or oscillation to a model in the flow. The latter feature was used in the present experiments.

C. Measurements

The unsteady separation and reattachment were studied for a range of values of the parameters T_0, α_i, α_f, and Reynolds number. T_0 was varied between 0.06 and 2 s. The values of α_i and α_f were typically 0 and 90 deg, respectively, for the flap-rise experiments (although other values were also investigated), and the Reynolds number range was $2.6 \times 10^5 < Re_{x0} < 2.6 \times 10^6$, corresponding to a freestream velocity between 3 and 30 m/s. In addition to flow visualization experiments, the time variations of wall pressure and flow direction were measured at various streamwise locations.

D. Instrumentation

A smoke-wire technique was used for flow visualization. In this technique, the wire is placed upstream of the region of interest, coated with oil droplets, and heated electrically, causing the droplets to vaporize. The resulting streaklines are photographed. For the wall pressure measurements, a model 237 Setra differential pressure transducer was used in conjunction with a Scanivalve system. A bidirectional probe was used to determine flow direction. It consisted of two total-head probes, 2 mm in diameter, arranged so that they were located at the same streamwise and vertical position, with one facing upstream and the other downstream. The two tubes were offset 1 mm in the spanwise direction. The pressure difference between the two tubes was measured using a second identical Setra pressure transducer, and the sign of this quantity was used to identify flow direction. A positive value signified forward flow, whereas negative values indicated reverse flow. Tests were carried out with this probe in the separated and reattached flow region behind a stationary flap, over the Reynolds number range of the unsteady experiments, to validate its use in this manner for detection of flow reversal.

The overall frequency response (uncompensated) of the pressure transducer, Scanivalve, and tubing was within 3 dB up to 50 Hz for both the static pressure and flow direction systems. This value proved to be adequate for the present experiments; although electronic compensation could have been used to increase it to 150 Hz, this was not done. As reported in Ref. 9, low-pass filtering of the data proved to be necessary in some instances to avoid problems of premature or incorrect detection associated with the fact that pressure fluctuation magnitudes were of the order of the mean pressure levels. Tests showed that different filter cutoff settings down to 10 Hz did not adversely affect the performance and yielded correct results for the range of parameters investigated.

III. Results and Discussion

As stated earlier, the aim of these experiments was to determine the state of the flow from relatively simple measurements and to identify the onset of separation (or reattachment) in a simple and reliable manner that would find ready application in active control. It is not simple to document the evolution of a separating flow in real time. The phenomenon of unsteady separation is inherently complex and criteria for its occurrence are not as easily defined as for steady flow. However, unsteady separation is always accompanied by flow reversal in the near-wall region. Hence, it was this feature that was chosen as the state of flow to be detected.

In the first phase of measurements, the nature of the flow was examined to study variations that resulted from changes of the relevant parameters and to determine the extent of the separated region and the scaling of the unsteadiness. It was found that, for the range of Reynolds numbers tested, the extent of the separated region was more or less constant after steady-state conditions were reached, with the mean reattachment point located between 12 and 13 flap heights downstream of the flap. The next step was to identify a candidate measurand for flow-state identification and to test its suitability to detect flow reversal in the near-wall region. In the following, we describe briefly, the nature of the unsteady flow and the results obtained from using wall static pressure measurements to detect flow reversal. A complete discussion of all of the results is to be found in Ref. 9.

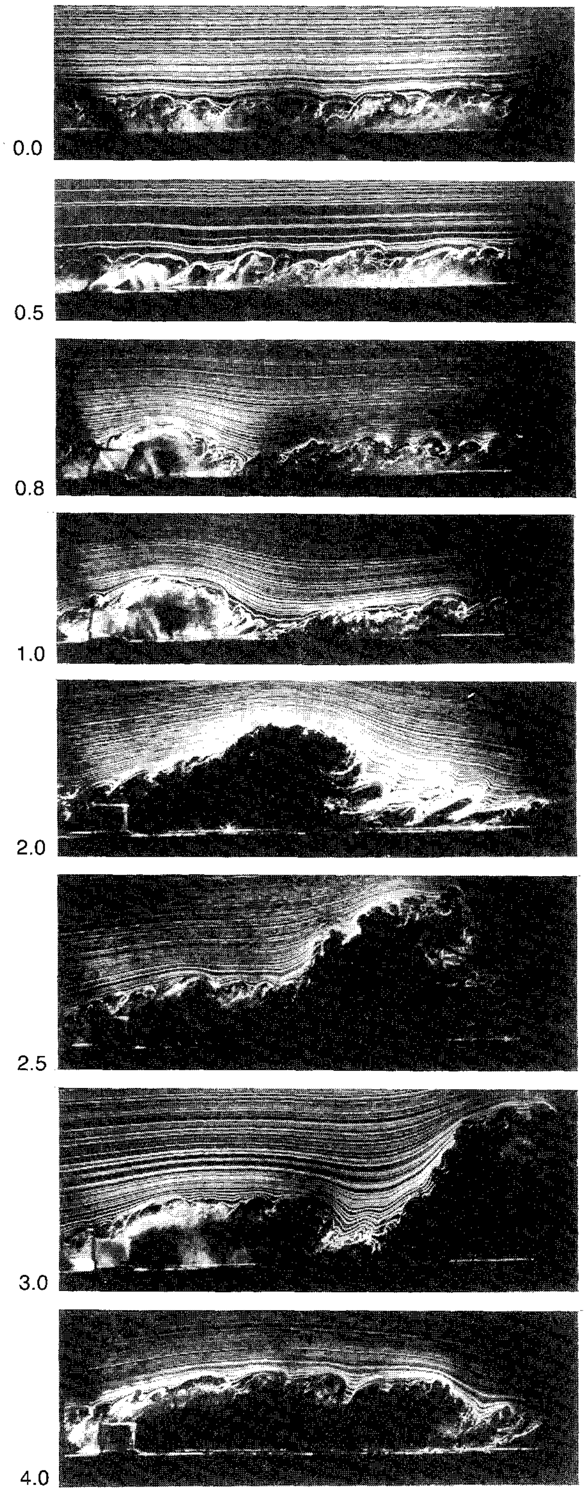

Fig. 2 Development of separation: $Re_{x0} = 6 \times 10^5$; $T_0 = 0.2$ s.

A. Nature of the Unsteady Separation

Some results of flow visualization experiments are presented first in order to describe the main features of the unsteady separation. Figure 2 shows a typical sequence of phase-conditioned photographs taken at different times before, during, and after the rise of the flap into the boundary layer. For the conditions shown, the value of Re_{x0} was 6×10^5 and the flap-rise time T_0 was 0.2 s. The times shown for each photograph are scaled by T_0, so that at $t/T_0 = 1$, the flap had just reached its final position.

The sequence of events in a flap-rise experiment are as follows. The flap is embedded in the wall initially and the turbulent boundary layer is fully attached with steady mean properties. As the flap rises, a vortex forms at the flap tip due to the difference in velocity on either side of the flap. At the same time, a reversed flow region evolves behind the flap. At some point during the motion of the flap, this initial vortex sheds from the flap and convects downstream. The strength and hold time of the vortex and, consequently, the features of the unsteady separation are strongly dependent on the rise time T_0. For large values of T_0, a longer time is available for vorticity to accumulate on the flap. However, the separated region has also had more time to grow and is larger in streamwise extent when the initial vortex is released. As a result, a well-defined vortex is not always seen. In contrast, at smaller rise times, such as that for the photographs in Fig. 2, the initial vortex releases from the flap before the separated region has had much time to grow. The development of the flow is governed by a balance between two mechanisms; one responsible for the accumulation of vorticity at the flap, and the other for the detachment and downstream convection of the shed vortex. As seen clearly in the sequence of photographs, the vortex is well defined and grows to a size of the order of the tunnel half-height as it convects downstream, and the separated region is established behind it. The separated region is far from being fully established when the flap reaches its final position. In this instance, the flow reached steady-state conditions about six rise times after the flap motion commenced.

The dynamical scaling of this process is described in detail by Acharya and Ramiz.[10] Two classes of behavior exist, depending on the value of the nondimensional flap-rise time or pitch-up time T_0U_0/h. For values greater than about 100, the response to the flap motion is essentially quasisteady. The hold time of the initial vortex on the flap is insignificant, and the time of detection of reversed flow at a location behind the flap is governed by the convective process and is determined solely by the rate at which the flap rises into the flow. For values of T_0U_0/h less than 100, unsteady effects become significant. The time for detection of flow reversal is larger than that predicted by quasisteady considerations. This is attributable to the proportionately larger hold time of the initial vortex on the flap under these conditions, when the flap has larger tip velocities during its motion into the flow. The time for detection of flow reversal can be thought of as the sum of the time during which the vortex rolls up and is held to the flap and the time taken to convect downstream following its release from the flap.

B. Flap-Rise Experiments

1. Wall Pressure and Flow Direction Measurements

The time variation of wall static pressure was measured for a range of values of U_0 and T_0, at a number of streamwise locations between $-2 < x/h < 20$. The flow direction was monitored over the same period at each of these streamwise locations at distances from the wall ranging from $0.1 < y/h < 4.0$.

A typical set of wall pressure data is shown in Fig. 3. The Reynolds number in this instance was 9×10^5, the rise time T_0 was 0.1 s, and the flap motion was from 0 to 90 deg. The pressure at a location $x/h = -11$ was used as the reference pressure to obtain c_p. The figure shows pressure-time traces recorded synchronously with the flap motion at streamwise locations for $-2 < x/h < 14$. A zero c_p line has been drawn for each trace. Also shown for reference, by vertical lines, are the times at which the flap started and finished its motion. Several features of the unsteady flow are apparent. The rise in the static pressure level upstream of the flap is caused by the introduction of the flap into the flow. There is very little delay in this signature with respect to the flap rise, and the pressure reaches its steady-state level shortly after the flap reaches its final position. At a location two flap heights downstream, a sudden drop in the pressure is observed some time

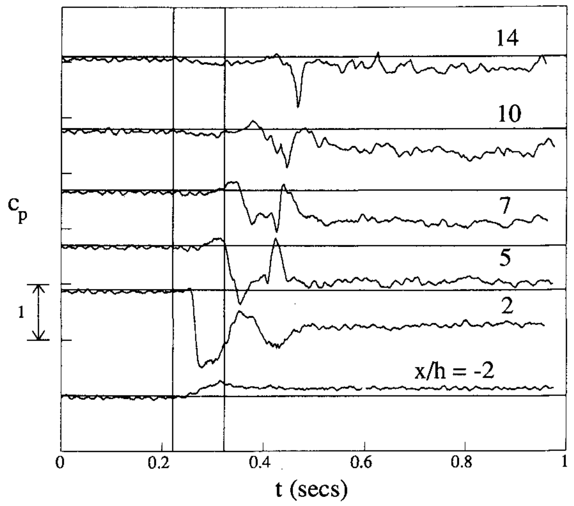

Fig. 3 Wall pressure changes during a flap-rise experiment: T_0 = 0.1 s; Re_{x0} = 9 × 10^5.

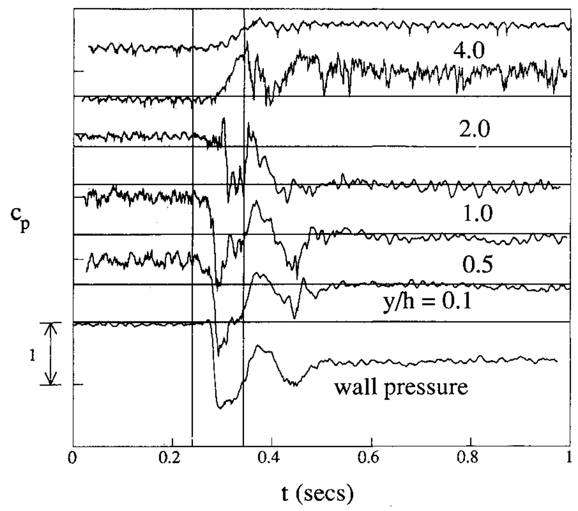

Fig. 4 Bidirectional probe response: T_0 = 0.1 s; Re_{x0} = 9 × 10^5; x/h = 2.

after the flap begins its extension. In this trace, as well as in those recorded farther downstream, one sees the signature of the initial vortex as it moves off the flap and is convected downstream. The delay in the arrival of this vortex at successive locations downstream, associated with its convective speed, is also clearly evident. The passage of the vortex is also detectable at x/h = 14, in the region downstream of reattachment; the presence of the separated region upstream of this point is indicated by a measurable increase of the pressure fluctuation level. Approximately four rise times were required after the flap motion commenced for steady conditions to be attained in this instance.

Figure 4 shows a sample of the flow direction data obtained using the bidirectional probe. These measurements were made at x/h = 2; all other conditions were the same as for the wall pressure data of Fig. 3. The traces shown were measured at five locations from the wall, ranging between $0.1 < y/h < 4.0$. The pressure difference between the upstream- and downstream-facing probes was normalized by the approach-flow freestream dynamic head. A zero c_p line has been drawn for each trace, and the direction of flow at each location is determined by the sign of c_p; a positive value indicates forward flow. The wall static pressure measured at this streamwise location has also been shown for reference. Several features of the flow are evident. The trace at y/h = 4 reflects an increase in the bidirectional probe signal associated with an increased concentration of streamlines in the outer flow due to the formation of the recirculation region beneath this point. The velocity increases and the static pressure drops in this region. The increase in fluctuation levels in the trace at y/h = 2 is due to the presence of the shear layer bounding the separated region. Flow reversal is seen only in the traces recorded at y/h lower than 1. It is also seen that flow reverses direction first nearest the wall; with a gradual delay as y/h increases. The signature of the initial vortex, as well as the unsteadiness in the flow as the separation develops, both of which were seen in the wall pressure, are also clearly observable in these traces.

Several realizations of the wall pressure data were obtained in order to examine the repeatability of these measurements. The ensemble-averaged traces of some of the data from Fig. 3 are plotted in Fig. 5. In each instance, the ensemble average was formed from 10 realizations. Although the random fluctuations are smoothed out, the gross features that are characteristic of the separation process, seen in the traces of Fig. 3, persist. The six solid lines, labeled a–f on Fig. 5, identify different time instants in the sequence of events. Line a corresponds to a time shortly after changes are detected in the static pressures close to the flap. The flow is approaching steady-state conditions at the last time line f shown. The four intermediate time lines follow the passage of a feature in the static pressure signal, near the initial minimum value, as the initial vortex proceeds downstream. A cross plot of the pressure at these different times, shown in Fig. 6, illustrates the manner in which the spatial pressure distribution changes with time during a flap-rise event. The pressure reaches a minimum value a short distance downstream of the flap (8 cm in this case). This occurs just as the initial vortex sweeps by the location. Thereafter, the pressure at this location rises and then drops once more to the steady-state value (time line f). The minimum pressure at locations farther downstream occurs at a later time instant and is not as low as at the 8-cm location. The initial vortex diffuses as it convects downstream; at locations beyond about 30 cm, no negative peaks are observed. A seventh time line, labeled r, has been added to this figure. This represents the static-pressure distribution at the instant t_a, when the first occurrence of reversed flow was detected by the bidirectional probe close to the wall at x/h = 2. It is seen that the response of the wall static pressure to the passage of the initial vortex and the formation of the separated zone varies substantially with streamwise location.

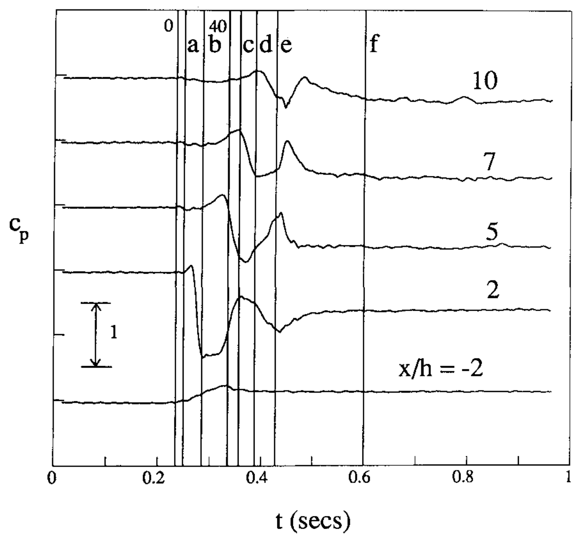

Fig. 5 Ensemble-averaged wall pressures: T_0 = 0.1 s; Re_{x0} = 9 × 10^5.

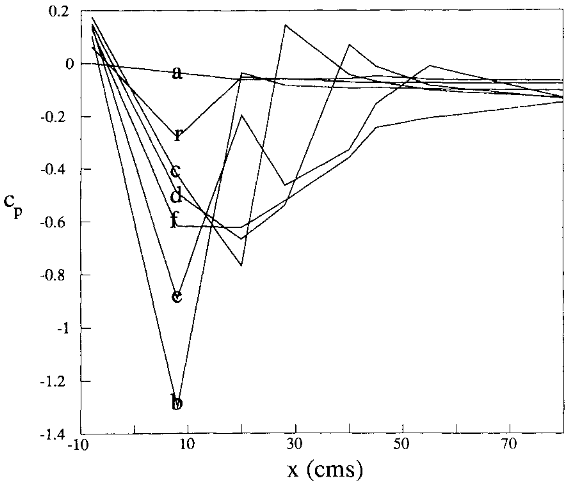

Fig. 6 Streamwise pressure variations: T_0 = 0.1 s; Re_{x0} = 9 × 10^5.

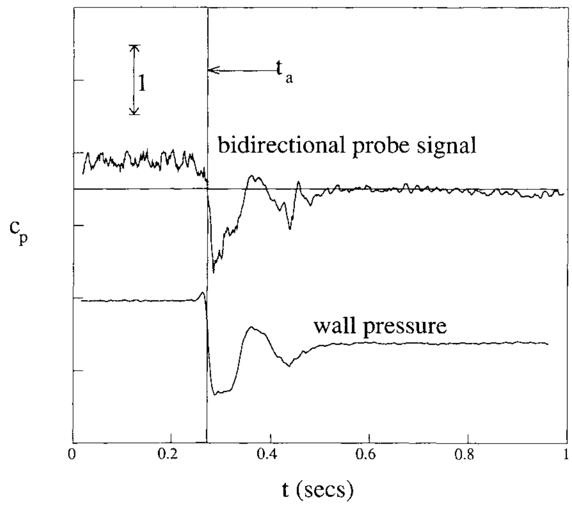

Fig. 7 Determination of t_a: T_0 = 0.1 s; Re_{x0} = 9 × 10^5; x/h = 2.

2. Performance of Selected Criteria for Detection of Flow Reversal

To detect a reversal in the direction of flow at any streamwise location in an unsteady situation, the static pressure was monitored at the detection location, as well as at a location upstream of the detection point. Different criteria for this purpose were developed and applied to these time series, and their suitability for this purpose was examined. Results obtained using two of the criteria will be discussed briefly. Data from two streamwise locations, x/h = 2 and 5, will be presented. Further details, as well as discussion of the performance of other criteria, can be found in Ref. 9.

The procedure used was the following. The ensemble-averaged wall pressure data obtained at one set of conditions (T_0 = 0.1, U_0 = 10 m/s, α_i = 0 deg, α_f = 90 deg) were examined to formulate the criteria. Next, each criterion was tested using individual wall pressure signals recorded over a range of each of the parameters. The results from each of the criteria were then examined to determine their usefulness and range of applicability.

An objective measure used to test the criteria is illustrated in Fig. 7. The bidirectional probe was used as a reference. Measurements were made with the probe placed 4 mm above the wall at the detection location, and the probe signal was examined to obtain the time t_a at which the first occurrence of reversed flow was detected after the start of the flap motion. The effectiveness of each of the criteria was determined by tests to see how accurately the time of first flow reversal was detected. Both t_a and t_d, the detection time, described later, were measured from the instant the flap motion was initiated.

Figure 8 illustrates the use of a threshold-value criterion for the wall pressure coefficient at the detection location. Based on tests with the measurements at the reference condition, the criterion was set to identify the time of flow reversal as the time when the value of c_p = -0.15 was reached. The figure compares this detection time t_d with t_a, the time obtained from the corresponding bidirectional probe measurement. Tests carried out with wall pressure signals over the range of parameters showed that this approach was viable for detection of flow reversal, although some scatter was introduced for T_0 values beyond 1 s, well into the quasisteady region.

A detection scheme based on the time derivative of the pressure is illustrated in Fig. 9. In a flap-rise experiment, the wall pressure drops rapidly as the separation front approaches the detection location. The pressure continues to drop further after flow reversal, but at a rapidly decreasing rate, leading to the sharp negative spike seen in the derivative of the wall pressure. This criterion was set to detect the minimum in the time derivative and identify the time at which this occurred as the detection time t_d. The figure shows a comparison of this value with the actual time of flow reversal t_a. It was found that the nature of the spike varied with flow conditions, with

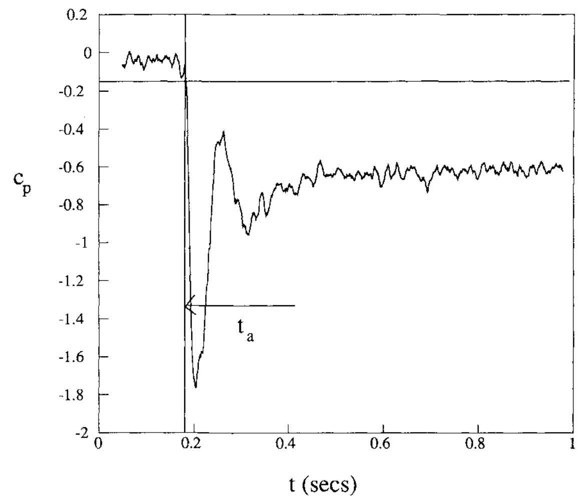

Fig. 8 Threshold criterion: T_0 = 0.06 s; Re_{x0} = 9 × 10^5; x/h = 2.

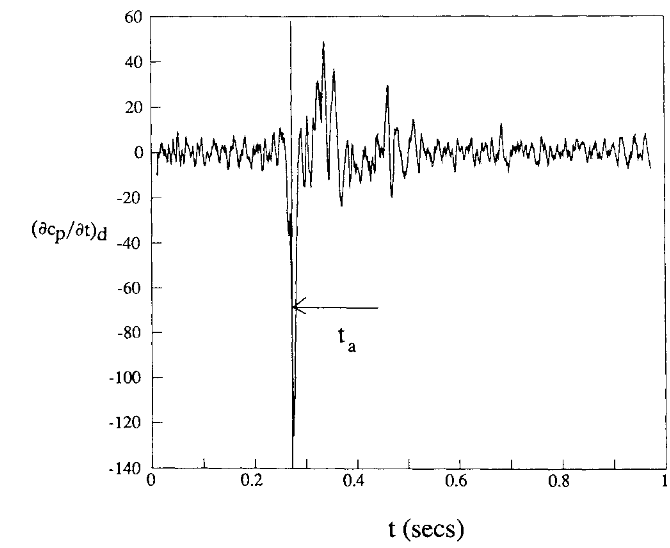

Fig. 9 Time derivative criterion: T_0 = 0.1 s; Re_{x0} = 9 × 10^5; x/h = 2.

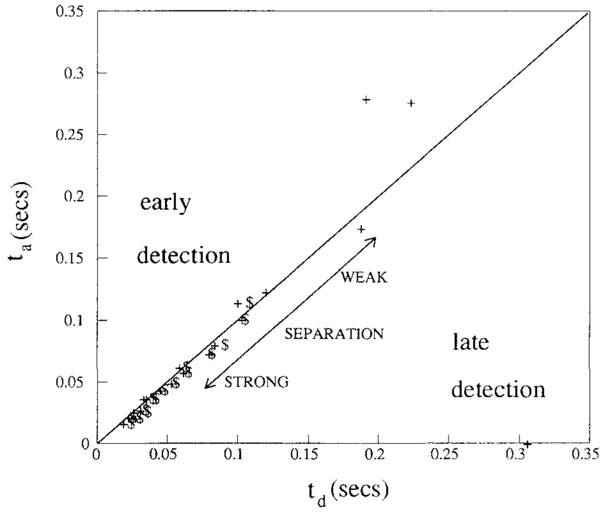

Fig. 10 Evaluation of criteria: + threshold criterion; $ time derivative criterion; $0.06 \le T_0 \le 2.0$ s; $9 \times 10^5 \le Re_{x0} \le 2.6 \times 10^6$; $2 \le x/h \le 5$.

a sharper spike being formed at higher velocities and the smaller rise times, when a stronger initial vortex was formed. A limitation on the applicability of this criterion was imposed by the fact that the magnitude of the spike decreased gradually with reduction in the flow velocity and increase in rise time to a point where the spike was of the order of magnitude of the changes due to random pressure fluctuations in the pressure signal. Under these conditions, the criterion failed completely to detect the occurrence of flow reversal.

An examination of the performance of these and other criteria for detection of flow reversal revealed that errors were introduced in the values of both t_a and t_d when the magnitude of the pressure fluctuations approached the mean pressure level. For instance, a premature indication of flow reversal resulted from the bidirectional probe measurements in some cases. To overcome this problem, the pressure signals were processed with a low-pass filter prior to the application of these criteria. It was found that the use of a properly designed filter consistently improved the detection ability under these marginal conditions and that filtering did not adversely affect the performance in situations where good results were obtained with unfiltered data.

3. *Evaluation of Performance*

The various criteria considered were evaluated by comparing the actual time of flow reversal t_a with t_d, the time of flow reversal detection. A sample of such a comparison is shown in Fig. 10. Data on the 45-deg line on such a plot imply perfect performance by the criterion in question, whereas locations to the left and right of this line correspond to early and late detections, respectively. Shown on the figure are data for the two criteria discussed. Both perform very well, except for some instances when the value of $T_0 > 1$ s, i.e., for so-called weak separations. For reasons already discussed, the threshold algorithms exhibited some scatter about the ideal performance line, whereas the time derivative criterion did not pick out flow reversal at all. Results showed that these two procedures yielded the best results over the domain of test parameters. Reference 9 contains a detailed discussion of the basis for the selection or rejection of the other criteria considered.

One advantage of the present approach to separation detection is the ability to tune these criteria. The error in detection, $t_d - t_a$, can be altered by changing the threshold value. If, for instance, early detection is desired for a certain range of flow conditions, it is possible to adjust the threshold value to reduce this value or make it negative. This feature might be exploited to advantage in active control applications to compensate for time lags introduced in the system by other factors.

C. Flap-Drop Experiments

We have restricted our discussion thus far to flow-state identification during the inception of an unsteady separated flow. It is also necessary to be able to determine when a separation gives way to flow reattachment. The ability of different criteria to monitor the wall pressure in an initially separated region and detect the occurrence of forward flow was also examined by conducting a series of flap-drop experiments. The flap was held at a nonzero initial angle (values of 90, 45, and 30 deg were used) until steady conditions were obtained. The flap was then moved into the wall with a ramp-type time-motion history while the wall pressure and flow direction were monitored. Figure 11 shows a typical result obtained using a threshold-value criterion on a filtered wall pressure signal. The flap motion was from 90 to 0 deg. The threshold level used ($c_p = -0.15$) was the same as for the flap-rise experiments. The time instants marking the beginning and end of flap motion are shown by vertical lines. The first instance of forward flow t_a, determined using the bidirectional probe, is also shown. In this instance, detection was slightly premature. It was found that, overall, a threshold-value criterion yielded good results in the flap-drop experiments. On the other hand, the time-derivative criterion either yielded erroneous results or failed because the spike, accentuated in the flap-rise experiments by the initial vortex, was much weaker here.

D. Combined Flap Motion

A limited number of experiments were conducted in which the flap was moved into the attached boundary layer, held for a prescribed length of time, and then brought back into the wall. The criteria developed for the flap-rise and flap-drop experiments were then applied to the measured wall pressure data. Figure 12 shows a sample result from this set of experiments and compares the threshold-value criterion with the actual times of occurrence of reverse and forward flow. This phase of the experiments established that schemes for the detection of individual occurrences of separation or reattachment could be combined successfully.

E. Controllability Issues

If the present flow-state detection scheme is to be incorporated successfully in a reactive control system, several requirements need to be met from a control standpoint. Im-

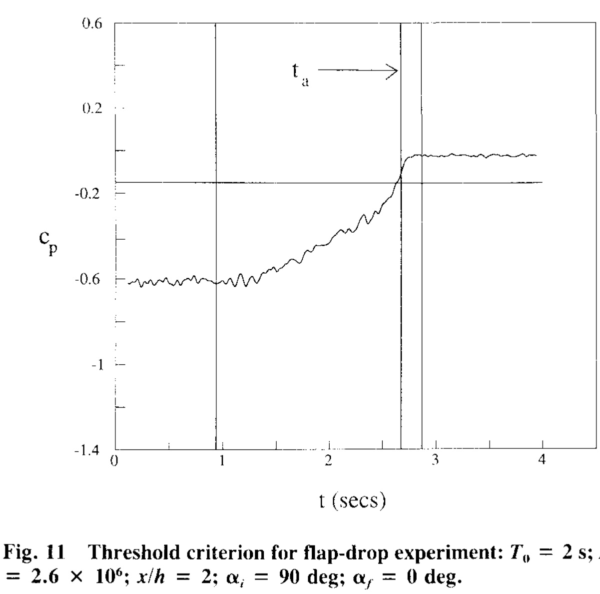

Fig. 11 Threshold criterion for flap-drop experiment: $T_0 = 2$ s; $Re_{x0} = 2.6 \times 10^6$; $x/h = 2$; $\alpha_i = 90$ deg; $\alpha_f = 0$ deg.

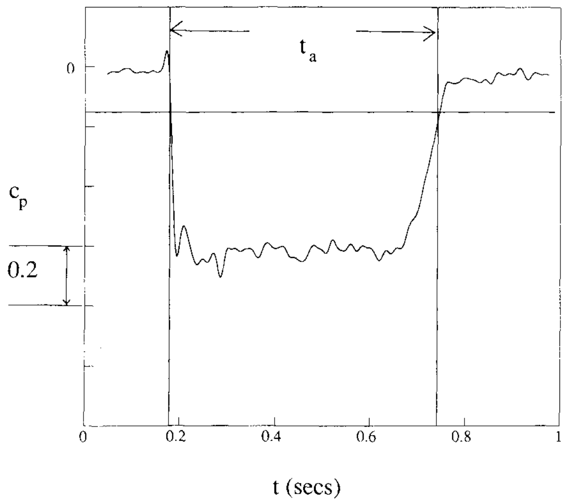

Fig. 12 Detection for combined flap motion: $T_0 = 0.1$ s; $Re_{x0} = 2.6 \times 10^6$; $x/h = 2$.

portant among these is a high level of repeatability in the pressure signal to ensure that the time of detection of change in flow state is unchanged, within defined limits, when the experiment is repeated several times. This requires that the unsteady separation must exhibit a high degree of coherence. This requirement was examined in the present experiments. Ten individual realizations of the pressure signal were acquired for each set of conditions tested, and the flow-state criteria were tested for each of the realizations. The data of Fig. 10 represent the average value from these tests. The scatter or uncertainty in detection time was ∓ 5% for the range of test parameters. As discussed earlier, it proved necessary to low-pass filter the signals prior to application of the criteria when the magnitude of pressure fluctuations approached the mean pressure level. Such filtering consistently improved the detection ability and did not adversely affect performance. It is, therefore, to be expected that such an approach to detection of flow state can be used for unsteady separations, such as the present flow, in which the process of separation is characterized by the evolution and movement of a strong vortex. The unsteady separation over a pitching airfoil would be an example of such a flow. The feasibility of incorporating the threshold criterion for the detection of flow reversal in a reactive control scheme has been demonstrated by Montividas et al.[11] In these experiments, the detection scheme was used in a control algorithm to actuate a pulsed-jet controller that successfully reduced the reattachment length of the separated region behind the flap as the flap executed random motions.

IV. Conclusions

A simple, nonintrusive technique for detection of flow reversal has been developed for a model flow that exhibits some of the characteristics of an airfoil leading-edge separation. The experiments have demonstrated that wall pressure data, together with prescribed criteria for detection of flow reversal, can be used effectively to identify the onset of both separation and reattachment in this unsteady flow. Two criteria, one based on a comparison of the wall pressure with a threshold value and the other on the time derivative of the wall pressure, were found to work best. Although this approach must be tested for different geometries and flow conditions, it should be successful in situations where the wall pressure signature clearly reflects the passage of a vortex. The procedures developed in this study thus have potential for utilization in the active control of unsteady separation in practical situations such as the flow over a pitching airfoil. The wall pressure could be monitored at a number of locations and processed simultaneously, using one or more of the criteria for the identification of flow reversal, to yield a signal indicative of the flow state at each measurement location. This information could then be used to activate or deactivate a suitably located separation controller within the flow.

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