Lift Response of a Stalled Wing to Pulsatile Disturbances

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The transient lift response of a low-Reynolds-number wing subjected to small amplitude pulsatile disturbances is investigated. The wing has a small aspect ratio and a semicircular planform, and it is fully stalled at a 20 deg angle of attack. Microvalve actuators distributed along the leading edge of the wing produce the transient disturbance. It is shown that the lift response to a single pulse increases with increasing actuator supply pressure and that the lift response curves are similar to each other when scaled by the total impulse. Furthermore, for fixed actuator supply pressure, the amplitude and total impulse of the transient lift response curve increases with increasing external flow speed. In this case, the lift response curves are similar when scaled by the dynamic pressure. The lift response to a single pulse can be treated as a filter kernel, and it can be used to predict the lift time history for the arbitrary actuator input signals. The kernel is similar in shape to transient measurements obtained by other investigators on two-dimensional wings and flaps. Comparisons between the model predictions and the experiments using multiple pulse inputs and square-wave modulated input signals at low frequencies are presented.

Nomenclature

C	=	calibration constant for convolution
C_L	=	lift coefficient
C_n	=	force coefficient normal to the plate surface
C_μ	=	momentum coefficient, $(\rho U_{\text{jet}}^2 h)/(0.5\rho U^2 c)$
c	=	chord at midspan of wing, m
f	=	frequency, Hz
h	=	actuator slot width, m
I_t	=	total impulse of the lift time curve $\int_{ti}^{tf} \Delta L(t)\,\mathrm{d}t$, N · s
K	=	approximation to the filter kernel obtained from experimental data, N
L_o	=	baseline lift of the wing without actuation, N
p_{act}	=	actuator supply pressure, Pa
S	=	planform area of the wing, m^2
St	=	Strouhal number, $\frac{fc}{U}$
t^+	=	time normalized by the convective time scale, $= tU/c$
U	=	freestream speed, m/s
u	=	arbitrary input signal
x	=	distance from actuation to trailing edge of the two-dimensional plate, m
α	=	angle of attack, deg
Γ_0	=	circulation in baseline flow, m^2/s
ΔL	=	lift force increment relative to the undisturbed lift, N
Δt_{on}	=	time actuator valve is open, s
Δt_{on}^+	=	time actuator valve is open and normalized by convective time
$\Delta \Gamma$	=	change in circulation, m^2/s
φ	=	phase between actuator input signal and lift response, deg

I. Introduction

THE ability of active flow control to increase lift or delay the onset of flow separation on wings at high angles of attack is well known for steady-state conditions [1,2]. In contrast, the implementation of active flow control in dynamic situations, such as in gusting flows or during rapid maneuvers, is not well understood, but it is important if one is to achieve control on time scales faster than the limits of quasi-steady aerodynamics. If a quasi-static approach to control is attempted on an airfoil in an unsteady flow or when undergoing rapid maneuvers, then at least two sources of error will occur. The first is related to the unsteady aerodynamic forces, for which dynamic changes in the external flow introduce time delays and amplitude changes in the forces and moments (even when the flow is fully attached). These effects are related to the time for vorticity to advect in the wake and to added mass effects, which are the foundation of Theodorsen's [3] classical theory. If the flow separates during a maneuver, as commonly occurs with helicopters and biological flyers, then phenomena such as dynamic stall and hysteresis will introduce additional time scales. Accurate models of these unsteady aerodynamic effects are important components for controllers capable of functioning in unsteady flow environments.

A second source of error is associated with the delayed response of the forces acting on the wing relative to the actuator input. A significant time delay can occur between the onset of actuation and the maximum lift response. During steady-state flight and actuation conditions, there are no transients to produce a time delay. By contrast, changing flight conditions require changes in actuator settings, and the resulting time delays between lift response and actuator input can be significant [3–5]. These actuation effects must also be modeled, so that the controller can match the response to

actuation with the unsteady aerodynamic effects and achieve the desired response.

For the most part, past studies focused on the steady-state behavior of the flow, for which only time continuous (e.g., sinusoidal) actuation is needed for producing changes. Early studies [6,7] determined that effective actuation frequencies should be scaled with convective time, $t^+ = c/U$, which is the time for disturbances to advect over a characteristic length of the wing. The amplitude of the steady-state lift response is usually correlated with the momentum coefficient C_μ. The frequency and amplitude scaling parameters have physical meaning through their connection with flow instabilities. When the airfoil is in a fully stalled state, then the convective time scale is comparable with the period of vortex shedding in the wake. There is a coupling between vortical structures in the wake and the separating flow from the airfoils, so that steady-state actuation at $St \sim \mathcal{O}(1)$ affects the coupling between the wake and the airfoil [8,9]. More detailed studies using numerical simulations of flow over a 2-D airfoil [10] identified three naturally occurring flow instabilities that exist during steady-state conditions and are important to the dynamics of the actuator-to-flow interaction mechanism that must be modeled for control. The instabilities are connected with the shear layer, the separation bubble, and the wake, and each has its own length scale and specific frequency scaling parameters. Adding unsteady aerodynamic effects on top of this already complex mix of instabilities suggests that new approaches to flow control may be necessary.

In attempting to better understand the problem, the response of the separated flow system to individual pulses from the actuator was studied. The transient behavior of the forces acting on wings in response to pulse-type or step input disturbances can be significantly different from the steady-state response. An extensive study of step input transient flow associated with reattachment and separation was conducted by Darabi and Wygnanski [5,11] on a 2-D deflected flat plate. Using step inputs from a zero-net-mass, voice coil driven actuator, it was shown that the total time it takes for the flow to reattach on a deflected flat plate was long, $\mathcal{O}(20-50t^+)$, in terms of convective time units and was largely dependent on the frequency and amplitude of excitation. For fixed values of the forcing parameters C_μ and St, the transient lift response to a step input scaled with the dynamic pressure and the convective time scale.

The transient response of the separated flow on 2-D airfoils to pulse-type actuation input was investigated by Amitay and Glezer [4,12]. The effects of flow transients occurring at the onset and termination of actuation were documented. Glezer et al. [9,13] also studied the lift response to short-duration pulses produced by combustion actuators and found that energetic pulses from the actuators, with time scales as short as $\mathcal{O}(0.05t^+)$, were effective in producing a momentary increase in circulation around the airfoil [9]. The relaxation time of the circulation back to the undisturbed state was long, on the order of $\mathcal{O}(5-10t^+)$. The effect of different pulse sequences on the circulation was also explored [13]. By increasing the number of pulses in a sequence from 1 pulse to 5 and 10 pulses, it was shown that the streamwise extent of the attached flow region was increased, and the net circulation above the airfoil was also increased.

In this work, short-duration pulsatile disturbances are used for the purpose of system identification of the separated flow around a low-aspect ratio three-dimensional wing. The response of the separated flow system to a single pulse gives an approximate impulse response model that can, within certain limits, be used to predict the large-scale features of the lift response to various time-varying actuator input signals. The model can also be used as part of a control algorithm to simulate actuator response.

The focus of this paper is on the lift response of the separated flow to transient and continuous pulsatile actuation. It is shown that a linear model is capable of predicting many characteristics to the actuator response that might otherwise be considered to be nonlinear effects. The details of the experimental procedure are given in the next section. The transient lift measurements in response to the different pulse amplitudes and different freestream conditions are given in Sec. III. The ability of the model to predict the response of transient and continuous input signals is examined in Sec. IV, and a

discussion of the limitations of the linear model are presented in Sec. V. The conclusions of the study are presented in Sec. VI.

II.   Experimental Procedure

The experiments were conducted in the Andrew Fejer Unsteady Flow Wind Tunnel at the Illinois Institute of Technology. Figure 1 shows the wind-tunnel test section with the model mounted on its sting. The test section dimensions were 610 by 610 mm with a length of 3,100 mm. Three different flow speeds were used during the experiments: 3, 5, and 7 m/s. The highest level of freestream turbulence level was measured to be 0.6% at an average speed of 3 m/s and over a bandwidth from 0.1 to 30 Hz.

The wing has a semicircular planform with the circular part forming the leading edge and the straight line forming the trailing edge. The center span wing chord c is 0.203 m. The leading edge is tapered with a 5:1 elliptic shape, following the designs used by [14], and the thickness-to-chord ratio is 0.069. The chord-based Reynolds numbers Re_c range from 47,000 to 109,000. A photograph of the wing with the plenum cover plates removed is shown in Fig. 2a, enabling the microvalve actuators to be seen. The valves are positioned radially along the leading edge, and the actuator jets blow outward and upward at a 10 deg angle from the chord line, as shown in Fig. 2b. The wing is constructed from Duraform® nylon using a 3D Systems selective-laser-sintering rapid-prototyping machine. The wing is fixed at an angle of attack of $\alpha = 20$ deg for all of the measurements in this study. The flow is fully separated, as shown by the smoke wire visualization photograph in Fig. 3. At a $\alpha = 20$ deg angle of attack, the blockage area ratio is 6%. The data presented in this paper are only the time-varying deviations from the steady-state lift. The standard blockage corrections are only applicable to the steady lift, so that it is not clear how corrections to unsteady lift should be made. As a result, no corrections for blockage were made to the data.

The semicircular planform was chosen because of its continuously varying leading-edge sweep angle, which was an intermediate shape between a rectangular planform and a high-sweep angle delta wing. Earlier investigations [15] focused on stabilizing and controlling the leading-edge vortex (LEV), for which it was determined that the sweep angle played an important role in the ability to stabilize the LEV. In particular, a rectangular planform did not allow a stabilized LEV to be formed, whereas a high-sweep angle delta wing would form a stabilized LEV. In the semicircular planform, the leading-edge sweep angle varied from 0 deg at the midspan to 90 deg at the tip, which allowed some control over the strength of the LEV with the actuator.

It was determined that the mechanical system supporting the wing had a resonant frequency at 19 Hz that introduced noise into the lift measurements. Precautions were taken to reduce the oscillations, but
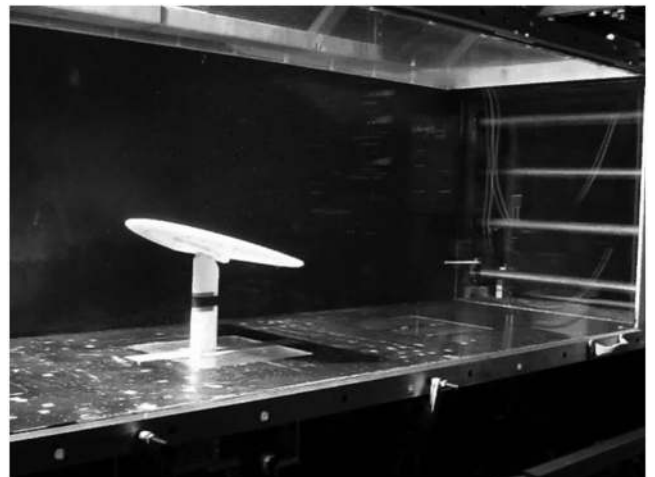

Fig. 1   Wind-tunnel test section showing the semicircular wing model mounted on its sting. Flow is from left to right.
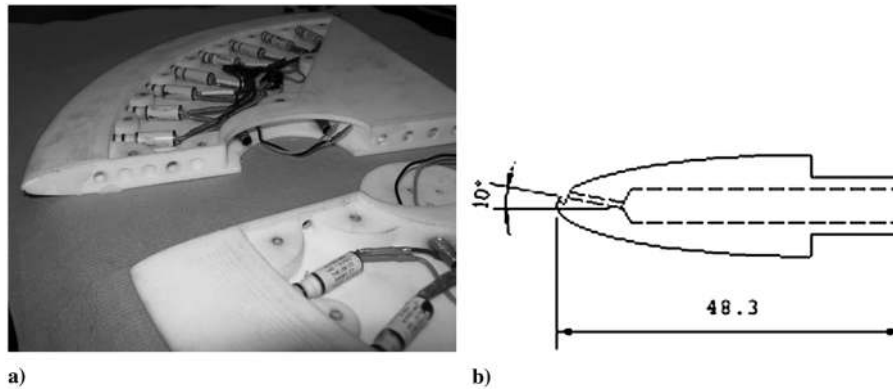
Fig. 2 The wing model components and leading edge: a) view of the disassembled wing model with the plenum cover plate removed (the 16 microvalve actuators can be seen positioned radially along the circular leading edge) and b) cross section of the leading edge, showing the dimensions (in millimeters) and the direction of the actuator jet blowing.

they could not be completely eliminated and were the principal source of noise in the lift signals. Spectra obtained at different wind-tunnel operating conditions indicated that the 19 Hz did not produce combination modes with other frequencies. Therefore, it is believed that the mechanical resonance had no significant influence on the fluid dynamics.

The pulsed blowing actuation system consisted of a regulated air supply, a plenum inside the wing, and 16 Lee microvalves designed to fit into the leading edge of the wing. The flow rates corresponding to the actuator microvalves, running continuously at 29 Hz with actuator supply pressures of 6.9 kPa (1 psi), 20.7 kPa (3 psi), and 34.5 kPA (5 psi), were 1.91×10^{-4} kg/s, 3.35×10^{-4} kg/s, and 9.26×10^{-4} kg/s, respectively. The valve open time was set at $\Delta t_{\mathrm{on}}^{+} = 0.42$ ($\Delta t_{\mathrm{on}} = 0.017$ s) for most of the data presented here. The value of Δt_{on} was based on a 29 Hz square-wave signal, which produced significant increases in steady-state lift during continuous pulsing experiments. The valves were controlled by a PC-based data acquisition system using a National Instruments 16 bit A/D converter and software written with Mathworks Data Acquisition Toolbox. The sampling rate was 1000 samples per second, giving an uncertainty of ± 0.0005 s for the pulse time interval.

The forces and moments acting on the wing were recorded with a 6 component balance (ATI Industrial Automation, Inc.: Nano 17). A known weight was added (and removed) to the wing before and after a set of measurements to check the calibration. The uncertainty in the force measurement was based on the repeatability of the calibration data and was estimated to be approximately 0.05 N, which is the total uncertainty, including bias and precision errors.

III. Results

The lift response to a single pulse input and its scaling with parameters, such as freestream velocity and actuator supply pressure, is described in this section. Unless otherwise noted, the time of the single pulse is 0.017 s ($0.25 < \Delta t_{\mathrm{on}}^{+} < 0.59$), which is small compared with the response times of the flow, $t^{+} \sim \mathcal{O}(10)$.

The data in Fig. 4 show the phase-averaged lift response to a single pulse of the actuator relative to the baseline lift. The phase-averaged signal was constructed by averaging 59 cycles. The 59 cycles of data were obtained in a continuous run with a 5 s delay after each actuator pulse to allow the flow sufficient time to reestablish equilibrium before the next pulse occurred. The flow speed was constant at 5 m/s for this set of measurements, and the results for five different actuator supply pressures are shown, ranging from 6.9 kPa (1 psig) to 34.5 kPa (5 psig). The higher frequency oscillations correspond to the 19 Hz mechanical resonance mentioned in the previous section.

Increasing the supply pressure to the actuator leads to an increase in the lift response. For a constant valve open time, increasing the supply pressure increases the amount of mass, momentum and energy injected into the flow. It is clear from the data in Fig. 4 that a pulse with more momentum produces a larger lift.

The transient response has three distinct regions, which are similar to those observed on 2-D airfoils and flat deflected flaps by other investigators [5,11,12]. Over a short initial period ($0 < t < 0.035$ s, $0 < t^{+} < 0.86$), immediately after the valve opens, a small decrease in lift is observed. In the controls community, this initial reversed-direction response is known as a nonminimum phase response. Nearly identical behavior on 2-D flaps was found by Darabi and
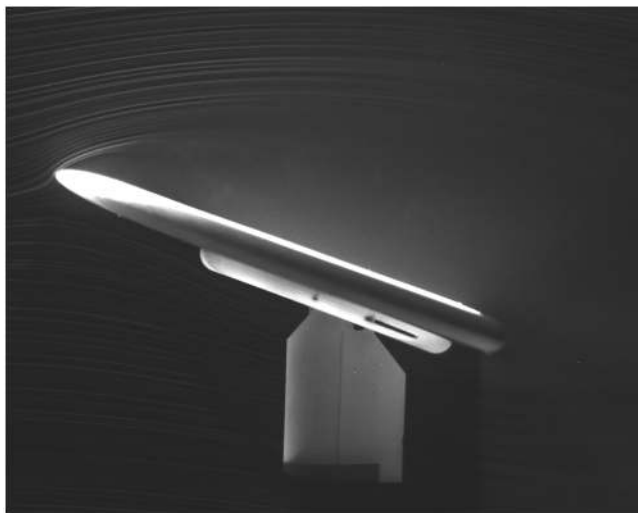

Fig. 3 Smoke wire flow visualization of the flow over the midspan section of the wing at $\alpha = 20$ deg. The separation occurs at the leading edge and is fully separated over the suction surface of the wing.
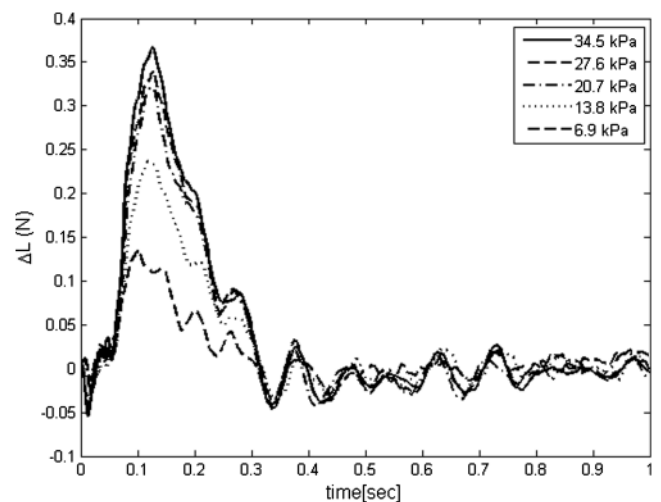

Fig. 4 Phase-averaged lift response to a single pulse disturbance by the actuator. Five different actuator supply pressures were used. The freestream speed was constant at $U = 5$ m/s.

Wygnanski [5] in their transient normal force measurements to a step input from the actuator. The minimum C_n value occurred at $t^+ = 2.5$ and showed a slight decrease with increasing C_μ. Their detailed study of the vorticity field determined that this adverse surge behavior is the result of the initial vortex formed by the actuator. Similar behavior was also seen in the pulse input response experiments by Brzozowski and Glezer [9]. The change in circulation $(-\Delta\Gamma/\Gamma_0)$ measured around their 2-D airfoil first decreased by about 12% at $t^+ = 1.8$, then it rapidly increased. During the next portion of the response from $(0.035 < t < 0.1$ s; $0.86 < t^+ < 2.5)$, the lift increased rapidly to its maximum value. The pulse input experiments reported in [9] show similar behavior and reach a maximum change in circulation at $t^+ = 2.3$. The step input experiments of [5] have a different response: a rapid increase until $t^+ = 5$ followed by a slower linear increase until the new final steady-state C_n value is reached. The final portion $(0.1 < t < 0.4$ s; $2.5 < t^+ < 10)$ of the response is a slow relaxation from the peak lift value back to the undisturbed flow state. The similarities of the transient lift response among the different separated flow systems suggest the fundamental fluid dynamic processes are the same, irrespective of the wing geometry, actuator location, or the type of actuator.

For a single pulse from the actuator, the momentum input to the flow can be increased either by increasing the pressure or by increasing the time that the valves are open. Increasing the actuator pressure will create a higher actuator jet velocity, whereas increasing the valve open time will maintain a constant actuator velocity for a longer period of time. Intuitively, one expects the effects on the flow may be different, because deeper penetration of the actuator jet into the oncoming flow most likely will have a different effect on the separated flow than a longer duration pulse at low speed. In either case, it is useful to consider the integral of the momentum flux from the actuator and the integral of the lift response from the wing.

The area under the lift time curve is a measure of the total impulse I_t and is obtained by numerically integrating the experimental data with the trapezoidal method. The dependence of the lift response on the square root of the actuator supply pressure is shown in Fig. 5 and includes two independent measurements. The relationship is repeatable and nearly linear over the range of supply pressures used.

Dividing each lift curve in Fig. 4 by its total impulse I_t collapses the data onto a single curve, as shown in Fig. 6. If the supply pressure continues to increase, then the nonlinear response of the valve and nonlinear response of the flow response will become important. For example, if the actuator were to completely reattach the flow over the
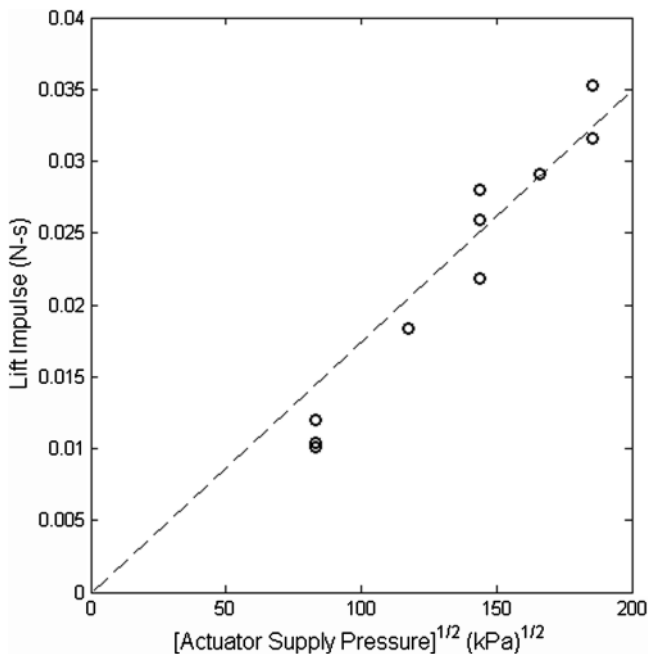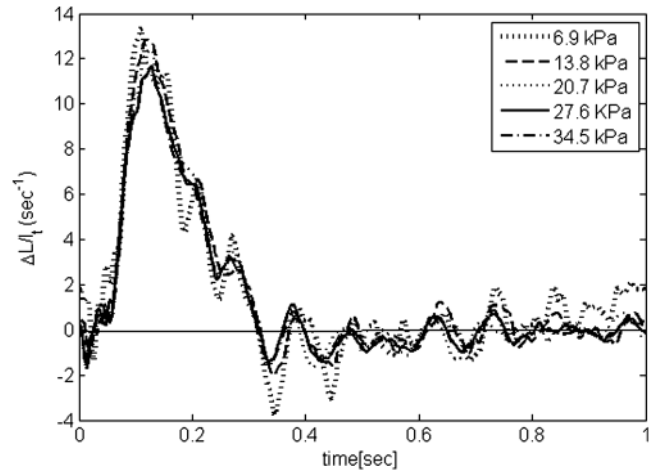

Fig. 6   Transient lift response to a single pulse disturbance scaled by the total impulse I_t. The flow speed is a constant 5 m/s, and the pulse duration time is 0.017 s.

wing, then the lift response will saturate, ending the linear response behavior. The nearly linear response exhibited by the wing's separated flow system suggests that the complete reattachment has not been reached yet.

The lift response to the single pulse disturbances at different freestream speeds is shown in Fig. 7. Again, the angle of attack is kept constant at $\alpha = 20$ deg, the actuator supply pressure is fixed at $p_{act} = 34.5$ kPa (5 psi), and the pulse duration time is constant is at $\Delta t_{on}^+ = 0.42$ s. The response curves show that the lift magnitude increases as the freestream speed increases. This observation was somewhat counterintuitive, because the ratio of the actuator pulse velocity to the freestream velocity is decreasing, which means that C_μ must also be decreasing. In this case, the lift is increasing while the momentum coefficient is decreasing. However, the strength of the vorticity in the separated shear layer at the leading edge is also increasing with increasing flow speed, whereas the momentum input from the actuator remains constant. It is speculated that a stronger vortex with increased circulation is formed at the higher flow speeds, thereby resulting in a larger transient lift response. The data in Fig. 7 also show a decrease in the relaxation time from the maximum lift to the steady-state value as the flow speed increases, which is consistent with a disturbance being convected downstream by the flow. This result suggests that scaling by the convective time scale is appropriate, which is examined next.

The lift is normalized by the dynamic pressure and planform area, in Fig. 8, to produce a lift coefficient for the transient $\Delta C_L = \Delta L/qS$. In combination with the convective time scaling, the data at

Fig. 5   Total impulse of the lift response and its dependence on supply pressure to the actuator. The data were obtained for $U = 5$ m/s.
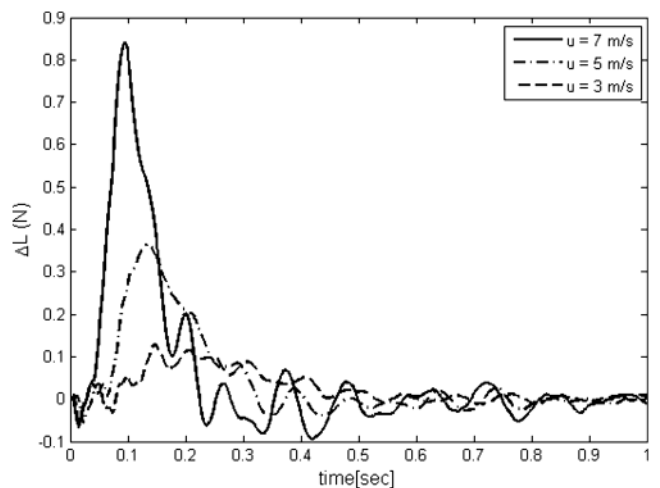

Fig. 7   Lift response at different freestream speeds. The momentum from the actuator is constant with a $p_{act} = 34.5$ kPa pulse and $\Delta t_{on} = 0.017$ s.
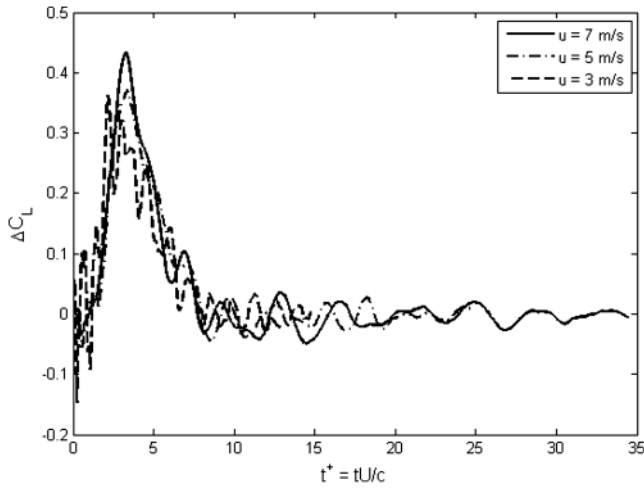
Fig. 8 Lift coefficient response to a single pulse showing dependence on the convective time. The actuator supply pressure was constant at 34.5 kPa, and the pulse duration time was 0.017 s.

a fixed actuator supply pressure are found to collapse onto a single curve. The data show that, for a given input of momentum by the actuator (constant supply pressure and valve open time), the transient response of the flow is governed by the external flow speed, and the response curves become similar in shape. There was concern that the collapse of the data in Fig. 8 may simply be the result of the lift coefficient saturating at a high value of the momentum coefficient. But, lower momentum coefficients can be achieved by using lower actuator supply pressures, and when lower actuator supply pressures are used, the data collapse equally well, indicating that the lift coefficient is not saturated.

IV. A Linear Model of the Lift Response

The impulse response of a linear system can be convolved with an arbitrary time-varying input signal to predict the system's output. In this experiment, it is assumed that the response of the separated flow to a short-duration pulse approximates an impulse response, because the pulse duration time is short, relative to the system response time. Furthermore, it is assumed that even though the detailed interactions between the actuator input and the response of the shear layer are certainly nonlinear, the results in the previous sections indicate some degree of linear behavior in the lift response over the range of operating conditions. In this section, the phase-averaged single pulse response is used as an approximation to an impulse response kernel, and its ability to predict the system output to the square-wave input signals is tested.

The lift response curve corresponding to $p_{act} = 34.5$ kPa, shown in Fig. 4, is used as the kernel $K(j)$ in the convolution to obtain a predicted output signal

$$w(k) = C \sum_j K(j)u(k-j)$$

where $u(k)$ is the arbitrary input signal. A square wave is used as the input signal $u(k)$ with a magnitude of 1.0. To find the calibration constant C, the total impulses of the 1-, 3-, 5-, and 10-pulse experiments were compared with the corresponding predicted total impulses. A value of $C = 0.85$ gave lift impulse predictions for the multiple pulse experiments that were within 27% of the measured values. The predicted and measured lift responses are shown in Fig. 9 for the 3-, 5-, and 10-pulse inputs. The differences between the predicted lift coefficient and the measurements were 15, 15, and 27%, respectively. In general, the model overpredicts the initial transient response and underpredicts the recovery during the decay. But even though the differences between the model prediction and measurements are large, the trends in the transient lift response with an increasing number of pulses from the actuator are captured by the linear model. The important trends explained by the model include

increasing lift amplitude with the increasing number of pulses, the basic shape of the ramp up in lift at the start of the pulse train, and the decay at the end of the pulse train.

It is also of interest to test the linear model's ability to predict the lift response to a continuous periodic type of actuation. The measured and predicted responses to different square-wave input signals is shown in Fig. 10a–10c. The actuation is a low-frequency modulation of a continuous train of square-wave pulses [with on and offtimes of $\Delta t_{on}^+ = 0.425$, equivalent to a $St = 1.1$ (29 Hz) square-wave carrier signal]. The low-frequency modulation signals are at frequencies of $f = 0.4, 1.4,$ and 5 Hz, corresponding to $St = 0.016, 0.056,$ and 0.2. The baseline lift that occurs without forcing is shown in each figure as the horizontal dash-dot line at $C_L = 0.8$.

Figure 10a compares the predicted lift to measured lift at $St = 0.016$ (0.4 Hz) modulation frequency. The phase between the actuation signal and the lift response at the fundamental forcing frequency was measured using a cross-spectral density function. With a 2.5 s period, the flow has a nearly quasi-steady lift behavior, and only a small phase shift ($\varphi = 29.8$ deg) exists between the control signal to the actuator and the lift response. The phase shift predicted by the model is $\varphi = 26.2$ deg. The percentage difference in amplitudes between the model prediction and the measured lift was 5.1%.

The low-pass filter character of the system becomes apparent when the forcing frequency is increased to $St = 0.056$ ($f = 1.4$ Hz). The data in Fig. 10b show that the square-wave input to the valve is rounded at the corners of the lift signal because of the attenuation of higher frequencies. The phase delay between actuator input and lift response becomes even more significant at the higher forcing frequency. The phase shift between the actuator input and the lift at $St = 0.056$ is $\varphi = 79.8$ deg. The linear model predicts a phase shift of $\varphi = 82.5$ deg, which corresponds to a 2.7 deg error. The model overpredicts the amplitude of the lift fluctuation in this case by 6.4%.

When the forcing frequency is increased to $St = 0.2$ (5 Hz), as shown in Fig. 10c, then the amplitude of the lift fluctuation is significantly reduced by the filtering effect of the kernel. The measured phase shift is $\varphi = 182$ deg. At this frequency, the model underpredicts the fluctuating lift force by 8.3% and overpredicts the phase ($\varphi = 243$ deg) by 61 deg.

Although the model inaccuracies are large, a number of important trends in behavior are explained by the linear convolution. For example, as the actuator frequency of pulsing increases, the average
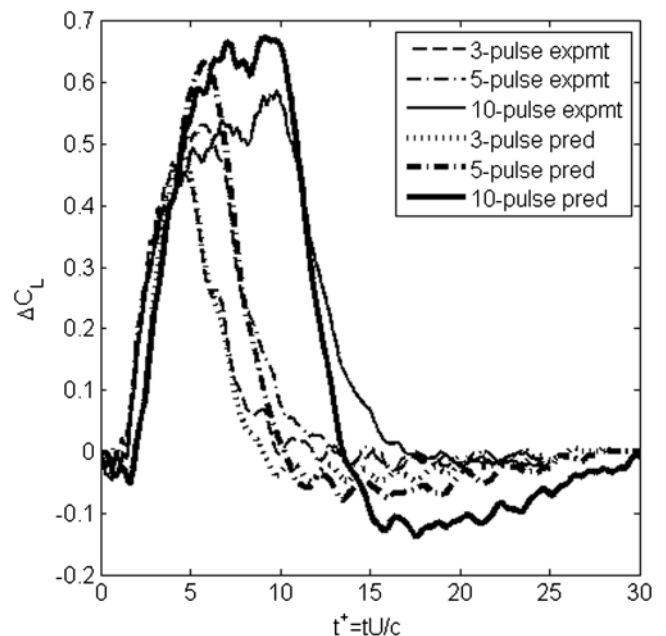

Fig. 9 Comparison of experimentally measured lift response and the lift predicted by convolving a 10-pulse square-wave signal with the impulse response kernel. The freestream speed was $U = 5$ m/s, and the valve supply pressure was 34.5 kPa.
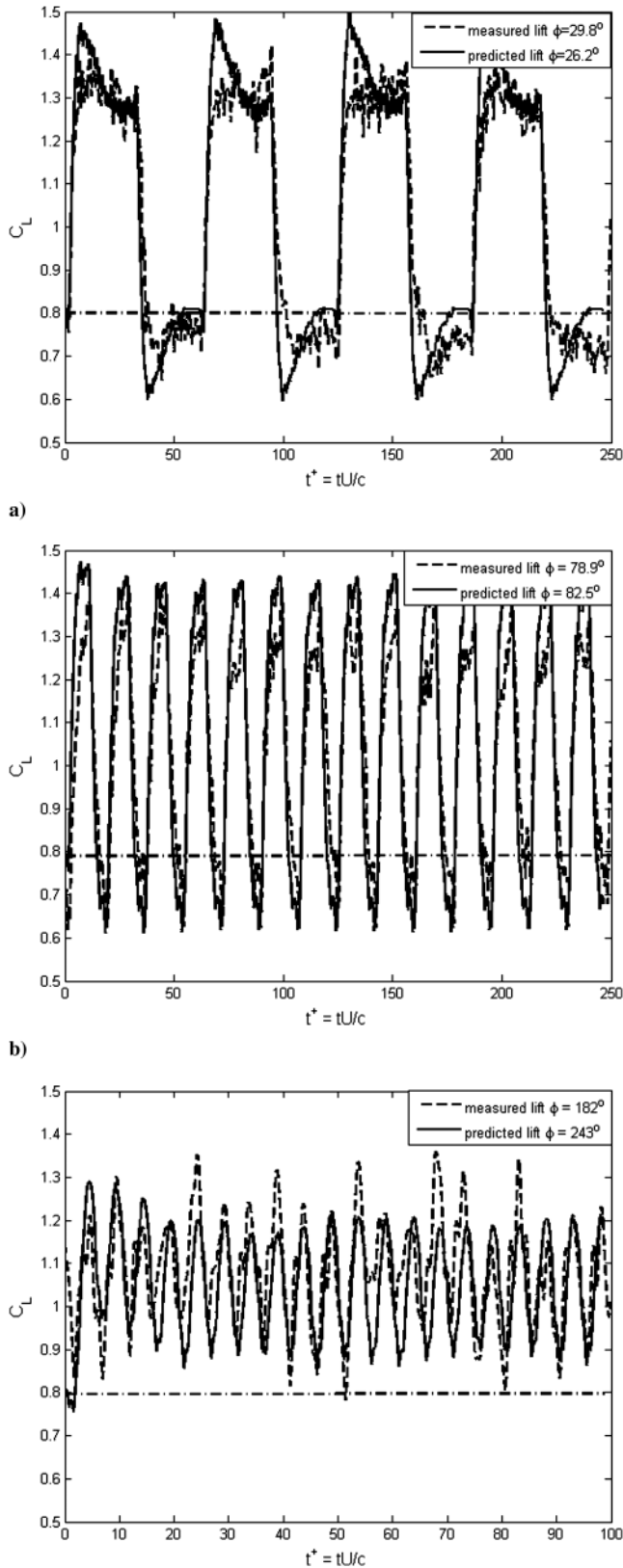
a)

b)

c)

Fig. 10 Comparison of the measured lift coefficient (dashed line) and the predicted lift (solid line) is shown for forcing frequencies a) $St = 0.016$ (0.4 Hz), b) $St = 0.056$ (1.4 Hz), and c) $St = 0.2$ (5 Hz). The baseline lift coefficient without actuation is 0.8.

value of the lift increases. The actuation can only produce positive lift perturbations, which has the effect of increasing the average lift above the baseline state. In the case of Fig. 10c, the mean lift coefficient shifts from $C_L = 0.8$ to $C_L = 1.1$. The lift fluctuations

oscillate about the new mean lift value rather than the baseline lift. Ordinarily, one might interpret the shift in the mean lift as a nonlinear effect, but the results show that the linear model gives a good prediction of the new mean lift.

In most studies of active flow control, the interest is focused on using continuous pulsed actuation to increase the time-averaged lift coefficient. The fluctuation level of the lift associated with pulsed blowing is usually not reported, but the linear model is capable of estimating the amplitude and phase of the unsteady component of lift.

V. Limitations to the Linear Model

There are three regimes for which the model may not give correct predictions: 1) steady blowing actuation; 2) the fully attached flow state; and 3) changes in the pulse on/offtime.

In the case of steady blowing, the model does not predict the correct steady-state response to steady blowing from the actuator, because steady blowing actuation has a fundamentally different effect on the flow than the unsteady actuation used to derive the model. Experiments show that steady blowing produces a significantly lower lift coefficient than with continuous pulsed blowing. However, the linear model incorrectly predicts that a higher lift will be achieved in steady state when using steady blowing.

When the flow is completely reattached to the wing, then the lift saturates. Additional actuator input does nothing to increase the lift. However, the linear model described in this paper cannot predict the saturation in lift. Because the output from the model is proportional to the input amplitude, it will predict ever-increasing lift response to increasing actuation amplitude.

Another limit of validity for this linear model is related to the pulse ontime and offtime in the pulse train. The multiple pulse data shown in Fig. 9 and the continuous modulation of pulses in Fig. 10 both use equal on/offtimes of 0.017 s. When the ratio of on/offtimes is changed, then the lift response changes in complicated manner. For example, increasing the pulse ontime, while keeping the same pulse frequency, reduces the lift increment. This effect was not expected, because the amount of momentum added by the actuator pulse to the flow increases with increasing pulse ontime. Apparently, the lift dependence on the shape of the actuator input signal is not a simple linear response.

Irrespective of the limitations described, the linear model proved to be useful for explaining the lift response under various conditions of unsteady actuation. Phenomena (such as the change in the mean lift coefficient, reduced amplitude of lift oscillations, and phase lags) were shown to be the result of a linear process. Once the approximate impulse response for a separated flow has been determined, then it is possible to determine the limits of achievable performance from that system. But, perhaps even more important is that the linear response of a separated shear layer to pulselike actuation has important implications for active flow control. In particular, transfer functions or state-space models that represent the separated flow system can be easily derived from the approximate impulse response function. With a model of the separated flow system, it then becomes possible to use the tools of linear control theory to design effective closed-loop controllers.

VI. Conclusions

The transient lift response to small amplitude pulselike disturbances is studied on a fully stalled wing. It is shown that the time integral of the lift (total impulse) is proportional to the supply pressure provided to the actuator. For a given flow speed, the transient responses of lift are similar when the data are scaled by the total impulse of the lift. In contrast to observations of steady-state separated flow control, the amplitude of the lift response increases with an increasing freestream speed and a fixed amplitude pulse from the actuator. Therefore, the transient response does not scale solely with the commonly used momentum coefficient. Instead, it is shown that for a fixed pressure (when the amplitude of the transient lift coefficient curves are plotted against time normalized by the

convective time unit), the curves collapse to a single response distribution. The transient lift response from a single pulse of the actuator is used as an approximation to the separated flow system impulse response, which can be used as a filter kernel to predict the lift behavior to various actuator input signals. This assumes that the system responds linearly to the actuator input. The linear approximation, and the use of the single impulse response as a filter kernel, is tested with multiple pulse finite time inputs and continuous amplitude modulated square-wave input signals with different frequencies. The shift of the mean lift from its baseline to a higher value with actuation is shown to be predicted by the linear filter and is a linear phenomenon.

Acknowledgments

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