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Engineering Notes

Experimental Investigation of Separation Control Using Upper-Surface Spoilers

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Introduction

THE control of flow separation over wings and airfoils has been a subject of intense study since its observation and characterization. Separation culminating in airfoil or wing stall provides a natural limit to the lifting ability of wings, thus affecting takeoff and landing performance and maneuvering capability. Commonly used techniques to delay stall include leading-edge flaps as well as slats [1]. The mature technology of flow control has also spawned a plethora of devices to control flow, both passive and active (e.g., blowing, suction, blowing and suction, oscillatory blowing/suction, moving surfaces, compliant surfaces, resonant cavities, etc.) [2–4]. Of these devices/actuators, few have realized application in a production vehicle.

The recent interest in extracting or emulating (sometimes coincidentally) biologically inspired technology has a long-standing precedent in aerodynamics. Wingtip sails as described by Spillman [5] are seen on many soaring birds, and leading-edge flaps are also seen to be deployed by birds in the form of the Alula feather. Before the Second World War, it was observed by German engineers that some birds appear to raise a feather on the upper wing surface when landing [6]. It was surmised that the action of the feather was to delay the forward progression of flow separation, thus delaying massive stall. An implementation of this idea (not entirely successfully) was evaluated on an aircraft using a strip of leather to simulate the action of the feather. Approximately 50 years later, studies conducted by Bechert et al. [6] evaluated the concept again with favorable results. In these studies, the spoilers (or flaps, as they designated them) were made from soft flexible material (plastic sheet) and were self-actuating. The investigations of Meyer et al. [7] indicated that the spoilers were effective for Reynolds numbers ranging from less than 150,000 to 1,000,000. Benefits of the spoilers are that they are passive, lightweight, do not require any form of control, and do not occupy internal wing volume. When not actuated, they were found to show a small performance degradation, depending on their design. This was attributed to the flap behavior with attached flow: the flaps may rise slightly, causing a negative localized camber; consequently, lift drops and drag increases slightly. This behavior was ameliorated by cutting a sawtooth pattern into the rear of the flaps, a naturally occurring embodiment seen in birds. Naturally, a self-actuating flap would need to be light to raise, but sufficiently rigid so as not to crumple. As noted by Schatz et al. [8], the flap should not protrude into the flow above the wake, as this would increase its size and thus drag; their computational data suggested that the flap should just touch the shear layer. The effect of the flap was attributed to it decambering the airfoil when actuated; this alters the pressure distribution to delay the forward stall progression. A similar operating mechanism was cited by Hu et al. [9] for the effect of stall delay by flexible membrane airfoils. Optimal flap angles were experimentally determined to be between 60 to 90 deg, depending on the flap design. Schatz et al. [8] suggested that the spoiler should be located close to the trailing edge to halt the initial onset of separation. They also found that increasing the flap length for their particular configuration increased the maximum lift coefficient. Most testing was conducted for a 12%-chord spoiler. Their computational data suggested that the spoiler could stabilize the separated-flow region and decrease the size of shed vortices.

A survey of the literature indicates few studies of these spoilers beyond those mentioned. However, their potential for performance enhancement on unmanned aerial vehicles and similar types of aircraft could be significant. Consequently, an experimental investigation has been undertaken to systematically evaluate the effect of several spoiler geometric parameters. Self-actuating spoilers were evaluated, with effects of location and design explored. Presented results include force balance and motion visualization.

Equipment and Procedure

Wind-tunnel tests were conducted in Embry-Riddle's 2 by 2 ft blower wind tunnel. This facility has a measured turbulence intensity of 0.5% and a jet uniformity within 1% in the jet core. Force-balance measurements were undertaken using a six-component NK Biotechnical sting balance. Calibration has shown the balance to be capable of resolving 0.009 N with an accuracy within 0.02 N. A dedicated interface coded in Visual Basic 6 was written for this balance. Each presented data point is the average of 5000 readings. Before testing, the balance's calibration was checked though the application of known weights. The model consisted of a SD 7062 profiled rectangular wing with a chord c of 0.1 m and span of 0.4 m, yielding an aspect ratio (AR) of 4. The wing was rapid prototyped from ABS (acrylonitrile butadiene styrene) plastic using Embry-Riddle's rapid-prototyping facilities. A transition strip, 0.1 mm thick, comprising a single layer of aluminum tape edged with pinking shears was placed at 5% of the chord.

Flexible spoilers were evaluated. The spoilers were 12% of the chord (i.e., 12 mm long) in length, as this dimension has been shown to be effective [6,7]. The spoilers were carefully implemented so as to lie conformal with the surface. The flexible spoilers were cut from 0.1-mm-thick plastic sheeting. Figure 1 shows renderings of the flexible-spoiler designs and designations. The flexible-spoiler designs were based upon observations of Bechert et al. [6]. They found that slits cut into the spoilers reduce their tendency to lift at low angles and so reduce lift. The slits tend to equilibrate the pressure gradient along the spoiler, diminishing its tendency to raise. In [6,7], the spoilers were attached to the wing using a hinge formed using Scotch tape; a similar attachment was used in this study. The spoilers were not constrained in motion, but the joint stiffness mitigated reversal of the spoiler at high incidence. Spoiler hinges were located at 68, 78, and 88% of the chord. Naturally, a potential issue with this type of passive-device attachment may then be the inability to fly inverted without the spoiler partially opening under its own weight. Consequently, the attachment method used in this study ensured that the spoilers were sufficiently rigid in structure and attachment such that they did not open with the wing inverted.

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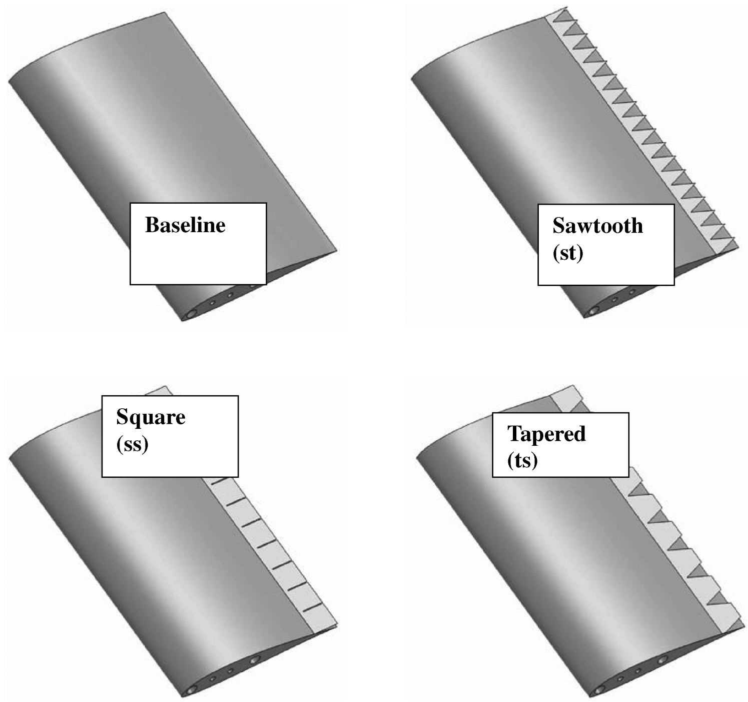

Fig. 1 Flexible-spoiler geometry renderings. Spoiler lengths are 12% of the chord.

The model's angle of attack was set and measured using a feedback loop in conjunction with a Midori angle sensor. Angle-of-attack repeatability was established as better than 0.1 deg. Wall corrections were applied using the method of Shindo [10] as well as that detailed in [11]. Wind-tunnel testing was conducted at a freestream velocity of 40 m/s, yielding a Reynolds number of 225,000 based on the reference chord length of 0.1 m. During testing, the models were pitched from −6 to 28 deg in 2 deg increments.

Results and Discussion

As the performance of the spoilers is generally dictated by their lift augmentation at high incidence, their behavior in this Note is primarily characterized through lift plots. The baseline wing refers to that without modification (i.e., a spoiler). Figures 2a–2f show the effect of the chordwise attachment location and geometry for the three flexible-spoiler configurations tested. The spoilers when attached were conformal with the surface and self-actuated at high incidence. A reduction in angle of attack would see the spoilers returning flush with the surface. No hysteresis was observed in the tests. Figure 2a shows the measured lift coefficient for the sawtooth configuration. The conformal behavior of the spoiler is clearly indicated by its negligible effect in the fully-attached-flow regime (i.e., incidence less than 5 deg). The spoilers were noted to slowly start raising at approximately 5 deg and were fully raised at approximately 12 deg. The spoilers were not stationary but oscillated rapidly through an angle of approximately 90 deg when deployed. As may be seen, the linearity of the attached-flow lift-curve slope is preserved to higher incidence, compared to the baseline wing, whereas lift is augmented notably at high incidence. The effect of chordwise location is indicated to be marginal. The square spoiler (Fig. 2b) shows similar behavior to that indicated for the sawtooth; however, chordwise location is noted to affect the data. The aft location (88%) shows the best high-incidence performance. It also shows slight decambering in the attached-flow regime. This was noted to correspond to the spoiler raising slightly in this incidence range. The tapered spoiler (Fig. 2c) shows similar performance to the sawtooth (Fig. 2a), with little chordwise placement dependency (for the range evaluated). Although this spoiler is similar to that tested in [6], this result is inconsistent with their data and suggests that the spoilers are sensitive to the airfoil geometry employed. Figures 2d–2f, compare the behavior of the three configurations at the same attachment locations. The square spoiler is clearly seen to be most effective at high incidence when attached at the 88% location (Fig. 2d). Moving the spoilers forward to the 78 or 68% location shows little difference between the three designs, although all show performance enhancement compared to the baseline wing (Figs. 2d–2f).

Although not included due to space limitations, most configurations show moderate drag-coefficient reductions for lift coefficients from 0.6 to stall. Additionally, for a given spoiler design, there are no significant differences in the drag polars for a given attachment location. The observed drag reductions are a consequence of the increase in the wing's lift-curve slope; to generate a given lift coefficient, the wing is at a lower geometric angle of attack [12]. The increase in the lift-curve slope is essentially due to the spoilers delaying the initial rounding and lessening of the lift-curve slope associated with the onset of limited trailing-edge separation. Consequently, the observed drag reduction may also be due to a small decrease in pressure drag.

The effects of the three spoiler configurations at the 88% location as well as the square spoiler at all three attachment positions on efficiency are summarized in Fig. 3. As may be seen, the noted drag-coefficient reductions yield a moderate increase in the lift-to-drag ratio L/D for all configurations presented for lift coefficients greater than 0.6. At the 88% location, the square spoiler shows a notable decrease in maximum L/D; this is due to the observed reduction in lift shown in Fig. 2b.

To gain insight into the temporal behavior of the flexible flap, its motion (square spoiler at 88%) was recorded using a Sony HDR-UX7 Handycam, which has the facility to capture images at 120 frames/second. The wing was set at 22 deg incidence. Figure 4 shows a recorded flap location trace deduced from measurements of the individual video frames. As may be seen, the flap appears to move in a low-frequency oscillation, with a higher-frequency oscillation superimposed on this motion. The average raised-flap position was approximately 50 deg, with oscillations of 40 to 45 deg around this mean. It should be pointed out that the acquisition rate may not have been high enough to fully characterize this high-frequency motion, but does indicate its existence. To extract the low-frequency motion, repeated time traces were passed through a Hanning window and ensemble-averaged. The resulting spectrum indicates the low-frequency oscillation to have a frequency of approximately 7.5 Hz. A higher-frequency oscillation at approximately 40 Hz is also suggested. Reference [7] suggested that self-adjusting spoilers tend to

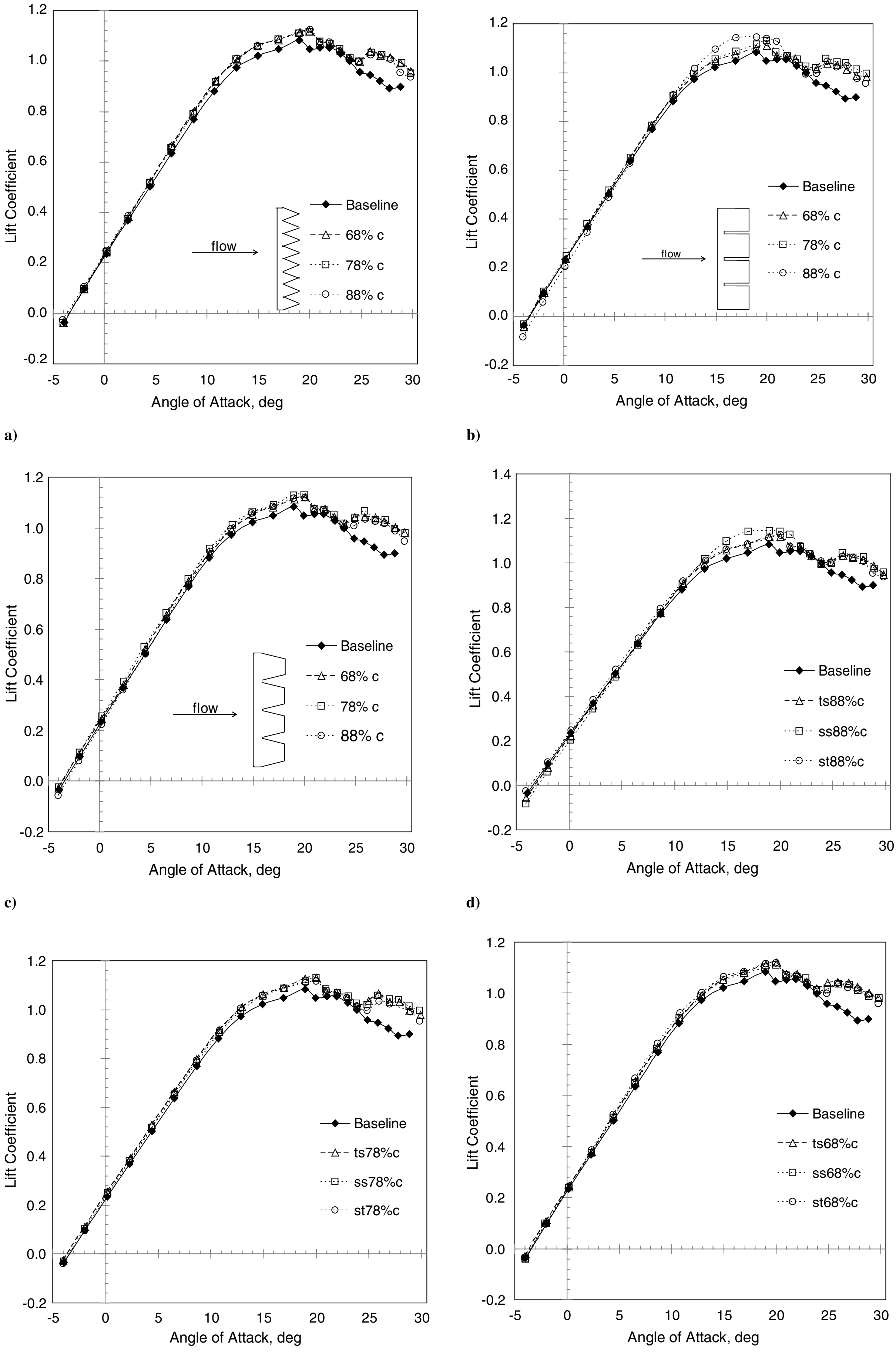

Fig. 2 Effect of spoiler location and geometry on measured lift coefficient: a) sawtooth, b) square, c) tapered, d) 88%c, e) 78%c, and f) 68%c.

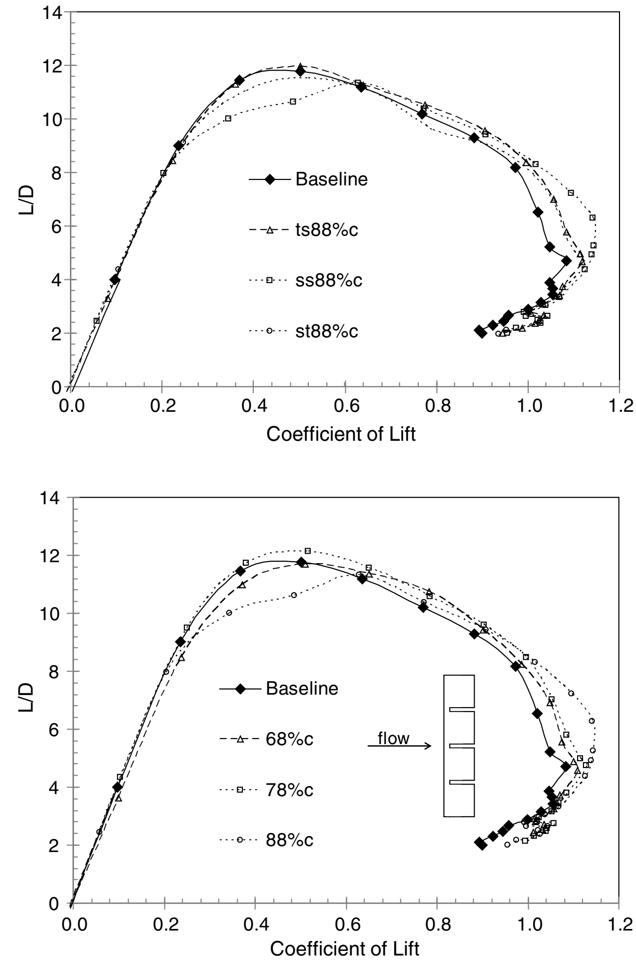

Fig. 3 Effect of spoiler geometry and location on measured L/D ratio.

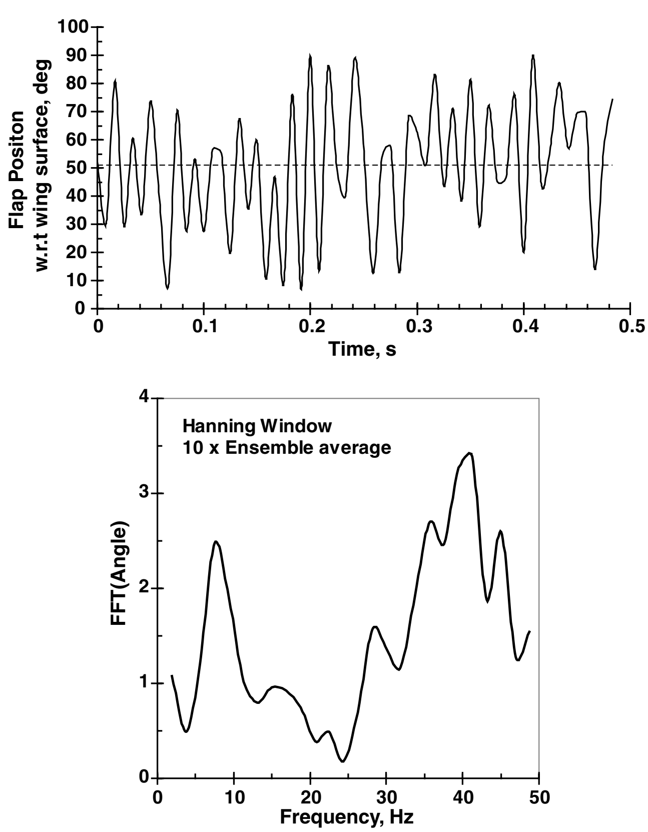

Fig. 4 Flexible-flap (square) motion history, 22 deg incidence, flap located at 88%*c*.

find a stable equilibrium position, a result not observed in this study. This may be a consequence of the method of spoiler attachment. In this investigation, the spoiler was attached such that raising requires the spoiler to flex; thus, the observed oscillations may be driven by the material's elastic properties in conjunction with the pressure gradient across the spoiler.

Conclusions

A low-speed wind-tunnel investigation was conduction to evaluate the performance of upper-surface spoilers. The spoilers, based upon avian observation, are typically conformal with the upper surface of the wing and self-actuate when separation manifests. Test were conducted using an $AR = 4$ rectangular wing with a SD 7062 section at a Reynolds numbers of 225,000. Testing involved the attachment of flexible spoilers fixed in position at chordwise locations of 68, 78, and 88%. The flexible spoilers were seen to self-raise with the onset of trailing-edge flow separation and then oscillate rapidly when deployed. For nominally-attached-flow conditions, the spoilers showed an increase in the wing's lift-curve slope with a concomitant reduction in the drag coefficient. All flexible-spoiler configurations showed a moderate increase in the recorded maximum lift coefficient, with a square slotted spoiler yielding the greatest augmentation. The flexible spoilers showed a secondary lift peak. Recorded images of the flap motion indicated a rapid oscillation superimposed on a lower-frequency oscillation around a mean, with angular excursions of approximately 45 deg from the mean.

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