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Engineering Notes

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Active Boundary-Layer Separation Control on a Multi-Element Airfoil

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Nomenclature

AOA	=	angle of attack
C	=	chord length of wing element (slat, main wing, flap)
C_L	=	lift coefficient
C_p	=	pressure coefficient
i	=	index for longitudinal orifice on main wing element
U_∞	=	freestream velocity, m/s
x	=	longitudinal coordinate of pressure tap referenced to wing element leading edge

I. Introduction

A fundamental and perennial motivation underlying research in fluid mechanics, especially in the field of aerodynamics, is the investigation of techniques that can be used to improve the high-lift performance of aircraft. Much research has been done in the area of modifying the design lines of various aircraft components to augment the total lift, most notably, the wings and other lifting surfaces. Advancements in this area have been aided mainly through the efforts of both experimentalists using wind tunnels and researchers applying computational fluid dynamics. Additionally, research has also proceeded along the path of employing various flow control techniques for the purpose of improving the high-lift characteristics of aircraft. It is important now to capitalize on this knowledge and to add to the existing database by exploring and devising new and improved techniques of controlling the flow field affecting the performance of lifting surfaces. This should be done in an attempt to produce an improved lift capability of aircraft in an efficient manner. The experimental investigation presently described is an attempt to do just that by employing a flow control technique to influence the flow field surrounding a standard, multielement airfoil geometry at a subsonic speed.

The primary motivation behind the development of high-lift systems is to ensure that high aerodynamic lift at low aircraft speeds is maintained during the liftoff and landing phases of the flight. Of course, high-lift could simply be achieved by adding area to the wing, but this has the obvious disadvantage of increasing the weight and possible complexity of the lifting system. One option would be to employ conventional lift-augmenting devices such as leading-edge slats and trailing-edge flaps. Over the years, various configurations of slats and flaps have been devised to achieve high-lift and yet the challenge has always been to minimize their adverse effects on the other aircraft systems due to aerodynamic interference. Active flow control can be applied to achieve a variety of objectives. This investigation was primarily concerned with flow control using piezoelectric devices as a means of achieving sizable increments in lift for aircraft, specifically at subsonic speeds by transferring turbulent kinetic energy and momentum into the boundary layer.

Researchers have discovered that physical mechanisms associated with the dynamics of vortices produce favorable effects with regards to the generation of high-lift [1]. Experiments have been conducted which have studied how vortex interactions in the shear layer of a separated boundary layer can contribute to the enhanced spreading rate of the shear layer [2]. Previous research results have shown that this phenomenon promotes boundary-layer reattachment. Bhattacharjee [3] observed that the process of "vortex pairing" increases the shear-layer-spreading rate. This phenomenon associated with vortices can be described as the amalgamation of neighboring vortex lumps into larger ones. The underlying premise is that vortex amalgamation reenergizes a separated boundary layer, which produces the favorable effect of an increment in aerodynamic lift. Experimental data from a previous study [4] have indicated that vortex amalgamation occurs when the forcing frequency is a subharmonic of the vortex passage frequency associated with the test article for a specified set of test conditions and model geometry.

II. Geometry

The test article used in this investigation was a three-element airfoil that consisted of a leading-edge slat, a main wing, and a trailing-edge flap. Landman [5] describes the details of its geometry and presents the entire attendant set of mechanical drawings. When the model is configured in the stowed position, the chord length is 18 in. and the span is 36 in. The aspect ratio was designed to establish a two-dimensional flow field over the model. The leading-edge slat and trailing-edge flap were affixed to the main wing so that the incident angles of both surfaces were 30 deg with respect to the main wing chord. The multielement model was instrumented with pressure transducers to obtain surface static pressure measurements that were used to compute the lift coefficient. The trailing-edge flap had 25 pressure tap locations, 19 of which were placed along the chord midspan. A total of six pressure taps were located spanwise near the trailing edge. A total of seven pressure taps were located along the centerline of the slat. All measurements were obtained with a pair of $3/16$ in. thick Plexiglas® sidewalls placed on the model to ensure that the observed flow field was two-dimensional. A photograph of the test article mounted in the Old Dominion University low-speed wind tunnel (ODU LSWT) is shown in Fig. 1.

III. Test Instrumentation

All measurements were obtained using the ODU LSWT in Norfolk, Virginia. The tunnel is a closed-return, fan-driven model with an operating total pressure of 1 atm. The test section is 4 ft wide, 3 ft high, and 8 ft long. Figure 1 shows the front view of the multielement airfoil installed in the test section with Plexiglas sidewalls to maintain a two-dimensional flow field over the center portion of the wing. The fan was driven by a 125-hp ac motor to

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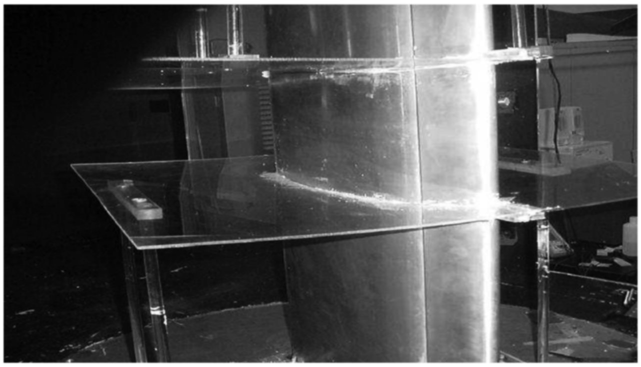

Fig. 1 Model mounted in test section of ODU LSWT.

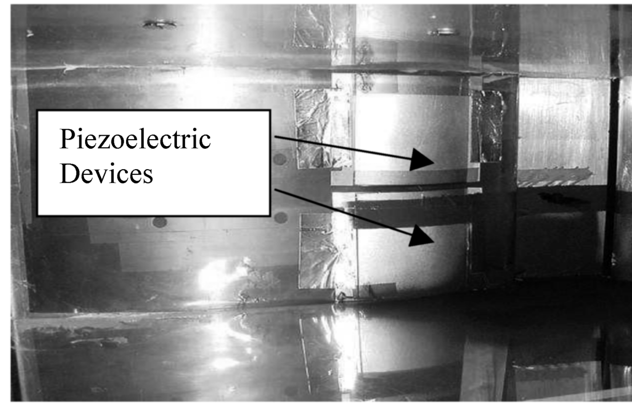

Fig. 3 Installation of piezoelectric devices on model.

deliver air speeds from 10 to 55 m/s. The air speed was calculated by determining the total pressure and static pressure, using a pitot pressure probe and two static pressure rings located on the ceiling of the tunnel near the interface of the contraction section and the working test section.

The central component of the data acquisition system for this experimental study was the 3497A Hewlett–Packard (HP) data acquisition/control unit, which was used to process measurements of both temperature and voltage. A 100-torr high-accuracy Baratron diaphragm pressure transducer was used to measure the differential pressure between the test section static and total pressures. This was required to compute the test section freestream velocity for both sensor calibrations and velocity measurements. These data were then communicated to a personal computer via a standard HP-IB parallel interface bus for processing.

The surface pressure measurements on the test article were obtained by using electronic scanning pressure transducers manufactured by Pressure Systems, Inc. [6] The particular pressure transducer that was used in this study was the 9010 pneumatic intelligent pressure scanner. The accuracy of the transducer is rated at $\pm 0.05\%$ full scale over a temperature range of -25 to 80°C with a measurement range from ± 10 in. of water to 750 psid. The reference port on each module was connected to the freestream static pressure in the test section to calculate the model surface pressure coefficient. The uncertainty of the pressure coefficient was calculated as 0.01059, based on nominal test conditions.

The piezoelectric devices used in this study were manufactured by the FACE International Corp. and have been given the designation of THUNDER™ devices. Research [7] has been done to characterize these actuators for a variety of engineering applications. These actuators are constructed from a composite of materials consisting of an aluminum outer layer and a stainless steel substrate sandwiched between a PZT material (lead zirconate titanate). The devices used in this study were of rectangular cross-sectional shape. Specifically, the model used was TH-7R with the overall dimensions of

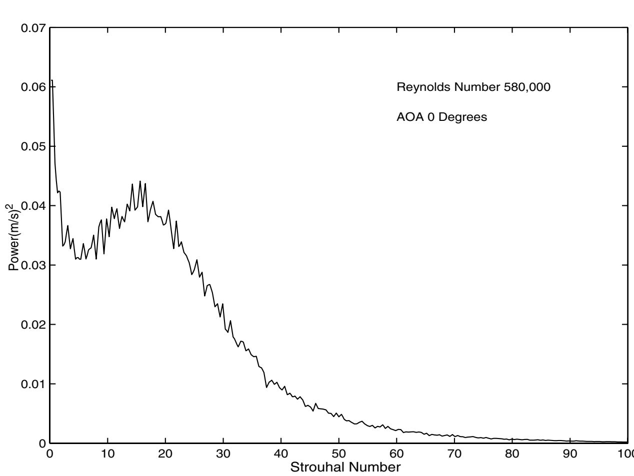

Fig. 2 Power spectrum at $V = 20$ m/s, 0 deg AOA.

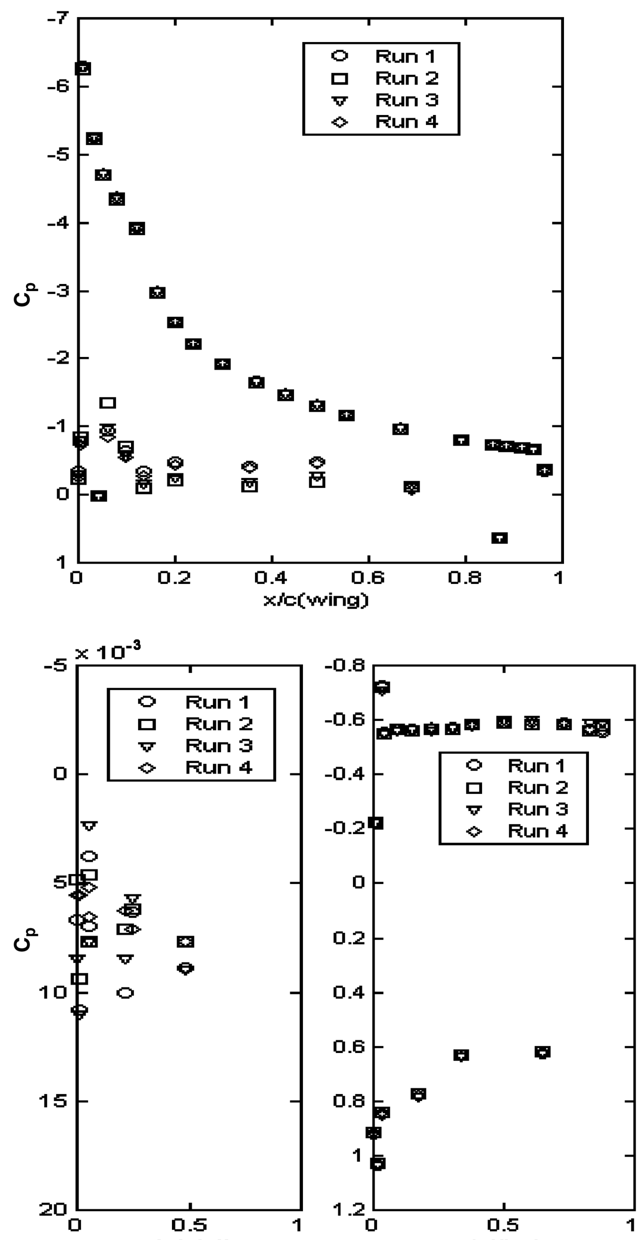

Fig. 4 Pressure distribution with piezoelectric devices at 15 deg AOA, $U_\infty = 20$ m/s at 0 Hz.

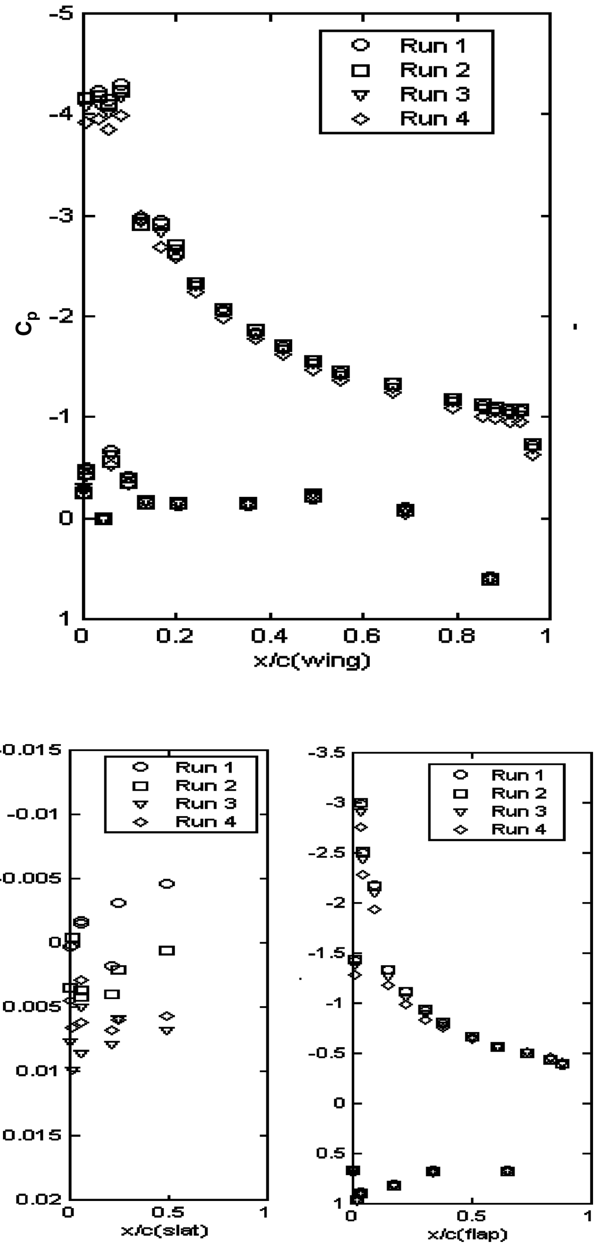

Fig. 5 Pressure distribution with piezoelectric devices at 15 deg AOA, $U_\infty = 20$ m/s at 320 Hz.

96.52 × 71.12 × 0.584 mm. In this study, the devices were simply supported with aluminum tape applied to both ends of the stainless steel substrate. The typical displacement for the TH-7R device is 7.62 mm at a frequency of 1 Hz and a drive voltage of 595 V peak-to-peak.

IV. Test Procedure

Preliminary work was done to determine the proper forcing frequency for the piezoelectric devices. This was accomplished by employing a TSI model 1201 hot-film cylindrical single-axis sensor to determine the passage frequency of the vortex system that forms at the trailing edge of the slat. Hot-film measurements were obtained without forcing and used as input to FFT analysis to produce a spectral plot of the flow field within the wake of the slat. Figure 2 shows the resulting spectral plot of the power vs the Strouhal number, which was based on the stowed chord length of the model and the freestream velocity. The data in Fig. 2 show that the rounded peak occurs roughly at a Strouhal number of 15, which corresponds to the vortex passage frequency.

The freestream velocity U_∞ was 20 m/s, the reference length (stowed wing chord length) was 18 in. with a Strouhal number of 15. The vortex passage frequency was calculated to be 656 Hz and the first subharmonic was therefore 328 Hz. Data were not collected at higher freestream velocities due to observed unsteadiness of the sidewalls attached to the model. A pair of piezoelectric devices were mounted to the lower surface of the main wing, roughly 1 in. from its trailing edge, as shown in Fig. 3. The piezoelectric actuators were driven with an operating frequency ranging from 0 to 320 Hz. The model was held fixed at 15 deg angle of attack. Surface static pressure measurements were simultaneously obtained to determine the state of the boundary layer for each of the operating frequencies.

The piezoelectric devices were first operated at a frequency of 0 Hz and then subsequently at 320 Hz. Data were obtained for four different test runs for each frequency for fixed flow conditions and model attitude. The data trend indicated consistently higher lift coefficients when the devices were operated at 320 Hz. Figures 4 and 5 show the pressure distributions on the model for four individual test runs for the test conditions stated. Generally, the data show that there was not a significant amount of variation in the pressure distributions on the main wing for each of the two selected operating frequencies. The distributions on the slat were questionable and could have been attributed to a malfunctioning pressure module. The most striking result from these plots is the fact that the boundary layer on the trailing-edge flap was attached when the devices were operating at 320 Hz, but was separated at 0 Hz. The lift coefficients are displayed in Table 1 for the different test runs and show that the piezoelectric devices caused a marked increment in lift coefficient on the main wing. Using the mean lift coefficient for each operating frequency, the piezoelectric devices were responsible for an increase of 10%. The test was also performed for device operating frequencies of 240 and 260 Hz. These cases demonstrated no significant effects on the state of the boundary layer.

It is understood that the lower the pressure gradient the more resistant the boundary layer is to separation. Distributions of the pressure coefficient gradient on the main wing element were plotted and compared for the various selected excitation frequencies of the piezoelectric devices. The pressure coefficient gradient was approximated at selected values of chordwise location by using the

Table 1 Lift coefficient on main wing with piezoelectric devices, $U_\infty = 20$ m/sec, at 15 deg AOA

	C_L, lift coefficient			
Frequency, Hz	Run 1	Run 2	Run 3	Run 4
0.0	1.470	1.580	1.579	1.504
320.0	1.714	1.723	1.678	1.637

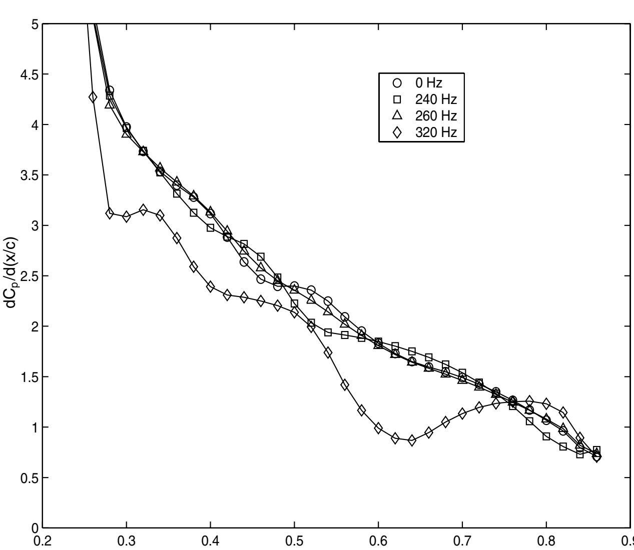

Fig. 6 Pressure coefficient gradient on main wing at 15 deg AOA, $V = 20$ m/s.

three-point forward difference formula [8] as shown in Eq. (1):

$$\frac{\mathrm{d}C_p}{\mathrm{d}x} \approx \frac{-C_p^{i+2} + 4C_p^{i+1} - 3C_p^i}{x^{i+2} - x^i} \tag{1}$$

These results are shown in Fig. 6 and indicate striking differences between the various frequencies. The distribution that had the lowest overall magnitude of adverse pressure gradient was for the excitation frequency of 320 Hz, which indicates that the boundary layer would be less susceptible to separation. Additionally, the distribution for 320 Hz exhibited a wavelike characteristic with an amplitude that was clearly larger than for the other three cases. The waviness in the distribution is apparently a result of the forcing frequency that induces variations in the boundary layer. Furthermore, this observation indicates the presence of vortex spreading at the highest frequency, as shown by the footprint of the enlarged vortex system made evident on the upper surface of the model, which is responsible for the marked increment in lift coefficient.

V. Conclusions

Based on the hot-film sensor data as shown in Fig. 2, the rounded peak occurred near a Strouhal number of 15, which corresponded to a vortex passage frequency of 656 Hz. A remarkable result from this study was the fact that the lift coefficient on the main wing increased by 10% when the model was instrumented with the piezoelectric devices tuned at 320 Hz, which was approximately the first subharmonic of the vortex passage frequency for this model.

Plots of the pressure gradient coefficient distribution on the main wing for the selected operating frequency of 320 Hz showed that the pressure gradient distribution demonstrated a wavelike characteristic, which was caused by the periodic interaction of the coherent system of vortices with the boundary layer on the main wing. Because this phenomenon did not occur for the other frequencies, it is reasonable to assume that the amplitude growth of the vortices was sensitive to selected operating frequencies.

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