An Investigation of the effect of Freestream Turbulence on the Laminar Separation Bubble on an SD7003 Airfoil

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Measurements and computations of the separation and reattachment locations are reported for the SD7003 airfoil with the chord Reynolds number in the range $2 \times 10^4$ – $4 \times 10^5$. Measurements are based on multi-line Molecular Tagging Velocimetry. Comparisons of experimental results with current computations and previous experiments point to challenges involved in the experimental determination of separation bubble characteristics. Results also bring into focus the facility dependent issues, specifically freestream turbulence, that impacts the experimental data. Preliminary results indicate a downstream/upstream movement of separation/reattachment, respectively, with added freestream turbulence. This observation may explain some of the discrepancies among the various experimental and computational results.

Nomenclature

$c$ = airfoil chord
$m_C$ = millichord, $1000m_C = 1c$
$b, s$ = airfoil span
$\alpha$ = angle of attack
$Re_c$ = Reynolds number based on chord
$X, Y$ = reference frame with $X$ aligned with chordline and normalized by chord
$X', Y'$ = lab reference frame (rotated with respect to quarter chord) and normalized by chord

1. Introduction

Low Reynolds number ($10^4$–$10^5$) flows, found in Micro Air Vehicles (MAVs), wind turbines and bio-mimetic applications are highly susceptible to the development of a Laminar Separation Bubble (LSB) under even small adverse pressure gradients. It is a fundamental flow phenomenon in aerodynamics and has been heavily studied; e.g. see Ref. 1-6.

In the present work, we investigate the characteristics of the laminar separation bubble on the SD7003 airfoil at different angles of attack over a chord Reynolds number in the range $2 \times 4 \times 10^5$. The specific focus is on the separation and reattachment locations. Previous studies of this airfoil point to discrepancies among data sets compiled by different investigations, for example see data presented in Ol6. Among the variables that may influence the characteristics of the laminar separation bubble is the freestream turbulence intensity (FSTI). Freestream broadband turbulence acts as an excitation source of the boundary layer instability upstream of separation and the Kelvin-Helmholtz instability downstream1, which may delay separation while triggering earlier transition and
subsequent turbulent reattachment. This would have the effect of shortening the LSB with increased FSTI and we suggest that this may be the reason for the results observed by Burgmann in Ref. 2 and Ref. 3 where the FSTI was reduced from 1.5% to 1.0% between the two experiments. In the work presented here, we address several experimental challenges that impact the accurate characterization of the separation bubble, in addition to possible effects of FSTI on the locations of separation and reattachment.

Comparisons are made using concurrent experiments at Michigan State University based on Molecular Tagging Velocimetry and computational efforts at the Air Force Research Laboratory at Wright-Patterson AFB. Separation and reattachment data from current experiments are also compared with previous studies under similar conditions. Preliminary results of the influence of FSTI on separation and reattachment are presented.

II. Experiments

The experimental facility at the MSU Turbulent Mixing and Unsteady Aerodynamics Laboratory is a 10,000 liter closed-loop water tunnel with full optical access to its 61cm × 61cm × 244cm free-surface test section. The flow management consists of two perforated-plate baffles and one honeycomb in the settling chamber, a 6:1 contraction, and a honeycomb and a fine mesh screen at the entrance of the test section.

![Figure 1. The geometric parameters and experiment's frame of reference is depicted above. The angle of attack, α, is the angle between the chord line and the freestream velocity vector. The coordinates (X',Y') are designated as the lab reference frame. Coordinate system designated by (X,Y) is used when data are shown in the airfoil frame of reference (i.e. chordline is aligned with the X-axis).](image)

The airfoil, depicted in Figure 1, has a nominal chord and span of $c = 203\text{mm}$ and $b = 460\text{mm}$, respectively, for an aspect ratio of 2.3. The airfoil is mounted between Plexiglas false walls and positioned in the middle of the test section. The angle of attack is controlled using a lever located on the outer wall and with an accuracy of ±0.4deg.

Single-component Molecular Tagging Velocimetry (MTV), as shown in Figure 2, is utilized for velocimetry. MTV can be considered as the molecular counterpart of PIV (Particle Image Velocimetry). In the present implementation of MTV, an Excimer UV laser is fired once to excite (“tag”) tracer molecules that are in solution and the resulting phosphorescent emission from the tracer is interrogated twice with a prescribed time delay to form an image pair. Correlation analysis of the image pair yields the velocity component perpendicular to the tagged line in the undelayed image (Figure 2a) for each line and each row of the image. The random uncertainty of the correlation technique, based on the RMS (root mean square), is approximately 0.05 pixels for typical measurements. The reader is referred to Koochesfahani and Nocera for further details on the MTV technique.

The sample image pair in Figure 2 is acquired using a Stanford Computer Optics (SCO) 4QuikE intensified CCD camera in dual-frame mode at 30 Hz with a resolution of 640 × 480 pixel. The resulting measurement spacing is 1.65mm or 8.13mC (“millichord”, or 0.00813c) in the streamwise direction (which is the same as the tag-line spacing) and 58µm or 0.29mC along the tag line (a factor of nearly 10 improvement in resolution over recent PIV measurements). To attain such a high spatial resolution, the field of view is restricted to only a fraction of the entire flow field; typically 0.18c × 0.14c. Measurements over a total of 12 such fields of view, as shown in Figure 3, are then conducted and stitched together to form a composite view of the results, as shown in Figure 5(a). The strength of the single-component MTV is its ability to make high resolution, near-wall measurements, which as it will be shown, is needed for accurate characterization of the thin separation bubble found on the SD7003 airfoil at low angles of attack. Image time series data are obtained over a 150s interval, which was determined to be sufficient for statistical convergence of velocity mean and RMS. We will focus here only on the mean velocity data.
The preliminary results of the influence of FSTI on separation and reattachment were determined with a similar experimental setup as described above, but utilized a PCO Pixelfly camera with a full frame resolution of $1392 \times 1024$ pixel. The spatial resolution was kept nominally the same as the previous experiments. A stainless steel woven mesh grid with a mesh size of 0.75in and a wire diameter of 0.12in was positioned approximately 2 chord lengths upstream of the leading edge. In the absence of the grid, the baseline FSTI in the frequency band $(0.8\text{Hz} - 6.5\text{Hz})$ was 0.3%. The presence of the grid increased the FSTI in the same frequency band to 0.9%. The overall FSTI (i.e. the entire frequency range) was about 1.9%, with 1.8% originating from low frequency oscillations of less than 0.12Hz.

### III. Computations

For these airfoil simulations, the governing equations are the unfiltered full compressible Navier-Stokes equations cast in strong conservative form after introducing a general time-dependent curvilinear coordinate transformation $(x, y, z, t) \rightarrow (\xi, \eta, \zeta, \tau)$ from physical to computational space. In terms of non-dimensional variables, these equations can be written in vector notation as:
\[
\frac{\partial Q}{\partial t} + \frac{\partial F_x}{\partial \xi} + \frac{\partial G_y}{\partial \eta} + \frac{\partial H_z}{\partial \zeta} = \frac{1}{\text{Re}} \left[ \frac{\partial F_x}{\partial \xi} + \frac{\partial G_y}{\partial \eta} + \frac{\partial H_z}{\partial \zeta} \right]
\]

Here \( Q \), shown in equation 2, denotes the solution vector and \( J \) is the transformation Jacobian. The inviscid and viscous fluxes can be found, for instance, in Ref. 8. In the expressions above, \( u, v, w \) are the Cartesian velocity components, \( \rho \) the density, \( p \) the pressure, and \( T \) the temperature. The perfect gas relationship \( p=\rho T/(\gamma M^2) \), Sutherland’s law for viscosity, and a constant molecular Prandtl number \( (Pr=0.72) \) are also assumed.

It should be noted that the above governing equations correspond to the original unfiltered Navier-Stokes equations, and are used without change in laminar, transitional or fully turbulent regions of the flow. Unlike the standard LES approach, no additional sub-grid stress (SGS) and heat flux terms are appended. Instead, a high-order low-pass filter operator is applied to the conserved dependent variables during the solution of the standard Navier-Stokes equations. This highly-discriminating filter selectively damps only the evolving poorly-resolved high-frequency content of the solution. This filtering regularization procedure provides an attractive alternative to the use of standard SGS models, and has been found to yield suitable results for several canonical turbulent flows\(^9,10\) on LES-level grids.

All simulations are performed employing the extensively validated high-order FDL3DI Navier-Stokes solver, described in more detail in Ref. 11,12. In this code, a finite-difference approach is used to discretize the governing equations, and all spatial derivatives are obtained employing a 6th-order compact-differencing scheme. In order to eliminate high-frequency spurious components, an 8th-order Pade-type low-pass spatial filtering operator\(^11,12\) is also incorporated. This filter is applied to the conserved variables along each transformed coordinate direction after each time step or sub-iteration. For transitional and turbulent flows, this filtering technique provides an effective implicit LES approach, as previously noted.

The original airfoil sharp trailing edge was rounded with a circular arc of radius \( r/c \sim 0.0004 \) in order to facilitate the use on an O-mesh topology. The computational mesh, Figure 4, consisted of \((651 \times 395 \times 151)\) points in the streamwise, normal and spanwise direction, respectively. Grid points were concentrated near the airfoil in order to

Figure 4. The airfoil section and mesh is shown. The grid density has been reduced for clarity.

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capture the transition process. For the three-dimensional simulations, which invoked periodicity in the spanwise direction, the mesh had a span $s/c = 0.2$. A very small computational time step $\Delta t U/c = 0.0001$ was prescribed in order to provide sufficient temporal resolution of the fine-scale fluctuations. Simulations were advanced in time for a total of 200,000 time steps with mean and RMS data collected during the last 100,000 iterations. Finally, all computations were performed employing a low freestream Mach number $M = 0.1$, as required with the present compressible Navier-Stokes solver.

IV. Results and Discussion

A typical whole-field mean velocity map from the current measurements is illustrated in Figure 5(a) for the particular case of $Re_c \approx 40,000$ and $\alpha \approx 3.6^\circ$. To aid the identification of the separation bubble location, negative mean velocity is labeled by black color. One can clearly see the presence of a thin separation bubble over the airfoil surface. The streamwise locations of separation and reattachment are estimated based on the mean velocity reversal at the first measurement point above the surface.

Comparisons of the measured mean streamwise velocity for the case described above with the corresponding computations is shown in Figure 5. Similar to experimental representation, black color is employed to label the reversed flow region in the computations as well. Overall, there is a good qualitative agreement between the two sets of results but we also note subtle differences. The “apparent” location of separation point is different, with the experiment indicating a farther downstream location. The maximum height of the LSB and its location are different. We also wish to draw attention to the fact that the cross-stream extent of the LSB immediately downstream of the separation point is very thin for this angle of attack, necessitating high-resolution near-wall measurements to capture the bubble details in the vicinity of separation. All previous experiments on the SD7003 do not appear to have sufficient resolution to resolve this zone properly. This issue will be discussed in more detail later.

![Figure 5. Comparisons of the mean streamwise velocity obtained from experiment (a) and computation (b). The magnitude of the velocity normalized by the freestream velocity is given by the color bar. Note that the black color is used to highlight the zone of negative streamwise velocity to aid in visual identification of the separation bubble.](image)

To quantify the LSB characteristics, comparisons of the separation and reattachment points at $Re_c \approx 40,000$ and four different experiments/computations are shown in Figure 6. The experimental uncertainty in identifying the separation and reattachment locations (based on the change in the sign of the velocity at the measurement location closest to the wall) in the Katz data is ±5.5$mC. Note that the figure includes two sets of AFRL computational results4 and two sets of experimental results3,5. Burgmann & Schröder3 employed PIV measurements with 2.5$mC spatial resolution in the streamwise and cross-stream directions compared to the current MTV resolution of 0.29$mC in the cross-stream direction. Good agreement is found in reattachment points between computation and current
experiments but the results from the current experiments show reattachment points that are consistently farther downstream than previous results of Burgmann & Schröder\(^3\). The separation points in the current experiments are consistently farther upstream compared to those reported by Burgmann & Schröder\(^3\), while both experimental results are still farther downstream compared to the computations. The variations in the data in Figure 6 are consistent with those presented in Ol\(^6\) for the SD7003 airfoil from different flow facilities.

The LSB characteristics for a lower Reynolds number, \(Re_c \approx 20,000\), are depicted in Figure 7. In this case we discuss the current experimental results with previous data of Burgmann et al.\(^2\) and Burgmann & Schröder\(^3\). The computational results for these cases are not yet available. The type of differences between the experimental results noted in Figure 6 for \(Re_c \approx 40,000\) also persist for this lower Reynolds number. We note, however, that the reattachment locations are now significantly different compared to the higher Reynolds number case.

The discrepancy among the separation data shown in Figures 6, 7 is potentially due to several issues. The sensitivity of the separation location to the angle of attack is particularly significant at low angles, as highlighted by the current calculations and experiments. This sensitivity may necessitate determination of the actual airfoil angle of attack with accuracy much better than the \(\pm 0.4^\circ\) achieved in the current experiments. Another source for the discrepancy is the near-wall resolution and the ability to discern flow reversal near the surface. Referring to Figure 8, which shows an enlarged view of the region near separation from the case discussed in Figure 5, the flow reversal region near the wall is extremely “thin” in the wall-normal direction. Unless the experiment has sufficient spatial resolution, the onset of flow reversal will be estimated to be farther downstream. Based on the computational results, we determine that if the first velocity data is located at 2m\(C\) above to the wall the estimate of separation location would be shifted 100m\(C\) (i.e. \(X/C = 0.1\)) downstream for the case shown in Figure 5 and 8. We believe that, even though the current MTV results have much improved spatial resolution, higher resolution may be needed for estimating separation points at low angles of attack. The discrepancy in separation data can be influenced by other possible sources such as subtle variation in the leading edge shape between the theoretical airfoil profile and that of the airfoil used in the experiment; three-dimensional effects, and the freestream turbulence intensity. The latter issue will be discussed briefly.

Figure 6. Comparison of separation and reattachment locations obtained from different studies of the flow over an SD7003 airfoil at a nominal 40,000 Reynolds number. The solid lines represent a smooth fit to the Katz\(^5\) data.
To assess the potential influence of freestream turbulence (FSTI), a preliminary experiment was carried out where a turbulence-generating grid was placed two chord lengths upstream of the airfoil leading edge. The addition of the grid increased the freestream velocity fluctuation from 0.3% to 0.9% in the frequency band (0.8Hz – 6.5Hz). The experiment was conducted at Re_e ≈ 25,000 and airfoil angle of attack α ≈ 6° twice, with and without the grid. MTV velocity data were obtained as described previously and the locations of separation and reattachment were obtained. The results are summarized in Figure 9. The general observation is that the separation location moved slightly downstream (by 30m_C), and the reattachment location moved noticeably upstream (by 120m_C) as a result of added FSTI. While these results are preliminary, they are encouraging since they seem to explain, at least in part, some of the discrepancies among different experiments and computations discussed earlier.

Figure 7. Comparison of separation and reattachment locations obtained from different studies of the flow over an SD7003 airfoil at a nominal 20,000 Reynolds number. The solid lines represent a smooth fit to the Katz^5 data. Reattachment location marked at X/C = 1 indicates an open separation bubble (i.e. reattachment does not occur over the airfoil surface).

Figure 8. Enlarged view of the region near separation from the computational results in Figure 5(b).
V. Conclusion

Characteristics of the separation bubble on a steady SD7003 airfoil at low Reynolds numbers were studied with Molecular Tagging Velocimetry. Separation and reattachment locations were compared with previous experiments and concurrent computations. Results reveal several challenges that exist in carrying out such experiments, such as the spatial resolution needed to detect the separation location, and facility dependent artifacts, such as the freestream turbulence. These issues complicate the validation of computational data against experiments in these cases. Preliminary results on the effect of added freestream turbulence show promise in explaining some of the noted discrepancies among the various experiments. More extensive experiments are required to fully understand and isolate this effect.

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References

