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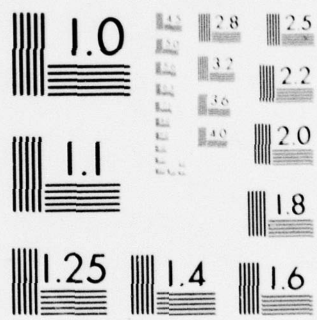

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VELOCITY MEASUREMENTS ABOUT A NACA 0012 AIRFOIL WITH A LASER VELOCIMETER

JUN 1978

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SUMMARY

A laser velocimeter was installed in the Langley 4- by 7-meter low-speed (V/STOL) tunnel to measure the velocity field about a wing with a NACA 0012 airfoil section. These measurements were compared at two low angles of attack (0°, 4.15°) with a two-dimensional viscous-flow prediction program. At 0°, the comparison provided confidence in the effectiveness and accuracy of the laser velocimeter. At 4.15°, the data indicated that a small laminar separation bubble with oscillating shear layer probably existed. The unique capability of the laser velocimeter in measuring absolute flow magnitude and direction without prior knowledge of general flow direction was demonstrated in the complex separated reverse flows over the wing at an angle of attack of 19.4°.

INTRODUCTION

The laser velocimeter (LV) is a non-intrusive velocity measurement instrument. Its application has been demonstrated in difficult situations where conventional devices either cannot survive or their presence would severely influence the measurement desired. Reference 1 describes the application of the LV in determining the velocity characteristics within turbine stages of an engine assembly where pressure probe blockage was found to affect the velocity measurement significantly. In very low velocity situations with large turbulent structure, the LV has been found to be very effective (see refs. 2 and 3). In this situation, measurement by conventional devices would have been very cumbersome with large rapid traversing mechanisms which would have inherently influenced the velocity field. In many situations, the direction of the velocity at the desired measurement location is not known. In this case, conventional measurement techniques require careful measurements of flow direction before precise velocity measurements could be obtained. Often the researcher is faced with the problem of obtaining velocity measurements where flow direction is unknown and insertion of conventional devices will cause damage to the instrument or the model. The determination of the in-plane velocity characteristics of a helicopter rotor system provides the most comprehensive use of the unique capabilities of the LV (ref. 4).

An LV system installed in the 4- by 7-meter low-speed (V/STOL) tunnel at Langley was designed to accomplish two objectives: (1) to demonstrate and verify the use of the LV in this facility by comparison with theoretical techniques, and (2) to determine the flow characteristics over a stalled three-dimensional wing.

SYMBOLS

The axes used for this investigation are presented in figure 1.

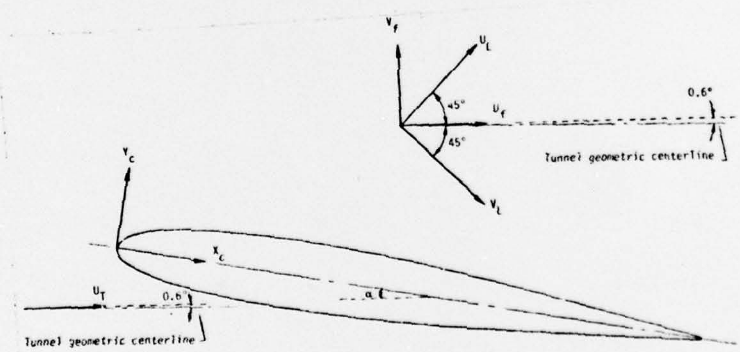

Figure 1. - Sketch of axis system used including directions of velocity components computed.

The velocity measurement position was referenced to the airfoil chord-line, and the velocity measurement magnitude was referenced to the free-stream direction. The units for the physical quantities defined in this paper are the International System of Units. Most quantities were measured in this system; however, some were measured in the U.S. Customary Units and converted by using factors given in reference 5.

c wing chord, 0.3048 m

N number of velocity measurements in one ensemble

N_i number of velocity measurements in i^{th} histogram interval as percent of N

U_f local velocity component, parallel to direction of free-stream velocity, m/sec

U_L local velocity component in LV optics coordinate system, 45° above tunnel centerline (see fig. 1)

U_R local total velocity, $\sqrt{U_f^2 + V_f^2}$, m/sec

U_T free-stream velocity determined from pitot-static probe, m/sec

V_f local velocity component, perpendicular to direction of free-stream velocity, m/sec

V_L local velocity component in LV optics coordinate system, 45° below tunnel centerline (see fig. 1)

X_c, Y_c coordinate axis relative to wing chord

x_c distance downstream from airfoil leading edge along chord, m

y_c distance above wing chord, perpendicular to it, m

α wing angle of attack, deg

APPARATUS

A fringe-type LV optics system operating in the backscatter mode was used for these tests. A sketch of the optics system is presented in figure 2, and a photograph is presented in figure 3. A high-speed burst counter was used to measure the period of the high-frequency signal contained in the burst from a particle traversing the sample volume. LV system control, data acquisition, and data reduction were handled by

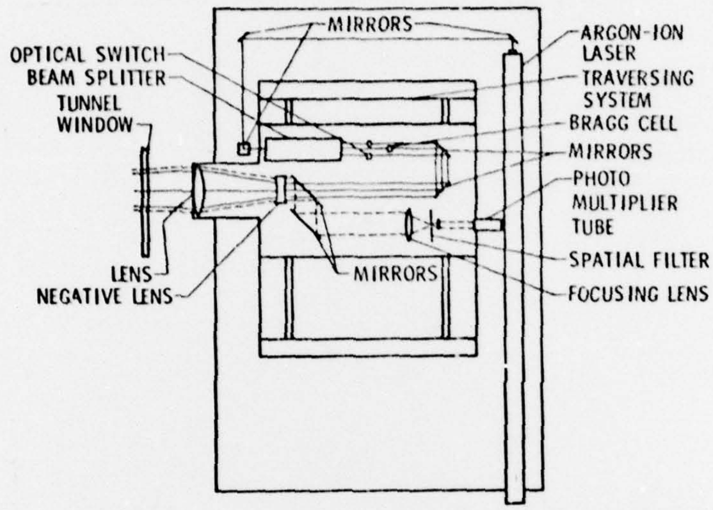

Figure 2. - Schematic of the LV optics.

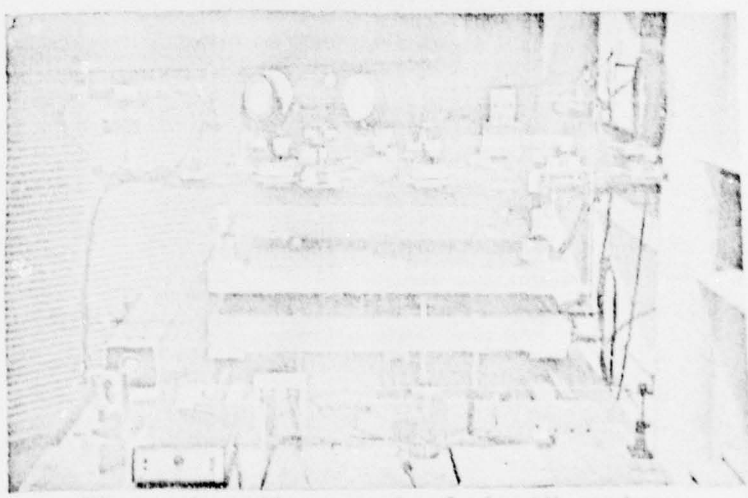

Figure 3. - Photograph of the LV optics.

a minicomputer. A complete description of the LV optical system, electronics system, and data acquisition and reduction is available in reference 6.

The model used in this investigation was a simple straight wing. It had a span of 2.438 m, a chord of 0.3048 m, and a NACA 0012 airfoil section. Velocity measurements were made at center span to obtain two-dimensional characteristics. The wing was supported by struts from the floor near the tunnel centerline with no balance measurements taken. The location of the strut mount to the wing was chosen as far outboard as structurally feasible to minimize flow disturbance at the wing centerline. A photograph of the model with crossing laser beams is presented in figure 4.

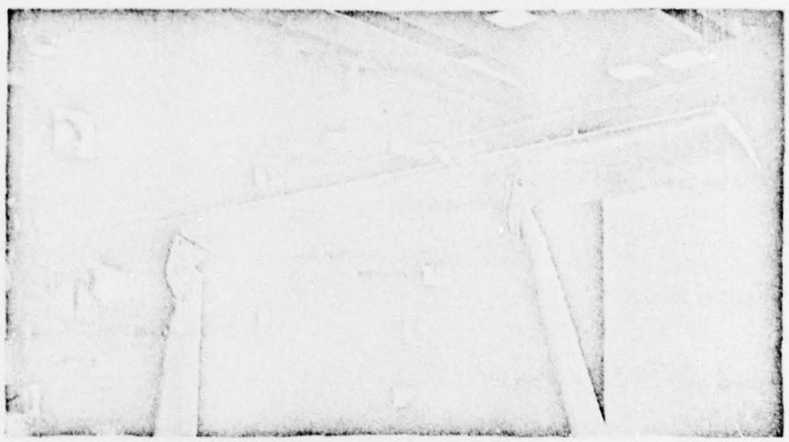

Figure 4. - Straight wing with NACA 0012 airfoil section installed in V/STOL tunnel with crossing laser beams.

This ivestigation was conducted in the Langley 4- by 7-meter low-speed (V/STOL) tunnel at a nominal free-stream Mach number of 0.15. The Reynolds number based on the wing chord was approximately 1×10^6. Local flow velocities were measured about the wing centerspan at three angles of attack: 0°, 4.15°, and 19.4°. The low angle-of-attack measurements were obtained to compare with a two-dimensional theoretical prediction technique (ref. 7), and the high angle-of-attack measurements were obtained to define the flow-field characteristics over a separated airfoil.

A pitot-static probe was mounted 2.5 m below and 1 m ahead of the the wing centerline to provide accurate reference for the free-stream tunnel dynamic pressure. A hygrometer was used to obtain wet bulb temperatures and, total temperature was measured in the settling chamber. Thus, the tunnel air density could be calculated, and with dynamic pressure measurements,the tunnel velocity could be accurately determined.

DISCUSSION

Velocity measurements at each measurement location were first reduced to histogram form. These data for the wing at $\alpha = 0°$ and 4.15° (relative to tunnel geometric centerline) along with a description of data reduction technique, histogram interpretation, and complete error analysis can be found in reference 6.

Free-stream velocity measurements were obtained with the LV in the clear tunnel at the location of the wing centerline. These data indicated an average upwash angle of 0.6° (relative to tunnel geometric centerline). The wing was installed with the chordline parallel to test-section centerline; therefore, the effective angle of attack was assumed to be 0.6°. It is known, however, that the presence of the wing and struts change this angle, but the magnitude of this change is not known.

Prediction Technique

The external forces generated on a body in a fluid are manifested in the velocity distribution of the fluid about the body. In developing a prediction technique, the calculations at the surface of the body are verified with conventional pressure and force measurements. Reference 7 presents an excellent comparison with measured surface pressures for this viscous-flow prediction. Since the local surface pressures are computed from predicted local surface velocities, it is justifiable to question the validity of the predicted velocities away from the surface. The need to verify these prediction velocities is evident. The use of conventional probes near the surface raises questions about the accuracy of the measurement because of the interferences caused by the presence of the probe. It was determined that the LV was a device capable of measuring this flow field without inducing any interference since nothing was present in the field but the wing and light beams.

The theory for this prediction technique (ref. 7) involves an iterative procedure which first obtains an inviscid-flow solution for the basic airfoil. It computes a boundary-layer solution based on the inviscid-flow solution and constructs a modified airfoil by adding the boundary-layer displacement thickness to the original airfoil. It obtains the inviscid solution for the modified airfoil and repeats these steps until appropriate convergence criteria are satisfied. The field point velocities are then computed from the vorticity distribution along the modified airfoil.

Experiment-Theory Comparison

At $\alpha = 0°$. - Velocity vectors as measured by the LV for the wing at $\alpha = 0°$ are presented in figure 5. Each velocity vector (arrow)

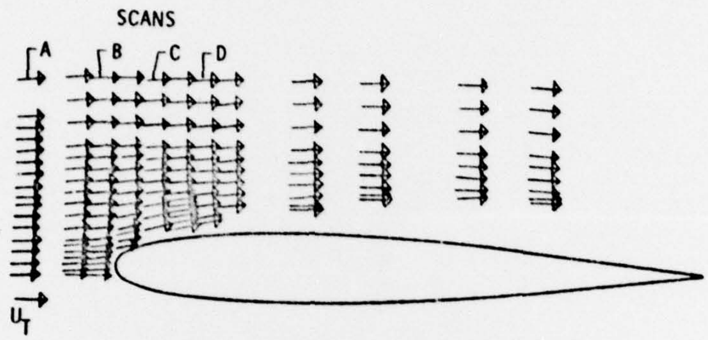

Figure 5. - Velocity vectors computed from measurements over the wing at a geometric angle of attack of 0°.

is an average of an ensemble of measurements taken over a short period of time at the desired location. This arrow plot indicates the relative location of the velocity measurements, magnitude and angle of the velocity vector. The velocity magnitude and direction is indicated by the length and orientation of the arrow. The position of velocity measurement is marked by the tail end of the arrow. The tunnel free-stream magnitude and direction reference is provided in the lower left corner of the figure.

The velocity measurements were obtained by positioning the sample volume at a desired chordwise station (x_c/c), and incrementing the entire optics package downward along this chordwise station. This was accomplished remotely and was completely controlled by the minicomputer. Four of these series of measurements (scans A, B, C, and D from fig. 5) are presented in more detail in figure 6. This figure presents a comparison between LV measured velocities and the two-dimensional viscous-flow prediction. The comparison is presented with the resultant velocity nondimensionalized by tunnel free-stream velocity as a function of the vertical position of the measurement nondimensionalized by wing chord.

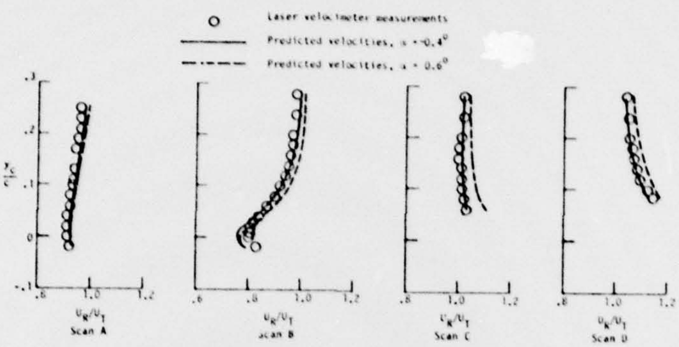

Figure 6. - Comparison of LV flow-field velocity measurements with a two-dimensional viscous-flow prediction. Wing geometric angle of attack = 0°.

The free-stream upwash angle without wing or supports was measured at 0.6° at this Mach number. Typically, flow angularity is affected by a model's presence. It is normally determined by model upright and inverted angle-of-attack ranges. Comparisons of balance data from these two conditions provides the total flow angularity. It is very difficult to obtain this type of measurement with discrete velocity measurements in the presence of the model. Since no balance measurements were obtained in this investigation, there is some uncertainty in the effective angle of attack of the wing. Predicted velocities were calculated first using the measured 0.6° tunnel flow angle without the wing. These are presented as dashed lines with maximum discrepancies on the order of 6 percent. Calculations were repeated with a one degree shift in angle of attack to provide an assessment of the effect of uncertainty in this measurement. These calculations are presented as solid lines with $\alpha = -0.4°$ and indicated better agreement with theory. It is obvious in these comparison that the precise measurement of these velocities depended on the precise determination of the effective angle of attack of the wing. It is justified to say, however, that these data provide a quantitative and qualitative measure of the accuracy and acceptability of LV measurements about a lifting surface.

At $\alpha = 4.15°$. - The velocity vectors as measured by the LV for the wing at a geometric angle of attack of 4.15° are presented in figure 7. Four of these series of measurements (scans A, B, C, and D from fig. 7) are presented in more detail in figure 8. As before, this presents a comparison between LV measured velocities and the two-dimensional viscous-flow prediction for the four scans with large

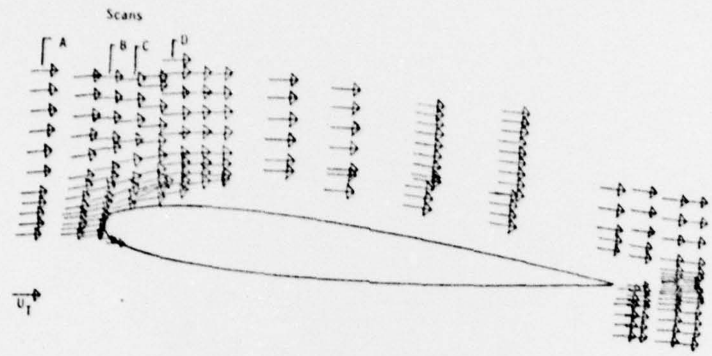

Figure 7. - Velocity vectors computed from measurements over the wing. Geometric angle of attack = 4.15°.

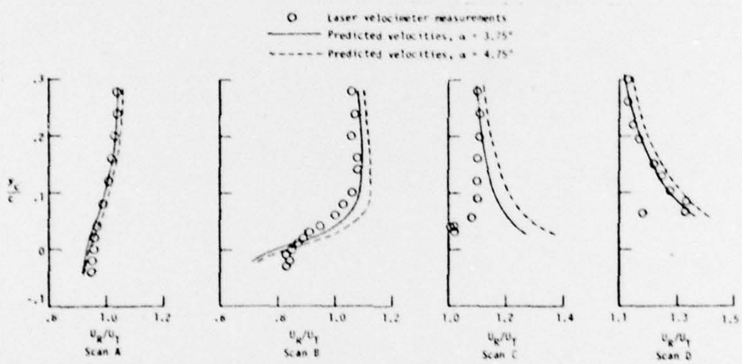

Figure 8. - Comparison of LV flow-field velocity measurements with a two-dimensional viscous-flow prediction. Wing geometric angle of attack = 4.15°.

velocity gradients. Predicted velocities using the measured 0.6° tunnel flow angle (without the wing) are presented as dashed lines. The agreement is not good particularly very near the leading edge (scans B and C). Based on the data presented for the wing at 0°, an adjusted flow angularity (-1.0°) was chosen to obtain an approximation of the effective angle of attack (3.75°). These data are presented as a solid line and show good agreement for scans A and D, but still poor agreement for scans B and C. The LV measured velocities for scan C particularly indicate a different shape in the velocity profile. This suggests that more than flow angularity uncertainty existed. The basic histogram data

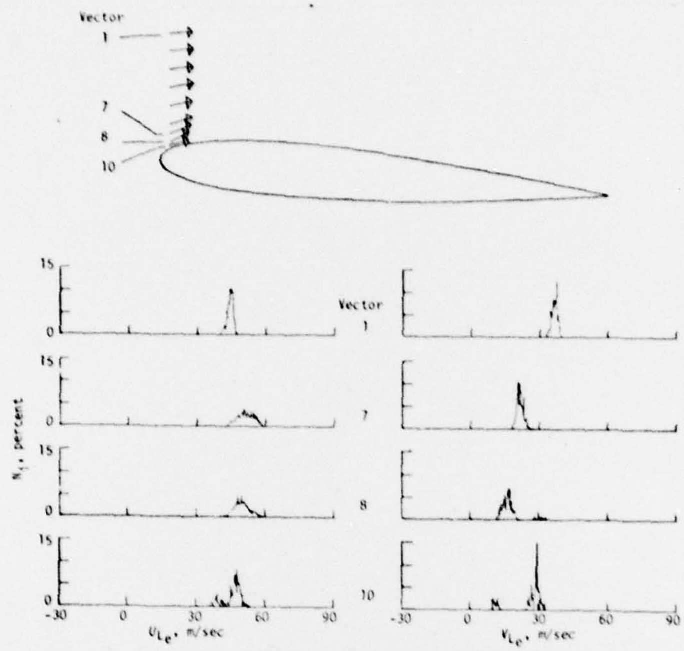

Figure 9. - Histogram data for scan C.
Wing geometric angle of attack = 4.15°.

for four of the velocity vectors within this scan are presented in figure 9. The local flow characteristics for these vectors are presented in histogram form for vectors 1, 7, 8 and 10.

A sketch of the wing cross-section with arrows indicating the position, direction, and relative magnitude of the mean velocity vectors is also provided in figure 9. A vector is an average of an ensemble of data acquired at the position desired. The histogram is a graphical representation of the variation of velocity measured over a time period. They are presented with N_i , percentage of that number of measurements within incremental velocity band, as a function of velocity. The basic LV coordinate system U_L component is presented on the left and the V_L component on the right. Interpretation of histogram information is provided in reference 6.

The histograms above the surface (vectors 1-7) are well defined Gaussian-type distributed velocity measurements. Very near the surface the histogram (vectors 8-10) has two peaks, which indicate two predominant velocity values. At this position and subsequent positions, the flow experiences an oscillation between the two values, sometimes with greater tendency to be at or near one value than the other, but spends little time between the two general values. This type of histogram has been shown to be generated by the passage of a transverse vortex through the measurement volume (ref. 8). Information presented in reference 9 indicated that this airfoil section should have a laminar separation bubble near the leading edge at this angle of attack operating at this Reynolds number. The most likely explanation of these double-peaked histograms and the very poor agreement with theory was that there existed a laminar separation bubble on the upper surface with a thin oscillating shear layer. If the shear layer were steady, the double peaks would probably not exist. As described in reference 6, the measurements leading up to this point indicated variation in velocity and angle. The position of the separation point, as measured in reference 9, is highly sensitive to slight wing angle-of-attack changes; therefore, it is possible that the separation point was moving with the tunnel flow angle oscillation. This unsteadiness in the separation point would trigger an oscillating shear layer.

The Airfoil at 19.4°

An arrow plot of the mean velocity field about the airfoil at α = 19.4° is presented in figure 10. Each velocity vector is presented

Figure 10. - Velocity measurements over the stalled wing (α = 19.4°).

with the length of the arrow indicating magnitude and direction of the vector relative to the airfoil. It is obvious from this figure that the airfoil is in a fully separated condition. The shear layer region between the free-stream and the separated turbulent area over the wing is broad, but easily discernable. The velocity field in the separated region indicates the existence of a large recirculating eddy with reverse flow near the airfoil surface. The velocity fluctuations within the shear layer were large; however, it the reverse flow region, the velocity fluctuations were smaller. A dashed line is provided indicating the approximate location of zero velocity in the separated region. At the trailing edge (see fig. 11), a very sharp shear layer

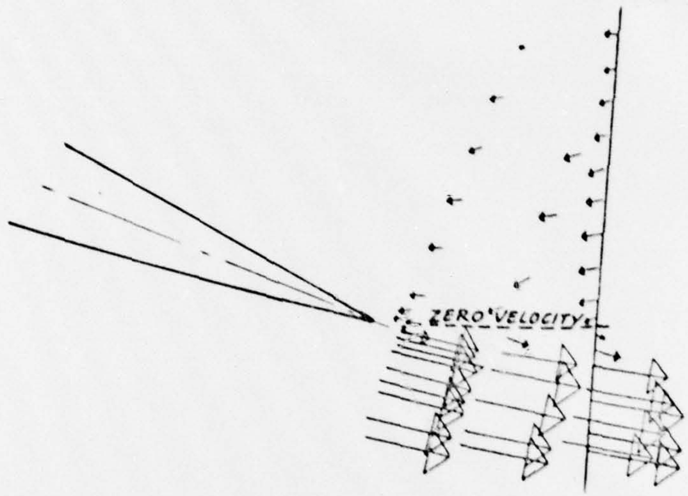

Figure 11. - Velocity measurements at the trailing edge of the wing at = 19.4°.

is evident with low, reversed flow velocities generated near the airfoil upper surface and with nearly free-stream velocity from the lower surface. The spatial distance across this shear layer is on the order of 0.005 x/c. The reverse flow in the wake region above the airfoil is also evident.

These velocity measurements were obtained without prior knowledge of the direction of the flow at each measurement point. The LV is unique in this capability unlike conventional probes which require this information to reduce ambiguity primarily caused by alinement requirements and support structure interference (ref. 10).

CONCLUSIONS

A laser velocimeter was installed in the Langley 4- by 7-meter low-speed (V/STOL) tunnel to measure the velocity field about a straight wing with a NACA 0012 airfoil section. The wing was installed at three geometric angles of attack: 0°, 4.15°, 19.4°. This was done to provide data at low angles of attack to compare with a well-accepted two-dimensional viscous-flow prediction program and at a high angle of attack to characterize the flow field in the separated region over a fully stalled wing.

The results of this investigation indicated that:

1. The laser velocimeter is an effective and accurate instrument for measuring the velocity field over a surface.

2. The precision of the laser velocimeter measurements for the wing at a geometric angle of attack of 0° depended on the precise determination of the effective angle of attack of the wing in the tunnel.

3. The data for the wing at a geometric angle of attack of 4.15° indicated that a laminar separation bubble probably existed with a thin oscillating shear layer.

4. The separated region over the wing in the fully stalled condition was well defined. Reverse flow measurements in this region demonstrated the unique capability of the laser velocimeter for measuring velocity magnitude and direction without prior knowledge of the flow direction.

5. The trailing-edge measurements at the highest angle of attack demonstrated the capability of the laser velocimeter in measuring the velocity characteristics across a very sharp velocity gradient.

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TITLE: Velocity Measurements About a NACA 0012 Airfoil With a Laser Velocimeter.

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ABSTRACT:

An investigation to measure the velocities about a NACA 0012 airfoil at two low angles of attack and post stall has been conducted in the Langley 4- by 7-meter low-speed (V/STOL) tunnel with a two-component laser velocimeter. This investigation had three basic objectives: (1) To verify the applicability and validity of the laser velocimeter in the 4- by 7-meter (V/STOL) tunnel; (2) To correlate the low angle-of-attack measurements with a two-dimensional flow-field prediction technique; and (3) To define the characteristics of the highly unsteady flow above an airfoil operating under post-stall conditions.

Velocities were measured about the wing at center span so that the three-dimensional effects of the straight aspect ratio wing would be minimized. Velocity measurements at low angle of attack indicated expected smoothly varying flow except for the wing at $\alpha = 4.75°$. A leading-edge laminar separation bubble was indicated by the velocity measurements. Velocity measurements at the post-stall condition provided a means of analyzing the flow characteristics in the separated region. A broad shear layer with highly unsteady characteristics was evident. Reverse flow near the airfoil upper surface was measured.

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