Aerodynamic Testing at Low Reynolds Numbers

J. F. Marchman*
Virginia Polytechnic Institute and State University, Blacksburg, Virginia

Published test results for the Wortmann FX63-137 airfoil at Reynolds numbers between 50,000 and 500,000 were examined and differences in those data analyzed to determine test factors that may affect the outcome of wind tunnel tests of wings and airfoils at low Reynolds numbers. Tests were conducted to examine the possible influences of different model mounting techniques on data accuracy. Wind tunnel turbulence and acoustic disturbances were found to significantly alter wing stall behavior and model test arrangement was shown to be the probable cause of the observed shifts in the zero-lift angle of attack between two sets of published data. Recommendations are made for a systematic evaluation of wind tunnel facilities for low Reynolds number aerodynamic research suitability and for the testing of all such wings or airfoils in several selected facilities.

Introduction

PLANS now exist for several types of aircraft that will operate in the 50,000–500,000 range of wing chord Reynolds number. These aircraft range from low, slow-flying, remotely piloted vehicles to large manned and unmanned aircraft that will cruise for very long periods of time at altitudes above 60,000 ft. At these low Reynolds numbers, the aerodynamic behavior of an airfoil or wing can exhibit some unusual characteristics.

The airfoil that has received the most attention in recent examinations of low Reynolds number wing aerodynamics is the Wortmann FX63-137 (Fig. 1). This airfoil, originally designed for sailplane use at Reynolds numbers of about 500,000, appears to be more successful than most at using the "laminar bubble," which characterizes low Reynolds number flow on the upper surface of an airfoil, to increase its maximum lift coefficient capability. In the laminar bubble, the laminar boundary layer over the front of the airfoil separates; however, before the flow can completely break away from the surface, laminar/turbulent transition occurs in the separated shear layer. If this turbulent shear layer can grow at a sufficient rate, the boundary layer can reattach as a turbulent boundary layer. This turbulent boundary layer may later separate, causing a gradual loss of lift as the separation point moves forward with an increase in the angle of attack. Because of this "bubble" behavior and its influence on stall inception and recovery, airfoils like the FX63-137, which exhibit high $C_{L_{max}}$ at low Reynolds numbers, also appear to exhibit stall hysteresis.

Stall hysteresis, a phenomenon where stall inception and stall recovery do not occur at the same angle of attack, can result in severe control problems in stall. Instead of an immediate stall recovery with released stick pressure, the angle of attack may have to be reduced by as much as 10 deg to reestablish an attached upper-surface flow. In Ref. 1, an Æ8 Wortmann FX63-137 at $Re = 200{,}000$ was shown to stall at an angle of attack of 22 deg with a drop in C_L from about 1.5 to below 1.0; recovery did not occur until the angle of attack was reduced to almost 10 deg.

Why then is this important in relation to wind tunnel testing? Simply put, if wind tunnel test results do not accurately predict stall hysteresis behavior, severe problems might result. The problem is that stall hysteresis behavior is very dependent on wind tunnel flow quality and acoustic properties. This influence has been examined to some extent by Mueller[2] and more recently by Marchman et al.[3] The implications of these effects in the use and interpretation of wind tunnel test results in this range of Reynolds number need to be examined.

An examination of wind tunnel airfoil test data for the 50,000–500,000 range of Reynolds number will reveal a number of inconsistencies among the test results. Some of these can be explained in terms of tunnel flow environment, but others cannot. The result is a seemingly wide disparity among data from various wind tunnel tests, leaving those who might wish to use these data in a quandry as to data accuracy and leaving those who have conducted the tests sometimes puzzled about their own results. Researchers are often at odds with other researchers regarding test data accuracy, data acquisition techniques, data measurement reliability, model accuracy, tunnel corrections, etc.

The following discussion seeks to examine some of the questions raised by examining published test results for the Wortmann FX63-137 airfoil in the Reynolds number range of 50,000–500,000. The objective is to alert both those who run wind tunnel tests and those who use the test results to the factors that may influence those test results and to the nature of those influences.

Previous Test Results

Low Reynolds number wind tunnel testing is, of course, nothing new. The Wright brothers' wind tunnel tests were well within the range of Reynolds numbers under discussion here. Since those early days, however, the emphasis has been on testing at ever higher Reynolds numbers with higher speeds, larger models, variable density tunnels, and boundary-layer tripping devices to simulate higher *Re* effects when they could not otherwise be created. Early tunnels were very "dirty" with high turbulence levels and noise. Hence, low Reynolds number effects such as the stall hysteresis loop were either not observed or were dismissed as "bad data" when they were observed. It really was not until the 1930s and 1940s when model airplane enthusiasts and, later, sailplane designers began to conduct serious wind tunnel tests, that some of the phenomena now associated with low Reynolds number flows began to be accepted as valid test results.[4]

Some airfoils do not exhibit extensive stall hysteresis in low Reynolds number, steady flow. The Clark-Y, which is typical of many early airfoil shapes and the basis for the whole NACA four-digit series of airfoils, was shown by Marchman and Werme[5] to exhibit only a very weak stall hysteresis loop at low Reynolds numbers. Many airfoils appear to experience

Presented as Paper 86-0779 at the AIAA 14th Aerodynamic Testing Conference, West Palm Beach, FL, March 5–7, 1986; received April 24, 1986; revision received Oct. 8, 1986.

*Wind Tunnel Director and Associate Professor, Aerospace and Ocean Engineering Department. Associate Fellow of AIAA.

more abrupt stall at lower Reynolds numbers, but show little evidence of stall hysteresis.

The effect of Reynolds number on low Reynolds number airfoil behavior was examined thoroughly by Abtahi and Marchman[1] for an Æ 8 Wortmann FX63-137 wing and three-dimensional effects for aspect ratios of 1–10 have been investigated by Bastedo and Mueller[6] and Marchman et al.[7] Essentially, it was shown that there is a range of Reynolds number between about 75,000 and 400,000 where the separation bubble behavior dominates the flow and determines the stall behavior. The limits of this Reynolds number range are dependent on the aspect ratio. As the aspect ratio decreases, the vortical flow around the wing tip becomes more of a factor in the overall upper-surface flow behavior. Below some aspect-ratio-dependent Reynolds number near 75,000–100,000, the airfoil behaves like a thin plate with separated upper-surface flow at almost all angles of attack. Above some Reynolds number between 300,000 and 500,000, the turbulent boundary layer appears strong enough to prevent the hysteresis loop phenomenon.

It appears, then, that a variety of test results exist for at least one airfoil, the Wortmann FX63-137, in low Reynolds number flow and, from this, one might conclude that there is no problem in conducting wind tunnel tests at this range of *Re* and in producing reliable, repeatable results. However, this is not the case—in fact, it seems that, as more test results are published, more questions arise regarding data reliability, test technique, and facility suitability.

The Wortmann FX63-137 is a rather unique airfoil that apparently sustains a laminar bubble over a wide range of angles of attack at low Reynolds numbers. There are other airfoils that might be less prone to aerodynamic behavior changes at low Reynolds numbers and that might not exhibit the data variations noted for the Wortmann. The FX63-137 is, however, an airfoil specifically designed for enhanced lift at low Reynolds number and has been the choice of the U.S. Navy and other agencies as the optimum candidate airfoil for low *Re* use. It is also the only airfoil for which low Reynolds number aerodynamic data are available from a variety of researchers in recent publications. Therefore, it is the obvious choice for use in the comparison of recent low Reynolds number aerodynamic test data.

Zero-Lift Shift

Figure 2 illustrates part of the problem in interpreting the accuracy of wind tunnel test results for low Reynolds number flows. Both sets of data[8] in this figure were taken for the same two-dimensional airfoil model, apparently using the same test apparatus and techniques at a Reynolds number of 200,000. The only noted difference in the tests was the level of turbulence in the wind tunnels, with the lower curve resulting from tests in a tunnel with higher turbulence levels. However, it is not really logical that such a shift in results should result from changes in the tunnel turbulence level. One would expect increased turbulence to increase $C_{L_{max}}$, yet here it is reduced. The effect appears to be a camber effect or an error due to a misalignment in the flow, yet the results apparently came from the same researchers using the same model and test techniques.

Every researcher who has ever conducted wind tunnel testing is aware that there is ample opportunity for error and uncertainty to play a role in any experimental study. Few researchers would ever claim that only their experimental data are correct or that only their own facilities are capable of producing accurate results; yet, one would hope that a better comparison of results could be achieved than those shown in Fig. 2. This variation in results does, however, provide a basis for comparison of similar results from other facilities.

Figure 3 compares lift coefficient data taken on the Wortmann FX63-137 airfoil at two facilities where research has recently been conducted on low Reynolds number aerodynamics. These two facilities are the Virginia Tech Stability Wind Tunnel in Blacksburg and the Notre Dame University low-speed wind tunnels in Indiana. The Virginia Tech results shown are taken from Ref. 1 and are Æ 8 data converted to two dimensions using a simple lifting line theory to correct for the slope of the lift curve, while the Notre Dame results[3] are two-dimensional data from a relatively small span model mounted between end plates.

It should be noted that the Wortmann FX63-137 is a complex airfoil contour with a large trailing-edge camber. All of the airfoil models used in the Virginia Tech tests[1,3,7] and discussed in this paper were constructed using coordinates provided by Mueller of Notre Dame and, within normal machining tolerances, should match the coordinates of test models used at Notre Dame.[2,6] The other sources of data[9,10] report using the same section and presumably used the same degree of care in model construction. Render's[10] paper reported the effects of varying the Wortmann coordinates.

The first difference that one notes in these data sets is the shift in the linear portion of the lift curve. While the slopes of the curves are virtually identical, the angle of attack for zero lift differs by about 3 deg. This shift is almost identical to that seen between the two sets of Stuttgart results in Fig. 2. Interestingly enough, the results from the Stuttgart tunnel 1, which has a low turbulence level of 0.02%, are very close to those from Virginia Tech where the tunnel turbulence level is also about 0.02%. The Notre Dame results closely match those from the Stuttgart tunnel 2, which has a higher turbulence level of 0.08%. Notre Dame also quotes turbulence levels of about 0.08% (at 30 m/s) in its tunnel.

Although the above might lead one to conclude that freestream turbulence is somehow responsible for the shift in the zero-lift angle of attack, this is not really a plausable explanation. Added freestream turbulence should produce no change in the lifting behavior of a wing in the linear portion of the lift curve. However, added turbulence should influence the stall characteristics of the airfoil and, for low Reynolds numbers, should influence the behavior of the stall hysteresis loop. This is indeed the case and will be discussed later.

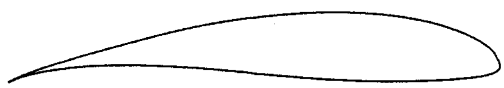

Fig. 1 Wortmann FX63-137 airfoil.

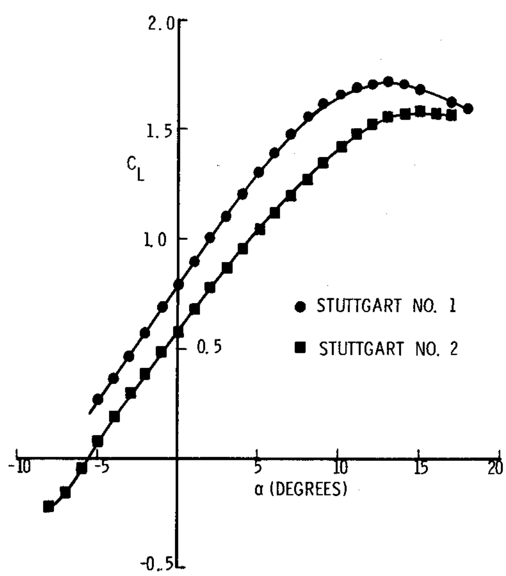

Fig. 2 Comparison of Stuttgart results.

As an indication of the fact that turbulence levels in the tunnel are not a satisfactory explanation for the shift in the lift curve, two further sets of results for the Wortmann FX63-137 are shown in Fig. 4 along with the previously shown data. These results are from Liebeck and Camacho[9] and from Render.[10] Both sets of data are from wind tunnels with turbulence levels of 0.1% or higher. The Liebeck-Camacho results closely match those from Virginia Tech, while those of Render fall close to the same data but, for some reason, exhibit a different curve slope. These data, all from quite competent researchers, indicate that tunnel freestream turbulence is probably not the cause for the difference in the zero-lift angle of attack sometimes seen when comparing results from different low Reynolds number wing tests.

One might be tempted to blame the noted disagreement in zero-lift angle of attack on model construction inaccuracies or on differences in model support configurations. As mentioned previously, every model tested was reported to be the same and the investigators at Virginia Tech and Notre Dame both used the exact same set of coordinates in constructing their test models. However, Render[10] reported results for tests where the concave lower surface of the Wortmann FX63-137 was gradually filled in, effectively reducing its camber. It is interesting to note that Render's results for a case where most of the airfoil's lower concave surface was filled are virtually an exact match for the Notre Dame results for the unaltered airfoil.

Figure 5 shows that as *Re* increases, the results of Bastedo and Mueller[6] approach those of Marchman et al.[7] for Æ 4 models. Bastedo and Mueller[6] and Mueller[2] appear to be the only investigators to have observed a shift in zero-lift angle of attack with changing Reynolds number. Indeed, Figs. 6 and 7 show that neither Render's[10] nor Marchman et al.'s[7] results display any shift of the lift curve with changing Reynolds number.

Model Mounting Evaluation

Most of the reported data for the low Reynolds number aerodynamics of the Wortmann FX63-137 are for two-dimensional tests where the model was mounted between the end plates. The type of end-plate mounting was, however, not always the same. Render[10] used the traditional approach of an end plate attached to the model. All Notre Dame tests,[2,6] however, used a system where there is a small gap between the wing model and the end plate.

Render[10] and Bastedo and Mueller[6] also used the above two different versions of end-plate mounting techniques for their finite-wing tests. All finite-wing tests at Virginia Tech,[1,3,7] however, employed a traditional, full three-dimensional model mounted on a single strut attached at the wing centerspan. The test conditions for these three sets of finite-wing results are shown in Table 1. Obvious differences in the tests, in addition to that of tunnel turbulence level, are in model blockage and types of mounting.

The data examined from Refs. 1, 3, 6, 7, and 10 are almost all force balance results obtained from strain gage balances. In some cases, the researchers also made force calculations from integrated surface pressure measurements and downstream wake momentum deficits. References 1, 2, and 7 all report that a comparison of measured force data with that from the other two methods gave excellent agreement, verifying the accuracies of the various balance systems and data acquisition systems employed. For further details on these systems and comparisons, one is referred to the appropriate references.

Since the Notre Dame results showed a shift of the lift curve with Reynolds number that was not seen in either of the other two sets of results, it is helpful to look for peculiarities in the Notre Dame tests. End-plate-mounted, semispan models sometimes give different results from tests using full three-dimensional models; full three-dimensional model test results are usually desirable. There are, however, standard correc-

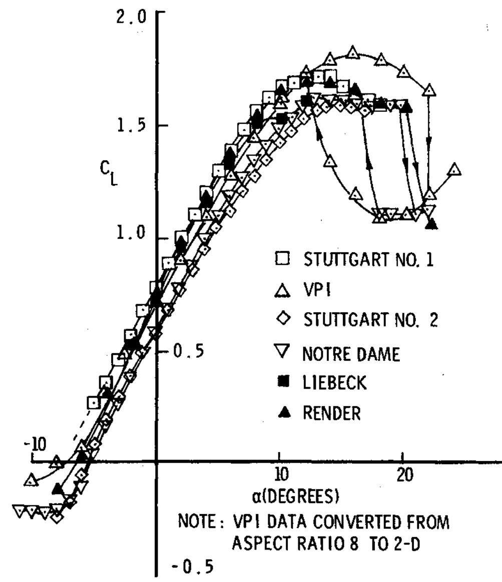

Fig. 4 Further comparison of Wortmann two-dimensional data.

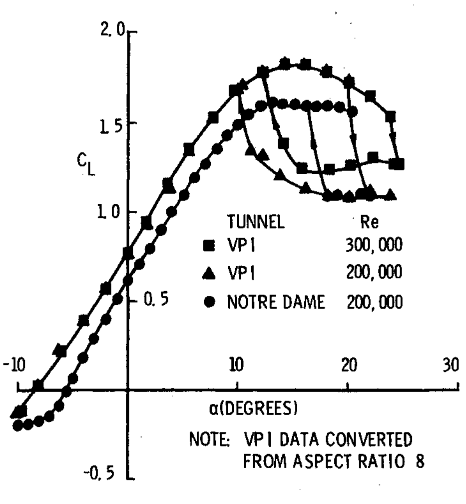

Fig. 3 Comparison of selected VPI and Notre Dame two-dimensional results.

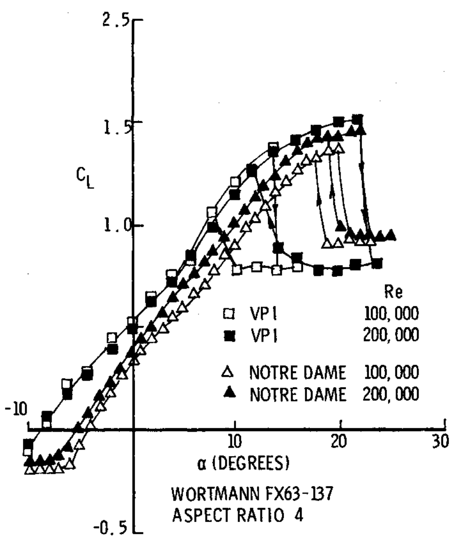

Fig. 5 Effect of Reynolds number on Æ 4 data comparison.

Table 1 Comparison of Wortmann FX63-137 test parameters

Tunnel type and size	VPI closed circuit, 6×6 ft	Notre Dame open circuit, 2×2 ft	Cranfield unknown, 8×6 ft
Reported turbulence,%			
At 10 m/s	0.018	0.03	~0.1
At 30 m/s	0.045	0.08	~0.1
Model chord, in.	5.000	6.00	13.5
Aspect ratios tested	4.0, 6.0, 8.0, 10,0	3.0, 4.0, 5.6, 2-D[a]	8.9, 2-D[a]
Velocity, m/s			
At $Re = 200,000$	~25	~19	—
At $Re = 300,000$	~38	—	~14
Model mounting employed	Strut[a] attached at wing center	Semispan/end plate with gap	Semispan wing end plate attached to wing
Corrections made to data	Calculated and found negligible	No corrections mentioned	Blockage, induced incidence mount plate drag

[a]Aspect ratios based on semispan mount: 2-D means uses of two end plates.

tions that can be applied to the semispan test results and these were applied to Render's[10] data. The method used at Notre Dame of mounting the model with a gap between model and end plate, while eliminating the necessity of subtracting the plate drag from the test results, does introduce other errors that, according to Pope and Harper,[11] can be quite large. Pope and Harper imply that, if the viscous effects are sufficient to essentially block any flow through the gap, these errors may be minimized; however, at the low Reynolds numbers of concern here, the effect of flow through the gap must be evaluated.

Even a very small leak through the gap may result in a small loss of lift that could represent a substantial portion of the wing's lift at very low Reynolds number conditions. At higher Reynolds numbers, this small leak would represent a less significant portion of the measured wing lift. The test results could then show a shift of the lift data to the left as Reynolds number increases. Since this is essentially the type of Reynolds number related shift noted in Refs. 2 and 6, a test was devised at Virginia Tech to examine the differences in mounting used at the two facilities and their effect on the resulting data.

To assure the validity of the single-strut force balance test methods used in Refs. 1, 3, and 7, a series of tests was first conducted to ascertain the effect, if any, of the mounting strut on the test data. One strut interference evaluation test used was that of testing a flat-plate model of identical planform to the previously tested Æ 6 Wortmann wing. If the strut was causing an effective flow angularity at the model and was thus causing a shift of the lift data, this same shift should appear in tests of a flat plate. Obviously, a flat plate must have zero lift at zero angle of attack. Tests over a wide range of Reynolds numbers showed that the strut caused no shift in the flat-plate zero-lift angle of attack. Further tests with inverted models and image struts gave no further reason to suspect that strut interference had adversely influenced the data taken at Virginia Tech.

A test was then devised to simulate the model mounting arrangement used in Ref. 6. An Æ 2, semispan model was mounted to a three-component strut balance through a flat plate that was rigidly attached to the strain gage strut shroud. The model was then rotated via the strut mount turntable to give changes in the model angle of attack. This arrangement, similar to that shown in Fig. 8, used the strut's side force balance to measure model lift. Model aspect ratio and end-plate size were chosen to match those used in tests at Notre Dame, even though a larger plate with boundary-layer suction would obviously be more desirable.

Using this arrangement, tests were conducted with a sealed gap between the model and plate and with an open gap. The

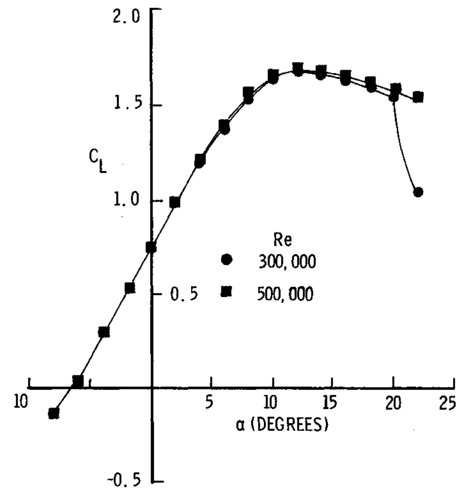

Fig. 6 Reynolds number effect on Cranfield two-dimensional results.

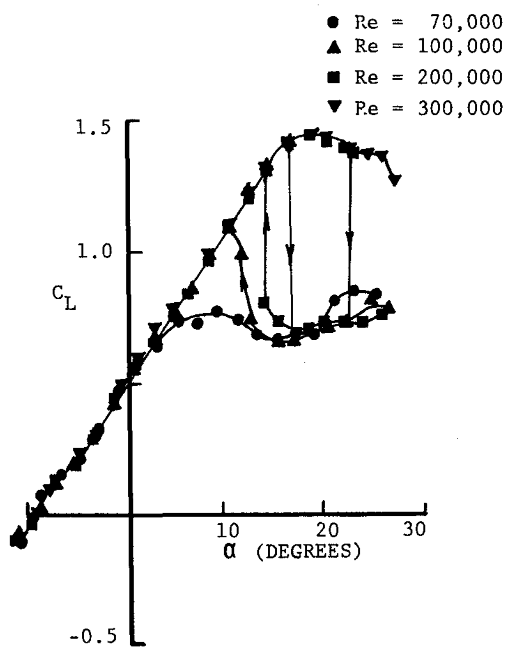

Fig. 7 Reynolds number effect on VPI results.

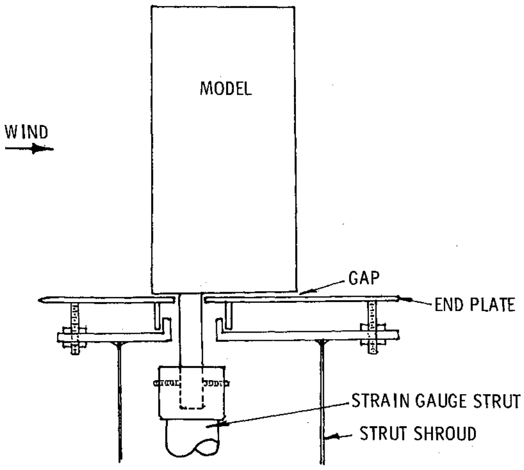

Fig. 8 Semispan model test arrangement.

seal was achieved by use of an oil-impregnated strip of very lightweight weather stripping tape attached to the end of the wing model. Initial tests with the open gap did not attempt to simulate the 0.1 mm gap reported in Ref. 6; however, Mueller has discussed with the author unpublished test results showing that gap size changes do not significantly alter his test results. The gap used in these initial tests was approximately 0.5 mm.

Figure 9 shows the results of these tests at a Reynolds number of 100,000 along with earlier VPI (full three-dimensional model, strut mounted) and Notre Dame (semispan, plate mounted, with gap) results. These results suggested quite strongly that the difference in the value of the zero-lift angle of attack data for the Wortmann FX63-137 wing tests at Virginia Tech and Notre Dame was due to the gap influence in the Notre Dame test arrangement.

Further testing was necessary to investigate the effect of gap size and Reynolds number. These tests, reported in Ref. 12, employed the test arrangement shown in Fig. 8, allowing precise alignment of the plate with the model and freestream flow and exact setting of the gap to desired values. Tests were conducted with gap sizes of 0.10, 0.50, 1.00, 1.50, and 2.00 mm as well as with a sealed gap. Runs were made at Reynolds numbers of 100,000 and 200,000 to match the test conditions of Ref. 6. The results of these tests are summarized in Figs. 10 and 11 where the data points are omitted for clarity.

Figure 10 shows that gap size, indeed, has little effect on the data as long as a gap is present. Any size gap produces essentially the same shift in the lift curve seen earlier in Fig. 9. The sealed gap, however, produces zero-lift angle of attack results that match those of Ref. 7.

Figure 11 shows that this shift in α_{L0} caused by the gap effect is a function of Reynolds number, with the lift curve shifting to the left as *Re* increases, just as reported in Refs. 2 and 6. With the gap sealed, the only effect of Reynolds number is the expected normal change in stall behavior as the Reynolds number increases.

These figures appear to show that the change in α_{L0} due to Reynolds number reported in Refs. 2 and 6 is a function of the test mounting configuration and is not due to the normal aerodynamics of the wing. None of the other test configurations reported in Refs. 1, 3, 7, 9, and 10 produced such a shift in α_{L0} with Reynolds number increases. They also indicate that even a gap as small as 0.1 mm does not eliminate this error. It appears that the gap must be sealed for accurate aerodynamic data determination if the semispan technique is to be used for low Reynolds number aerodynamic tests.

Flow visualization studies showing flow streamlines on the end plate for the sealed and open gap cases were also reported in Ref. 12. These showed that the flow through the gap is sufficient to cause large changes in flow separation patterns on the wing at the wing/plate intersection. The loss of lift due to

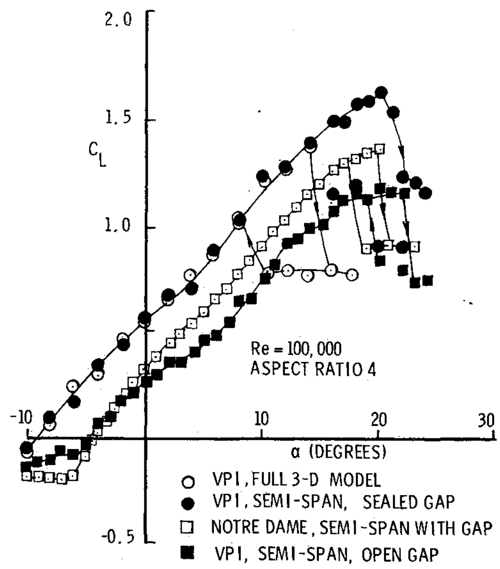

Fig. 9 Comparison of semispan and strut mount test results.

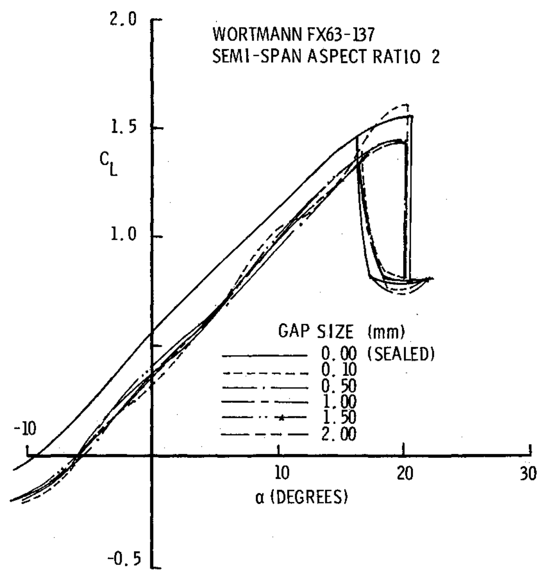

Fig. 10 Effect of gap size on α_{L0}.

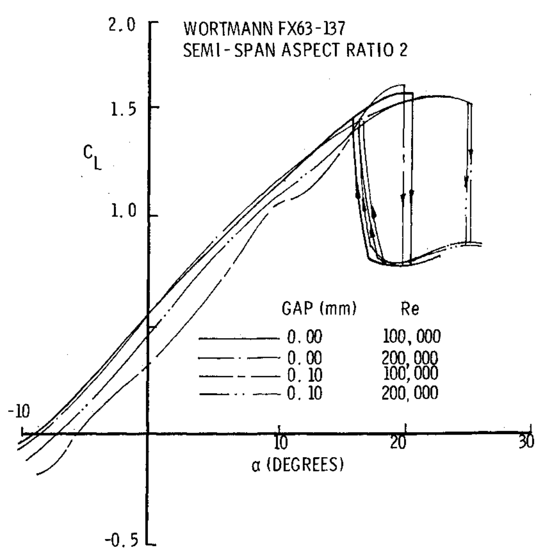

Fig. 11 Influence of Reynolds number on gap effect.

the gap appears to result primarily from very early upper-surface separation on the wing due to gap flow. While this effect may be limited to a small portion of the wing near the end plate, the effect is obviously quite pronounced for the Æ=2 semispan case. The gap-induced error might well be less significant if higher-aspect-ratio models were tested; however, one must assume that for small-aspect-ratio models (even where two end plates are used and two-dimensional behavior is assumed) the gap effect may cause substantial errors in low Reynolds number wing aerodynamic behavior.

Tunnel Flow Disturbances

The other major difference noted among sets of published low Reynolds number aerodynamic data for the Wortmann FX63-137 airfoil is the extent of the stall hysteresis loop. The results of Render[10] and Liebeck and Camacho[9] show no stall hysteresis, while those of Marchman et al.[1,3,7] and Mueller[2,6] exhibit a clear loop. Mueller[2] has previously discussed the role of both acoustic disturbances and turbulence increases in low Reynolds number tests. Both types of disturbances are known to be capable of altering the behavior of the laminar bubble and, hence, stall characteristics. Their effect is essentially an earlier transition to a turbulent shear layer, which enhances the possibility of reattachment of the separated boundary layer and reduces the size of the stall hysteresis loop.

This effect can be seen in comparing the stall hysteresis behavior in several of the previous figures (Figs. 3-5) where results from the Virginia Tech Stability Wind Tunnel with its 0.02% turbulence level have a much larger hysteresis loop than results from the higher-turbulence facility. Data from other sources such as Liebeck and Camacho[9] and Render[10] showed no hysteresis loop, suggesting that either their tunnel flow quality was too poor to result in a loop or the existence of a loop was overlooked.

The above results point out the importance of an excellent flow environment for low Reynolds number aerodynamic testing. Marchman et al. reported some results of the effects of both freestream turbulence increases and acoustic disturbances on stall hysteresis in Ref. 3, where the two types of disturbances were examined independently. Figures 12 and 13 show some of the results, indicating that both flow turbulence and noise of sufficient level and frequency can independently result in a large reduction in hysteresis loop size.

The effect of a disturbance is dependent on the frequency of the disturbance. This is illustrated by Fig. 14 where different sound frequencies were found capable of inducing reattachment of the separated flow at different angle of attack within the hysteresis loop. Other illustrations of this frequency dependence can be found in Ref. 3.

Drag Measurement

Drag has always been the most difficult aerodynamic force to measure and the low drag forces occurring in low Reynolds number flows make the problem even more difficult. The two primary methods used to measure drag are the measurement of the wake momentum deficit and the use of a force balance. Many researchers have relied on the former method at low Reynolds number since it is a two-dimensional technique and most research has been for the two-dimensional case. The momentum deficit method has inherent flaws at higher angles of attack because of rotational momentum losses. For three-dimensional drag measurement, a force balance must be used or momentum deficits must be measured along the entire wing span and integrated. Most of the drag measurements of Refs.

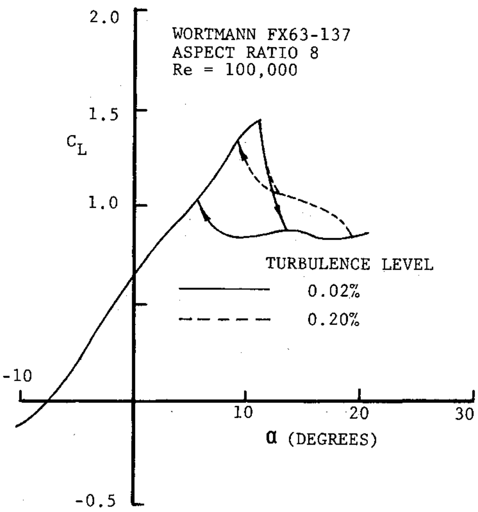

Fig. 13 Turbulence influence on stall hysteresis.

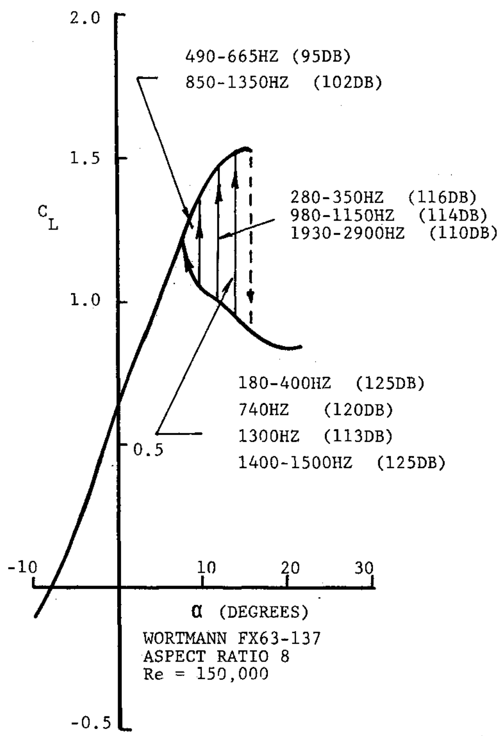

Fig. 14 Sound frequencies needed to induce attached flow.

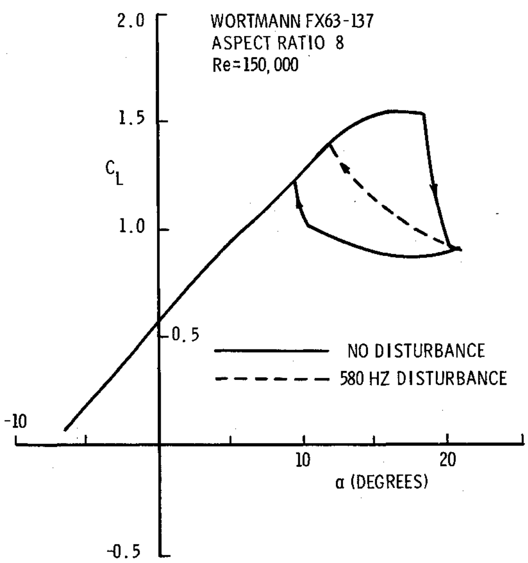

Fig. 12 Acoustic disturbance influence on stall hysteresis.

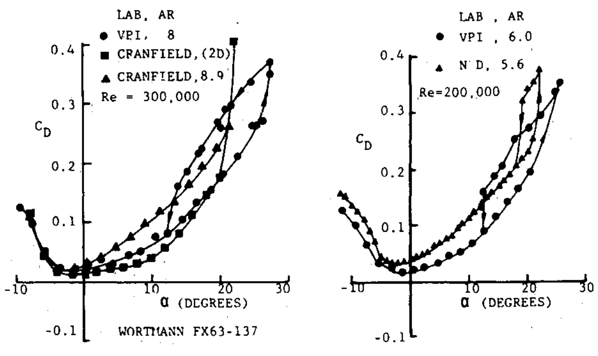

Fig. 15 Comparison of drag results.

1-3, 6, 7, and 10 were made via the force balance and in several of these the authors reported good correlation between both methods of drag measurement at low-to-moderate angles of attack.

Examination of the drag coefficient data reported in the above-cited references shows the difficulty of making accurate measurements at the lowest Reynolds numbers of the studies. The Notre Dame balance[6] is specifically designed for smaller forces and appears capable of more consistent drag measurement at Reynolds numbers of 100,000 or less when compared to the systems used at either Cranfield[10] or Virginia Tech.[1,3,7] Measurements of drag were made at these lower Reynolds numbers at Virginia Tech and, while a curve faired through the data is consistently repeatable, there is increased data scatter, especially at Reynolds numbers below 75,000. Some of this scatter is to be expected in view of the separated flow existing over almost the entire range of angle of attack in this region of "thin-airfoil" aerodynamic behavior.

Comparison of actual test technique effects on drag measurement at low Reynolds number is best made at Reynolds numbers of 200,000 and 300,000 where there is very little scatter in any of the data sets and where there is more common ground in terms of test parameters for comparison. Figure 15 compares the drag data for similar aspect ratio Wortmann FX63-137 wings from three different laboratories. It is seen that there is a good agreement in the general trends, i.e., the zero-lift drag coefficient and points of inflection in the curves are consistent. Beyond that, however, the Notre Dame[2] results are generally higher than those from Virginia Tech[7] and the Cranfield[10] results fall on both sides of the Virginia Tech results for the higher-aspect-ratio case. It should be noted that the Cranfield two-dimensional drag data are in better agreement with the Virginia Tech $AR = 10$ results than with the Notre Dame two-dimensional data. The differences in Reynolds number do not appear to be sufficient to account for the differences in the two-dimensional drag data of Refs. 2 and 10.

It is quite possible that the drag at nonzero-lift angles of attack reported in Refs. 2 and 6 is influenced by the same model/end-plate gap effect that appears to alter the lift results. The theoretically predicted effect of a gap is to decrease the wing's effective aspect ratio and thus increase induced drag. As mentioned earlier, Pope and Harper[11] cite up to 47% increases in induced drag due to the gap effect. Any test system employing a semispan model with a gap must be highly suspect in its measurement of drag due to these possible induced drag errors. This appears to be especially true for low-aspect-ratio models at low Reynolds numbers.

Conclusions

The preceding examination of previously published results and of current tests to examine model mounting influences indicates the complexity and uncertainty associated with low Reynolds number aerodynamic testing. Contradictions in test results from apparently carefully conducted studies by competent researchers serve to illustrate the frustrations inherent in low Reynolds number aerodynamic research.

Of the test parameters investigated, that causing the greatest alteration in test data appears to be the use of a model/plate gap in semispan model testing. This test technique appears capable of altering the zero-lift angle of attack by several degrees, as well as having the predicted effect of decreasing the effective aspect ratio and thus increasing the induced drag. Wind tunnel turbulence and acoustic disturbance effects appear to alter primarily the wing's stall behavior with little or no influence on prestall behavior.

The examination of semispan model/end-plate gap influences on aerodynamic data shows that the gap not only can cause higher drag (lower effective aspect ratio) as discussed by Pope and Harper,[11] but can also result in a shift of the zero-lift angle of attack for the Wortmann FX63-137 airfoil at low Reynolds number. This error may be reduced for higher-aspect-ratio models; however, to avoid the problem entirely, semispan model tests should be conducted only with sealed model/end-plate junctions. Testing of the full three-dimensional wing is always preferable where the test section size and available balance systems permit such tests.

When comparative tests are to be performed in two or more different facilities, a common model or a set of models from a single extrusion should be used, especially when testing shapes such as the Wortmann. Otherwise, it is much too easy to blame differing results on small perturbations in model shape. On a shape that relies on separated and reattached flows for its performance, such a source of data variation must be eliminated where possible, although tests by Render,[10] where the shape of the Wortmann FX63-137 was altered, indicate that small changes in shape do not produce significantly different results for this particular airfoil.

The noted effects of freestream turbulence and of acoustic disturbances must also be considered when conducting wind tunnel tests or when using the results from such tests. While these may affect only stall behavior, a designer using the test results of either Liebeck and Camacho[9] or Render[10] would be unaware of the existence of stall hysteresis. The user of the Notre Dame[2,6] results would be aware of the existence of a hysteresis loop, but perhaps not of its full extent. One might assume that the 4-deg drop in angle of attack needed for reattachment of the stalled flow, as indicated by the results of Ref. 6 shown in Fig. 6, is acceptable and then be surprised to find in flight tests that a 10-deg reduction in angle of attack is really required, as indicated by the data in Ref. 1.

Further studies need to be conducted to systematically study the individual influences of both freestream turbulence and acoustic disturbances. It is clear that these may act independently, but a study should seek to determine whether their effects overlap or are cumulative in nature, i.e., will a hysteresis loop, already small due to wind tunnel turbulence, be further decreased or even eliminated if also exposed to the right acoustic disturbance?

Theory and the experimental results of Ref. 3 indicate that both turbulence and acoustic disturbance influences depend on both the level and the frequency of the disturbance. This indicates that, for correct interpretation of wind tunnel test results, not only the level of turbulence and noise needs to be known but also the dominant frequencies of those disturbances. It must also be known how these levels and frequencies change with tunnel speed. This information simply does not exist for most wind tunnels and even if it did, there would be little ability to make use of the information.

The critical disturbance frequencies and levels were shown in Ref. 3 to vary with Reynolds number and angle of attack and it must be assumed that they will vary considerably with airfoil shape. In other words, the critical disturbance frequencies may vary enough from one airfoil shape to another to make a full interpretation of test results impossible, even when all airfoils are tested in the same facility. For example, the figures presented earlier show that for the Wortmann FX63-137 airfoil, testing in the Virginia Tech wind tunnel results in a larger stall hysteresis loop than does testing in the Notre Dame wind tunnel. Tests on a different airfoil might result in a reversal of this trend if, for the different airfoil, some disturbance frequency that was particularly adept at altering the boundary-layer flow on that particular airfoil shape was present at a critical level in the Virginia Tech facility and not at Notre Dame.

Essentially, this points out the need for testing any airfoil or wing for low Reynolds number use in several different facilities. Preferably, these selected facilities would have as low a level of noise and turbulence as possible and would have documented turbulence and noise spectra at several speeds. Obviously, such facilities should also be of sufficient instrumentation to allow testing of reasonable size models with minimal need for blockage or other corrections.

References

[1]Abtahi, A. A. and Marchman, J. F., "Aerodynamics of an Aspect Ratio 8 Wing at Low Reynolds Numbers," *Journal of Aircraft*, Vol. 22, July 1985, pp. 628-634.

[2]Mueller, T. J., "Low Reynolds Number Vehicles," AGARDograph 288, Feb. 1985.

[3]Marchman, J. F., Sumantran, V., and Schaefer, C. G., "Acoustic and Turbulence Influences on Stall Hysteresis," AIAA Paper 86-0170, Jan. 1986.

[4]Schmidz, F. W., "Aerodynamics of the Model Airplane," Ludwig Prandtl P for 1941, Translation by Redstone Scientific Information Center.

[5]Marchman, J. F. and Werme, T. D., "Clark-Y Airfoil Performance at Low Reynolds Numbers," AIAA Paper 84-0052, Jan. 1984.

[6]Bastedo, W. G. and Mueller, T. J., "Performance of Finite Wings at Low Reynolds Numbers," *Proceedings of Conference on Low Reynolds Number Airfoil Aerodynamics*, University of Notre Dame, Notra Dame, IN, Rept. UNDAS-CP-77B123, June 1985, pp. 195-205.

[7]Marchman, J. F., Abtahi, A. A., Sumantran, V., and Sun, Z., "Effects of Aspect Ratio on Stall Hysteresis for the Wortmann Airfoil," AIAA Paper 85-1770, Aug. 1985.

[8]Miley, S. J., "A Catalog of Low Reynolds Number Airfoil Data for Wind Turbine Applications," Dept. of Aerospace Engineering, Texas A&M University, College Station, Feb. 1982.

[9]Liebeck, R. H. and Camacho, P. P. "Airfoil Design at Low Reynolds Number with Constrained Pitching Moment," *Proceedings of Conference on Low Reynolds Number Airfoil Aerodynamics*, University of Notre Dame, Notre Dame, IN, Rept. UNDAS-CP-71B123, June 1985, pp. 27-51.

[10]Render, P. M., "Airfoil Measurements at Low Reynolds Numbers," COA Rept. 8508, Cranfield, England, May 1985.

[11]Pope, A. and Harper, J. J., *Low Speed Wind Tunnel Testing*, Wiley, New York, 1966.

[12]Marchman, J. F. and Kuppa, S., "Semi-Span Model/End-Plate Gap Effects in Low Reynolds Number Aerodynamic Test Results," Dept. of Aerospace and Ocean Engineering, Virginia Polytechnic Institute and State University, Blacksburg, July 1986.