A COMPARATIVE STUDY OF HARDWALL AND HYBRID ANECHOIC TEST SECTION AERODYNAMICS

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Abstract

Research is underway to evaluate the aerodynamic performance of two different wind tunnel test sections. These test sections are the hardwall test section and the hybrid anechoic test section, a novel design where the port and starboard walls are replaced by tensioned Kevlar fabric with the goal of making the walls acoustically transparent yet aerodynamically impervious. Having applications in noise reduction of wind turbines, aircraft, naval vessels, and more, the anechoic test section will benefit from a full characterization of its aerodynamic performance as compared to that of a traditional hardwall section. This characterization includes the comparison of lift data produced by airfoils in both test sections, as well as detailed measurements of and around the Kevlar walls. Deeply tied to this comparison is the consideration of the appropriate method to correct the anechoic data for the confining effects of the Kevlar walls. This report presents a new addition to the formulation of one such correction method, the panel method correction. The panel method is then compared to the conventional correction method and is shown to have higher fidelity, suggesting that it be adopted for use in full production wind tunnel tests.

Motivation

The Virginia Tech Stability Wind Tunnel performs testing using both a standard hard-walled, aerodynamic test section and a novel Kevlar-walled, anechoic test section. The aerodynamic test section is used for wind tunnel testing in areas such as UAV testing, airfoil testing, and research into vortical flows. Applications for the anechoic test section are, for example, the collection of noise data from wind turbine blades, research of surface roughness effects on pressure fluctuations in the boundary layer, and study of rotors embedded in a boundary layer. The anechoic test section has the advantage in all these cases of providing detailed acoustic measurements without the need for an open-jet test section.

Traditionally, acoustic measurements have been performed with open-jet test sections equipped with microphones placed outside the jet. The hybrid anechoic test section of the Virginia Tech Stability Wind Tunnel represents an important new wind tunnel design that is becoming increasingly utilized because of its ability to enable noise measurements with low aerodynamic interference. Studies by Remillieux, Crede et al. (2008), Devenport, Burdisso et al. (2010), and Devenport, Burdisso et al. (2012) have detailed the characteristics of the anechoic test section and the methods for correcting the experimental data to yield free-flight performance. However, no study has yet been performed to directly compare the characteristics of the aerodynamic and anechoic test sections. Such a study is required to increase scientific understanding of the operation of this novel type of anechoic test section and confirm and extend the validity of the correction methods currently used with the anechoic test section. The initial findings of exactly this study are presented here.
Background and Problem Statement

Existing Expertise of Correction Methods

Wind tunnel data is corrected for both lift interference, the effect of the tunnel walls on the streamline curvature around an airfoil, and blockage, the effect of the reduced test section area on flow velocity past the airfoil. The Virginia Tech Stability wind tunnel corrects for both lift interference and blockage effects in both of its test sections.

In the aerodynamic test section, pressure data measured from airfoils is corrected with equations derived from a method of images analysis of the test section (Allen and Vincenti 1944). The effects of blockage and lift interference are calculated as shown below in Equations 1 and 2

\[
\frac{u'_{sw}}{U_\infty} = \Lambda \sigma \quad (1)
\]

\[
\alpha' = \alpha + \frac{\sigma}{2\pi} \left( C_l + 4C_{m0.25c} \right) \quad (2)
\]

where \( u'_{sw} \) is the increase in streamwise velocity due to the blockage of an airfoil, \( U_\infty \) is the freestream velocity in the tunnel, lamba is a dimensionless function of the symmetric component of the airfoil geometry, sigma is a dimensionless parameter related to the chord-to-height ratio of the wind tunnel walls, alpha is the angle of attack in radians, \( C_l \) is the coefficient of lift of the airfoil, \( C_{m0.25c} \) is the pitching moment coefficient about the airfoil’s quarter-chord location, and where quantities with the prime superscript indicate the corrected quantity.

Pressure data measured from airfoils in the anechoic test section at the Stability Wind Tunnel are currently corrected with a modified and extended version of the traditional hardwall corrections above as documented in Devenport, Burdisso et al. (2010). The new correction equations are shown in Equations 3 and 4

\[
\frac{u'_{pw}}{U_\infty} = \Omega \frac{u'_{sw}}{U_\infty} \quad (3)
\]

\[
\Delta \alpha \sim C_l \frac{c}{h} \quad (4)
\]

where the subscript pw indicates porous, or Kevlar, walled values, the subscript sw indicates solid, or hard, walled values, omega is a dimensionless value between 0 and 1, c is the chord of the airfoil, and h is the height of the test section. Omega acts to scale the blockage effects of hard walls to a smaller value for use with flexible, porous Kevlar walls. The scaling constant currently employed is an empirically determined 0.42. As explained in Devenport, Burdisso et al. (2010), Equation 4 provides a new way to calculate the angle of attack correction as compared to the traditional hardwall correction of Equation 2.

Continuing investigation of the modified hardwall correction has exposed areas for improvement, however. Devenport, Burdisso et al. (2012) present a new direction in anechoic section corrections which uses a panel method code developed from first principles to appropriately model the boundary conditions of the test section completely \textit{a priori}. The panel method code uses a 2D representation of the test section where the port and starboard walls are divided into 20 panels each with control points at the center of each panel. Similarly, the geometry of the airfoil under consideration is placed in the appropriate location between the two paneled walls to match the actual test setup in the wind tunnel, and the airfoil is fit with panels and control points, as well. The panel method code is derived from that of a 2D inviscid flow solver. The inviscid assumption that viscosity is negligible is appropriate as long as the boundary layer on the airfoil remains small and therefore attached. For this reason, the panel method code is not valid after an airfoil has stalled.
The panel method code is unique from other wind tunnel panel methods because of its treatment of the boundary conditions at the port and starboard walls. Both the deflection and the pressure across the walls can vary in the Kevlar-walled arrangement of the Stability Tunnel’s anechoic test section. In order to model these changes effectively, the panel method consists of two loops, an inner and an outer loop. The inner loop solves the 2D inviscid flow problem to find the pressure distribution along the airfoil and walls for a given initial deflection of the walls. The inner loop iteratively adjusts the pressure inside the test section and chambers until a mass flow condition out of each chamber is met. Once the inner loop converges to a pressure distribution, the solution moves to the outer loop. Here, the port and starboard walls are subject to their respective pressure distributions, and the walls’ deflections are adjusted so that the tension in each wall produces static equilibrium with the pressure load acting on it. This new deflection solution is then input to the inner loop for another set of pressure iterations. This process continues until the deflection solution of the outer loop converges.

The panel method corrections scheme shows promise but is still relatively untested. Studies have been conducted (Devenport, Burdisso et al. 2010, Devenport, Burdisso et al. 2012) that relate the panel method performance to free-flight behavior, but a comprehensive review that also compares the performance to the standard hardwall section is still lacking. Thus, this study makes a direct comparison of the hardwall and anechoic test section aerodynamics. Furthermore, it is proposed to make specialized measurements of the boundary conditions to increase the accuracy of the new panel method code.

Specifically, these boundary conditions are the deflection and pressure distribution over the Kevlar walls. It is a goal of this research to experimentally measure the deflection distributions of the walls as well as their midspan pressure distributions with the hope that this measured data will then be compared to the panel method pressure distribution and adjustments made to the panel method accordingly.

**Objectives**

The objectives of this study are threefold:
1. To assess the aerodynamic accuracy of Kevlar-walled test sections
2. To identify the fundamental mechanisms contributing to aerodynamic corrections in such test sections
3. To formulate improved aerodynamic corrections

The approach to meeting these goals is to perform duplicate tests of identical airfoils in the hardwall and anechoic test sections. During all tests, there will be direct measurement of key boundary conditions in both test sections, including wall deflections and pressure distributions of the anechoic test section sidewalls. Using these boundary condition measurements, computational modeling of the anechoic test section and its correction schemes will be evaluated.

**Experimental Setup**

**Preparation of Airfoils**

The present study makes a direct comparison of the aerodynamics of the hardwall and anechoic test sections of the Stability Wind Tunnel by observing pressure data measured on airfoils in both test sections. Specifically, three airfoils were tested recently by the author: a 0.203m and 0.914m chord NACA 0012, and a 0.610m chord DU00-W-212. Plans are made to also test a 0.914m chord DU00-W-212 to-be fabricated from rapid-prototyped ABS plastic. Additionally, data taken in both test section with a 0.914m chord DU96 may be used in the analysis. The
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airfoils have been selected for their quality of fabrication and to ensure a broad range of profiles with which to validate the correction schemes.

All five airfoils span the entire 1.83m height of the test sections and are instrumented for pressure measurements about their midspans. The NACA 0012 0.203m chord consists of machined aluminum plates joined at the chordline and has 38 pressure taps offset approximately 150mm from midspan. The NACA 0012 0.914m chord is constructed of a composite fiberglass exterior enclosing a core of steel ribs and polyurethane foam. It has approximately 80 pressure taps similarly to all the larger chord models. The DU00-W-212 0.610m chord is fabricated from 72 aluminum laminates, each 25.4mm thick in the spanwise direction and has a removable leading edge 1m in span that extends back to the 40% chord location. The laminates are held in compression by 12.7mm diameter threaded rods that run the entire span of the airfoil. The DU00-W-212 0.914 m chord is being built with somewhat different construction, consisting of 50.8mm thick aluminum laminates in addition to longer, 355.6mm thick ABS sections. There are 4 ABS sections interspersed between a total of 8 aluminum laminates that provide structural support and also house the pressure taps and instrumentation. Finally, the DU96 airfoil is made of a fiberglass exterior similar to the NACA 0012 0.914m chord.

The sets of the NACA 0012 and DU00-W-212 airfoils allow for comparison of correction schemes on identical profiles over differing aspect ratios ranging from 0.11 to 0.50 for the NACA 0012 airfoils and from 0.33 to 0.50 for DU00-W-212 airfoils. Additionally, the symmetry of the NACA airfoils allows for the isolation of the correction effects due to blockage as opposed to those due to lift interference when the airfoil is tested at zero angle of attack. The DU96 model further increases the diversity of profiles with which to validate the correction schemes.

**Testing in the Stability Wind Tunnel**

Tests have been performed by the author in the Stability Wind Tunnel with each of the three 0.203m and 0.914m chord NACA 0012, and a 0.610m chord DU00-W-212 being tested in both the aerodynamic and anechoic test sections. The 0.203m NACA0012 was tested at a Reynolds number of 0.5 million. The 0.914m NACA0012 was tested at Reynolds numbers of 2.0 and 3.9 million. The DU00-W-212 was tested at Reynolds numbers of 2.3 and 2.6. Tests were made with the airfoils both clean and tripped. Pressure measurements on the airfoils and wake measurements behind the airfoil were taken to allow the calculation of the lift, moment, and drag produced by the airfoil at each test condition. Additionally, two novel measurement systems were implemented in the anechoic test section to measure the boundary conditions on the Kevlar walls. The processing and analysis of the data from the recent testing is ongoing, and below is presented the initial.

**Results and Analysis**

**Aerodynamic Test Section**

Tests in the aerodynamic test section provide a baseline with which to compare the anechoic results and a basis for which to compare with data from other sources. The aerodynamic lift curve from the recent tests in the Stability Wind Tunnel for one test case is shown in Figure 1 in addition to numerical data from the viscous flow solver XFOil and experimental data from both NACA Langley (Ladson 1988). These plots show the results for a clean NACA0012 airfoil at a Reynolds number of 4 million. Note that the data all pass through the origin as this NACA 0012 is a symmetric airfoil with zero lift at zero angle of attack. Both experimental data sets are
seen to reach positive stall at 16 degrees angle of attack. The XFOIL result, being accurate only for non-separated flows, shows a more gradual stall onset in the range 19-20 degrees angle of attack.

An important difference between these data is the difference in slopes of the three curves. XFOIL produces a slope in the linear region of 0.1090 degrees^{-1}. The Ladson data has a slightly lower slope of 0.1033 degrees^{-1}, and the Virginia Tech data has a slope slightly lower at 0.09685 degrees^{-1}. Amongst these data, one might classify the Ladson data as most trustworthy due to its acceptance in the aerodynamics community (McCroskey 1987). Comparing against Ladson, the slope of the XFOIL result is 5% larger and that of the Virginia Tech data is 6% smaller. The discrepancy between XFOIL and the other two experimental results is not unexpected given that the viscous modeling of the boundary layer in numerical codes such as XFOIL is not able to capture all the finer details of separation and turbulence over the airfoil surface.

The disagreement between Ladson and Virginia Tech is not negligible but is, in fact, within the limits of the experimental variation that might be expected between tests made at different wind tunnels. Potential factors leading to the difference between the data are differences in turbulence levels in the respective wind tunnels, differences in surface preparation of the airfoils in the two tunnels, variation in hardwall correction formulations between Ladson and the Stability Wind Tunnel, and variation in Mach numbers. Analysis of the data for a boundary layer-tripped airfoil show much better agreement between Ladson and Virginia Tech which suggests that either of the first two factors above may be the cause of the slope difference observed. The overall agreement between Ladson and the Stability Tunnel is good, thus validating the aerodynamic test section as a baseline against which to compare the anechoic test section results.

**Addition to Panel Method Formulation**

Before proceeding with comparison of the aerodynamic and anechoic test section aerodynamics, measurements were made to improve the accuracy of the panel method correction of the anechoic test section. Following on the discussion in the Background and Problem Statement section above, there are two conditions for mass flow into and out of the port and starboard chambers that are variably used in the Stability Wind Tunnel. The first enforces zero mass flow into and out of each chamber. The second considers the chambers to be connected, as through the control room of the wind tunnel, and enforces zero total mass flow out of the test section through the sidewalls of the test section. It has not yet been determined which of these formulations is more physically realistic, but here is presented a single, improved formulation that is believed to more accurately model the flow physics of the Stability Wind Tunnel’s anechoic chambers. Because of their arrangement in the Stability Wind Tunnel control room, the port and starboard chambers are connected above and below the test section, although the area connecting them is covered with Kevlar cloth. Rather than assume one of two mass flow conditions in the inner loop, the author measured the effective free-flow leakage area between the port and starboard chambers. The effective free-flow leakage area was found to be approximately 0.15 m^2, or approximately the equivalent of a 40 cm by 40 cm square duct connecting the chambers.

Applying this leakage area to the inner loop of the panel method, the results are as shown in Figure 2 for a selected test of the NACA 0012 0.91m chord airfoil. The leakage result is expected to fall between the result for the sealed and the unsealed chambers because the leakage area allows for more flow between
the test sections than the sealed condition but less flow than the unsealed condition. Indeed, the data processed with the leakage formulation, as it is called, lies between the data processed with the sealed and unsealed formulations throughout the linear region of the airfoil’s lift curve. It is noted that the leakage data is biased towards the sealed scenario which is appropriate given that a 40 cm by 40 cm square duct would be relatively small compared to the total area of the Kevlar walls from which the driving force of the mass flow originates. The remainder of the calculations presented below employ the new leakage formulation of the panel method.

Comparison of Aerodynamic and Anechoic Test Sections

After testing in the aerodynamic test section, tests were performed in the hybrid anechoic test section at Virginia Tech. With the same airfoil and under the same conditions, the lift curve using two correction methods is shown in Figure 3. The two correction methods are the modified hardwall corrections described in Devenport, Burdisso et al. (2010) and the new panel method approach found in Devenport, Burdisso et al. (2012) as described previously. The overall shape of the anechoic data is mostly the same as for the aerodynamic data except for the positive stall angle. Whereas the aerodynamic data shows stall at 16 degrees angle of attack, the anechoic data does not stall until 17-18 degrees. This difference may be due to slight changes in the surface preparation of the airfoil, or more likely, to the change in the boundary condition at the sidewalls of the test section. Interestingly, the negative stall angles of the data from the two test sections are approximately the same which suggests there may be some asymmetry in the tension and/or porosity of port and starboard Kevlar walls.

Data from the other airfoils tested recently in the Stability Wind Tunnel is currently being analyzed and should provide further comparisons of the aerodynamic and anechoic test section aerodynamics.

Comparison of Correction Methods in Anechoic Test Section

For both anechoic corrections, the correction serves to lower the slope of the uncorrected data which is not displayed in Figure 3. The panel method correction lowers the slope further than the modified hardwall correction and aligns quite well with the corrected aerodynamic data. Indeed, the panel method corrected data is nearly indistinguishable from the aerodynamic data everywhere between the stall points except between -1 and -9 degrees angle of attack where the anechoic data is slightly undercorrected.

Looking just at the anechoic data, there are two major differences between the two correction methods. First, the panel method correction makes a larger correction to blockage than the modified hardwall correction as shown by lower magnitude of the maximum lift coefficient. Second, the panel method correction makes a larger correction to the lift interference as shown by the stretching of the angle of attack values of the panel method corrected data as compared to the modified hardwall corrected data.

With greater blockage and lift interference corrections, the panel method correction shows better agreement with the aerodynamic data. This agreement is not surprising given that the panel method correction derives fully from first principles rather than partly from empirical knowledge as the modified hardwall correction does. In addition to the clean tests at a Reynolds number of 4 million, the NACA 0012 airfoil was also tested at the same Reynolds number tripped, and at a Reynolds number of 2 million, both clean and tripped. The comparison between the two anechoic correction methods and the agreement of the panel method correction with the aerodynamic
data at these other conditions are qualitatively similar to the results presented above.

**Conclusion**

The goal of this research is to understand the physical reasons for the anechoic section’s unique characteristics and to show that the aerodynamic performance of each wind tunnel is the same after the appropriate corrections are applied. With a partial analysis of the measured data, progress is being made towards these ends. This paper presents first the results of the aerodynamic test section at the Stability Wind Tunnel as compared to accepted data from other sources. Then, it is shown a new leakage formulation of the anechoic panel method correction that that demonstrates better agreement with standard aerodynamic data for the NACA 0012 0.91m chord airfoil. The panel method is found to provide greater agreement with the aerodynamic data than the modified hardwall correction for the same airfoil. Side-by-side comparison of the two test sections with the remaining airfoils will hopefully be a powerful reinforcement of the usefulness of the anechoic test section and an insight into its fundamental operating principles. The advances made in the fundamental knowledge of lift interference corrections and blockage effects in the anechoic test section will benefit future testing across multiple disciplines in aeronautics research performed at Virginia Tech.

**Figure 1.** Lift curves for a NACA 0012 clean airfoil at a Reynolds number of 4 million. Comparison is made between the airfoil measured in the aerodynamic test section at the Stability Wind Tunnel and data measured by Ladson and also numerical Xfoil results. Here the Stability Tunnel and Ladson results are in fairly good agreement.

**Figure 2.** Lift curves for a NACA 0012 clean airfoil at a Reynolds number of 4 million in the Stability Wind Tunnel. The data are compared for three different formulations of
the panel method correction corresponding to three different mass flow conditions in the anechoic chambers.

**Figure 3.** Lift curves for a NACA 0012 clean airfoil at a Reynolds number of 4 million in the Stability Wind Tunnel. Comparison is made between corrected data from airfoil measurements in the aerodynamic test section with the hardwall correction and in the anechoic test section with the modified hardwall correction (2010) and the panel method correction (2012).

**References**


