THE BEVERLI HILL EXPERIMENTS FOR SMOOTH-BODY TURBULENT FLOW SEPARATION - RETROSPECTIVE, LESSONS LEARNED, AND FUTURE PROSPECTS

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Abstract

Virginia Tech, with support from NASA-Langley, has acquired high-quality turbulence model validation data for three-dimensional smooth-body flow separation. The geometry, called the BeVERLI Hill (Benchmark Validation Experiments for RANS and LES Investigations), has been studied at subsonic Reynolds numbers between 250k and 650k based on the hill height. Experimental data have been obtained for the hill at nominal zero, 30, and 45 degree orientations and include extensive oil flow visualizations, surface pressures, skin friction via oil film interferometry and laser Doppler velocimetry, and mean and fluctuating velocities using particle image velocimetry, laser Doppler velocimetry, and pitot-static rakes. Detailed boundary conditions and oncoming boundary layer data have also been measured. This paper will discuss the challenges encountered with obtaining turbulence model validation data for smooth-body flow separation. In particular, we will discuss the role of computational fluid dynamics in helping design the experiment, the challenges associated with tunnel and test article geometry, the challenges of establishing reference conditions, and the role of multiple diagnostic techniques for estimating bias errors in the experimental measurements. We conclude with some recommendations for future experiments on smooth-body turbulent flow separation.

Keywords: CFD, RANS, turbulence models, validation experiments, subsonic flow

1. Background

1.1 Validation Experiments

Validation experiments differ from traditional experiments which are usually conducted to assess the performance of a system or to explore the physical phenomena that occur. A validation experiment is an experiment conducted with the express goal of assessing a mathematical model's accuracy [1]. This mathematical model typically takes the form of a set of partial differential or integral equations along with their submodels. Since these equations are generally too complicated to solve exactly, we have to rely on approximate numerical solutions to these models. If the numerical approximation errors are sufficiently small, then we can still draw conclusions as to the accuracy of the mathematical model. If the numerical approximation errors or experimental uncertainties are too large, then the validation assessment can be polluted, and these additional error/uncertainty sources typically get attributed to the model. Validation experiments often occur at the unit or benchmark level, where only one or two physical phenomena are present. At this level, most or all initial and boundary conditions are measured, including the geometry, and a wide range of experimental outcomes are obtained. In addition, most or all measurements include a rigorous assessment of the experimental uncertainties. However, validation experiments can also occur at the system or subsystem level, where much less is known about initial and boundary conditions as well as the experimental uncertainties.

Oberkampf and Smith [2] developed criteria for assessing the rigor of model validation experiments in computational fluid dynamics. These criteria include information about the experimental facility, the instrumentation, the boundary and initial conditions, the fluid and material properties, the test conditions, and the experimental measurements. The criteria are rated on a completeness scale, where the lowest level (0) indicates little or no information available about an attribute and the highest level (3) indicates that detailed information is provided on all aspects of the attribute, the assumptions used, and the measurement uncertainties.

1.2 BeVERLI Hill Validation Experiment

Over the past 5 years, we have conducted turbulence model validation experiments on the BeVERLI Hill (Benchmark Validation Experiments for RANS and LES Investigations) for three-dimensional smooth-body flow separation. We examined subsonic Reynolds numbers between 250k and 650k based on the hill height (H ≅ 0.186 m), and experimental data have been obtained for the hill at nominal zero, 30, and 45 degree orientations. The acquired data includes extensive oil flow visualizations, surface pressures, skin friction via oil film interferometry (OFI) and laser Doppler velocimetry (LDV), and mean and fluctuating velocities using particle image velocimetry (PIV), LDV, and pitot-static rakes. Detailed boundary conditions, scanned hill geometry, and the upstream boundary layer data have also been obtained.

The flow at each of the nominal orientations provided different challenges for turbulence modeling. For the zero degree orientation, which contains left/right geometric symmetry for the oncoming flow, the wake proved to be asymmetric, with the asymmetry switching sides at very low frequencies. Strouhal numbers of 0.003 based on the hill width (0.0006 based on the hill height) were observed in both wind and water tunnel experiments [3]. For the 45 degree orientation, which also contains left/right geometric symmetry, the wake transitioned from symmetric at the lower Reynolds numbers to asymmetric at higher Reynolds numbers. While this asymmetry was consistently observed on one side in the experiment, computations with ideal geometry and uniform inflow conditions found the asymmetry to manifest on either side, sometimes due simply to different grid resolutions [4].

The 30 degree orientation, which does not contain a left/right geometric symmetry, was the subject of a blind CFD turbulence modeling challenge [5],[6],[7]. While the hill and tunnel geometry, grids, and boundary conditions were all made available to the computors, the experimental results (oil flow visualization, surface pressure, skin friction, mean velocities, and turbulence statistics) were withheld until the July-August 2024 AIAA Aviation meeting in Las Vegas, Nevada. The locations used for comparing computational predictions to the experimental data are shown below in Figure 1. They include two lines for surface skin friction coefficient (data from OFI and LDV), two lines for surface pressure coefficient (data from static pressure taps), 7 lines for velocities and velocity statistics (data from a combination of LDV, PIV, and a boundary layer rake), and two PIV planes on the hill. The LDV data are available only at the lower Reynolds number. We have two diagnostic techniques (OFI and LDV) to measure skin friction in overlapping locations, and two diagnostic techniques (LDV and PIV) to provide mean velocity and turbulence statistics in nearly overlapping locations (LDV point 1 and PIV plane 1 in Figure 1). The latter two velocity locations correspond to velocity profiles 1 and 5, and are approximately 1.5 cm apart. Note that while the top-down view shown here has the Z (or x3) coordinate shown positive down, the surface contour plots shown later will have the Z coordinate shown positive up (a bottom-up view).

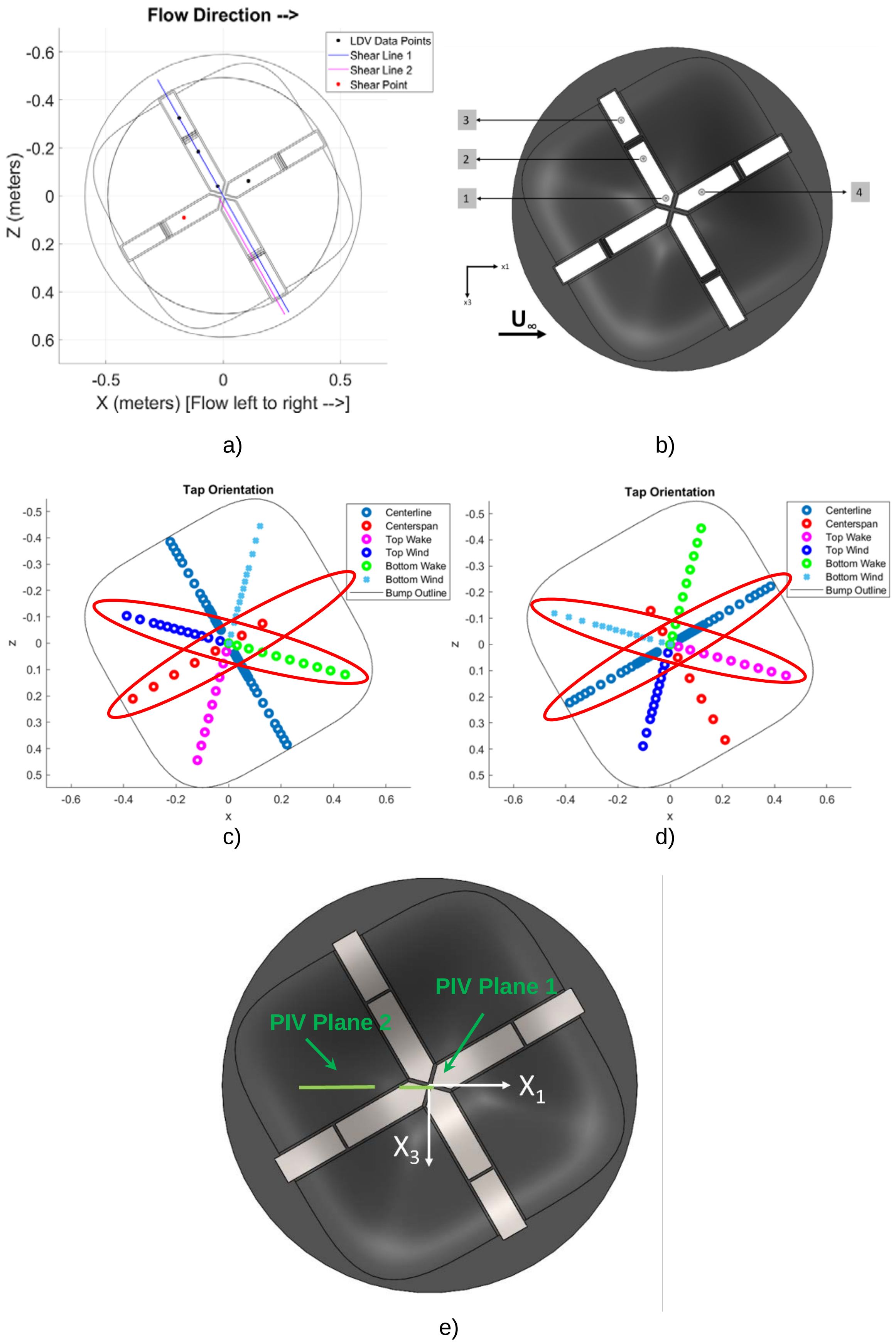


Figure 1 – Data locations for the 30 degree BeVERLI Hill: a) skin friction coefficient via LDV and OFI, b) LDV velocity profile locations, c) pressure tap locations in 300 degree orientation, d) pressure tap locations in 30 degree orientation, and e) PIV planes.

The computational participants can be found in Ref. [6] and include 40 submissions from 9 organizations, with 6 different CFD codes, 6 different RANS turbulence models, and 1 scale-resolving approach (IDDES). The breakdown of turbulence models and their variants is as follows:

- Spalart-Allmaras (5 variants): 25
- Menter k-ω SST (2 variants): 8
- k-ω (2 variants): 2
- Full Reynolds stress model (SSG-LRR): 1
- Wray-Agarwal: 1
- Improved Delayed Detached Eddy Simulation (IDDES): 1
- Langtry-Menter 4-equation Transitional SST: 2

Two contributors used incompressible CFD codes. Computations were performed on both *as-designed* (idealized) and *as-built* (scanned) geometries for the BeVERLI Hill, but in all cases, the wind tunnel itself is idealized to have a constant cross-sectional area. The wind tunnel test section was extended upstream in order to match the experimentally-reported boundary layer properties 1.93 m upstream of the center of the hill, and extended downstream in order to avoid the need to compute the diffuser, as such computations exhibited flow separation (not present in the facility) unless the geometrically complex vortex generators were included. The boundary conditions and idealized wind tunnel geometry are shown in Figure 2 on a coarse mesh. The hill is centered at X = Z = 0 m, and Y = 0 m is flush with the wind tunnel wall. The reference pressure is found by averaging the 7 wall static pressure taps located 1.85 m upstream of the hill center on the opposite wall. Other reference conditions (reference velocity, density, temperature, etc.) are found by using the specified stagnation pressure and temperature along with isentropic relations. The reference pressure is matched by adjusting the back pressure, but all results for each simulation are nondimensionalized with the reference conditions obtained from that simulation.

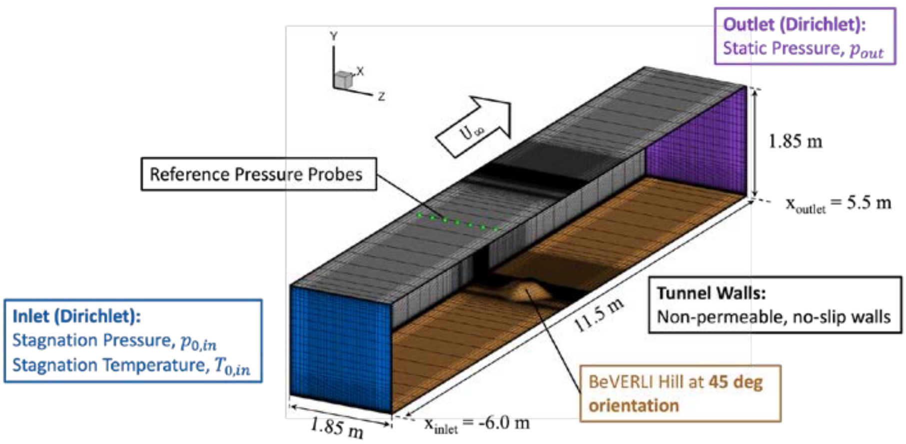


Figure 2 – Boundary conditions and idealized wind tunnel geometry for as-designed grids showing the seven static pressure taps used to measure the reference pressure.

2. Lessons Learned

This section describes some of the key lessons learned during the BeVERLI Hill validation experiments. Some other aspects of validation experiments were reported by Gargiulo et al. [8].

2.1 Pre-Test Computations

Pre-test computations were found to be crucial to achieving a high-quality validation data set. These computations established the boundary conditions that needed to be measured in the experiment. They provided insight into feature locations (specifically the flow separation region) and gave an idea of the order of magnitude of the quantities to be measured, which aided in instrumentation scaling. They also gave initial indications of phenomena such as flow separation, flow asymmetries, and large-scale unsteadiness. Although not employed during this experimental campaign, pre-test sensitivity analysis computations could also be used to determine the sensitivity of the desired output quantities to uncertainties in the measured input quantities (see Section 3.1).

2.2 Geometry Specification

Traditional wind tunnel experiments often go to great lengths to reproduce free flight conditions, including the use of wind tunnel wall corrections and porous walls for transonic experiments. However, since validation experiments are meant to provide the most accurate picture of the flow in the tunnel, approaches to extrapolate the conditions to actual flight conditions should be avoided. It is becoming increasingly well understood that validation computations should include as much information about the actual test article and wind tunnel geometry as possible, including the boundary layer development on the wind tunnel walls. Here we leverage ongoing work being conducted under the NATO Applied Vehicle Technology (AVT) 387 activity on Common Research Wind Tunnels (CRWT) to advance the validation of the computational fluid dynamics modeling of large-scale wind tunnels [9]. One of the key questions being addressed under CRWT is just how accurately a wind tunnel's geometry and boundary conditions must be measured, and then how much of that information should be included in the validation simulations.

The use of idealized (e.g., as-designed) wind tunnel and test article geometry can be a significant source of bias errors during validation assessments. In the BeVERLI Hill validation challenge, we chose to use idealized wind tunnel geometry, but included both idealized (as-designed) and scanned (as-built) hill geometries. The idealized wind tunnel was chosen initially because the scans of the large upstream settling chamber and contraction region were not available, although these are being investigated under CRWT. This choice resulted in a significant challenge in matching the reference pressures, as discussed in Section 2.3 below. Even when geometry scans are available, no matter how accurate they are performed, they will contain noise that must be removed. Under-smoothing the scans results in (nonphysical) noisy CFD simulations and potentially larger grid sizes. Over-smoothing can create bias errors in the physical geometry, especially in highly curved regions such as wind tunnel contractions and test articles.

For the BeVERLI Hill, the use of as-designed versus as-built geometry primarily affected the surface quantities. Figure 3 shows the tap orientation and the pressure coefficient over the BeVERLI Hill for the Menter k-ω SST model and four different variants of the Spalart-Allmaras model at Re_H = 650k. While the geometry effects are hard to discern in the full view (Figure 3b), the pressure variations and quite evident in the zoomed in view near the top of the hill (Figure 3c). It is unclear at this point whether these variations are actually characteristics of the as-built geometry, or whether they come from insufficient smoothing of the scanned points. The variations shown in Figure 3d near X = 0.57 m are real effects, however, and are due to a slight shimming misalignment between the BeVERLI Hill's circular base region and the wind tunnel panel. It was confirmed that this shimming could not be achieved perfectly, and there were locations with up to a 2 mm step.

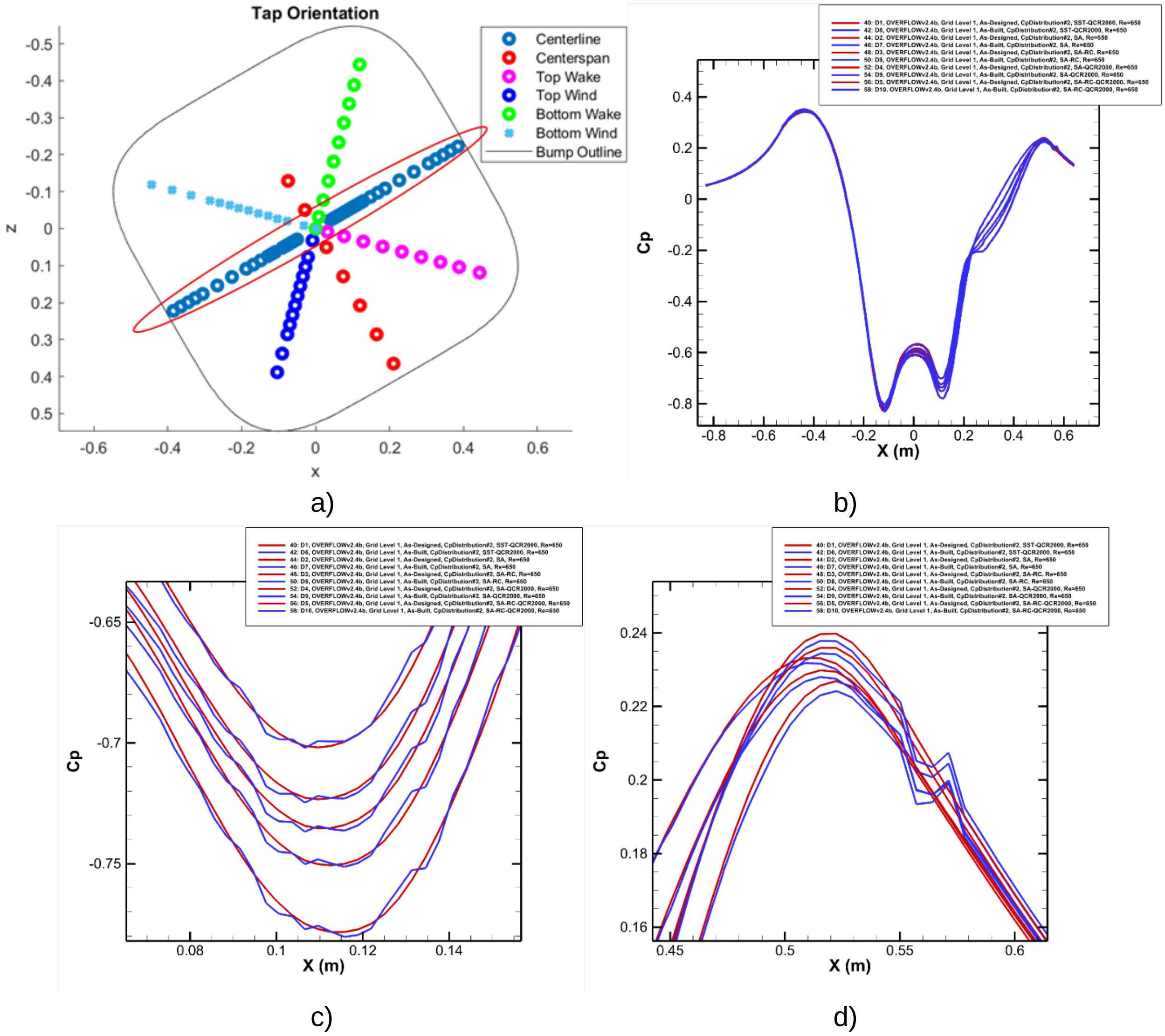


Figure 3 – Effects of as-designed (red) versus as-built (blue) geometry on the pressure coefficient over the BeVERLI Hill: a) tap locations, b) full pressure distribution, c) zoom of the low pressure region near the top of the hill, and d) interface between the BeVERLI Hill circular mounting plate and the idealized tunnel.

2.3 Reference Conditions

All comparisons between CFD and experimental data should be done with nondimensional quantities (e.g., pressure coefficients, drag coefficients, normalized velocity). Although wind tunnels often have a calibrated "free stream" condition determined in empty tunnel conditions, no equivalent free stream values are available in the CFD computations when a test article is inserted in the tunnel. For subsonic wind tunnels, the reference conditions are generally determined from the specified stagnation pressure and temperature measured in the experiments, along with one or more experimental static pressure taps on one or more wind tunnel walls. If these static "reference" pressure taps are placed too close to the test article, then they will be influenced by the presence of the test article. In this case, obtaining the correct reference conditions relies on the ability of CFD (and the turbulence model) to correctly predict the effect of the test article on the reference pressure. If the reference pressure taps are placed too far away from the test article, then achieving the correct reference conditions relies on CFD and turbulence model's ability to correctly predict the axial wind tunnel pressure gradients that occur due to boundary layer growth. Discussion of the best approach to determining the reference conditions was an ongoing thread through the 5 years of the BeVERLI Hill project.

Differences between the geometry used in the CFD solution and the actual wind tunnel geometry can also adversely affect the ability to match the proper reference conditions. When as-designed wind tunnel geometry is used, as was done in the BeVERLI Hill experiments, there is the potential to create a bias error in the reference pressure. These biases can be extremely damaging as they will impact the comparison of all results between CFD and experiment. The reference pressure was determined as an average of 7 static pressure taps located 1.85 m upstream of the BeVERLI Hill on the opposite wall (see Figure 2). As part of the CRWT efforts [9], a minor misalignment of the wall inserts resulted in an off-design flow expansion between the end of the contraction and the beginning of the nominally straight test section. As this was the same region where the 7 reference pressure taps were located, matching the reference pressure at this location resulted in a bias error of $\Delta Cp_{ref} \approx -0.015$ in the pressure coefficients measured in the empty wind tunnel. In order to remove this bias error, a procedure was used to correct the experimentally-measured reference pressures to an as-designed (i.e., idealized) wind tunnel reference value. Using CFD and experimental data from the empty tunnel, the CFD was curve fit and adjusted by a constant value (ΔCp_{ref}) to match the test section pressures away from the affected area in a least squares sense. These adjustments for Re_H = 250k and 650k are shown in Figure 4 a) and b), respectively. For more details of this experimental reference pressure correction, see Reference [7].

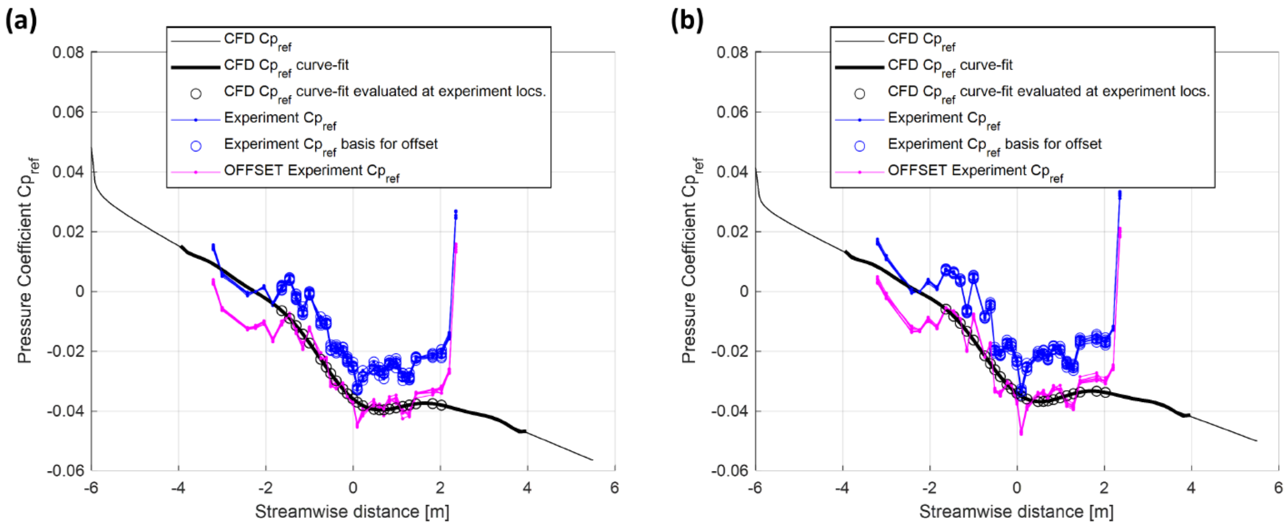


Figure 4 – Comparison of CFD and experimental wall pressure distributions on the starboard wall of the Virginia Tech Stability Wind Tunnel for 7 runs, before and after offset procedure, at a Reynolds number of a) 250k and b) 650k (from Reference [7]).

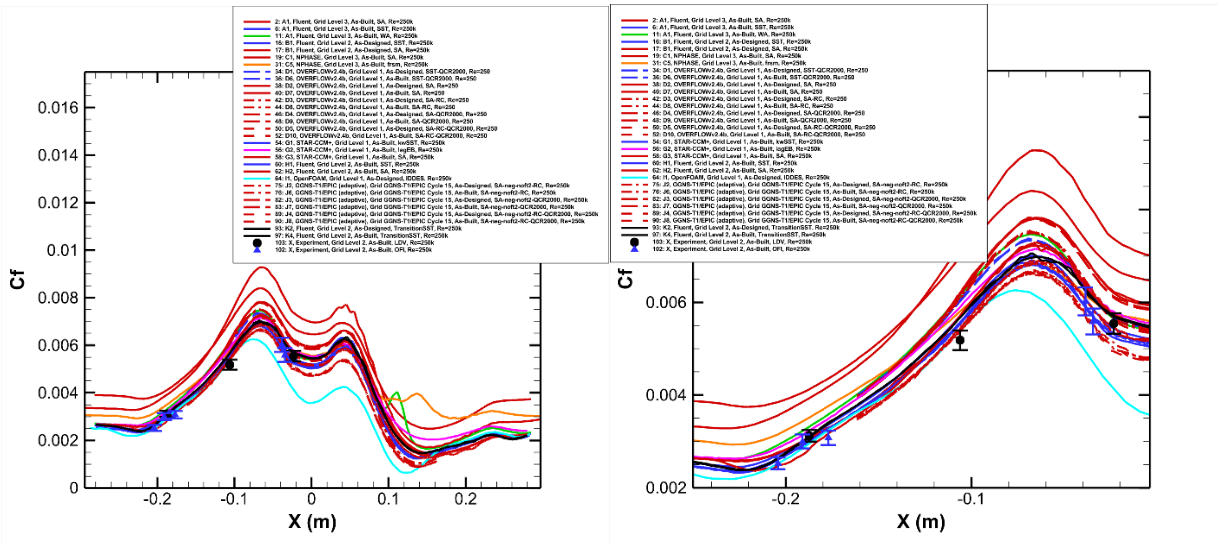
2.4 Multiple Diagnostic Techniques

In addition to repeat runs to reduce random experimental measurement uncertainty, for a validation experiment, it is important to use design of experiments techniques to help identify correlated bias errors. Bias errors can be extremely damaging to model validation experiments as they can lead to incorrect assessment of model accuracy, or even get inserted into models if the data are used for model calibration. To mitigate the effects of experimental bias errors, a wide range of experimental conditions should be measured and recorded during the experimental data acquisition process. For example, if the relative humidity is measured and recorded for each run, a possible correlation that exists between the humidity and one or more of the experimental output measurements can be found. Once these correlated bias errors can be identified, they can be converted to random uncertainties, which scale as $1/\sqrt{N}$, where N is the number of replicate measurements. For other suggestions on ways to reduce experimental bias errors, see Reference [1].

Short of replicating an experiment in a different facility, one of the best methods for identifying experimental bias errors is to use multiple diagnostic techniques to measure the same quantity. Each diagnostic technique has its own sources of measurement bias. If multiple techniques agree (within their estimated uncertainty), then it provides a high level of confidence that the experimental uncertainties have been estimated accurately, with no remaining bias errors.

In the BeVERLI Hill experiments, we employed multiple diagnostic techniques to measure the skin friction and the mean and statistics of the velocity profiles. The skin friction coefficient measurements from OFI and LDV are shown in Figure 5a. Examining the zoomed-in view in Figure

5b, the two diagnostic techniques are in excellent agreement near X = -0.185 m and X = -0.025 m, suggesting that the bias errors are significantly smaller than the reported experimental uncertainties. The large model variations are suspected to be a combination of turbulence model differences, incomplete iterative convergence, issues matching the reference pressure, and the use of incompressible flow solvers. The mean velocities and velocity statistics have been measured with both LDV and PIV at two locations very near the top of the hill; however, the PIV data are still being processed.



a) b)

Figure 5 – Comparison of CFD and experimental wall pressure distributions on the starboard wall of the VT SWT for 7 runs, before and after offset procedure, and at a Reynolds number of: a) 250k and b) 650k (from Reference [7]).

3. Future Prospects

3.1 Pre-Test Sensitivity Analysis

A major question in validation experiments is just how accurately input quantities (such as inflow values, reference pressures, and geometry) should be measured. Often times it takes significant resources (both time and money) to drive down measurement uncertainty, whether it be through replicate runs, the use of multiple diagnostic techniques, or other means. CFD can be used to conduct a pre-test sensitivity analysis to help determine which inputs and their uncertainties have the biggest impact on the outputs to be measured. Local sensitivity analyses can be conducted at the planned test conditions to determine the matrix of sensitivities $\partial\vec{y}/\partial\vec{x}$, where $\vec{x}$ is the vector of inputs and $\vec{y}$ is the vector of outputs. This information, along with any knowledge (or estimates) of the magnitude of the uncertainties in the inputs, can be used to prioritize which inputs require smaller measurement uncertainty.

3.2 Recommended Validation Experiments

For validation experiments, it is not required that the inflow and geometry be perfect, but they should be well quantified. Research is needed into understanding the role of nonuniform (measured) inflow variations and as-built geometry on wind tunnel measurements. Some work in this area is already being conducted by our group at Virginia Tech under the NATO CRWT project [9]. While initial CRWT efforts focus on empty wind tunnel measurements and simulations, the next phase of the work will include a (yet to be determined) test article.

In order to improve turbulence models, additional experiments are needed that employ a wide range of nonintrusive diagnostic techniques to measure mean and fluctuating velocities in turbulent shear layers. Canonical studies of phenomena such as pressure gradient, streamline curvature, flow separation, flow reattachment, and relaminarization are all of interest.

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5. Copyright Statement

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