DEVELOPMENT OF A NEW BOUNDARY LAYER CONTROL TECHNIQUE FOR AUTOMOTIVE WIND TUNNEL TESTING

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Abstract

Many different boundary layer control techniques are used in ground vehicle aerodynamic testing including suction, blowing, ground-boards, and rolling roads. In this paper an alternative boundary layer control method is discussed. Low momentum flow in the boundary layer can be energized using circulation from a rotating cylinder protruding through the floor. A comparison study shows that this application, if effective, may be a more cost-efficient solution than current road vehicle boundary layer control techniques. Furthermore, a boundary layer flow survey was conducted in the Wichita State University 7'x10' wind tunnel as a baseline in order to conduct future proof-of-concept testing. The survey showed a displacement thickness growth from 1" at the test section entrance to 3" at the start of the diffuser. Testing in a pilot tunnel has also been completed with the results showing that a boundary layer profile with an initial momentum displacement thickness of 0.098 in. could be reduced by 40-45% with rotational velocities of approximately 5000rpm. The goal of this paper is to document a two week pilot study for this alternative boundary layer control technique to determine possible application to the 7'x10' wind tunnel.

1 Introduction

To ensure the proper handling and performance of road vehicles an accurate aerodynamic assessment must be obtained. The only way to accurately measure the force and moments affecting these qualities is in a controlled wind tunnel environment. However, a wind tunnel cannot exactly match the airflow around a road vehicle due mainly to the floor boundary layer. This area of low momentum flow is not present when considering the normal situation of a road vehicle moving through stationary air. It was once thought that the boundary layer influence was negligible as long as the displacement thickness was less than 10% of the vehicle ground clearance [1]. This opinion has since been reconsidered when testing showed a measurable difference on lift and other parameters with decreasing displacement thickness, even on models with significant ground clearance [2]. That is why techniques have been developed to minimize boundary layer effects for automotive testing. The way this is accomplished is by removing or reenergizing this area of low-momentum flow.

In this paper, the techniques commonly used for boundary layer control are compared. Highest consideration is given to cost and simplicity while still considering other important parameters such as flow quality. Then an alternative technique for boundary layer control is proposed that utilizes the spinning cylinder Magnus effect to energize the boundary layer.

2 Background

The boundary layer thickness is defined as the height at which the local velocity, V, is 99% of the incoming velocity, V_∞. Other parameters used to describe the boundary layer development along the wind tunnel floor are displacement thickness

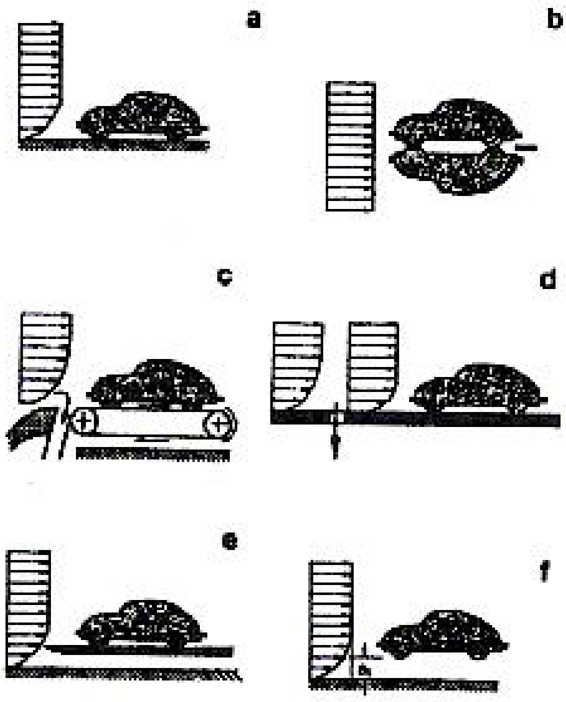
$$\delta_1 = \int_0^\infty \left(1 - \frac{V}{V_\infty}\right) dy \qquad (1)$$

and momentum thickness

$$\delta_2 = \int_0^\infty \frac{V}{V_\infty}\left(1 - \frac{V}{V_\infty}\right) dy \qquad (2)$$

The magnitude of these parameters can be directly related to the amount of energy lost in the incoming flow due to viscous effects encountered at and near the wall.

There are many well known techniques used to solve the natural wind tunnel boundary layer problem, each with their own advantages and disadvantages. The figure below from Hucho[3] illustrates the many possibilities that are available including: a.) no correction b.) reflection model c.) rolling road d.) simple suction e.) ground plane f.) ground offset g.) distributed suction h.) tangential blowing i.) distributed blowing and j.) boundary layer fence. A short comparison of some more commonly used techniques, and their places of application, was made as a first step in evaluating the merits of each system.



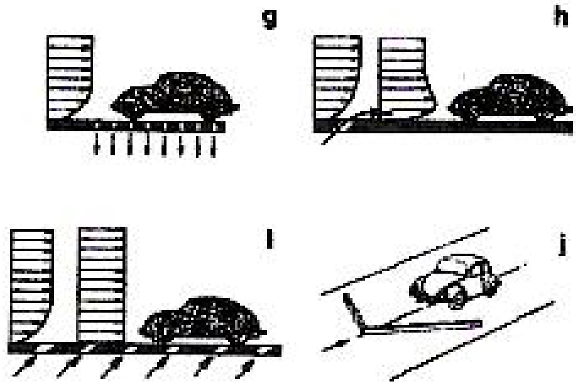


Fig. 1: Boundary Layer Control Techniques [3]

2.1 Rolling Road

Of these techniques only the rolling road technique can, in principle, match all the on road airflow properties. This technique is especially valuable in high performance road vehicle testing, such as in Formula 1 racing, where underbody design is crucial. In the MIRA Model Wind Tunnel the local air velocity in the test section remains within ±1 per cent of free-stream velocity all the way down to the rolling belt surface [4]. In some cases it is even possible to incorporate the tire movement along with the body aerodynamics. In a less exotic implementation the rolling road does not span the entire test section width but still gives a very good flow representation.

However, this ability to match true flow quality comes at a hefty price. Implementing a rolling road system into a wind tunnel is a very costly and complex process. The equipment required to move the surface synchronously with the airflow is expensive to implement and even more so to maintain. Often it is also impossible to use an external balance so an internal balance system must be used. Furthermore, any tunnel not exclusively used for road vehicle testing would not want to install and remove the bulky equipment whenever it is not being used. Overall this technique is only feasible in an environment where cost is of no option and the flow must be modeled with absolute precision.

2.2 Suction Systems

Systems designed to "suck off" the boundary layer are a widely used alternatives to rolling roads. These systems come in a variety of implementations [5&6] but they all have the same general principle: remove the boundary layer by sucking it through the floor and reintroduce the same volume flow downstream. Some systems apply suction at the test section entrance, resulting in a fresh new boundary layer developing behind the suction location. This boundary layer will be much smaller than without the suction, but it will still grow along the test section floor. In order to avoid this boundary layer the vehicle may need to be placed slightly off the floor even though this violates the geometric similarity slightly. Often this problem can be solved by using a distributed suction approach that continually removes the boundary layer throughout the perforated test section floor. Usually the suction velocity requirements for flush-mounted systems can require a significant amount of power. This can also be alleviated some by using an upstanding scoop to take advantage of the natural pressure gradient to assist the suction.

Suction systems provide a very viable alternative to the rolling road approach. However, the drawbacks to this type of system include a certain amount of power requirements for the suction and reintroducing the flow. Also required is a significant amount of space to duct the flow around the test section before reinsertion. While their implementation is much more affordable the flow quality does suffer. Since the object of these systems is to remove a portion of the flow in the test section the use of such a system can produce unintended pressure gradients, flow angularities, and turbulence which can significantly affect the flow quality especially if the system is not properly tuned [7&8]. Furthermore, if the flow is not re-introduced in the same amount as it was taken off then the conservation of mass is violated resulting in excess negative pressure in the test section. In this case extra tunnel venting is needed to relieve the pressure difference.

2.3 Blowing Systems

Another widely used system type is the blowing approach. This approach relies on injecting high momentum flow from a narrow slot tangentially along the floor. It is the only method in which a profile can be generated where the velocity near the floor is greater than the freestream. This can be beneficial in that this allows some leeway in the uniform flow position placement. For example, if the blowing occurred at the test section entrance and the model was several feet back an overdeveloped profile could be generated so that the boundary layer growth would result in a nearly uniform profile at the model. This reduces the boundary layer growth problem dealt with in the suction cases.

While this technique is employed in several tunnels including the German-Dutch DNW Wind Tunnel and Lockheed's Low Speed Wind Tunnel in Marietta Georgia, it has its own drawbacks. First, the momentum is added in the form of a very thin jet of air that often needs to travel at greater than four times the freestream velocity [9]. Moving flow at that speed requires a significant amount of compressor power which can become expensive quickly. This can also create a very noisy environment in the test section. Furthermore, the introduction of this degree of momentum next to the floor distorts the velocity profile well above the floor. These flow angularity effects are an order of magnitude smaller than those encountered in suction systems [9].

2.4 Other Techniques

The most common system remaining is the ground board approach. In this method the vehicle is placed directly on an elevated platform. This platform creates its own new boundary layer that is normally much smaller than the tunnel's natural boundary layer. The implementation is very simple, easy to remove, and quite inexpensive in comparison to other techniques. The tunnel used in this work has the ground board as its main capability for road vehicle simulation.

Just as in suction the boundary layer is only new at the ground board front edge. When the ground board is put into the test section it creates a disturbance that causes the dynamic pressure in the test section to be different and often unknown. Also these ground boards, if not designed carefully, can have flow separation at their leading edge. This phenomenon was observed in NASA Langley's Full Scale Tunnel causing the boundary layer on the ground board to be greater than that on the test section floor [10].

The other technique worth mentioning is the reflection plane model technique. Theoretically this technique, with proper post-processing, will give a true representation of a road vehicle without having to worry about the boundary layer altogether. By mounting two identical models symmetrically on the test section centerline the true ground similarity is reproduced.

The similarity technique is not used very often because the test requires two models so the cost of construction for the customer is doubled. This also forbids full scale testing since not very many tunnels in the world are capable of holding two vehicles. Since models must be used similarity to full scale is an added concern. With the current state of technology this technique is nearly obsolete.

Often the best solutions to the problems encountered in boundary layer control involve using a combination of methods. For example most rolling roads have a suction system installed ahead of them to give a fresh boundary layer. Another interesting approach was used in the Daimler Chrysler Aero Acoustic Full Scale wind tunnel [11]. An upstanding scoop suction system was immediately connected to a tangential blowing system. Therefore as soon as the flow is removed from the floor it is immediately reintroduced in an energized state.

All of these techniques are well documented in their performance and some may be applicable in current focus on the Wichita State University 7'x10' wind tunnel. With recent upgrades [12] it has become a highly advanced facility and the addition of a boundary layer control system would mean an increase in ground vehicle testing. Most of these techniques are, however, either too expensive or not sophisticated enough for the resolution available in the data gathered. The future goal of this work is to find an alternative that befits a tunnel of its sophistication with a cost appropriate to a university tunnel.

3 Proposed Boundary Layer Control Concept

Since cost and simplicity is of greatest importance it is hard to justify using a more expensive method discussed above. Therefore, in order to obtain the improvement desired to attract more automotive testing, a study was performed to design an alternative idea for boundary layer control.

In order to keep the design simple and space efficient there would be no ducting or complicated volume movement in the boundary layer. This also means keeping the power supply required to a minimum. The system must be as non-intrusive to the flow as possible to reduce angularity effects. Finally, the system must provide a significant momentum addition to the boundary layer. To meet these requirements the decision was made to consider a partially exposed rotating cylinder mounted in the test section floor to energize the boundary layer.

A rotating cylinder in uniform flow has been shown, in many experimental investigations, to create lift. This force is referred to as the Magnus force. The lift is generated by inducing a component of circulation, Γ, into the flow. This effect is also predicted in inviscid, potential flow, as the result of a vortex in a uniform flow.

The Kutta-Joukowski theorem gives the following relationship between lift per unit span, L', and vortex strength, Γ:

$$L' = \rho \cdot V_\infty \cdot \Gamma \quad \text{or} \quad C_L = \frac{\rho \cdot V_\infty \cdot \Gamma}{q \cdot d} \qquad (3)$$

For the case of a cylinder we will assume:

$$\Gamma = \oint V \cdot ds = \eta \cdot \int_0^{2\pi} V \cdot r \cdot d\theta = \eta \cdot 2\pi \cdot \omega \cdot r^2 \qquad (4)$$

Where η represents nonlinear effects caused by viscous interactions.

The cylinder lift is not what is most important in these two equations. Instead the induced velocity profile from the rotating cylinder is the main concern of this analysis. The goal of boundary layer control is to create a uniform velocity profile. Figure 2 shows if we consider vector addition of an oversimplified boundary layer velocity profile with the profile created by a potential vortex the result is that of a uniform profile.

Fig. 2: Velocity Profile Manipulation

While potential theory describes the physics qualitatively correct, there are viscous effects that must be considered. Since these effects are difficult to estimate the efficiency factor, η, is applied to Equation (4) using data from Hoerner [12] shown in Figure 3.

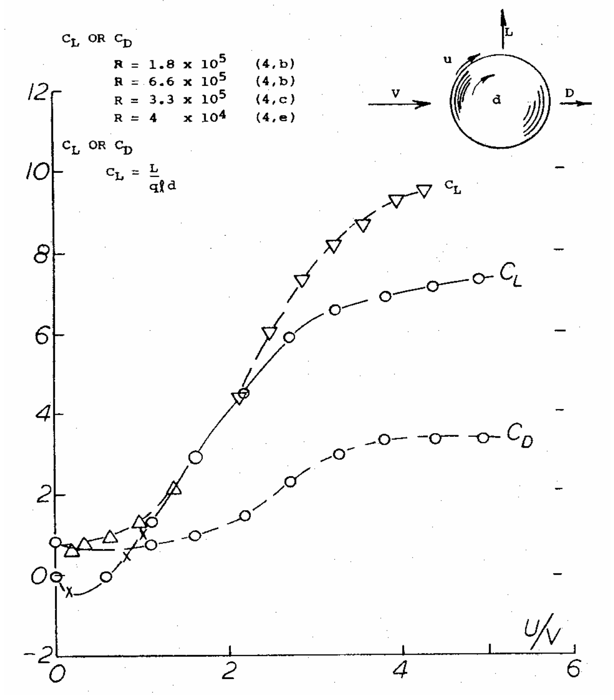


Fig. 3: Lift Generated by a Rotating Cylinder in Uniform Flow [12]

Since this data was experimentally collected, the viscous effects are included in the values obtained. The quantities plotted in Figure 2 are lift coefficient with respect to the cylinder's diameter, C_L, versus the cylinder velocity relative to the incoming flow, U/V (equivalent to the author's V/V_∞). What is most interesting in this survey are the circulation, Γ, and rotational velocity, ω. Through simple algebraic manipulation of Equations (3) and (4) these values are extracted and plotted in Fig. 4.

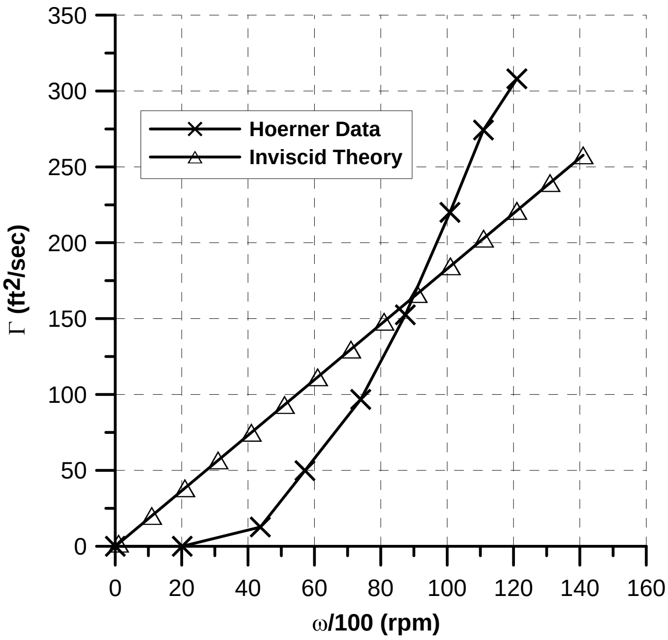


Fig. 4: Comparison of Potential and Experimental Circulation Values vs. Rotational Velocity

From Figure 4 it is evident that the linear theory over-predicts the circulation in the lower range and under-predicts it at the higher speeds. This plot was done for a fully exposed cylinder of radius 2 inches. By increasing the radius size, higher values of circulation can be obtained at lower rotational velocities and the intersection of these two curves occurs at a much lower rotational speed. Obviously there are limits on the size of cylinder that can be used, the amount of exposed arc, and the maximum rotational velocity attainable. Further into this study a sensitivity study is planned to find these limits.

For the time being the interesting assessment of Figure 4 is the difference in the curves' shapes. The curve-fit equations show the theory to be linear and the experimental values follow a quadratic profile. This means the efficiency factor, η, will be a function of rotational velocity, not a constant value. The form of which is,

$$\eta = a\omega + b + c\omega^{-1} \qquad (5)$$

where a, b, and c are constants.

Now using Eqn. (4) including the correction factor, η, we can solve for corrected circulation, Γ_{corr}. In turn using Γ_{corr} in Eqn. (4) will give the true rotational velocity needed to reach the desired circulation.

So what circulation is needed to fill the momentum lost in the boundary layer? Since the boundary layer shape is determined by its velocity profile it seems logical to consider the streamwise velocity profile generated by the rotating cylinder added to the incoming boundary layer. This vector addition gives the new augmented boundary layer profile. As a first approximation we will consider the velocity initially equal to V_E and decrease linearly away from the tunnel floor. This approximation does not take into account the exposed cylinder thickness or vertical component of velocity lost at the wall. So by simply adding the initial velocity profile to the profile generated by the circulation from the rotating cylinder we can graphically see the reduction in boundary layer thickness.

4 Description of Facilities

There were two different facilities used in this investigation; the Walter H. Beech Memorial Wind Tunnel (BMWT) and the Boundary Layer Tunnel. Both facilities are located on the Wichita State University Campus, in the National Institute for Aviation Research (NIAR) and the department of Aerospace Engineering respectively.

The BMWT is the main reason for conducting this survey in order to attract more automotive customers. The tunnel was recently remodeled to include a more powerful and efficient 2500Hp drive system as well as a new heat-exchanger and honeycomb flow straighteners. It is a closed-loop, low speed wind tunnel, characterized by a 7ft by 10ft test section. The layout of this facility is illustrated below in Figure 5.

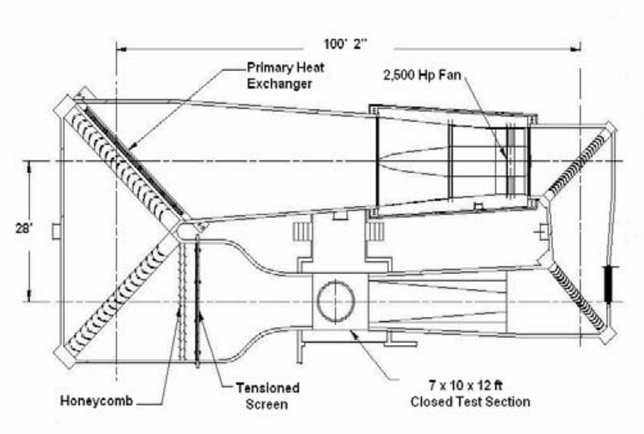


Fig. 5: Walter H. Beech Memorial Wind Tunnel Diagram [13]

After the upgrade the tunnel's flow quality had to be documented, including a boundary layer survey. The survey test matrix consisted of nine different locations and eight velocities at each location. Velocity profiles were recorded using a boundary layer mouse with 15 pitot static readings over a height of two inches connected to a PSI8400 pressure module. The survey results are included in the following section.

The other facility utilized in this study is the Boundary Layer Tunnel which was used predominately to study the proposed system's effectiveness.

This facility, shown in Figure 6, is an induction type tunnel driven by a variable speed centrifugal fan in an open atmosphere environment. It is equipped with an inclined manometer board as a check to the portable Scanivalve device used to record pressure information in this test. The Scanivalve was controlled through a Visual Basic addin to an Excel spreadsheet, written by Monal P. Merchant, a current MS Student at WSU.

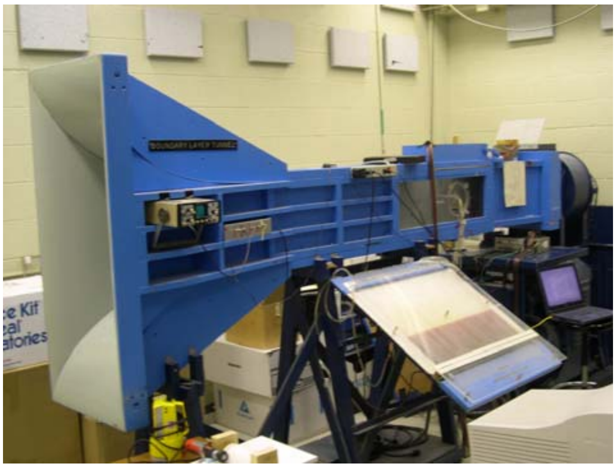


Fig. 6: Boundary Layer Tunnel

The experimental setup used to test the rotating cylinder effect on the boundary layer used a laminated shelf with a 6 inch piece of 3.5 inch outside diameter PVC pipe. A slot with beveled edges was cut through the shelf and the cylinder was mounted using model aircraft tires fixed inside the pipe with a steel axle running through their center. The axle was attached to wooden blocks with bearings mounted inside them to allow free rotation. The cylinder was driven by a rotary tool with another small model aircraft wheel attached to the rotary mount. Figure 7 illustrates the setup described.

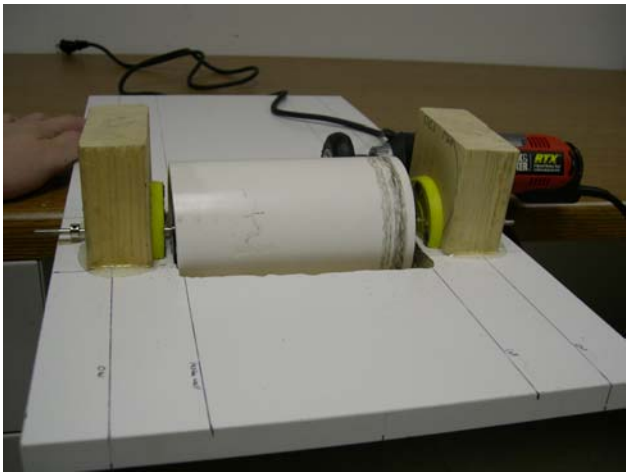


Fig. 7: Experimental Boundary Layer Control Setup

5 Experimental Boundary Layer Measurements

Two boundary layer measurements sets have been taken to date. The first set is the boundary layer profile characterization of the BMWT test section and the second was the measurements in the Boundary Layer Tunnel.

Results from the BMWT showed the boundary layer thickness varied from approximately 1 inch at the inlet to above 3 inches at the test section exit.

The thickness values above the boundary layer probe height used were extrapolated using a second order polynomial fit. To illustrate the shape of the boundary layer, a nominal profile for the centerline point is shown in Figure 8.

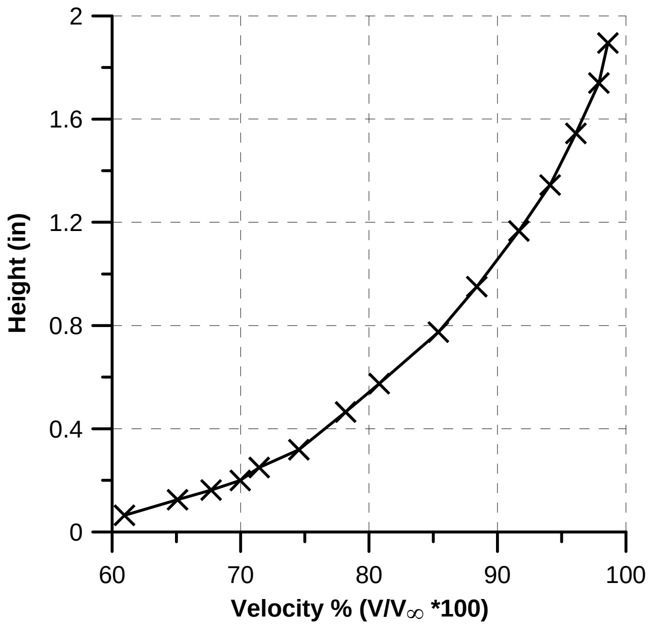


Fig. 8: BMWT Nominal Boundary Layer Profile

The second set of data taken for this research was the boundary layer profile augmentation study in the smaller Boundary Layer Tunnel. This was a basic test performed to see if the proposed method would be able to produce results in a simple setup and potentially in the BMWT. It is a starting point in order to direct future testing and not intended to be the final method validation.

First, a baseline survey was conducted for three different velocities in order to characterize the boundary layer in the test section. The Boundary Layer Tunnel has a hinged test section ceiling where measurements were taken. A trip was used in the inlet region in an attempt to force a turbulent profile. The profiles were nearly the same for each speed so no further effort was put into adjusting the trips. For comparison purposes the profile for the Boundary Layer Tunnel is plotted along with the BMWT profile in Figure 9.

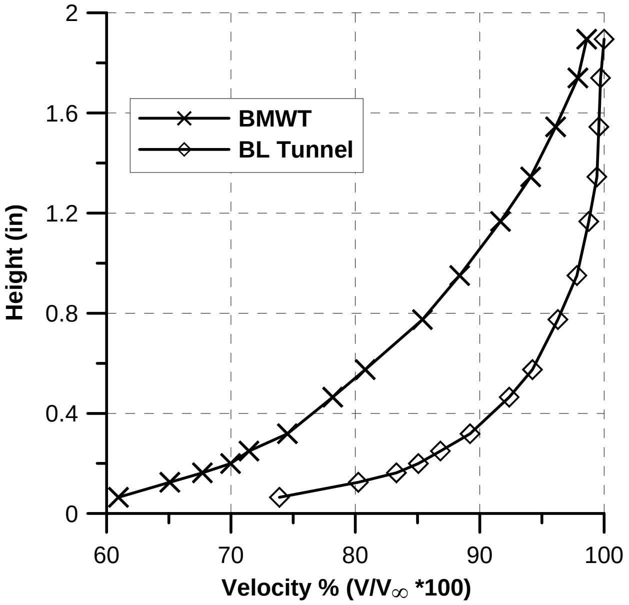


Fig. 9: Boundary Layer Profile Comparison

The two profiles were not expected to match, but it is interesting to note the difference in shape while their thicknesses' were nearly the same.

After characterizing the baseline boundary layer the experimental setup shown in Figure 7 replaced the ceiling, allowing the bottom section of the cylinder to be exposed to the incoming flow. Measurements were then taken for the tunnel maximum velocity setting with the cylinder at rest and spinning on the low and subsequently medium velocity settings of the rotary tool, corresponding to 4100rpm and 6500rpm respectively. The boundary layer mouse was placed a distance of 3 inches behind the rotating cylinder in the initial run. From the results, plotted in Figure 10, a first order calculation of Equation (2) using trapezoidal integration showed the profile with the non-rotating cylinder has a δ_2 value 250% of the baseline case that was taken without the cylinder in the flow.

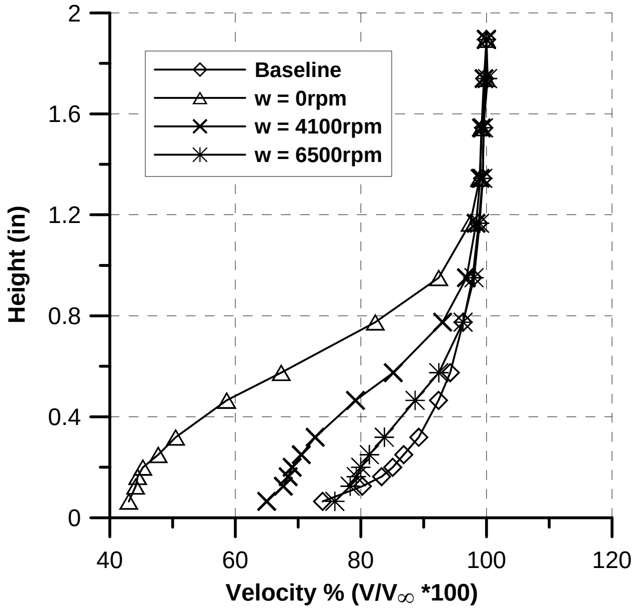


Fig. 10: Initial Cylinder Test Results

From this plot we can see the stationary cylinder significantly increased the size of the boundary layer from the baseline profile. It was thought the boundary layer rake was simply too close to record an accurate measurement. However, it is apparent the rotating cylinder does energize the boundary layer and change the profile. From the initial still velocity to the medium rotational velocity there is a large difference in the area under the curve, which equates to the momentum displacement thickness. Another observation shows the medium velocity δ_2 is only 116% of the baseline.

A second test was done with the boundary layer mouse mounted 11 inches behind the cylinder, at the test section exit. The test was repeated and the results are plotted in Figure 11.

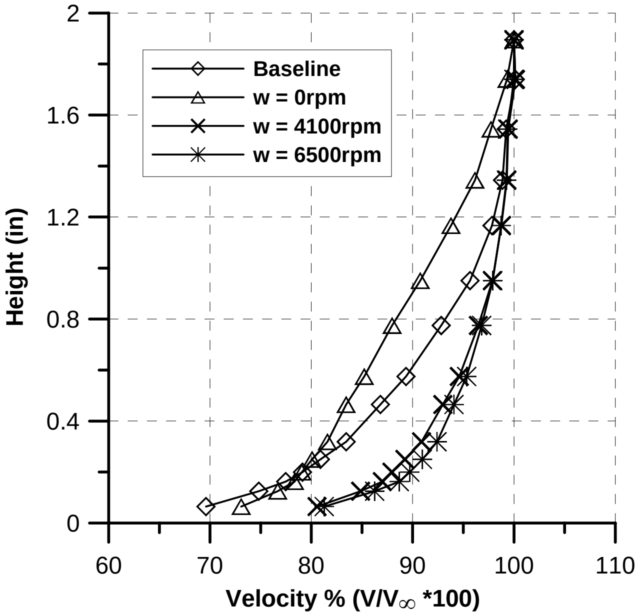


Fig. 11: Second Cylinder Test Results

The second test results indicated the cylinder rotating at 4100rpm and 6500rpm could actually reduce the boundary layer momentum thickness to 59.7% and 54.6% of the baseline profile, respectively. It was also evident that the cylinder's affect on the measurements was greatly reduced to where the profile with the non-rotating cylinder and the baseline profile were much more similar in shape. While the limited speed range of the current rotary tool allowed only two rotational velocities, Figure 10 illustrates the improvement achieved in momentum thickness reduction.

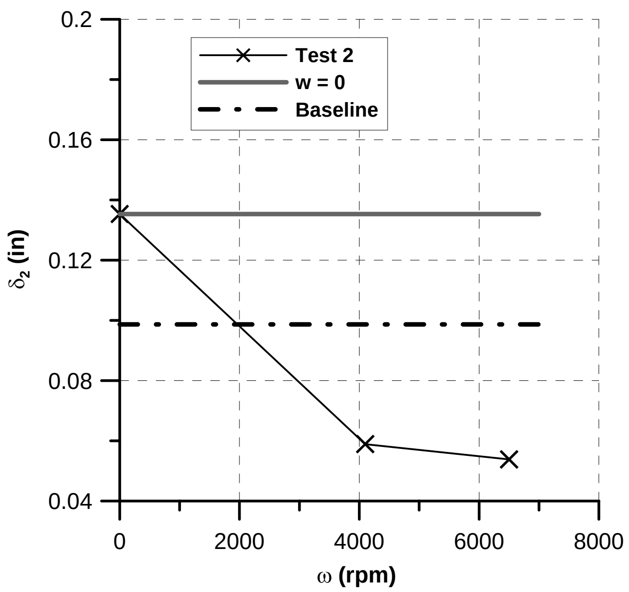


Fig. 12: Momentum Thickness Reduction vs. Rotational Velocity, ω

These pilot test results seem to indicate the method discussed can be successful in application.

6 Conclusions & Recommendations

Boundary layer control systems vary widely in cost, complexity, performance, and the theory behind the approach. Most are quite difficult to implement. Therefore if a system is to be designed for a university tunnel such as the Walter H. Beech Memorial Wind Tunnel where cost and complexity must be minimized while still holding to expected standards of such an advanced wind tunnel, a new approach should be sought out.

The theory behind the approach discussed here relies on simple potential flow theory adjusted for viscous effects using documented experimental data. The pilot testing performed so far produced some encouraging results and will be pursued further. The cylinder testing showed promise in being able to modify the boundary layer through the introduction of circulation into the flow. However, further testing is needed to determine this technique's effectiveness.

It would be beneficial to investigate three influencing parameters in the Boundary Layer Tunnel. The first is the boundary layer mouse placement with respect to the cylinder. The importance of determining the influence on the measurement location is because it directly affects the amount of space needed in the cylinder's vicinity before a model can be installed. Secondly, the exposed cylinder surface should be quantified to know to what extent the introduction of the cylinder affects the boundary layer behavior. If there is an optimum for the cylinder size, placement, and rotational velocity the system efficiency could be improved. Finally, a parameter not considered in this first study is the cylinder roughness. Since the dimples on a golf ball provide considerable effect to the Magnus forces encountered during its rotation, it seems the same would be true for this case.

With the information gained from this initial study it appears this technique is a wellsuited candidate for more consideration. While there are still practical hurdles to overcome, the basis for this theory seems well rooted.

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