Determination of Aerodynamic Correlation Parameters of a Vehicle

Cing Lee¹, Peter Doval¹, Joshua Anderson¹, Lee Xiong¹
Zhenyu Xu², R.S. Amano³, Anthony Coffey

Department of Mechanical Engineering, University of Wisconsin-Milwaukee, Wisconsin, 53201

This study involves helping Manufacturing Company reduce overall production time, starting from concept through production, by finding and correlating the parameters of drag force, lift force, side force, pitching moment, yawing moment, and rolling moment of an Ahmed body, representative of a vehicle. The correlation parameters for the Ahmed body are between the computational fluid dynamics software Star-CCM+ and actual wind tunnel testing at the University of Wisconsin-Milwaukee’s (UWM) wind tunnel at a 0.3 scale prototype made from SOS rapid prototyping material. This small scale Ahmed body will be compared to the correlation parameters gathered from a full scale testing of an Ahmed body in the Wichita State wind tunnel also. The results of all three tests will be compared to see if they are in agreement with each other. The wind tunnel testing at UWM will utilize a 6-axis force/torque sensor having the capability to measure all the parameters. If the CFD results are within 5% of the actual wind tunnel testing, the project will validate the accuracy and reliability of CFD and further allow its usage to replace wind tunnel testing with confidence.

Nomenclature

C_d = drag coefficient
C_l = lift coefficient
c = Speed of Sound in a Fluid
F_d = drag force
F_l = lift force
L = Characteristic Length
k = Ratio of the Specific Heat at Constant Temperature to the Specific Heat at Constant Volume
R = Ideal Gas Constant
Re = Reynolds Number
T = Temperature
V = air Velocity
μ = Dynamic Viscosity
ρ = Density of Air

I. Introduction

To keep up with the demand of the modern world, it is always in a corporation’s best interest to reduce cost and production time. Not only for profit, but the savings can provide a competitive edge being use to fund other purposes such as researching new technologies, expanding the corporation or stabilizing product cost to fit the demands of their customers’ needs. There are many ways to reduce cost and production time, but technological advancement can play a vital role in a corporation’s long term success. Specialized equipment or computer simulations have the ability to decrease costs by reducing wages or improve production operations by reducing time from the overall process.

Manufacturing Company would like to reduce overall time from concept to production by 35% before the year 2012. With new models of vehicles always being created, wind tunnel testing is needed to evaluate the complex turbulent flow around the vehicle to better understand the capabilities and restrictions of new models. However,

¹ Student
² Student AIAA Member
³ AIAA Associate Fellow
wind tunnel testing can be time intensive and securing an applicable wind tunnel can tap into additional resources. For example, the Walter H. Beech Wind Tunnel at Wichita State University was built in 1948 with a total cost of $165,000 and recently had a 6 million dollar upgrade in 2005 to improve “the tunnel's test section, control room, fan and balance”\(^1\). This state-of-the-art wind tunnel has the capabilities to provide “private industry, government agencies and educational institutions with the facilities, equipment and research staff to meet their needs involving projects in aerodynamic testing and research”\(^2\), but since wind tunnel takes high amounts of power to run, renting it can be costly. In addition, time slots for renting may conflict with other researchers utilizing the same facility and if the wind tunnel is far away, traveling and time can become a problem. What if there were a way to obtain accurate results without applying the actual physical testing and resources needed along with it. Fortunately technology is evolving, giving rise to Computational Fluid Dynamics (CFD) software which has the capabilities to define flow scenarios and calculate various results such as lift and drag forces. However, engineers must practice engineering with the codes and ethics of the profession. To issue out a product that does not live up to its standard may have dire consequences especially if failure occurs. Therefore, results must be as accurate as they can be no matter how they are obtained either through actual physical testing or software or a combination of the two.

Again, the purpose of this project is to help reduce overall time from concept to production and to accomplish this Manufacturing Company would like to replace some physical testing with CFD software simulation such as Star-CCM+ to obtain various results. More specifically, the goal is to correlate actual wind tunnel testing results with Star-CCM+ results to see how accurate they are. The parameters that will be compared are the drag force, lift force, side force, pitching moment, yawing moment and rolling moment of a vehicle. Wind tunnel testing is chosen for the actual test results to compare with computational fluid dynamics tests, since test parameters such as air velocity or room temperature are more easily controlled in this environment than in a real world setting. To represent a simple vehicle shape, the Ahmed body is used and will undergo testing in the University of Wisconsin-Milwaukee’s wind tunnel, as shown in figure 1. To obtain the actual parameters, a 6-axis force/torque sensor from ATI Industrial Automation will be mounted on the Ahmed body. Manufacturing Company would like the difference between the computational fluid dynamics results and wind tunnel results to be less than 5% to validate how reliable and accurate CFD can be.

![Ahmed Body](image.png)

**Figure 1 – Ahmed Body**

### II. Background Information and Theory

#### A. STAR-CCM+

STAR-CCM+ was first introduced in 2004, created by the company CD-adapco where “STAR” stands for "Simulation of Turbulent flow in Arbitrary Regions"\(^3\) and “CCM” standing for “computational continuum mechanics”\(^4\). CD-Adapco was founded in 1987 in Melville, New York. Their main focus is creating and distributing computer software to aid engineers in their projects and research. Their best assets are their
computational fluid dynamics products including their “legacy CFD package, STAR-CD”\(^4\), which was the software before STAR-CCM+. However, CD-Adapco felt that to upgrade their CFD product further, they must “completely rewrite their computational fluid dynamics algorithms and tools”\(^4\), which will enable the production of better simulations and results. The new and improved version became STAR-CCM+. While similar CFD software at the time required expensive desktop computers to run the complex computational calculations, STAR-CCM+ utilizes a “client-server architecture”\(^4\) that shifts the calculations to a remote machine making it possible for even laptops to solve problems. STAR-CCM+ can solve problems dealing with fluid flows, solid flows, heat transfer, and even stress. Its capabilities allow it to take on diverse problems involving “multi-physics and complex geometries”\(^3\).

B. Wind tunnel Testing

The research on automobiles and aircraft in their actual working environment or free flight and the demand for improvements gave rise to wind tunnel testing. Even though in a wind tunnel the air is moving against a stationary body, as opposed to the real world where the body is in motion through the air, the aerodynamic effects on and around the body are the same.

The origins of wind tunnel use can go as far back as the 1700s when Robins “invented a whirling arm apparatus to determine drag and did some of the first experiments in aviation theory.”\(^5\) What he used was a 5 foot long apparatus capable of having air speed up to 20 feet per second. In 1871, the first enclosed operating wind tunnel as we know them today was invented by Wenham who was also a council member of the Aeronautical Society of Great Britain at the time. However, wind tunnels were often limited in the volume and speed of airflow that they could produce, which would not be applicable for certain projects. Due to this, bigger and more powerful wind tunnels were built to allow more capabilities. In 1916, a wind tunnel with an 11 foot diameter inlet and 500 horsepower electric motor was built at the Washington Navy Yard by the US Navy. Just 25 years later, in 1941 the US built the largest wind tunnel at that time at Wright Field in Dayton, Ohio capable of testing large scale aircraft models at air velocities of 400mph.

Typically, a wind tunnel works by either blowing or sucking air through a duct or tunnel. Somewhere along the tunnel, there will be a test section where the object of interest is mounted and can be viewed for research. A fan is usually the working element to move air through the tunnel and the bigger the wind tunnel, the more may be needed, leading to an “array of multiple fans … used in parallel to provide sufficient airflow”\(^5\). Turbogas engines or electric motors can be used to power the fans. However, the way the fan blade moves makes it a turbulator causing the air flow to be very turbulent, which may need to be laminar for certain applications to provide accurate results. Therefore, a section within the duct is normally used containing “closely spaced vertical and horizontal air vanes”\(^5\) which “are used to smooth out the turbulent airflow before reaching the subject of the testing”\(^5\). The cross-section of the tunnel is more suitable as circular instead of square to provide smoother air flow since the corners can give rise to turbulent flow. Also, to reduce surface drag and turbulence the inside face of the wind tunnel should be as smooth as possible with the object of interest mounted in the center.\(^5\) The size of the test section may limit the size of the object of interest as it must be small enough to make sure its boundary layers do not interact with the walls’ boundary layers.

Early on, wind tunnels were extremely useful for understanding aerodynamics and helped advance aeronautical engineering applications. It was used to study tall buildings and the additional forces they were seeing since they were exposing large surfaces to the wind. This also helped set building codes for occupant safety. The Automobile industry made more use of wind tunnels to study ways to make vehicles run more power efficient. As technology advanced, the use of wind tunnels started to experience a decline. In fact, “in the USA many wind tunnels have been decommissioned in the last 20 years, including some historic facilities”\(^5\). Some problems facing wind tunnels today are their “declining or erratic usage, high electricity costs, and in some cases the high value of the real estate upon which the facility sits”\(^5\). Yet, with the rise of CFD software, data from wind-tunnel testing is needed to prove the accuracy of these CFD programs and as such may still have some usefulness, but as CFD programs become more accurate and reliable, physical wind tunnels may see more decline.

C. Ahmed Body

An Ahmed body is known as a “simplified car model” or “generic car-type bluff body with a slant back”\(^6\). It has simple geometry, which allows for easy prototyping, but more importantly it has some of the main features of air flow found on real cars. The Ahmed body has already been widely used which leads to plentiful experimental data, which is useful for comparison. It was first invented or used in experiments in 1984 by Ahmed and Ramm. It helps demonstrate how the drag of a body is mainly the effect of pressure drag generated at the rear portion of the body. The slanted back, usually ranging from 25\(^\circ\) to 35\(^\circ\) provides complicated wake arrangement to study “with a
separation zone and counter-rotating vortices coming off the slant side edges, whose strength is mainly determined by the base slant angle. It is found that the max drag force occurs with the Ahmed body having a slant of 30° where above it there are weaker “counter-rotating vortices.”

There have been more studies on Ahmed bodies over the years using different types of turbulence models and simulations. Lienhart ran experiments for Ahmed bodies at 25° or 35°, which were 5° below and above the critical angle of 30° to show the differences in the flow patterns. Han and Chometon used RANS models to obtain great flow structure results, but lacked velocity profile comparisons, which is because RANS is said to have difficulties predicting the “mean velocity and turbulence intensity profile for this flow.” Kapadia used Detached Eddy Simulations (DES) and had results comparable to RANS models. Hinterberger, Garcia-Villalba, and Rodi from the University of Karlsruhe in Germany used Large Eddy Simulations (LES), which captured the flow structure well compared to experiments. They concluded that “the agreement of the time-averaged quantities is good although some discrepancies are present, especially in the lower part of the slant back” demonstrating that the experiment was an improvement but additional improvement may provide better results.

III. Project Details

A. Preliminary lift and drag Force calculations

These calculations were done to help get a rough idea of what to expect from the simulations and actual lift and drag forces when it comes to testing. The equations were obtained from Fluid Mechanics Fundamentals and Applications by Yunus and Cimbala. It also helped in searching for an applicable sensor before simulations from STAR-CCM+ were completed. The results showed that obtaining a sensor that measures above 100N may be unnecessary since the higher the range of a sensor, the lower the resolution becomes.

<table>
<thead>
<tr>
<th>Force (N,actual model)</th>
<th>Force (N, 1/3 scaled model)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drag</td>
<td>8.093</td>
</tr>
<tr>
<td></td>
<td>0.902</td>
</tr>
<tr>
<td>Lift</td>
<td>29.338</td>
</tr>
<tr>
<td></td>
<td>3.268</td>
</tr>
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</table>

B. Simulations using STAR-CCM+

Training done on March 1st through March 3rd helped provide a better understanding of STAR-CCM+ and its capabilities as well as its requirements to simulate real life fluid dynamics problems.

<table>
<thead>
<tr>
<th>Reference Velocity (m/s)</th>
<th>Frontal (Reference) Area (m²)</th>
<th>Reference Air Density (kg/m³)</th>
<th>Cell Count</th>
<th>Drag Coefficient</th>
<th>Drag Force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>20</td>
<td>0.01008</td>
<td>1.18415</td>
<td>5,009,889</td>
<td>0.302</td>
</tr>
<tr>
<td>Case 2</td>
<td>20</td>
<td>0.01008</td>
<td>1.18415</td>
<td>4,784,630</td>
<td>0.313</td>
</tr>
<tr>
<td>Case 3</td>
<td>20</td>
<td>0.01008</td>
<td>1.18415</td>
<td>5,482,967</td>
<td>0.315</td>
</tr>
<tr>
<td>Expected</td>
<td>20</td>
<td>0.01008</td>
<td>1.18415</td>
<td>5,000,000</td>
<td>0.299</td>
</tr>
</tbody>
</table>
Case 1 produced the best results of the three most recent runs. In this case, the prism layer stretching was set to a value of 1.1 while Case 2 and 3 used values of 1.2 and also had additional prism layers added. This change was made to better capture the boundary layer by expanding the prism layer section. The results seem to show a high sensitivity to prism layer stretching. It is therefore recommended that a value close to 1.1 be used in future simulations.

C. Force/Torque Sensor

ATI Industrial Automation was the first choice to contact and obtain specifications on their 6 axis force/torque sensor. The Nano43 and Mini40 were the ones sought after for their desirable specifications, as shown in figure 2. However, when combined with needed accessories such as Interface board, power supply, cable lines and data acquisition USB cards, the price came out to be around 5-6 thousand dollars, which is quite expensive. The budget for the project did allow for the price range, but the real problem was that the sensor would take about 3.5 weeks to arrive, which was too long of a waiting period. The production team needed time to build the sensor and then calibrate it before it could be shipped out. This lead to the team, with input from their mentors, deciding the best course of action given the circumstances was to order the sensor and continue refining the simulations during the wait. The sensor could then be used to complete the wind tunnel testing phase of the project using the CEAS Support for Undergraduate Research Fellow program during the summer.

![Figure 2 – The MINI40 multi-axis force/torque sensor purchased by ATI Industrial Automation](image)

D. Prototype of Ahmed Body

The prototype will be one third of the actual size. This is a functional scale value since the CFD simulations showed no interactions between the boundary layers of the walls and Ahmed body. As shown with the dimensionless analysis, the scaled prototype will still have a Reynolds Number very close to turbulent flow. Therefore, any smaller will result in the flow becoming completely laminar, which will not be suitable for extracting valuable data. A Pro/Engineer-Wildfire solid model file of the prototype was constructed to show dimensions. The prototype was built at a manufacturing company facility using their SLS rapid prototyping machine. It was then sanded down and clear coated to provide smooth surfaces for the wind tunnel testing.

IV. Analysis and Discussion

Much of the effort throughout the semester for this project has been put toward the development of an accurate CFD simulation using Star-CCM+. Recent simulations have finally achieved error of less than 5% when comparing the drag force coefficient to experimental values stated in reference literature⁹. However, the experimental lift coefficient value stated in our reference literature was drastically different from our simulated values. To our best understanding, the literature lift coefficient value is incorrect. Much has been accomplished in the fine tuning of the simulations and many simulation parameter target values and settings have been determined regarding wind tunnel
aerodynamics. The following list summarizes target parameter values and settings determined through repeated simulations using Star-CCM+ in this application.

Meshing models -
- Hexahedral volume mesh
- Prism layer mesher

Physics models -
- K-Omega turbulence model family
- Constant density
- Steady state
- Turbulent flow

Meshing values
- <1mm surface size on Ahmed body
- <10mm minimum surface size on tunnel floor
- 6-8 prism layers on Ahmed body and tunnel floor
- Prism layer stretching ~1.1
- <10mm prism layer thickness on Ahmed body and floor

Boundary conditions -
- No-slip on Ahmed body and floor
- Slip on walls and ceiling
- Apply slip to floor near inlet

Figure 3 - Screenshot from Star-CCM+ showing close-up of hexahedral and prism layer cells near the surface of the Ahmed body.

It was discovered during the final simulations that results were very sensitive to changes in the prism layer of the mesh. The prism layers are used to more accurately capture the viscous region than the hexahedral (cube) cells which fill most of the fluid region. The flow of the fluid through the wind tunnel is generally uniform in direction and velocity. In such areas the hexahedral cells are adequate because each cell has a face orthogonal to the flow (see Figure 3). Where this flow changes is in and near the boundary layer developed from no-slip surfaces. In these areas (most important are around the Ahmed body) the flow follows the contour of the surface. Each prism layer is built parallel to such surfaces which allows the fluid flow to remain normal to the face of each cell (see Figure 3). This generally produces the most accurate results in CFD simulations.

V. Conclusions

Accomplishments of this project include the selection and purchase of a six-axis force and moment sensor for use in UWM’s wind tunnel, successful correlation of drag force from CFD simulation to referenced experimental
results, and the production of a 0.3 scale Ahmed body for use in the wind tunnel. Correlation of CFD data to experimental data was a large step in the project and has set the foundation for continued research in the wind tunnel. Once the sensor arrives and is calibrated, new experimental data will be collected and compared to the CFD results. It is expected to see similar experimental results for drag as seen in other reference literature on Ahmed body testing. Once drag correlation of less than 5% error is achieved between simulation and new experimental results, the project will look into the additional parameters desired, such as lift force, side force, pitching moment, rolling moment and yawing moment. These should be simple additions once correlation of experiment to simulation drag values is achieved.

Based on knowledge gained throughout the semester, it is recommended to further investigate the effects of changes in the prism layers around the Ahmed body of the CFD simulation. Recent simulations have seen high sensitivity to adjustments of these prism layers and a better understanding of this region will be valuable. It is also recommended that the simulations be run at different velocities to observe changes in drag values. In general, simulations will need to be refined and tailored to match the configuration of the actual wind tunnel test.

Acknowledgments

The authors would like to acknowledge Krishna Guntur for his extensive help in the simulation work.

References

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Appendix

A. Sensor Information

Table 3 – Specifications of 6-axis force and torque sensor models available from ATI Technologies
<table>
<thead>
<tr>
<th>Description</th>
<th>Nano17Ti</th>
<th>Nano17</th>
<th>Nano25</th>
<th>Nano43</th>
<th>Mini40</th>
<th>Mini45</th>
<th>Mini85</th>
<th>Gemma</th>
</tr>
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<tbody>
<tr>
<td>Max Fry</td>
<td>7.2</td>
<td>12</td>
<td>50</td>
<td>8</td>
<td>20</td>
<td>120</td>
<td>420</td>
<td>30</td>
</tr>
<tr>
<td>±b (±N)</td>
<td>32</td>
<td>50</td>
<td>250</td>
<td>98</td>
<td>80</td>
<td>580</td>
<td>1900</td>
<td>130</td>
</tr>
<tr>
<td>Max Tsy</td>
<td>1.6</td>
<td>4</td>
<td>50</td>
<td>4</td>
<td>40</td>
<td>100</td>
<td>340</td>
<td>100</td>
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<tr>
<td>±b=ln (±Nm)</td>
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<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Weight*</td>
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<td>0.02</td>
<td>0.14</td>
<td>0.09</td>
<td>0.11</td>
<td>0.20</td>
<td>1.4</td>
<td>0.56</td>
</tr>
<tr>
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<td>0.01</td>
<td>0.07</td>
<td>0.04</td>
<td>0.05</td>
<td>0.09</td>
<td>0.64</td>
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<td>0.67</td>
<td>0.98</td>
<td>1.69</td>
<td>1.57</td>
<td>1.77</td>
<td>3.4</td>
<td>2.97</td>
</tr>
<tr>
<td>in (mm)</td>
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<td>17</td>
<td>25</td>
<td>43</td>
<td>40</td>
<td>45</td>
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<td>Height*</td>
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<td>0.57</td>
<td>0.85</td>
<td>0.45</td>
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<td>0.62</td>
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<tr>
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