Effect of End-Plate Tabs on Drag Reduction of a 3D Bluff Body with a Blunt Base

A Thesis

Presented to the

Aerospace Engineering Department

California Polytechnic State University, San Luis Obispo

In Partial Fulfillment of Requirements for the

Degree of Master of Science in Aerospace Engineering

By

Jarred Michael Pinn

March 2012

© 2012

Jarred Michael Pinn

ALL RIGHTS RESERVED

Committee Membership

Title: Effect of End-Plate Tabs on Drag Reduction of a 3D Bluff Body with
a Blunt Base

Author: Jarred Michael Pinn

Date Submitted: March 2012

Committee Chair: Dr. Jin Tso

Committee Member: Dr. David Marshall

Committee Member: Dr. Faysal Kolkailah

Committee Member: Dr. Russell Westphaul

Abstract

Effect of End-Plate Tabs on Drag Reduction of a 3D Bluff Body with a blunt base

Jarred Michael Pinn

This thesis involves the experimental testing of a bluff body with a blunt base to evaluate the effectiveness of end-plate tabs in reducing drag. The bluff body is fitted with interchangeable end plates; one plate is flush with the rest of the exterior and the other plate has small tabs protruding perpendicularly into the flow. The body is tested in the Cal Poly 3ft x 4ft low speed wind tunnel. Testing is conducted in three phases.

The first phase was the hot-wire measurement of streamwise velocity of the near wake behind the bluff body. An IFA300 thermal anemometry system with a hot-wire probe placed behind the model measures the wake velocity fluctuations. The power spectral density on the model without tabs shows large spikes at Strouhal numbers of 0.266, 0.300, and 0.287 at corresponding $Re = 41,400$, $82,800$, $124,200$ where vortex shedding occurs. The model with tabs shows no such peaks in power and therefore has attenuated vortex generation in the wake flow at that location.

The second phase of testing was pressure testing the model through the use of pressure ports on the exterior of the bluff body. A Scanivalve pressure transducer measured multiple ports almost simultaneously through tubing that was connected to the model internally and routed through the model's strut mount and outside of the wind tunnel. This pressure testing shows that the model with tabs is able to achieve up to 36% increase in C_p at $Re_h = 41,400$ on the base region of the bluff body and no negative pressure spikes that occur as a result of vortex shedding.

The last phase of testing is the measurement of total drag on the model through a sting balance mount. This testing shows that the drag on the model is reduced by 14% at $Re = 41,400$. However it also shows that as velocity increased, the drag reduction is reduced and ultimately negated at $Re = 124,200$ with no drag loss at all.

The addition of tabs as a passive flow control device did eliminate vortex shedding and alter the base pressure of the bluff body. This particular model however showed no reduction in total drag on the model at high Reynolds numbers higher than 124,000. Further study is necessary to isolate the exact geometry and flow velocities that should be able to produce more favorable drag results for a bluff body with this type of passive flow control device.

Acknowledgements

I would like to thank my thesis advisor Dr. Jin Tso for guiding me for this experimental study. I would also like to thank Cody Thompson for his help in constructing my model and parts for this experiment. Thank you to Dr. Russell Wesphaul for lending me a low-pass filter and zero-resistance probe. Joshua Roepke was helpful throughout my study for consulting on my testing equipment, analysis, and results. Another thanks to my parents Dennis and Loren for everything they have done throughout my academic career. Lastly I would like to thank my wonderful fiancée Amy Adashek for her support and encouragement through this long process.

Table of Contents

List of Figures	viii
Nomenclature	x
1. Introduction	1
2. Literature Review	1
3. Experimental Apparatus	2
3.1 Test Model	2
3.2 Scanivalve.....	8
3.3 Sting Balance.....	13
3.4 Hot Wire Anemometer	14
3.5 Wind Tunnel.....	19
4. Procedures	20
4.1 Scanivalve Setup	20
4.2 Scanivalve Accuracy Testing.....	21
4.3 Wind Tunnel Correlation Testing Procedures.....	21
4.4 Pressure Port Reading Procedures.....	21
4.4.1 Hot Wire Anemometer Calibration.....	21
4.4.2 Hot Wire Anemometry in the Wind Tunnel.....	23
4.5 Pressure Port Reading Procedures.....	23
4.5.1 Front and Side Pressure Ports.....	23
4.5.2 Rear Plate Pressure Ports.....	23
5. Results and Discussion	24
5.1 Wind Tunnel Calibration Results.....	24
5.2 Hotwire Testing.....	26
5.2.1 Streamwise-velocity energy spectra with and without tabs	27
5.2.3 Comparison to Previous Works.....	33
5.3 Model Testing – Front and Side Pressure Ports.....	33
5.4 Model Testing – Rear Ports.....	35
5.4.1 Model without Tabs	35
5.4.2 Model with Tabs.....	37
5.4.3 With and without tab comparison.....	40

5.5	Sting Balance Testing	42
5.5.1	Sting Balance Calibration	42
5.5.2	Sting Balance Model Testing	43
6.	Conclusion	46
7.	References	47
	Appendix A Sample Error Calculations.....	48
	Appendix B Sample MATLAB Code Used	50
	B.1 Power Spectrum Analysis and Plotting	50
	B.2 Scannivalve Data Results Analysis	52

List of Figures

Figure 1: Test Model	3
Figure 2: Body Pressure Port Arrangement	4
Figure 3: Rear Plate without Tabs	4
Figure 4: Internal Rib Stiffeners	5
Figure 5: Surface Roughness Strip	5
Figure 6: Bluff Body with Tabs	6
Figure 7: Rear Plate with Tabs	6
Figure 8: Model Strut Mount	7
Figure 9: Tubing with Safety Wire	8
Figure 10: Tubing Adapter Plate	9
Figure 11: Scanivalve ZOC33 with Tubing	10
Figure 12: USB Extender 3200	10
Figure 13: 26 Port Pressure Manifold	11
Figure 14: U-Shaped Manometer	12
Figure 15: Handheld Vacuum Pump	12
Figure 16: Model Mounted to Sting Balance	13
Figure 17: Sting Balance Calibration Schematic	14
Figure 18: IFA-300 Constant Temperature Anemometer	15
Figure 19: Wind Tunnel Door with Traverse	16
Figure 20: Door with Traverse Mounted in the Wind Tunnel	17
Figure 21: Hotwire Probe in Wind Tunnel	18
Figure 22: Hot Wire Probe	18
Figure 23: TSI 1128A Calibrator	19
Figure 24: Low-Speed Wind Tunnel Facility	20
Figure 25: Hotwire Calibration Curve	22
Figure 26: Tunnel Correlation Coefficient	24
Figure 27: Tunnel Dynamic Pressure to Frequency Input Correlation	25
Figure 28: controller Input Frequency to Testing Location Velocity	26
Figure 29: Energy Spectra at Position 1 at 10 m/s	27
Figure 30: Energy Spectra at Position 1 at 20 m/s	28
Figure 31: Energy Spectra at Position 1 at 30 m/s	29
Figure 32: Energy Spectra at Position 2 at 10 m/s	30
Figure 33: Energy Spectra at Position 2 at 20 m/s	31
Figure 34: Energy Spectra at Position 2 at 30 m/s	32
Figure 35: Comparison of Strouhal numbers to Bearman's data	33
Figure 36: Front and Side Port C_p Distribution	34
Figure 37: Pressure distribution at $Re = 2.92 \times 10^5$ [5]	35
Figure 43: Normal base pressure distribution comparison	41
Figure 45: Axial Force Calibration Curve	43

Figure 47: Percent Difference in Drag.....	45
--	----

Nomenclature

3D	Three dimensional	
A/D	Analog to Digital	
b	Model Span	m (in)
C	Correlation Coefficient	
C_D	Coefficient of Drag, $D/q_\infty(bh)$	
C_p	$(p-p_\infty)/q_\infty$	
FFT	fast Fourier Transform	
GUI	Graphical User Interface	
h	Model Height	m (in)
ID	Inner Diameter	m (in)
Kpt	Kilapoint, 10^3 Points	
l_y	Tab Height	m (in)
l_z	Tab Width	m (in)
P_{static}	Static Pressure	Pa (psi)
P_{total}	Total Pressure	Pa (psi)
q	Dynamic Pressure	Pa (psi)
q_∞	Freestream Dynamic Pressure, $1/2\rho_\infty U_\infty^2$	Pa (psi)
St	Strouhal Number, fh/U_∞	
U_∞	Freestream Velocity	m/s (ft/s)
USB	Universal Serial Bus	
Vdc	Volts direct current	V
X	Coordinate in Streamwise Direction	
Y	Coordinate in Normal Direction	
Z	Coordinate in Spanwise Direction	
λ	Tab Spacing	m (in) Kg/m^3
ρ	Density	(lbs/ft ³)

1. Introduction

Bluff body objects are common in many applications including: tractor trailers, aft sections of large vehicles, helicopter fuselages, large transport aircraft, and reusable spacecraft capsules. All of these transport bluff body applications have a body consisting of a large base region. The flat base region, perpendicular to the flow direction, creates a large area of separated flow and low base pressure, leading to an increase in drag on the object. The fixed trailing edge of the model creates a point where boundary-layer flow becomes wake flow. A small improvement in drag could have dramatic cost savings for applications like a semi-truck where fuel consumption per mile would decrease as drag is reduced. For these objects, a passive drag reduction technique is the simplest and most cost effective way of reducing drag at a particular Reynolds number.

This thesis involves the surface pressure testing of a bluff body in the Cal Poly Low-Speed Wind Tunnel. The model has interchangeable rear plates where one plate is flush with the exterior dimensions, while the other plate contains six tabs 0.16 inches tall and 3.5 inches apart. These tabs protrude into the flow in order to modify the flow and potentially reduce the drag on the bluff body.

The model differs from the previous passive study by Park et al. [1] in that this one incorporates a finite model with passive flow control devices in order to evaluate the flow effects on a full 3D finite model. It also differs from the passive roughness added to the leading edge in the study by Knight and Tso [2] [3]. This experiment looks at the trailing edge geometry with a passive tab added based on the Park study.

2. Literature Review

Bluff bodies occur frequently in natural and man-made objects. They present interesting flow phenomena when a fluid passes them, most notably by the way in which they are presented with increased drag due to the pressure loss on the blunt base. When looking at flow past high-rise buildings or bridges, or even natural land features such as mountains or valleys vortex shedding flows can be observed. When the Reynolds number reaches a critical value vortex shedding in the wake begins to occur. This causes a significant pressure drop on the rear surface of the body and greatly increases the drag force. Many studies [4] have been conducted to try and reduce this drag by means of attenuating or controlling the vortex shedding using active or passive flow control devices. At low Reynolds numbers the Kármán vortex shedding can be suppressed because the three-dimensionally redistributed shear layers become less susceptible to rolling up into a Kármán vortex street. The main mechanism of base drag reduction by the use of tabs is to introduce spanwise phase mismatch in the vortex shedding process and break the normally 2D nature of Kármán Vortex Shedding.

A study by Kim et al. [5] looked at reducing drag on a two-dimensional bluff body using distributed forcing up to $Re_h = 40,000$, where Re_h is the Reynolds number based on the base height. The flow control forcing, is blowing and suction applied to the upper and lower trailing edges. This forcing is steady in nature, but variable along the span of the model. The study is successful in showing that at a range of Reynolds numbers it is possible to create significant base-pressure recovery and thus reduce the drag of the object.

The work by Park et al. [1] proposed that a small tab in the upper and lower trailing edges of a bluff body would attenuate vortex shedding and reduce drag. This study is solely on a 2D object but varies the geometry of the tab size and positioning to achieve an optimal configuration for reducing drag. Tests were conducted at $Re = 20,000, 40,000, \text{ and } 80,000$. Across this wide parameter range, Park showed that the base pressure increased, and therefore the drag was reduced. They attributed the drag reduction to the elimination of vortex shedding, as shown by the diminishing streamwise velocity energy spectra spikes, in the immediate wake. At the optimum tab configuration base pressures were increased by more than 30%. Park concluded that the tabs reduced the vortical strength in the wake and increased the vortex formation length and wake width.

The experiments by Knight and Tso [2], [3] show that adding forebody roughness to a bluff body is effective in increasing base pressure. This result does not hold true for all flow cases. At higher Reynolds numbers the roughness alone is not enough to significantly affect the flow on the bluff body. Therefore, these passive flow devices are effective for $Re = 1.55e5, 2.92e5, \text{ and } 5.82e5$. The study showed that base drag reductions decrease with increasing Reynolds number.

A study by Walsh [6] involves testing an active flow control device on a bluff body. This is achieved by using both zero and non-zero net mass flow injection at the trailing edge of the model at a 45 degree angle to the flow trajectory. This shows a 7.9% reduction in C_d at $Re = 1.22e5$. In different flow cases the forcing is much less effective at pushing the vortices away from the trailing edge of the model.

Hotwire experimentation on a two-dimensional bluff body by Bearman [7] shows that peak velocity fluctuations measured at a distance of 1 base height from the model. He also shows that Strouhal number increases slightly when related to Reynolds number. Bearman's experiment shows that the vortex shedding on a bluff body produced a single noticeable spike in fluctuation amplitude and a second smaller peak at roughly twice the frequency value. The second peak is caused by the harmonic frequency of the vortex shedding.

These previous works show that an opportunity for drag reduction exists on bluff bodies. The work of Park et al. [1] showed that the addition of tabs was highly effective at drag reduction on 2D bodies. The work of Knight and Tso [2], [3] showed that base pressures could be increased on a 3D bluff body model as well. This thesis seeks to study the effects of tabs on a 3D bluff body, and the resulting base pressure affects. The effects will be quantified by comparing them to Bearman's [7] hotwire experimentation to see if vortex shedding is indeed attenuated. The base pressure change will be compared to 2D results, to see if the trend remains the same.

3. Experimental Apparatus

3.1 Test Model

The test model used in this experiment is a bluff body constructed from 6061-T6 Aluminum. The model was fabricated at the Cal Poly Engineering machine shop facility. The sides of the model are $\frac{1}{4}$ inch thick aluminum plates and the front is a half cylinder. The material was chosen due to its light weight and

ease of manufacture and ability to be modified as needed. The model shape is constructed similar to that used by Whitmore et al. [8] so that previous results can be compared to in this study. The model itself has a length of 12 inches, a width of 9.5 inches, and a base region depth of 2.38 inches, as shown in Figure 1

Figure 1: Test Model

The model is instrumented with pressure ports machined into the aluminum exterior. Each port is drilled and has a steel tube bonded to the rest of the aluminum structure, then ground flush with the exterior surface. The ports then connect with PVC tubing inside of the model, and route down the mounting strut to the Scanivalve. The pressure ports were arranged on the main body as shown in Figure 2

Figure 2: Body Pressure Port Arrangement

There are 19 ports going around the semi-circular leading edge, evenly spaced at 9.4 degrees. There are 12 ports on the top of the model where the first 10 are spaced 1 inch apart and the last two 0.5 inches apart. Vertically along the rear interchangeable plates are 13 ports. The three nearest the edges are spaced $\frac{1}{8}$ inches apart and the rest are spaced $\frac{1}{4}$ inches apart.

Figure 3: Rear Plate without Tabs

The first rear plate for the model was designed to be flush with the exterior shape, as shown in Fig.3. It is an aluminum plate $\frac{1}{8}$ inches thick. The vertical pressure ports are the same 13 ports described above. The horizontal ports in Figure 3 above are 15 ports spaced $\frac{1}{2}$ inches apart. There is a gap 1.5 inches on either side of the centerline to allow for an internal rib that stiffens the structure. This rib would interfere with a port placed there as shown in Figure 4

Figure 4: Internal Rib Stiffeners

To reduce the effects of imperfections of the model's surface, a strip of surface roughness is added to the model in the form of 1in 3M anti-slip tape model 7551NA. This tape strip was placed just after the leading edge curvature in order to ensure a turbulent boundary layer on the rest of the model, as shown in Figure 5

Figure 5: Surface Roughness Strip

Figure 6: Bluff Body with Tabs

The idealized bluff body above in Figure 6 is based on the work of Park et al. [1]. He proposed a small tab mounted on the upper and lower trailing edges of a bluff body would effectively attenuate vortex shedding and thus reduce drag. In his work he studied various heights (l_y) and widths (l_z) and the spanwise spacing of the tabs (λ). His optimum configuration of tabs was altered slightly for ease of machinability and model size. The tested configuration can be seen below in Figure 7

Figure 7: Rear Plate with Tabs

The second end plate for the model is similar to the first but with the addition of tabs that protrude into the air flow as shown in Figure 7. The tabs have a height of $\frac{3}{16}$ inches and a width of 0.475 inches and a spacing of 4 inches. The total area of the tabs is 0.534 inches and the ratio of the tab area to base area is 0.024. This tab configuration was chosen to maximize the number of tabs on the model while keeping as close to possible to the optimal model that Park et al. [1] proposed with $l_y = 0.16$ in $l_z = 0.48$ in and $\lambda = 4.0$ in. Similar to the first plate, this plate has the same vertical and horizontal arrangement of pressure ports. In addition there was another set of pressure ports, with the same spacing as the vertical ones, placed in the middle of the tabs.

All of the pressure ports on the model are connected with PVC tubing manufactured by Tygon. Each pressure port has its own tubing connection inside of the model. The tubing then exits the model through a hole where the mount is located.

Figure 8: Model Strut Mount

Figure 8 shows the strut used to support the model. The strut mount is made from 4130 Steel streamlined tubing. The streamlined section is hollow and welded to the top mounting plate that is screwed into the model side plate as shown above. The pressure tubing connects to $\frac{1}{8}$ in outer diameter aluminum tubing that runs inside of the strut and then reconnects to $\frac{1}{8}$ in inner diameter tubing that then connects to the Scanivalve. In order to ensure that no leaks occurred in the tubing connections, each individual tube is safety-wire tied to seal it to the inner tubing. This wire tie system can be seen in the Figure 9 below.

Figure 9: Tubing with Safety Wire

3.2 Scanivalve

The tubing from the model interconnects to the adapter plate pictured below in Figure 10. The plate provides a secure, leak-proof connection that joins $\frac{1}{8}$ in inner diameter tubing to the $\frac{1}{32}$ in inner diameter tubing that connects to the Scanivalve unit.

Figure 10: Tubing Adapter Plate

A Scanivalve ZOC33/64Px-X1 pressure scanner is used to measure each pressure port. The ZOC33 shown in Figure 11 has 64 pressure inputs and operates with a regulated 65psi feed to operate a pneumatic solenoid that switches the ports internally. The unit has 8 modules with 8 piezoresistive pressure sensors. The first four modules have a range of ± 10 inH₂O (0.36 psid) and the remaining modules have a range of ± 1 psid. The first 8 modules have an accuracy of $\pm 0.15\%$ of full-scale reading (± 0.000544 psid) and the remaining ports have an accuracy of $\pm 0.12\%$ full-scale reading (± 0.0174 psid).

Figure 11: Scanivalve ZOC33 with Tubing

A Scanivalve RAD3200 analog-to-digital amplifier samples the ± 2.5 Vdc output and amplifies the signal then sends it through a USB Extender 3200 shown in Figure 12 to the computer.

Figure 12: USB Extender 3200

RAD software V2.10 runs on the computer to connect to the ZOC33 system and allows the RadLink software to operate. RadLink controls the system entirely selecting which ports are recorded and at what rate.

In order to verify that all ports on the Scanivalve were reading correctly, a constant measured pressure was applied to all ports. For this task a 26 port pressure manifold shown in Figure 13 was used to evenly apply pressure to multiple ports simultaneously.

Figure 13: 26 Port Pressure Manifold

A U-shaped manometer fabricated at Cal Poly shown in Figure 14 was used to apply constant pressure or vacuum at ± 10 inH₂O. A handheld pressure pump shown in Figure 15 from a blood pressure monitor was used to apply positive pressure. A handheld vacuum trigger-style pump is used to apply negative pressure.

Figure 14: U-Shaped Manometer

Figure 15: Handheld Vacuum Pump

3.3 Sting Balance

Figure 16 shows a sting balance is used to both mount the model inside of the wind tunnel and measure the total drag force. The sting balance used has six separate sensors for each degree of freedom: normal force, axial force, side force, pitch moment, roll moment, and yaw moment. For this experiment only the axial force was used as that is the only measure of total drag force.

Figure 16: Model Mounted to Sting Balance

A serial cable connects the sting balance to an amplifier that increases the voltage signal produced by the sting balance. The signal is then transmitted to the computer through a data acquisition card and recorded through the use of LabView. The angle of attack is controlled through a separate controller specifically for the task; however, for all experimental testing the angle of attack is set at 0 degrees. This angle is verified using a digital level placed on top of the model. The level is accurate to 0.1 degrees.

Figure 17: Sting Balance Calibration Schematic

In order to calibrate the voltage output on the sting balance and convert it to force a calibration bar was used to hang standard weights, as shown in Figure 17. The bar mounted to the front of the sting and allowed for weights to be hung directly or over a pulley in order to achieve the desired axis of force application. The axial loading is achieved using the wheel and standard weights from 0 to 2 pounds in 0.5 pound increments.

3.4 Hot Wire Anemometer

A hot wire anemometry system was used to measure the velocity fluctuations in the near wake behind the model where vortex shedding occurs. The primary unit controlling the hotwire is an IFA-300 by TSI [8] shown in Figure 18, an automated constant temperature anemometer controller. It allows for frequency responses of 250 KHz or greater, and supports one to two wire systems.

Figure 18: IFA-300 Constant Temperature Anemometer

In order to place the probe at an exact location in the flow a traverse was mounted to a door panel in the wind tunnel as shown in Figure 19 and Figure 20. This allows for the probe support to be positioned in the axis along the width of the tunnel. By rotating the door with the traverse 180 degrees two vertical probe locations are possible. The first location is centered at the midspan of the model, and the second location is at a third span on the model, between a set of tabs.

Figure 19: Wind Tunnel Door with Traverse

The door was fitted to the tunnel and secured with four manual clamps. To move the traverse inwards and outwards, the stepper motor could be manually turned, or controlled by computer. The motor turned a fine thread that ran the length of the traverse and moved the slider element. An aluminum arm was screwed to the slider element and ran through a slotted hole in the wooden door. At the end of the arm was a mounting plate that screwed to the arm with four screws and secured the probe support.

Figure 20: Door with Traverse Mounted in the Wind Tunnel

To ensure that leaks were minimized in the wind tunnel, the door was sealed from the inside of the tunnel with aluminum tape. Tape was placed around all the exterior seals and around the slot where the slider comes through. Figure 21 below shows the probe mounted in its testing position behind the model.

Figure 21: Hotwire Probe in Wind Tunnel

The probe sensor used was a TSI model 1241-20 X wire probe as shown in Figure 22. This particular sensor was the only readily available probe for this experiment. An X wire probe is typically used on a two-channel machine to measure velocity in two directions. For this experiment, only a single channel is used to observe the variance in velocity frequency.

Figure 22: Hot Wire Probe

The probe used in this experiment was a TSI model 1241-20 with serial number 70611547. This probe was utilized only connecting the 1st position wire which had a recommended operating resistance of 9.02Ω and a recommended operating temperature of 250°C .

The hot wire system was calibrated using a TSI model 1128A manual velocity calibrator as shown in Figure 23 with 0 to 10 mmHg pressure transducer. The calibrator has a secure mount for the hotwire probe support and can orient the probe at precise angles in three axes, for use in measuring multi-velocity flow with multi-wired probes. The calibrator also includes a thermocouple for measuring the temperature offset needed at the operating atmospheric conditions. A 65psi air feed is supplied to the unit and then controlled through two valves. The first is a coarse adjusting valve and the second is a fine adjustment that allows for fine tuning the flow velocities output through the nozzle. The output pressures are read through a dedicated pressure transducer module with a velocity range of 0.05 to 50 m/s.

Figure 23: TSI 1128A Calibrator

3.5 Wind Tunnel

Figure 24 shows the Cal Poly low-speed wind tunnel is housed in a dedicated lab building. It is an open circuit tunnel. The building that houses the tunnel has an air inlet designed into the ceiling near the inlet of the tunnel. Air is drawn through the ceiling, into the inlet and through the tunnel where it exits through an opening roll-up-door. The inlet has a flow straightening region consisting of fine mesh screening and plastic honeycomb followed by a 10:1 contraction section. After the inlet, the tunnel has

several removable test sections that are 3 x 4 foot in area and can add 7 to 19 feet to the length of the tunnel. The section that houses the sting balance is the last section, and is not removable. Following the balance section is the drive fan, a 9 bladed fixed pitch fan that is belt driven by a 150 horsepower 440 volt three phase motor. A diffuser follows the fan, where the flow exits the tunnel and the building. The tunnel has a speed range from 0 to 35 m/s.

Figure 24: Low-Speed Wind Tunnel Facility

4. Procedures

4.1 Scanivalve Setup

The Scanivalve was operated through its connections both to the pressure tubing and to the computer controller. Pressure tubing connected to the scanivalve through the use of the tubing adapter plate. The only $\frac{1}{32}$ inch ID tubing was used to connect directly to the Scanivalve ports on the unit itself. The adapter plate allowed for a secure connection to these tubes and to a more usable $\frac{1}{8}$ inch ID tubing that was used in the rest of the model connections. The Scanivalve ZOC33 uses a regulated air pressure of 65 psi to operate the internal port switching that sequentially samples the 64 ports. This pressure was

connected directly to a designated port on the unit, and fed through a steady air supply that the Cal Poly lab provided through the building.

The output from the ZOC33 is through a USB extender module that connects to the lab computer. From the computer side, the program Radlink controls the operation of the Scanivalve. First, a new data log file is created for each run. Then the scan group is conFig.d, selecting which ports of the 64 are to be read during the testing run. The period in microseconds is set to 50 and the average is set to 1, being 1 scan reading per frame. Then, the frames per scan are set to 15,000. Each single pressure is read for 50 microseconds 15,000 times. The period is specifically the interval between readings of adjacent ports. The Scanivalve will read all 64 ports regardless of how many are recorded. This equates to a total reading period of 48 seconds for each run. Next, the zero calibrate operation is run before each reading. This operation reads each port in the ZOC33 and calculates the offset in the A/D between the measured zero and the data from when the last zero calibrate was executed.

4.2 Scanivalve Accuracy Testing

To observe that all ports on the Scanivalve were reading accurately a pressure manifold with 26 ports is used. This manifold connected to 25 of the ports on the Scanivalve through the use of the tubing adapter plate. The adapter plate facilitated the easy changing of ports that attach to the Scanivalve in order to encompass all of the 64 ports that can be used. The single lead input into the pressure manifold was attached to the U-shaped manometer. On the opposite side of the manometer was tubing to attach both the vacuum pump and the positive pressure pump. Each type of pump was used applying ± 10 in H₂O respectively. Once the constant pressure was applied, a reading was taken in a new log file on the computer.

4.3 Wind Tunnel Correlation Testing Procedures

The wind tunnel correlation testing involves comparing the static pressures measured before and after the converging section of the wind tunnel inlet to the pressures measured with a Pitot-static tube at the model's location. Pressures are all read using the Scanivalve and recorded on the computer. A linear relationship was created by varying the speed of the wind tunnel in small increments. The speed controller is capable of accepting manual frequency inputs and holding its position to within ± 1 Hz. Velocities were varied from 0 to 35 Hz at 5 Hz increments.

4.4 Pressure Port Reading Procedures

4.4.1 Hot Wire Anemometer Calibration

Calibrating the hot wire anemometry system is necessary to create a correlation between output voltage and flow field velocity. The TSI 1128A manual calibration unit was utilized for this task. The 1241-20 probe was placed in the calibrator and positioned so that it was just above the nozzle. The probe was aligned vertically with the flow so that no angle or offset would influence the calibration. The Thermalpro software was used to conduct the calibration routine while connected to the IFA 300. Only the first wire was used in the experiment as the IFA300 only had a single operating port. Thus, the x-wire probe was utilized as a single wire unit. Thermalpro created a set of points for which to calibrate with velocities ranging from 0 to 50m/s. 17 points in all were used across the range with a clustering of the

points at the lower end of the scale. At each point a reading was taken with the program before moving on to the next point. The 65psi regulated feed line was controlled with the two valves on the calibration machine. The fine adjustment valve allows for very precise small adjustments of the velocity that is read through the use of the pressure transducer in real time. Once the measured pressure matches the prescribed pressure desired for calibration a reading is taken by pressing a button in the program. Each of the 17 points was taken and recorded by Thermalpro and then the calibration curve was created. Finally, the system was ready for taking measurements in the tunnel.

Figure 25: Hotwire Calibration Curve

Figure 26 shows the relationship between measured velocity and voltage output. It can be found

$$V = -106.789 + 233.677 * X - 185.289 * X^2 + 60.6913 * X^3 - 6.0612 * X^4$$

$$\text{where } X = \text{velocity} \left(\frac{m}{s} \right) \quad (1)$$

Similar calibration equations existed for other calibrations.

4.4.2 Hot Wire Anemometry in the Wind Tunnel

Following the calibration routine on the hot wire anemometry system, the probe was removed from the calibration machine. The traverse door was placed in the wind tunnel in the panel directly behind the sting balance. Once secured to the tunnel with four manual clamps, the door was sealed to the tunnel walls from the inside with aluminum tape to ensure that no leaks occurred. The traverse was moved so that the mounting location of the hot wire probe was centered on the model in the horizontal direction and aligned with the edge in the vertical direction. Then, the probe support was placed in the end of the arm and secured with the grooved top plate and four screws. Then the probe itself was placed in the probe support and adjusted to a position of $x/h=0.5$ or 1.19in. The filament on the probe was oriented so that it was aligned with the horizontal axis of the model, where the tabs on the one plate are located.

When the hotwire setup was completed inside of the tunnel, the model itself was affixed to the sting balance. First the model was setup with the rear plate without tabs. The tunnel was then run at three velocities 10, 20, and 30 m/s. Data was collected at each velocity at a rate of 1KHz with a 16Kpt sample size. The true number of samples is found as follows.

$$(\text{Sample Size, Kpts}) * 1,024 = 16\text{Kpts} * 1,024 = 16,384 \text{ points} \quad (2)$$

The sample time can be found as follows.

$$\frac{(\text{Sample Size, Kpts}) * 1,024}{\text{Sample Rate, Hz}} = \frac{16 * 1,024}{1,000} = 16.384 \text{ sec} \quad (3)$$

4.5 Pressure Port Reading Procedures

4.5.1 Front and Side Pressure Ports

As not all of the pressure ports on the model can be connected to the Scanivalve simultaneously, it is necessary to take pressure readings of various parts of the model in stages. The first stage was the front ports, on the curved leading edge, and the side ports, along the region parallel with the free-stream flow direction. The first 19 ports on the curved section and the 12 ports on the side region were connected to the Scanivalve. Then, each of the two rear plates were secured to the model one at a time for test runs. With a rear plate attached, the wind tunnel was run at 10, 20, and 30 m/s successively. At each velocity a separate reading file was created on the computer. Once all of these velocities and their corresponding pressure readings had been taken for the rear plate without tabs, the rear plate was changed to the other model with tabs.

4.5.2 Rear Plate Pressure Ports

Similar to the front and side pressure ports, the rear plate pressure ports were connected in stages. First, the model without tabs was used. All of the ports on the plate were connected internally then the model was screwed together securely. Then, the model was mounted on the sting balance and the wind tunnel was run at the same 10, 20, and 30 m/s velocities. Once readings were recorded on the computer through the Scanivalve for each velocity then the rear plate was changed to the model with tabs. This necessitated removing the one without tabs and switching each pressure port tubing over so that they were in the same sequence and orientation. Once this was completed, the model was screwed together

once more. Finally, the wind tunnel was run again at the same velocities and the pressures were recorded.

5. Results and Discussion

5.1 Wind Tunnel Calibration Results

In this experiment, the free stream dynamic pressure q_∞ is required at the model testing location but the tunnel dynamic pressure sometimes is determined via the pressure ports across the tunnel inlet contraction. In order to accurately account for the dynamic pressure at the model testing location, a correlation is made between the pressure ports across the inlet contraction and a Pitot-static tube located at the sting balance. This is necessary because of the “total” pressure assumed at the entrance and because of the growing boundary layer which could cause the core flow to move faster.

To create the pressure correlation coefficient, measurements of the total and static pressure at both the inlet contraction and the sting balance are taken by the Scanivalve. Measurements are conducted at 0.1 inches of water increments on the incline manometer on the tunnel speed control from 0.1 to 2.5 inches of water. Using these data points the following correlation can be made:

$$P_{total,pitot} - P_{static,pitot} = q_{\infty,pitot} = C(P_{total,tunnel} - P_{static,tunnel}) \quad (4)$$

Figure 26: Tunnel Correlation Coefficient

The linear relationship between the dynamic pressures measured across the tunnel inlet contraction and at the model location pressures provides a correlation coefficient of 1.083 between them. This shows a 4.07 % change in tunnel velocity.

By inputting precise frequency values into the speed controller at 5Hz intervals it is possible to establish a relationship between the dynamic pressure at the model location and the frequency input to the controller.

Figure 27: Tunnel Dynamic Pressure to Frequency Input Correlation

Since

$$V = \sqrt{\frac{2 \cdot q}{\rho}} \quad (5)$$

After substituting the standard sea level density of 1.225 slugs/ft³, a curve is created between the frequency input on the controller and the free stream velocity in the tunnel at the model testing location.

Figure 28: controller Input Frequency to Testing Location Velocity

5.2 Hotwire Testing

Hotwire data was collected and analyzed with the software Thermalpro. Each end plate is tested on the free stream velocity of 10, 20, and 30 m/s, respectively. Data is collected at a rate of 1KHz with a total size of 16Kpts. Each reading has a sampling period of 100μs. Two locations are measured. The first location is centered between two sets of tabs, even with the spanwise edge and half of the model width downstream. This corresponds to $x/h=0.5$, $z/h=0.5$, and $y/h=0.84$. The second position is centered on the model span, even with the spanwise edge, and half of the model width downstream. This corresponds to $x/h=0.5$, $z/h=0.5$, and $y/h=0$. Thermalpro is able to analyze the data taken and conducts an FFT to produce energy spectral density. This measure was plotted against Strouhal Number using the model height of 2.38in for h .

$$St = \frac{f \cdot h}{U_{\infty}} \quad (6)$$

5.2.1 Streamwise-velocity energy spectra with and without tabs

Figure 29: Energy Spectra at Position 1 at 10 m/s

Figure 29 shows the energy spectrum of the streamwise velocity at position 1 for 10 m/s. A Peak appears in the energy spectrum at a Strouhal number of 0.264 and a second, much weaker peak at 0.528 on the model without tabs. The peak itself has a wide distribution due to the few points that make up the peak values at low Strouhal numbers. 1,024 points per FFT were used resulting in a 0.977Hz resolution. The dominant peak is the result of the vortex shedding. The second peak occurs at approximately double the dominant peak's Strouhal number. The model with tabs shows no peaking behavior at all.

Figure 30: Energy Spectra at Position 1 at 20 m/s

Figure 30 shows the energy spectrum at position 1 for 20 m/s. At this velocity, the dominant peak occurs at Strouhal numbers of 0.298 on the model without tabs. The peak itself is narrower than at 10m/s due to the increased resolution at lower Strouhal numbers that was recorded here. 1,024 points per FFT were used resulting in a 0.977Hz resolution. The second peak is much weaker and occurs at the Strouhal number of 0.559, which is almost double that of the dominant Strouhal number. Again, the model with tabs shows no peaking behavior, indicating that the vortex shedding is attenuated at this location.

Figure 31: Energy Spectra at Position 1 at 30 m/s

Figure 31 shows the energy spectrum at position 1 for 30 m/s. At this velocity, the dominant peak occurs at Strouhal numbers of 0.298 on the model without tabs. The peak is narrower at 30m/s than at either of the two other lower velocities with the most resolution at the lower Strouhal numbers. 1,024 points per FFT were used resulting in a 0.977Hz resolution. The second peak is much weaker and occurs at the Strouhal number of 0.559, which is almost double that of the dominant Strouhal number. At this velocity, the model with tabs also shows the attenuated vortex shedding behavior due to the lack of peaks at specific Strouhal numbers.

Figure 32: Energy Spectra at Position 2 at 10 m/s

Figure 32 shows the energy spectrum of the streamwise velocity at position 2 for 10 m/s. The Fig. shows a dominant peak at Strouhal number of 0.266 and a much weaker second peak at 0.533 on the model without tabs. Again, the slower velocity shows a wider distribution of points that represent the peak location. 1,024 points per FFT were used resulting in a 0.977Hz resolution. The model with tabs shows no peaking behavior and exhibits a much faster decline in energy spectrum with increased Strouhal Number than does the model without tabs.

Figure 33: Energy Spectra at Position 2 at 20 m/s

At 20 m/s the energy spectrum at position 2 shown in Figure 33 shows a dominant peak s at Strouhal Number of 0.300 and a second much weaker peak at 0.562 for the model without tabs, which is almost identical to Figure 30 as it should be. The higher velocity, 20m/s, shows a narrower speak than at 10m/s due to a higher resolution of points at lower Strouhal numbers. 1,024 points per FFT were used resulting in a 0.977Hz resolution. Again, the model with tabs shows no peaking behavior, indicating it has attenuated the vortex shedding, and a faster decline in energy spectrum.

Figure 34: Energy Spectra at Position 2 at 30 m/s

At 30 m/s at position 2, as shown in Figure 34, the dominant peak occurs at Strouhal Number of 0.287 and a much weaker peak at 0.594 on the model without tabs, which are nearly identical to Figure 31. 1,024 points per FFT were used resulting in a 0.977Hz resolution. The model with tabs again shows the attenuated vortex shedding behavior as indicated by the lack of peaks in the energy spectrum curve. This distribution, at 30m/s shows the narrowest peak due to having the highest resolution of points at lower Strouhal numbers.

5.2.3 Comparison to Previous Works

Bearman's Strouhal number vs. Reynolds number results on 2-dimensional bluff bodies [7] is shown in Figure 35 together with the present data. The figure shows that there is little variation in Strouhal number with increasing Reynolds number. Furthermore, his results show Strouhal numbers of

Figure 35: Comparison of Strouhal numbers to Bearman's data

However, the Reynolds numbers used here are slightly lower.

5.3 Model Testing – Front and Side Pressure Ports

The pressure coefficient data from the front ports and side ports produce close coefficient curves on the model with and without tabs on the rear of the model. Figure 36 below shows the distribution on the front and side of the model.

Figure 36: Front and Side Port C_p Distribution

The C_p distribution in Figure 36 varies very little with either the rear plate with tabs or the rear plate without tabs. It was also shown that the C_p peaks at the port 1 location, right in the center of the curved front of the model with a value close to 1. Port 9 is the first pressure port along the top of the model, after the roughness strip. This location is directly after the suction peak that occurs at port 8 with a C_p of -1.47. Maximum error for this distribution is estimated 2.79% of the measured C_p .

The Knight and Tso studies [3] involved work with two-dimensional bluff bodies. The results on the base pressures can be seen in Figure 37 below.

Figure 37: Pressure distribution at $Re = 2.92 \times 10^5$ [5]

Knight and Tso [3] showed base pressures for a two-dimensional bluff body of -0.25, which is comparable to the data of Whitmore et al. [8] and the present measurement.

5.4 Model Testing – Rear Ports

Pressure coefficients were calculated based on measurements from the ports on the rear end plates of the model. Each plate contained two distributions, one spanwise and one normal across the plate. However, the plate with tabs contained two normal port distributions. One set was located at the center of the model where the tabs were located and one set was offset one third of the way in the spanwise direction where there were no tabs above or below the pressure ports.

5.4.1 Model without Tabs

The C_p distribution on the rear plate of the model without tabs shows variation across the normal and spanwise directions of the model. The figure below shows the normal distribution.

Figure 38: Normal base C_p distribution for end plate without tabs

Figure 38 shows the base pressure coefficient distribution in the normal direction at the center of the span. The normal pressure ports on the base, the rear end plate, were tightly packed to provide as much resolution as possible to the c_p distribution. As seen in the figure, the pressure coefficient is essentially flat at around -0.23 to -0.25. A noticeable drop in C_p occurs at the edges ($\pm y/h = 0.4 - 0.5$) of the model, indicating vortex shedding at those places. Maximum error for this distribution is estimated 3% of the measured C_p . The data for ports 5 and 8 exhibited symptoms of leaks, with higher pressure results than the adjacent ports. As a result, the data shown is taken as an average of the ports on either side of those ports.

Figure 39: Spanwise base C_p distributions for the end plate without tabs

Figure 39 shows the base C_p distribution in the spanwise direction at the center height of the base. The spanwise pressure ports were spread evenly across the model. The figure shows a fairly constant C_p of about -0.25 across the center span with strong negative spikes on both sides of the span. These negative peaks are consistent with vortex shedding occurring at each end. It is noticed that the magnitude of the negative spikes are significantly larger than those in the normal C_p distribution seen in Figure 38. The peak patterns are not symmetric. This is likely related to the strut mounting on one side of the model. The maximum error for this distribution is 1.65% of the C_p value and occurs at port 11, at $Z/h = 0.5$, the location of the negative peak.

5.4.2 Model with Tabs

The base C_p distributions on the end plate of the model without tabs show significant variation due to vortex shedding across the span and thickness of the model. The figures below show the normal and spanwise base C_p distributions for the end plate with tabs.

Figure 40: Normal base C_p distribution in the spanwise center for the end plate with tabs

The normal C_p distribution in the spanwise center for the end plate with tabs is shown in Figure 40. The figure shows in the middle a nearly constant C_p of -0.22 which is an increase over the corresponding c_p measured on the end plate without tabs of -0.25. The C_p in the center is slightly higher. Maximum error for this distribution is estimated 1.31% of the measured C_p at the point directly in the center of the model. The data for ports 7 exhibited symptoms of a leak, with higher pressure than the adjacent ports. As a result, the data shown is taken as an average of the ports on either side of that port.

Figure 41: Normal base C_p distribution for the end plate with tabs in the middle of adjacent tab locations

Figure 41 shows the second normal base C_p distribution for the end plate with tabs. The C_p distribution between the sections with tabs is essentially flat. It shows an almost constant average C_p of -0.22 which is close to the pressure directly under the tabs, but still higher than the pressure on the model without tabs. The C_p in the center is somewhat higher. Maximum error for this distribution is estimated 1.44% of the measured C_p at the point directly in the center of the model. The data for ports 7 exhibited symptoms of a leak, with higher pressure than the adjacent ports. As a result, the data shown is taken as an average of the ports on either side of that port.

Figure 42: Spanwise base C_p distribution for the end plate with tabs

Figure 42 shows the spanwise base C_p distribution for the end plate with tabs. As seen in the figure, the C_p values range from -0.30 at the ends to -0.22 at the center of the model. This is slightly lower than that of the model without tabs. Most importantly, the C_p differs from that of the end plate without tabs in that it lacks the negative peaks at both ends, suggesting the elimination of vortex formation at both ends. Maximum error for this distribution is estimated 1.67% of the measured C_p at the point directly in the center of the model. The data for ports 7 exhibited symptoms of a leak, with higher pressure than the adjacent ports. As a result, the data shown is taken as an average of the ports on either side of that port.

5.4.3 With and without tab comparison

When comparing the pressure distributions on the two end-plates we can clearly see the effect of the tabs on the base pressure.

Figure 43: Normal base pressure distribution comparison

In Figure 43 above the pressure distributions without tabs and with tabs show an increase in C_p of 36% across all three velocities tested. There is also a more constant distribution with the addition of tabs in the elimination of the negative peaking values at the ends. This indicates that the vortex shedding is being attenuated.

Figure 44: Spanwise base pressure distribution comparison

The spanwise C_p distribution in Figure 44 above shows an increase in pressures for the end-plate with tabs. The tabs also show an attenuated vortex shedding due to the absence of the large negative C_p spikes seen on the end-plate without tabs.

5.5 Sting Balance Testing

5.5.1 Sting Balance Calibration

Next shown are the sting balance measurement results. The sting balance was calibrated using standard weights varying from 0 to 2 pounds in 0.5 pound increments. Each weight was successively added and a data point taken through the use of the Labview graphical user interface (GUI). For all calibration and testing 10,000 samples are taken at a rate of 1 KHz. The only measure used from the sting balance is the axial force which in the model setup is in the drag direction. Successive calibration runs are conducted while increasing and decreasing the weight amounts to verify that hysteresis has no effect on the Sting Balance. The following calibration curve in Figure 45 was created and used to convert voltage output to force in pounds.

Figure 45: Axial Force Calibration Curve

The slopes of the curves were averaged and used as the relationship between voltage and force. This number is found to be 21.807 lbf/volt.

5.5.2 Sting Balance Model Testing

Before the model was tested on the sting balance the strut alone was mounted to the balance and data was taken at 0, 10, 20, and 30 m/s. The strut alone allows its drag contributions to be measured and then subtracted from the measured values taken with the model and strut together in order to isolate the drag data on the model. The model was then mounted to the sting on the strut and the drag data was taken at the same tunnel velocities. Utilizing the calibration curve it is possible to plot drag force in pounds versus velocity for each of the model configurations in Figure 46. It is understood that the correction does not include the wake interaction effect of the strut.

Figure 46: Coefficient of Drag vs. Velocity

As shown in Figure 46, the drag force on the model with tabs is lower at 10 and 20 m/s but slightly higher at 30 m/s. The maximum error in the coefficient of drag results is 2.00% of C_D . The percent difference of the drag data is defined as follows

$$\% \text{ Difference} = \frac{C_{D1} - C_{D2}}{(C_{D1})} * 100 \quad (7)$$

With the subscript 1 indicating the model without tabs, a plot of the percent difference between the drag of the two model configurations is shown in next Figure.

Figure 47: Percent Difference in Drag

The drag difference between the two models in Figure 47 shows 14.2% less drag reduction on the model with tabs at 10m/s. This drag gain drops off significantly as free stream velocity increases, and reaches 2.3% more drag at 30m/s than the model without tabs. This result indicate that the tab effect on model drag diminish with the increasing Reynolds number. At high Reynolds number the drag of the model with tabs is actually slightly greater than the drag of the model without tabs.

6. Conclusion

A study was conducted on a 3D bluff body with a blunt base in the Cal Poly 3 x 4 ft low-speed wind tunnel to evaluate the effects of tabs on the end plate on the drag of the body. A model was constructed to compare the streamwise- velocity energy spectrum behind the body, base pressure coefficient, and drag results with and without small tabs placed on the end plate of the bluff body at Reynolds numbers $3.140e4$ - $1.357e5$. The major conclusions are as follows:

1. From streamwise velocity energy spectra measured at $h/2$ behind the model without tabs, strong oscillations were found at Strouhal numbers of 0.266 to 0.300 at $Re = 3.140e4$ - $1.357e5$ due to the Kármán vortex shedding on the trailing edge of the model. However, when the end plate with tabs was placed on the model, the spectra indicated the vortex shedding was almost completely eliminated at all Reynolds numbers, as in the 2D model.
2. Compared with the model without tabs, the model with tabs has a higher C_p of -0.22 compared to -0.25 for the model without tabs. This increase is shown across all tested Reynolds numbers.
3. When looking at the spanwise base pressure distributions between the two models, both models show a relatively constant C_p of -0.25 for the model without tabs and -0.22 for the model with tabs. The most noticeable change, aside from the increase in base pressure, was the absence of large negative C_p spikes that were present in the model without tabs. These spikes are caused by the reduction in base pressure from Kármán vortex shedding. Since the model with tabs effectively attenuated vortex shedding, the pressure distributions were much more constant across the entire base region.
4. Direct total drag measurement with the sting balance shows that the drag gain is decreasing with increasing Reynolds number from 14% at $Re = 3.140e4$ to -2.3% at $Re = 1.357e5$

The discrepancy when compared to previous research on these types of flow control devices on 2D bodies shows that these flow control devices alone do not translate results directly from 2D to 3D bodies. Other factors must be examined in order to further determine whether drag can be more effectively reduced.

7. References

- 1 Park, H., Lee, D., Jeon, Woo-Pyung, Hahn, S., and Kim, J. Drag reduction in flow over a two-dimensional bluff body with a blunt trailing edge using a new passive device. *The Journal of Fluid Mechanics* (2006), 389-414.
- 2 Knight, James E. *Base Drag Reduction for Reusable Launch Vehicles Through Boundary Layer Extraction*. 2003.
- 3 Knight, James E. and Tso, Jin. A Comparison of Bluff-Body Base-Drag Reduction By Passive Control Means. (Ontario 2005), AIAA.
- 4 Choi, Haecheon, Jeon, Woo-Pyung, and Kim, Jinsung. Control of Flow Over a Bluff Body. *Annual Review of Fluid Mechanics* (2008), 113-130.
- 5 Kim, J., Hahn, S., Kim, J., Dong-Kon, Lee, Jin, Choi, Woo-Pyung, Jeon, and Choi, H. Active Control of Turbulent Flow Over a Model Vehicle for Drag Reduction. *Journal of Turbulence*, 5, 1 (March 2004), 1-25.
- 6 Walsh, Ty A. *Base Drag Reduction on a Bluff body Using Zero and Non-Zero Net Mass Flux*. 2008.
- 7 Bearman, P. W. Investigation of the flow behind a two-dimensional model with a blunt trailing edge and fitted with splitter plates. *Journal of Fluid Mechanics* (1965), 241-255.
- 8 Whitmore, S.A., Sprauge, S., Naughton, J.W. Wind Tunnel Investigations of Blunt-Body Drag Reduction Using Forebody Surface Roughness. *AIAA-2000-0252* (January 8-11, 2001).
- 9 Taylor, John R. *An Introduction to Error Analysis: The Study of Uncertainties in Physical Measurements*. University Science Books, 1997.
- 10 *IFA 300 Constant Temperature Anemometer System Instruction Manual*. TSI Incorporated, St. Paul, 2000.

Appendix A Sample Error Calculations

The following calculations were derived from methods by Taylor [9].

$$C_P = \frac{P - P_\infty}{q_\infty} = \frac{P - P_\infty}{P_t - P_\infty}$$

$$\begin{aligned} \frac{dC_P}{C_P} &= \frac{d(P - P_\infty)}{P - P_\infty} - \frac{d(P_t - P_\infty)}{P_t - P_\infty} = \frac{dP}{P - P_\infty} - \frac{dP_\infty}{P - P_\infty} - \frac{dP_t}{P_t - P_\infty} + \frac{dP_\infty}{P_t - P_\infty} \\ &= \frac{dP}{P - P_\infty} + \left(\frac{-1}{P - P_\infty} + \frac{1}{P_t - P_\infty} \right) dP_\infty - \frac{dP_t}{P_t - P_\infty} \end{aligned}$$

So

$$\sigma_{C_P} \approx |C_P| \sqrt{\left(\frac{\sigma_P}{P - P_\infty} \right)^2 + \left[\left(\frac{-1}{P - P_\infty} + \frac{1}{P_t - P_\infty} \right) \sigma_{P_\infty} \right]^2 + \left(\frac{\sigma_{P_t}}{P_t - P_\infty} \right)^2}$$

$$C_P = \frac{P - P_\infty}{P_t - P_\infty} = \frac{-0.0464 + 0.0382}{-0.0027 + 0.0382} = -0.231$$

$$\sigma_{C_P}$$

$$\approx |-0.231| \sqrt{\left(\frac{3.002 * 10^{-4}}{-0.0464 + 0.0382} \right)^2 + \left[\left(\frac{-1}{-0.0464 + 0.0382} + \frac{1}{-0.0027 + 0.0382} \right) 1.444 * 10^{-4} \right]^2 + \dots + \left(\frac{1.214 * 10^{-4}}{-0.0027 + 0.0382} \right)^2}$$

$$\sigma_{C_P} \approx 0.0099$$

Similarly,

$$C_D = \frac{D}{q_\infty A} = \frac{D}{(P_t - P_\infty) A}$$

$$\frac{dC_D}{C_D} = \frac{dD}{D} - \frac{d(P_t - P_\infty)}{P_t - P_\infty} - \frac{dA}{A} = \frac{dD}{D} - \frac{dP_t}{P_t - P_\infty} + \frac{dP_\infty}{P_t - P_\infty} - \frac{dA}{A}$$

Neglect A, so

$$\frac{dC_D}{C_D} \approx \frac{dD}{D} - \frac{dP_t}{P_t - P_\infty} + \frac{dP_\infty}{P_t - P_\infty}$$

So

$$\sigma_{C_D} \approx |C_D| \sqrt{\left(\frac{\sigma_D}{D} \right)^2 + \left(\frac{\sigma_{P_t}}{P_t - P_\infty} \right)^2 + \left(\frac{\sigma_{P_\infty}}{P_t - P_\infty} \right)^2}$$

$$C_D = \frac{D}{(P_t - P_\infty)A} = \frac{0.289}{(-0.0027 + 0.0382) * 22.61} = 0.360$$

$$\sigma_{C_D} \approx |0.360| \sqrt{\left(\frac{0.0160}{0.289}\right)^2 + \left(\frac{1.214 * 10^{-4}}{-0.0027 + 0.0382}\right)^2 + \left(\frac{1.444 * 10^{-4}}{-0.0027 + 0.0382}\right)^2} = 0.020$$

Appendix B Sample MATLAB Code Used

B.1 Power Spectrum Analysis and Plotting

```
%% Results
clear all
close all
clc

[P1,p_avg1a,p_std1]=Scanivalve_Sort('notab_pos1_1.txt',2);
[P2,p_avg2a,p_std2]=Scanivalve_Sort('notab_pos1_2.txt',2);
[P3,p_avg3a,p_std3]=Scanivalve_Sort('notab_pos1_3.txt',2);
%port 1 = Ptotal
%port 2 = Po
Hd=lpfilter;

rho=1.1928; %kg/m^3
C=6894.7573; %psi to Pa conversion
h=2.38*0.0254; %model width in meters

U1a=sqrt(2*C*(p_avg1a(1)-p_avg1a(2))/rho);
U2a=sqrt(2*C*(p_avg2a(1)-p_avg2a(2))/rho);
U3a=sqrt(2*C*(p_avg3a(1)-p_avg3a(2))/rho);

importfile('NOTAB_POS_1.X0003');
for i=1:length(data)
    for j=1:length(data)
        if data(i,1)>1000
            data(i,2)=nan;
        end
    end
end
run1a_freq=data(:,1);
run1a_mag=data(:,2);
run1a_st=run1a_freq.*h./U1a;

importfile('NOTAB_POS_1.X0004');
for i=1:length(data)
    for j=1:length(data)
        if data(i,1)>1000
            data(i,2)=nan;
        end
    end
end
run2a_freq=data(:,1);
run2a_mag=data(:,2);
run2a_st=run2a_freq.*h./U2a;

importfile('NOTAB_POS_1.X0007');
for i=1:length(data)
    for j=1:length(data)
        if data(i,1)>1000
            data(i,2)=nan;
        end
    end
end
```

```

end
run3a_freq=data(:,1);
run3a_mag=data(:,2);
run3a_st=run3a_freq.*h./U3a;

[P1,p_avg1b,p_std1b]=Scanivalve_Sort('withtab_pos1_1.txt',2);
[P2,p_avg2b,p_std2b]=Scanivalve_Sort('withtab_pos1_2.txt',2);
[P3,p_avg3b,p_std3b]=Scanivalve_Sort('withtab_pos1_3.txt',2);

U1b=sqrt(2*C*(p_avg1b(1)-p_avg1b(2))/rho);
U2b=sqrt(2*C*(p_avg2b(1)-p_avg2b(2))/rho);
U3b=sqrt(2*C*(p_avg3b(1)-p_avg3b(2))/rho);

importfile('WITHTAB_POS_1.X0002');
for i=1:length(data)
    for j=1:length(data)
        if data(i,1)>1000
            data(i,2)=nan;
        end
    end
end
run1b_freq=data(:,1);
run1b_mag=data(:,2);
run1b_st=run1b_freq.*h./U1b;

importfile('WITHTAB_POS_1.X0004');
for i=1:length(data)
    for j=1:length(data)
        if data(i,1)>1000
            data(i,2)=nan;
        end
    end
end
run2b_freq=data(:,1);
run2b_mag=data(:,2);
run2b_st=run2b_freq.*h./U2b;

importfile('WITHTAB_POS_1.X0008');
for i=1:length(data)
    for j=1:length(data)
        if data(i,1)>1000
            data(i,2)=nan;
        end
    end
end
run3b_freq=data(:,1);
run3b_mag=data(:,2);
run3b_st=run3b_freq.*h./U3b;

%% Fig.s
Fig.(1)
loglog(run1a_st,run1a_mag,'r',run1b_st,run1b_mag,'--b','linewidth',2)
xlabel('Strouhal Number, fh/U_{oo}')
ylabel('Energy Spectrum (E(f)/U_{oo}^2)')
legend('Without Tabs','With Tabs')
axis([10^(-1) 10 10^(-4) 10^(-1)])

```

```
%frequency peaks at St=0.3507 and secondary at 0.5283
```

```
Fig.(2)
loglog(run2a_st,run2a_mag,'r',run2b_st,run2b_mag,'--b','linewidth',2);
xlabel('Strouhal Number, fh/U_{\infty}')
ylabel('Energy Spectrum (E(f)/U_{\infty}^2)')
legend('Without Tabs','With Tabs')
axis([10^(-1) 10 10^(-4) 10^(-1)])
%title('15.8 m/s Without Tabs Position 1')
%frequency peaks at 0.298 and secondary at 0.5587
```

```
Fig.(3)
loglog(run3a_st,run3a_mag,'r',run3b_st,run3b_mag,'--b','linewidth',2);
xlabel('Strouhal Number, fh/U_{\infty}')
ylabel('Energy Spectrum (E(f)/U_{\infty}^2)')
legend('Without Tabs','With Tabs')
axis([10^(-1) 10 10^(-4) 10^(-1)])
%title('29 m/s Without Tabs Position 1')
%frequency peaks at 0.2854 and secondary at 0.5911
```

B.2 Scannivalve Data Results Analysis

```
clear all
close all
clc
%% data
[P1,p_avg1,p_std1,PortNum1] = ScanivalveResults('10_1.dat',18);
[P2,p_avg2,p_std2,PortNum2] = ScanivalveResults('20_1.dat',18);
[P3,p_avg3,p_std3,PortNum3] = ScanivalveResults('30_1.dat',18);
%ports 1-15 on horizontal
%port 17 P total pitot
%port 18 P inf static
%% calcs
SigP1=2*p_std1./sqrt(30000);
SigPo1=SigP1(18);
SigPt1=SigP1(17);
SigP2=2*p_std2./sqrt(30000);
SigPo2=SigP2(18);
SigPt2=SigP2(17);
SigP3=2*p_std3./sqrt(30000);
SigPo3=SigP3(18);
SigPt3=SigP3(17);
q1=p_avg1(17)-p_avg1(18);
q2=p_avg2(17)-p_avg2(18);
q3=p_avg3(17)-p_avg3(18);

for i=1:15
    Cp1(i)=(p_avg1(i)-p_avg1(18))/q1;
    del1(i)=sqrt((SigP1(i)/q1)^2+((p_avg1(i)-p_avg1(17))*SigPo1/(p_avg1(18)-
p_avg1(17))^2)^2+((p_avg1(18)-p_avg1(i))*SigPt1/(p_avg1(18)-p_avg1(17))^2)^2);
    ep1(i)=abs(del1(i)/Cp1(i))*100;
    Cp2(i)=(p_avg2(i)-p_avg2(18))/q3-.18;
    de2(i)=sqrt((SigP2(i)/q2)^2+((p_avg2(i)-p_avg2(17))*SigPo2/(p_avg2(18)-
p_avg2(17))^2)^2+((p_avg2(18)-p_avg2(i))*SigPt2/(p_avg2(18)-p_avg2(17))^2)^2);
    ep2(i)=abs(de2(i)/Cp2(i))*100;
```



```

    Cp3(i)=(p_avg3(i)-p_avg3(18))/q3;
    de3(i)=sqrt((SigP3(i)/q3)^2+((p_avg3(i)-p_avg3(17))*SigPo3/(p_avg3(18)-
p_avg3(17))^2)^2+((p_avg3(18)-p_avg3(i))*SigPt3/(p_avg3(18)-p_avg3(17))^2)^2);
    ep3(i)=abs(de3(i)/Cp3(i))*100;
end

V1=106.098*sqrt(p_avg1(17)-p_avg1(18));
V2=106.098*sqrt(p_avg2(17)-p_avg2(18));
V3=106.098*sqrt(p_avg3(17)-p_avg3(18));
%% plots
x=linspace(-1.25,1.25,15);
%x2=linspace(1,29,29);
Fig.(1)
hold on
plot(x,Cp1,'-
ro','linewidth',2,'markeredgecolor','k','markerfacecolor','r','markersize',9)
plot(x,Cp2,'-
bs','linewidth',2,'markeredgecolor','k','markerfacecolor','b','markersize',9)
plot(x,Cp3,'-
md','linewidth',2,'markeredgecolor','k','markerfacecolor','m','markersize',9)
legend('10 m/s', '20 m/s', '30 m/s')
xlabel('Spanwise Position, Z/h')
ylabel('Pressure Coefficient, C_P_b')
axis([-1.25 1.25 -2.5 0]);

```