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**Hybrid Multi-Material Rotor (HMMR) Phase 2:
A Low-Frequency, High Amplitude Hydrodynamic-
Fluid-Structure-Interaction Experiment**

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Abstract

As part of the second phase of the Defense Advanced Research Projects Agency's (DARPA)'s Hybrid Multi-Material Rotor (HMMR) program, the Pennsylvania State University Applied Research Laboratory (ARL) conducted a fluid-structure-interaction (FSI) experiment in their 12-inch diameter recirculating water tunnel. The goal of the experiment was to produce and accurately measure a low-frequency, high-amplitude structural motion that was induced by unsteady fluid dynamic forces. The resulting dataset would be used for development and validation of FSI codes. The test model used was a fin that was swept forward into the flow to simulate a propeller crashback type event. A cylinder was mounted upstream of the fin to produce a low-frequency periodic flow oscillation. The experimental plan was divided the testing into three parts; (1) Part 1: empty test section, (2) Part 2: cylinder only, and (3) fin and cylinder or forced-fin testing. The empty test section configuration was performed to provide inlet conditions for computational models. The cylinder only testing was required to confirm the required CFD models to produce the oscillatory flow-field experienced by the fin. This part of testing was done twice, first with a smooth cylinder (Part 2a) and then with the cylinder leading edge roughened (Part 2b). The forced fin testing (Part 4) produced a rich dataset that includes synchronized measurements of the fin constraint loading (lift, drag, torque and drag moment), time-resolved velocity field spanning from one diameter downstream of the cylinder to beyond the fin and the fin tip motion

(deflections and twist). The objective of this document is to present how the measurements were acquired, summarize the measurements that were acquired and present key observations produced from the dataset. It is divided into four sections: (1) Part 1 – Empty Test Section, (2) Part 2a – Smooth Cylinder Only, (3) Part 2b – Rough Cylinder Only and (4) Part 4 – Forced Fin. This document will help provide the path forward on how to make proper comparisons between the experiment and FSI code results as the processing of the computational results will need to mimic that of the experimental data processing.

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1 Introduction

As part of the second phase of the Defense Advanced Research Projects Agency's (DARPA)'s Hybrid Multi-Material Rotor (HMMR) program, the Pennsylvania State University Applied Research Laboratory (ARL) conducted a fluid-structure-interaction (FSI) experiment in their 12-inch recirculating water tunnel. The goal of the experiment was to produce and accurately measure a low-frequency, high-amplitude structural motion that was induced by fluid loading. The resulting dataset would be used for development and validation of FSI codes. The test model used was a fin that was swept forward into the flow to simulate a propeller crashback type event. A cylinder was mounted upstream of the fin to produce a low-frequency periodic flow oscillation. The original experimental plan was to divide the testing into four parts; (1) empty test section, (2) cylinder only, (3) fin only and (4) fin and cylinder or forced fin testing. However, in the end, the report contains results for the empty test section (Section 2), a smooth cylinder only (Section 3), a roughened cylinder only (Section 4) and a roughened cylinder with the fin (Section 5). Section 6 contains conclusions about the experiment. A description of the water tunnel facility and tunnel monitoring instrumentation is provided at the beginning of each results section in this report, allowing each section to be read as a standalone document.

2 Part 1 – Empty Test Section

This section contains the results from the empty test section and includes information about the correlation of the drive impeller to tunnel velocity and flow surveys across the test section.

2.1 Experimental methods

This section describes details of the test facility, measurement instrumentation and test matrix.

2.1.1 Test facility

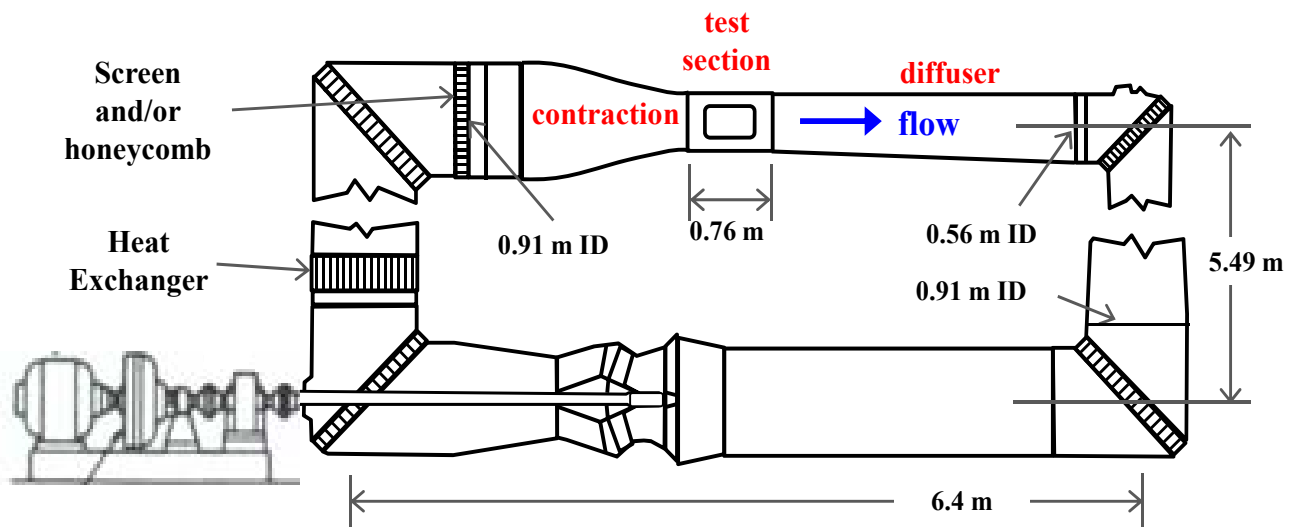


Figure 1. Schematic of the 12-inch water tunnel located at Pennsylvania State University's Applied Research Laboratory.

The experiment was conducted in the 12-inch diameter recirculating water tunnel at the Pennsylvania State University Applied Research Laboratory, schematically shown in Figure 1. The tunnel is powered by a 112 kW motor and has either a cylindrical or rectangular test section. For the current study the cylindrical test section was used, which has an inlet diameter of 0.305 m and is 0.76 m long. The test section is designed such that the diameter gradually increases from the inlet to a maximum diameter of 0.307 m at the test section outlet. This gradual increase in diameter is designed

to minimize the influence that boundary layer growth on the tunnel walls has on the local free-stream velocity. Throughout testing the tunnel pressure was maintained at 138 kPa, though the absolute pressure can be varied from 20 to 414 kPa. Additional tunnel details can be found in Madavan *et al.* (1984, used the rectangular test section), Deutsch & Castano (1986) and Fontaine & Deutsch (1992).

The global coordinate systems used throughout the entire experiment has X increasing in the streamwise direction with the origin at the test section inlet, Z aligned with the cylinder and increasing into the flow with the origin located at the fin base, and Y completing the right-handed coordinate system and the origin located at the test section centerline. The test section inlet position was selected as the origin because the seam provides a consistent reference position to use throughout the entire experiment.

2.1.2 Instrumentation

This section describes the instrumentation used for measurements of the water tunnel pressure, temperature, impeller rotational frequency and two-component velocity flow field.

2.1.2.1 Laser Doppler velocimetry

Laser Doppler velocimetry (LDV) was used to provide time-resolved flow-field measurements. Laser Doppler velocimetry (LDV) is a randomly sampled, point measurement of two velocity components. The random sampling is because the frequency that tracer particles pass through the measurement volume determines the acquisition rate. Hollow glass sphere particles (iM30K Glass Microspheres, 3M) were used as tracer particles. The LDV system was mounted on a 3-axis linear traversing table. The relative motion between the LDV table and the test section was measured and shown to be less than 50 μm . The relative motion was checked by mounting a video camera on the traversing table and imaging a precision target mounted on the tunnel test section. The relative motion was then monitored with use of a pair of accelerometers (W352C67, PCB) having a sensitivity of 100

mV/g with one mounted on the traversing table and the other on the test section. The LDV system used an argon ion laser (Innova 70C-5, Coherent), which had a nominal beam diameter of 1.5 mm. The laser beam was then separated into blue and green beams with a multicolor beam generator (fiberlight 450200, TSI), which also coupled the beams to fiber optic cables. The fiber optic cables were then connected to a fiber optic probe head (9832, TSI), which outputted four beams (2 green and 2 blue beams) through a 350 mm ($\kappa = 3.97^\circ$) lens (9253-350, TSI). Light reflected from the tracer particles within the measurement volume back towards the fiber optic head was coupled to a separate receiving fiber optic cable. The received light is then separated by wavelength and converted to electrical signals with a photodetector (PDM1000, TSI). The electrical signals are then processed with a multi-bit digital burst processor (FSA 35500-3, TSI). The burst processor band pass filters the signals and then uses both the Fast Fourier Transform (FFT) and autocorrelation techniques to determine the burst frequency, which is correlated to the tracer particle velocity. The burst processor also outputted the power to control the Bragg cell in the beam separator. The measured two components of velocity were then recorded with an LDV acquisition software package (Flowsizer, TSI) along with the traverse position. Typically 20,000 velocity measurements were acquired at each probe location. An estimate of the probe volume (V_p) can be made following the analysis of Tropea et al. (2007) assuming a Gaussian beam with the volume edge being defined as when the beam intensity falls to e^{-1} of the maximum intensity. The resulting probe volume is assumed to have an ellipsoid shape and equal to

$$V_p = \frac{\pi d_w^3}{6 \cos(\kappa) \sin(\kappa)}.$$

Here d_w is the beam waist diameter within the probe volume ($= 4f\lambda_b/\pi d_{wo}$), f is the lens focal length, λ_b is the wavelength of the beam and d_{wo} is the beam waist diameter before the lens. In the current study the maximum beam wavelength was 514.5 nm and the nominal beam waist diameter before the lens was 1.5 mm, which results in a nominal volume of 0.027 mm³ ($d_w \sim 150 \mu\text{m}$, probe length ~ 1.5 mm).

The LDV uncertainty is estimated using established methods for calculating uncertainty. The total uncertainty includes calibration uncertainty, uncertainties associated with bias error corrections and statistical uncertainty. Estimated uncertainties in the mean are $\approx \pm 2.2\%$. The reported RMS uncertainty is $\approx \pm 2.7\%$. In addition to the traverse uncertainty, a fixed bias error in position of approximately one-half of the probe volume diameter and length exists.

2.1.2.2 Tunnel monitoring

The tunnel conditions were monitored throughout testing, which included measurements of the water temperature, tunnel pressure (total and static) and the water tunnel impeller rotational frequency. All of these signals were sampled at 1 kHz. The tunnel temperature measurement was used to estimate the water properties including density and viscosity. The total pressure was measured with a Kiel probe mounted upstream of the test section contraction. The tunnel diameter at the Kiel probe location was 0.914 m. In this section a single static pressure measurement was also acquired. From these, a crude estimate was obtained for the total volumetric flow rate into the test section. Additional flush-mounted static pressure ports were located along the length of the test section (50, 121, 225, 329, 434, 538 and 642 mm downstream of the test section inlet). The ports were located circumferentially 45 degrees from the axis of the cylinder. The difference between the total and static pressure measurements was used to provide a real-time measure of the local free-stream velocity. The total and static pressure measurements were acquired with pressure transducers (dxd-series, Heise). All the tunnel monitoring measurements were recorded with a standard computer with a commercial data acquisition software package (LabView, National Instruments).

The water temperature was recorded in degrees Fahrenheit ($^{\circ}\text{F}$), which was then converted to degrees Celsius ($^{\circ}\text{C}$) with the standard relationship $^{\circ}\text{C} = (^{\circ}\text{F} - 32) \cdot (5/9)$. The acquired temperature was then used within the data acquisition system to determine the density, kinematic viscosity and vapor pressure of the water. The density was outputted in units of slugs per cubic feet, which was converted

to kilograms per cubic meter by multiplying by 515.24 (1 slug = 14.59 kg; 1 ft = 12 in; 1 in = 0.0254 m). Similarly the kinematic viscosity was converted from square feet per second to square meters per second using the conversions: 1 foot = 12 inches; 1 inch = 0.0254 m.

To minimize error associated with zero velocity offset between individual pressure transducers, the recorded pressure was determined from the output voltage minus the sensor voltage recorded under no-flow conditions. Thus, at the start of every test a measurement of the tunnel pressure was acquired prior to starting the tunnel. The data acquisition system recorded the pressure in units of pounds per square inch (psi), which was converted to Pascals (Pa) using the conversion

$$1 \text{ psi} = 6,894.76 \text{ Pa.}$$

The total pressure measurement was then combined with the local static pressure measurements to determine the local tunnel velocity. This was accomplished by applying the Bernoulli equation between the two measurements, which gives the following relationship

$$U(X) = \sqrt{\frac{2(P_{total} - P_{static}(X))}{\rho}}.$$

Here U is the local free-stream velocity at X where the static pressure measurement (P_{static}) was acquired, P_{total} is the total pressure and ρ is the water density. It should be noted that all the pressure measurements were acquired at the same height (the height is dependent on the location of the transducers, not the pressure ports), which is the reason elevation is omitted from the above equation.

2.1.3 Test matrix

During Part 1 of testing the only flow parameter varied was the tunnel impeller rotational frequency, which was varied from 53 to 300 rpm. This has a corresponding nominal tunnel velocity of 2.5 to 15 m/s. Measurements were acquired with the LDV system spanning $165 \text{ mm} \leq X \leq 580 \text{ mm}$, - $152 \text{ mm} \leq Y \leq 152 \text{ mm}$ and $85 \text{ mm} \leq Z \leq 199 \text{ mm}$. The entire measurement suite (static and total

pressure, water temperature and LDV) were acquired throughout testing, though since LDV is a point measurement only a single location was measured at any given time.

2.2 Tunnel bulk velocity

Instead of using individual velocity measurements at multiple locations within the test section flow, an average tunnel velocity was determined.

2.2.1 Reference velocity

The section describes the reference velocity's dependence on impeller frequency and streamwise location.

2.2.1.1 Tunnel frequency dependence

Throughout testing the average of three static pressure ports located at $X = 225, 329$ and 538 mm downstream of the test section inlet were used as the reference tunnel velocity (V_{ref}). These transducers were chosen because they span the downstream location where the fin would eventually be installed. Figure 2 shows the velocity determined from each static pressure measurement as a function of the tunnel impeller frequency. This shows that there is minimal scatter between individual velocity measurements and the reference velocity is linearly related to the tunnel impeller frequency (f_{imp}) over the range tested. Note that during forced fin testing the velocity was below 4 m/s, but data was acquired over a wider range at this point because the final test velocity was uncertain. The data was linear curve fit, which resulted in

$$V_{ref} = 0.0504 f_{imp} - 0.1636 .$$

Below a tunnel impeller frequency of ~ 80 rpm the tunnel had to be operated in “manual mode”, which requires an operator to regularly update the speed controller to maintain the tunnel at the desired impeller frequency. As a consequence, if the operator was not paying careful attention to the tunnel

impeller frequency the tunnel velocity could deviate significantly. Even with careful attention to the tunnel impeller frequency, speeds below ~53 rpm could not be steadily maintained independent of the operator's effort.

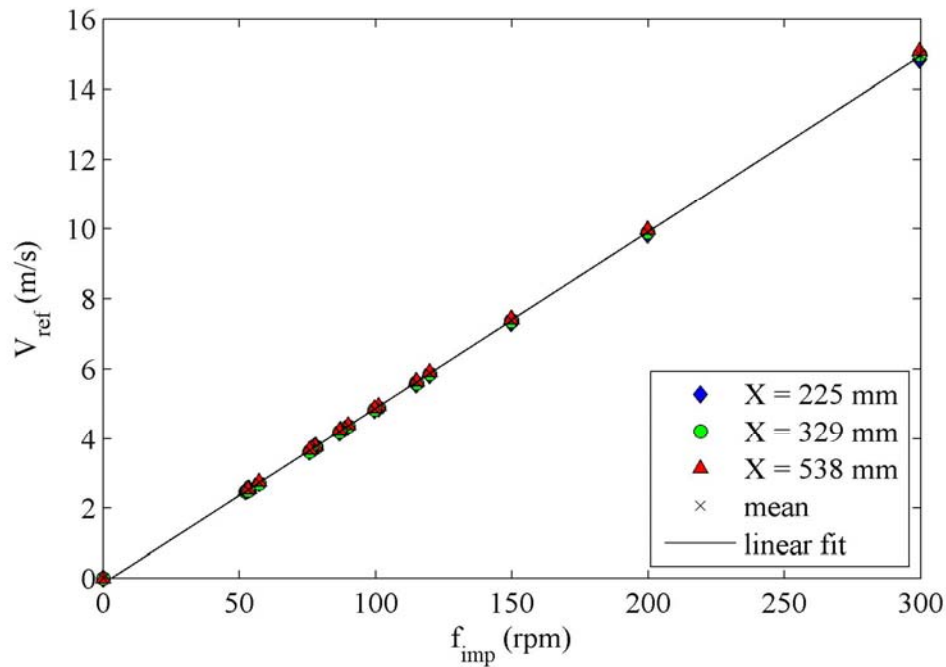


Figure 2. Free-stream velocity determined from static pressure measurements at $X = 225, 329$ and 538 mm plotted versus the tunnel impeller frequency (f_{imp}). The mean of these three measurement defines the reference velocity (V_{ref}) used throughout the experiment. Also included is the linear fit to the acquired data ($V_{ref} = 0.0504 f_{imp} - 0.1636$).

2.2.1.2 Streamwise dependence

The relative velocity, $(V(X) - V_{ref})/V_{ref}$, was then plotted versus the downstream distance in Figure 3 to quantify the streamwise variation in free-stream velocity. Here a significant change was observed upstream and downstream of the region used to determine the reference velocity. In particular the velocity upstream was at least 5% above V_{ref} , and downstream the velocity was approximately 5% above V_{ref} . Upon inspection this was attributed to a blockage effect. The large deviations nominally correspond to the locations of the windows, which were machined flat for optical access, thereby reducing the cross-sectional area of the test section. This results in a local increase in the tunnel diameter in the region of the optical windows. Estimates of the velocity change associated

with the given local area change results in the flow upstream and downstream of the windows being approximately 4% higher than V_{ref} . This is consistent with the results and matches within the accuracy of the measurements.

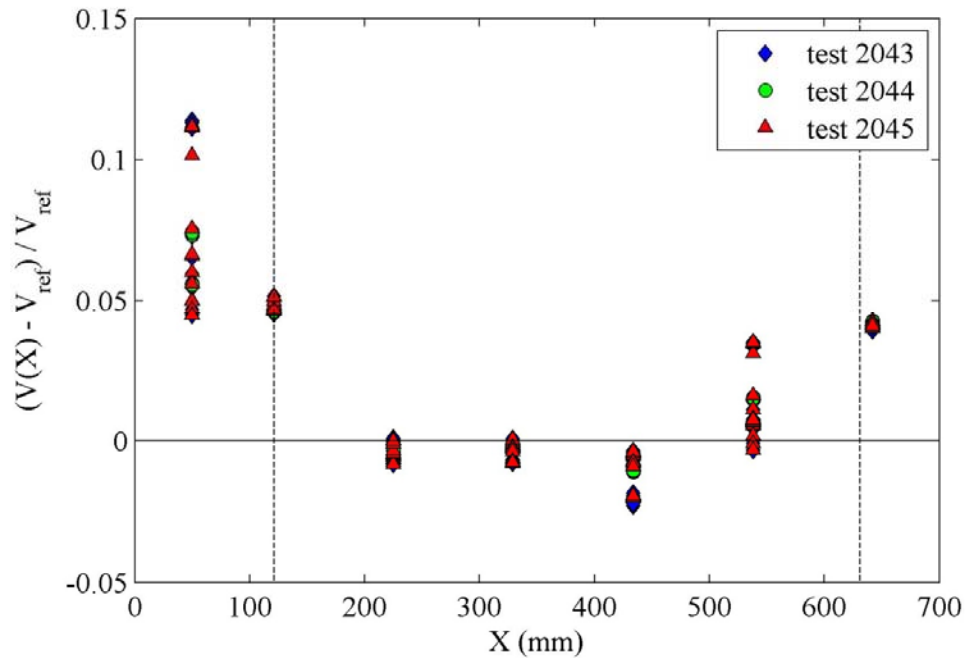


Figure 3. The relative velocity as a function of downstream distance from the test section inlet. The dashed lines nominally correspond to the beginning and end of the tunnel windows, which are contoured to be flat resulting in a local change in the tunnel area.

2.2.1 Centerline Velocity (LDV)

Figure 4 compares velocity measurements determined from the static pressure measurements with those from the LDV system. The velocity is shown for a range of tunnel impeller frequencies and plotted versus the downstream distance from the test section inlet (X). The data shows reasonable agreement between the two measurement methods. This plot also shows that there was minimal increase in the streamwise velocity with increasing downstream distance. Typically an empty test section will show an increase in velocity with downstream distance due to boundary layer growth on the tunnel walls, which effectively reduces the test section diameter. However, the ARL 12-inch water

tunnel is designed with a slightly increasing diameter with downstream distance to accommodate the boundary layer growth and maintain a nearly constant free-stream velocity.

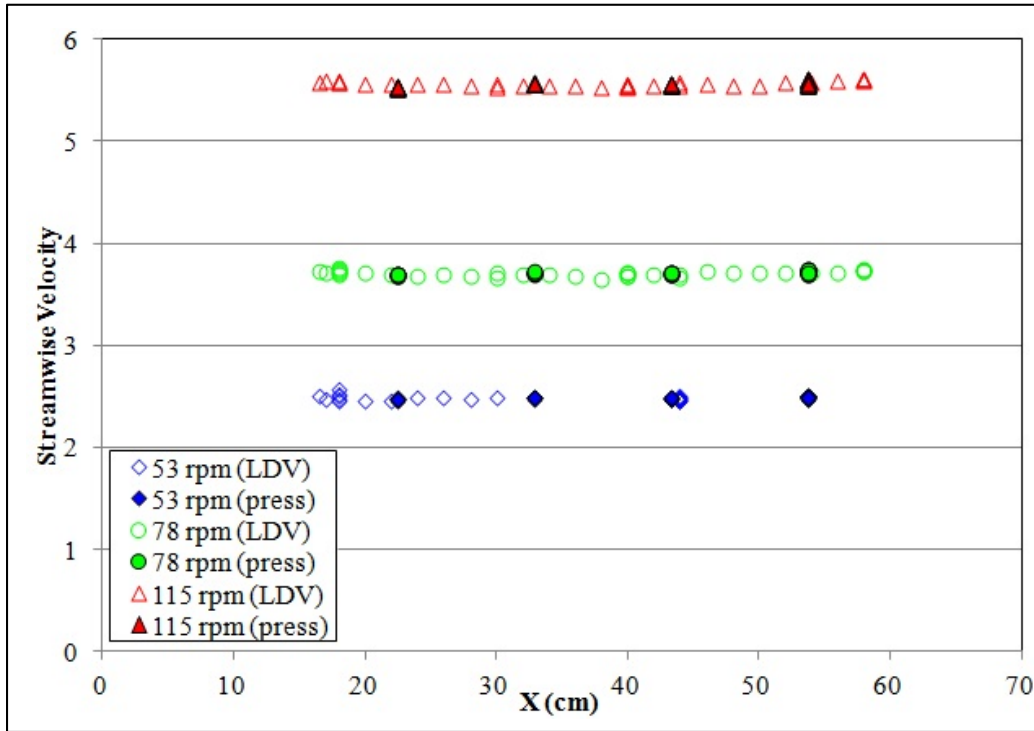


Figure 4. Streamwise velocity component (U) plotted versus the downstream distance from the test section inlet. The data was determined from LDV (open symbols) and static pressure measurements (solid symbols). Three separate test conditions are shown ($f_{imp} = 53, 78$ and 115 rpm), though a subset of data were acquired at other test speeds.

The above plot shows the general trend, but it is important to establish the difference between the tunnel centerline velocity (measured with LDV) and the reference velocity (measured with static pressure). The two measurements are close given the above plot. However, Figure 5 makes a more detailed comparison by plotting the centerline velocity (U_c) scaled with the reference velocity (V_{ref}) versus the downstream distance from the test section inlet. There is reasonable agreement between the two measurements as the results are nearly constant at a value approaching unity. Specifically the LDV measurements are biased on average 1.8% below V_{ref} with a scatter (twice the standard deviation) of 1.3%. Thus the variation in the LDV centerline velocity throughout the entire measurement section of

the test section relative to the reference velocity is 2.2%. Note that this value is lower than that observed with just comparing the static pressure measurement, because the LDV requires optical access. There was no optical access where the large deviations were observed so no LDV measurements were acquired in this region. It should also be noted that the low centerline velocity bias is not surprising when compared to the downstream dependence on the static pressure results, because one of the measurements used to determine V_{ref} appears to be outside the flat region corresponding to the optical access windows.

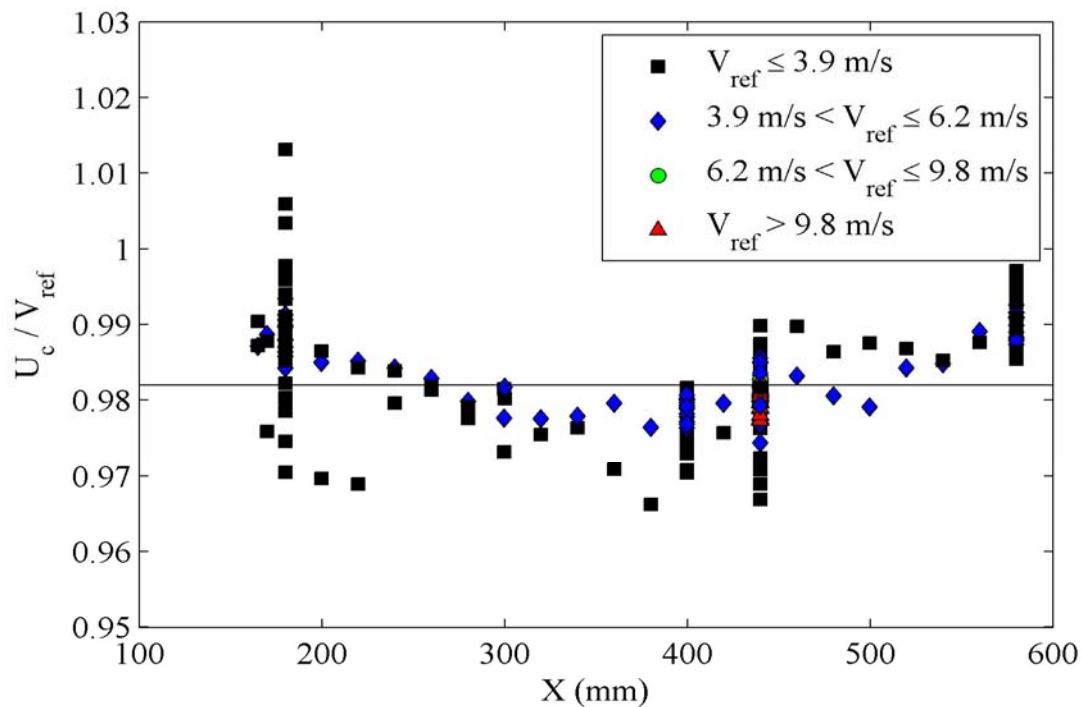


Figure 5. The centerline ($Y = 0$ mm and $Z = 140$ mm) velocity (U_c) measured with LDV scaled with the reference velocity (V_{ref}) plotted versus downstream distance from the test section inlet. The solid line corresponds to mean value from all the measurements, which is 0.982. The majority of the measurements were acquired below 4 m/s because it was assumed that forced fin testing would require lower speeds.

2.3 Tunnel velocity profiles

Although the setup is very canonical with an empty test section velocity, profiles were measured across the test section with laser Doppler velocimetry. These data will provide boundary conditions for FSI calculations for later configurations (i.e. Part 2a, Part 2b and Part 4).

2.3.1 Traverse profiles

The LDV system was traversed across the tunnel width at three streamwise positions ($X = 180, 400$ and 580 mm). At each of these positions profiles spanning the entire width (Y-direction) of the tunnel were acquired at tunnel frequencies spanning from 53 to 115 rpm ($2.5 \text{ m/s} \leq V_{\text{ref}} \leq 7.4 \text{ m/s}$). The streamwise velocity component of these profiles was scaled with the centerline velocity (U_c) and plotted in Figure 6. These profiles show that the velocity profile is relatively flat across the width of the tunnel except near the tunnel walls where a developing boundary layer is present. It is also apparent from the profiles that the region influenced by the boundary layer increases with increasing downstream distance (i.e. the boundary layer thickness is increasing with downstream distance). Profiles were also acquired in the Z-direction, but optical access limited the measurements to ± 75 mm from the tunnel center. As expected based on the Y-direction profiles, these profiles are nearly constant.

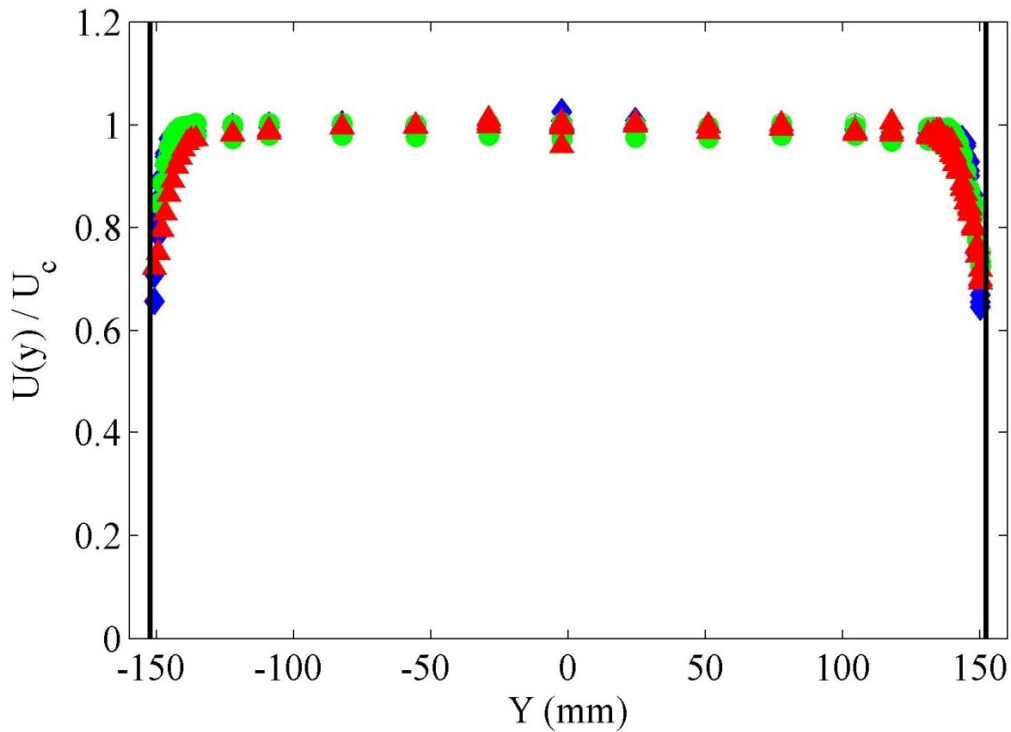


Figure 6. Streamwise velocity profiles scaled with the centerline velocity (U_c) and plotted versus Y -position. Data was acquired at tunnel impeller frequencies of 53, 57, 78 and 115 rpm, and at (blue) $X = 180$ mm, (green) $X = 400$ mm and (red) $X = 580$ mm. The solid lines are provided to show the tunnel wall locations ($Y = \pm 152.4$ mm). These profiles were acquired at the mid height of the tunnel ($Z = 140$ mm).

2.3.2 Tunnel wall boundary layers

It is important to characterize the boundary layer growth on the tunnel walls as it establishes boundary conditions for the FSI simulations. The boundary layer thickness (δ) was defined as the distance from the wall that the streamwise velocity component achieves 99% of the local free-stream velocity (U_∞), which from Figure 6 it is apparent that this nominally equals the tunnel centerline velocity (U_c). The thickness was determined on both tunnel walls ($Y = \pm 152.4$ mm) at three streamwise positions ($X = 180, 400$ and 580 mm) over a range of tunnel speeds. Figure 7 shows the resulting boundary layer thicknesses scaled with the downstream distance from the tunnel inlet (X) and plotted versus the downstream distance based Reynolds number ($Re_X = U_\infty X / \nu$). These values are also provided in Table 1. Included for comparison is the curve provided in White (2006) for a turbulent boundary layer on a zero-pressure-gradient flat plate. While the current data does not match this curve

in magnitude, a similar trend is observed. The discrepancy is expected as the current data has no well-defined leading edge, transitions from a curved to flat surface (as observed in the streamwise dependency of the centerline velocity) and has a slight adverse pressure gradient to minimize the influence of boundary layer growth on the free-stream velocity.

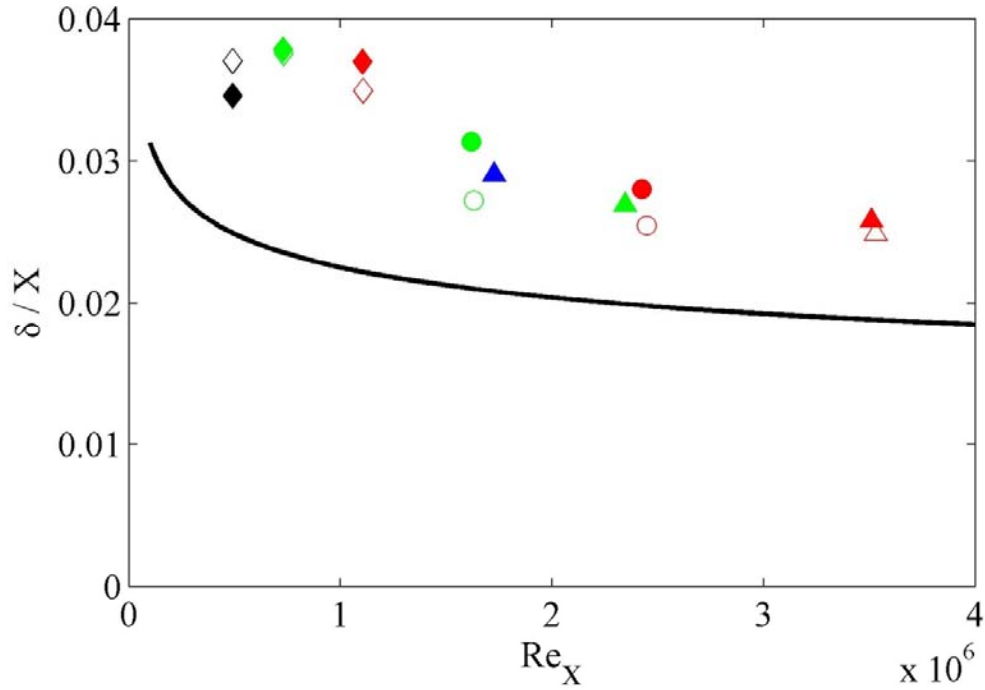


Figure 7. The measured 99% boundary layer thickness (δ) scaled with the downstream distance from the tunnel inlet (X) is plotted versus the downstream distance based Reynolds number ($Re_X = U_\infty X/\nu$). Data was acquired at $X = (\diamond) 180$, $(o) 400$ and $(\Delta) 580$ mm at a tunnel impeller frequency of (black) 53, (blue) 57, (green) 78 or (red) 115 rpm. Solid symbols were acquired on the +Y tunnel wall, and the open symbols were acquired on the -Y tunnel wall. The solid curve is from White (2006) for a zero-pressure-gradient, flat plate turbulent boundary and provided here for reference.

Table 1. Tabulated 99% boundary layer thickness (δ) measurements on the tunnel walls, where δ_1 corresponds to the boundary layer forming on the $-Y$ tunnel wall and δ_2 is the boundary layer forming on the $+Y$ tunnel wall. These measurements were acquired with the LDV system and the test section empty.

X (mm)	U_∞ (m s^{-1})	Re_X $\times 10^6$	δ_1 (mm)	δ_2 (mm)
180	2.42	0.49	6.7	6.2
180	3.59	0.73	6.8	6.8
180	5.44	1.1	6.3	6.7
400	3.66	1.6	10.9	12.5
400	5.49	2.4	10.2	11.2
580	2.67	1.7	---	16.8
580	3.64	2.3	---	15.6
580	5.46	3.5	14.4	15.0

The measured boundary layer thicknesses (δ) were then used to scale the streamwise velocity profiles in Figure 8. Here the streamwise velocity was normalized with the local free-stream velocity (U_∞) and plotted versus the wall-normal distance from the given tunnel wall (y_n), which was scaled with the boundary layer thickness. Using this traditional method for scaling the boundary layer data, the data acquired over a range of downstream distances and tunnel velocities collapse on top of each other. This shows that both boundary layers are developing in a similar fashion, and they are both fully developed. Furthermore, the profiles are in excellent agreement with the traditional $1/7^{\text{th}}$ velocity profile ($U/U_\infty = (y_n/\delta)^{1/7}$), which is included in the plot for comparison.

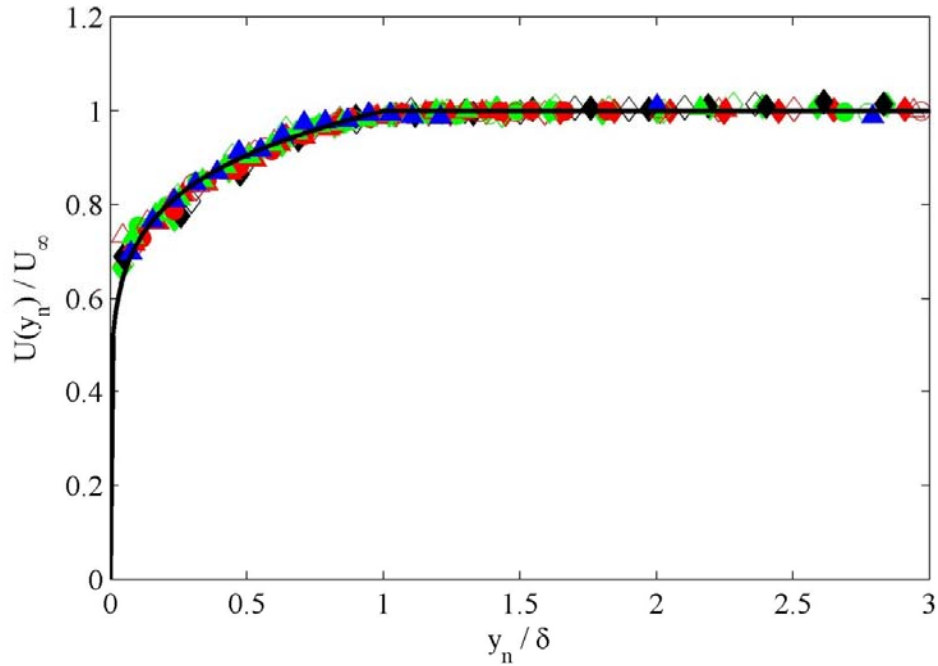


Figure 8. The streamwise velocity profiles with the developing tunnel wall boundary layers scaled with the local free-stream velocity (U_∞) plotted versus the wall-normal distance (y_n) scaled with the boundary layer thickness (δ). Open symbols correspond to data on the tunnel wall located at $Y = +152.4$ mm, and closed symbols correspond to data acquired at the tunnel wall located at $Y = -152.4$ mm. The data was acquired at $X = (\diamond) 180$, $(o) 400$ and $(\Delta) 580$ mm at a tunnel impeller frequency of (black) 53, (blue) 57, (green) 78 or (red) 115 rpm. These profiles were acquired at the mid height of the tunnel ($Z = 140$ mm). The solid curve corresponds to the traditional $1/7^{\text{th}}$ velocity profile ($U/U_\infty = (y_n/\delta)^{1/7}$) for $y_n \leq \delta$.

2.4 Free-stream turbulence levels

Figure 9 shows the fluctuating streamwise (u') and fluctuating vertical (w') velocity components scaled with the reference velocity (V_{ref}) plotted versus the either X , Y or Z directions. Excluding data within the boundary layer, the average streamwise and vertical fluctuating velocity values are 1.29% and 0.59% of the reference velocity. These values are noted in each plot with the solid red line. Due to a lack of dependence on the velocity and downstream distance, these results suggest that the measured value is the noise floor of the LDV system and the true turbulence levels are lower. This conclusion is further supported by the free-stream turbulence measurement range being close to the estimated measurement accuracy of the LDV system and historical data acquired in the current facility that showed the empty test section turbulence level was $\leq 0.3\%$.

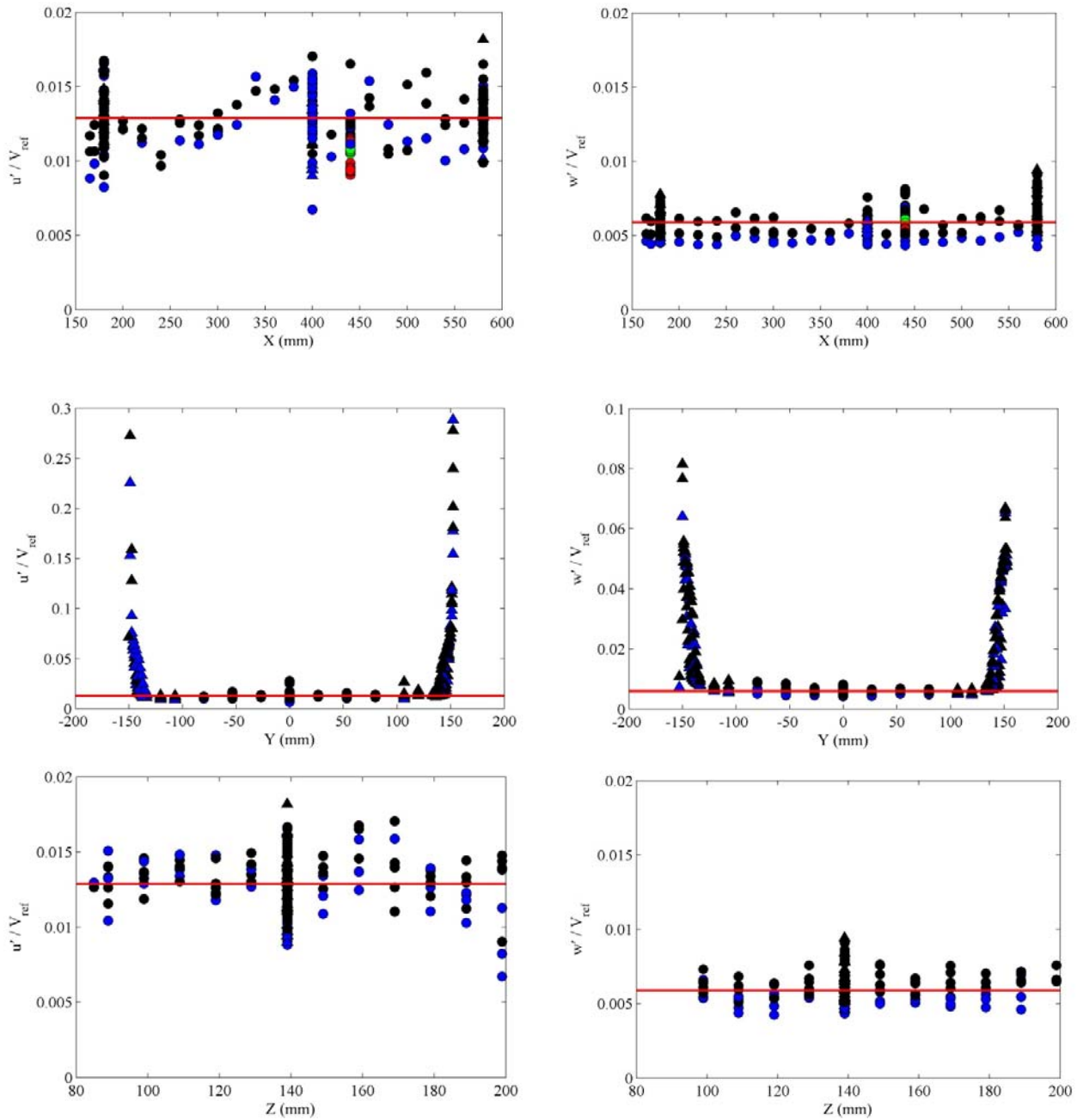


Figure 9. Fluctuating velocity profiles (left – X-velocity component; right – Z-velocity component) scaled with the reference velocity plotted versus (top) X-direction, (middle) Y-direction and (bottom) Z-direction. The red line in each plot corresponds to the average value of the given velocity component (u' or w') excluding the data points within the boundary layer. Also the data points within the boundary layer are only shown in the Y-profiles for clarity. The symbol colors correspond to the reference velocity as shown in Figure 5.

3 Part 2a – Smooth Cylinder Only

The first configuration considered is the canonical flow from a smooth cylinder located upstream of the test section.

3.1 *Experimental methods*

This section describes details of the test facility, cylinder geometry, instrumentation and test matrix.

3.1.1 Test facility

Laser Doppler velocimetry (LDV) measurements during Part 1 showed that the free-stream turbulence within the test section of the 12-inch water tunnel was below ~1% (the minimal measureable range of the LDV system). Historical data acquired in this facility indicates that the empty test section free-stream turbulence level is below 0.3%. The LDV measurements were acquired along the test section centerline at tunnel velocities spanning the range tested in Part 1. These measurements confirmed that there was minimal variation in the test section centerline velocity for a given tunnel impeller frequency. The same 12-inch tunnel setup from Part 1 was used for Part 2a testing, except that a smooth cylinder was added at an upstream location in the test section.

3.1.2 Test model (smooth cylinder)

The test model for Part 2a is a 60 mm diameter, hydraulically smooth cylinder spanning the entire diameter of the test section. Though the test section was rotated 90° for Part 2a to facilitate LDV measurements of the cross-stream (Y -direction) velocity component, the same global coordinate system used throughout the experiment is employed. Figure 10 shows a sketch of the test section layout with the cylinder. The mechanical drawings for the cylinder and test section assembly are provided in Appendix A. The global coordinate system used throughout the entire experiment has X increasing in

the streamwise direction with the origin at the test section inlet, Z is aligned with the cylinder and increasing into the flow with the origin located at the fin base, and Y completing the right-handed coordinate system with its origin located at the test section centerline. The test section inlet position was selected as the origin because the water tunnel forward flange face (shown in Figure 10) provides a consistent reference position to use throughout the entire experiment. Thus the center of the cylinder is located at $X = 49$ mm, which coincides with the first test section static pressure measurement. The cylinder was instrumented with four dynamic pressure transducers, two static pressure ports and a single accelerometer mounted inside the cylinder, oriented to measure vibrations in the cross-flow or Y -direction.

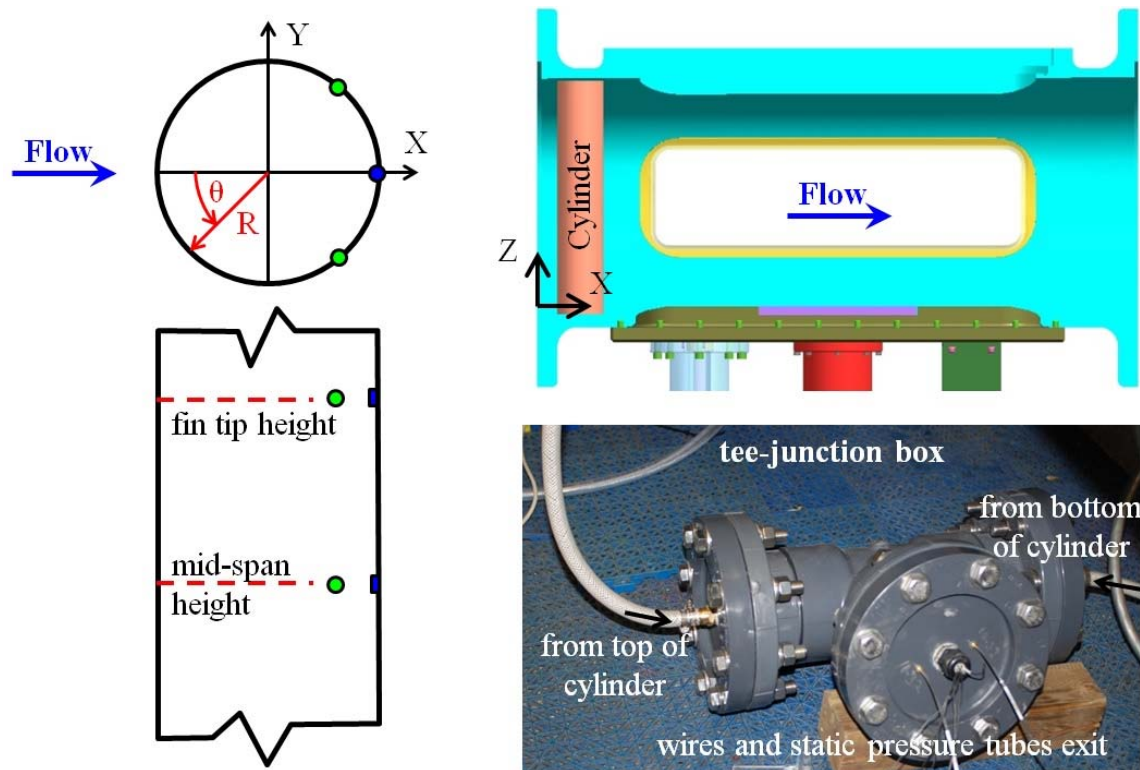


Figure 10. (left) Schematic of the instrumentation layout within the cylinder. The green dots indicate locations of the dynamic pressure transducers, which are located at $\theta = \pm 130^\circ$ at the fin (not shown) tip height ($Z = 230$ mm) and the mid-span height ($Z = 115$ mm). The blue dots indicate the locations of the static pressure ports, which are at the same heights and $\theta = 180^\circ$. (upper right) Schematic of the test section during the cylinder only (Part 2) testing. The global coordinate system used throughout the experiment is also shown. (lower right) A picture of the tee-junction box used to bring the pressure transducer wires, accelerometer wire and static pressure tubes to the exterior of the tunnel.

3.1.3 Instrumentation

This section describes the cylinder transducers, LDV and PIV measurement systems and tunnel monitoring instrumentation.

3.1.3.1 *Cylinder instrumentation (accelerometer, dynamic pressure and static pressure)*

The accelerometer (303M231 – SN24870) was mounted inside of the cylinder to quantify the rigidity and vibration of the cylinder mounted in the test section as well as a triggering source for the particle image velocimetry (PIV) measurements. Four dynamic pressure transducers (105C02, PCB) were mounted in the cylinder. Two were positioned at the height corresponding to the fin (not shown in Figure 10) tip ($Z = 230$ mm) and two at the height corresponding to the mid-span of the fin ($Z = 115$ mm). As shown in Figure 10, the dynamic pressure sensors were positioned at $\pm 50^\circ$ from the trailing edge of the cylinder ($\theta = \pm 130^\circ$). These sensors were used to measure the shedding frequency from the cylinder as well as to estimate the lift force induced on the cylinder, which was used for planning purposes for the forced fin (Part 4) experiment. Two static pressure ports were also mounted in the cylinder. Similar to the dynamic pressure transducers, the static pressure ports were positioned at the fin tip height ($Z = 230$ mm) and fin mid-span height ($Z = 115$ mm). However, the azimuthal position was at the cylinder trailing edge ($\theta = 180^\circ$). The ports were plumbed to small tubing that was taken out of the tunnel with the use of a tee-junction box, which was also used to get the wires for the accelerometer and dynamic pressure transducers out of the tunnel. Each of the static pressure lines were then plumbed to a pressure transducer (dxd-series, Heise). The dynamic pressure transducers were powered with integrated circuit piezoelectric (ICP) power supplied internally through the data acquisition system. The accelerometer was powered with an external ICP sensor signal conditioner (480B21, PCB Piezotronics). The outputted signals from both the dynamic pressure transducers and the accelerometer were then recorded with a dynamic acquisition card (cDAQ-9178, National Instruments) and recorded with commercial acquisition software (LabView, National Instrumentation).

The static pressure signals were recorded within the same acquisition program, but through a separate acquisition card (USB-6259, National Instruments).

3.1.3.2 Flow-field measurements (LDV and standard PIV)

Direct measurements of the flow-field were acquired with either LDV or PIV. LDV is a point measurement that provides two components of velocity at rates in excess of 1 kHz. Conversely, PIV provides two-components of velocity in a two-dimensional plane, but data can only be acquired at rates of ~ 10 Hz. Thus LDV provides increased temporal resolution at the expense of spatial resolution, while PIV provides increased spatial resolution at the expense of temporal resolution. The LDV system is described in greater detail in the Part 1 – Instrumentation section, but the basic details are provided here for completeness. An argon ion laser (Innova 70C-5, Coherent) was used to produce a pair of blue and a pair of green laser beams, which coupled to a fiber optic probe head (9832, TSI). The probe head was fitted with a 350 mm lens (9253-350, TSI), which focused the four beams into a single measurement volume. The nominal probe size was estimated as having a diameter of 150 μm and a length of 1.5 mm. Traditional LDV measurement techniques were used to process the scatter light to determine the particle velocity. Each position typically acquired 20,000 velocity measurements before moving to the next point of interest with the use of a 3-axis linear traversing table.

The LDV uncertainty is estimated using established methods for calculating uncertainty. The total uncertainty includes calibration uncertainty, uncertainties associated with bias error corrections and statistical uncertainty. Estimated uncertainties in the mean are $\approx \pm 2.2$ %. The reported RMS uncertainty is $\approx \pm 2.7$ %. In addition to the traverse uncertainty, a fixed bias error in position of approximately one-half of the probe volume diameter and length exists.

The 2D (X- and Y-velocity components) PIV measurements were acquired in the double-frame, double-pulse mode in one of two planes ($Z = 115$ or 188 mm). The PIV system was mounted on the test section, thus minimizing any possible relative motion between the imaging system and the flow-

field. The PIV plane was illuminated with a light sheet that entered the flow through the optical window on the +Y side of the test section and was aligned in the streamwise direction. The beam of a pulsed Nd:YAG laser (Gemini PIV, New Wave Research) operating at 532 nm wavelength was used to form the light sheet. The beam was formed into the light sheet with the use of a cylindrical lens attached directly to the laser. It was anticipated that the maximum shedding frequency would be 15 Hz at freestream velocities, sufficient to excite the fin. Given the Nyquist criterion for sampling twice this frequency, the maximum laser repetition rate of 15 Hz was insufficient for time-resolved measurements, which required a minimum data rate of 200 Hz in the current study. Consequently the standard PIV measurements were used to produce phase-averaged flow-field measurements. This was accomplished using the cylinder-mounted accelerometer as a triggering source, which was preferred over the dynamic pressure transducers because the rigidity of the cylinder served as a low pass filter. The accelerometer signal was first sent to a low-noise preamplifier (SR560, Stanford Research Systems) for additional band-pass filtering. Then the signal was amplified (483A08, Piezotronics) before being sent to a delay generator (565, BNC). The delay generator used the signal to output a transistor-transistor-logic (TTL) signal based on the level and slope of the filtered and amplified accelerometer signal. The TTL signal was then sent to the PIV system and used as a reference time. The delay relative to the reference time determined the phase of the given measurement and was controlled in the PIV acquisition software (DaVis 8, LaVision). The filtered and amplified accelerometer signal was also sent to a multimeter (111 True RMS multimeter, Fluke), which provided a real-time estimate of the shedding frequency. This estimated shedding frequency was used during acquisition to determine the phase step size and total number of steps to acquire. These values and ranges for all the PIV measurements are provided in Table 2.

The light from the illuminated plane was scattered with the use of hollow glass sphere particles (iM30K Glass Microspheres, 3M), which have a nominal diameter of 18 μm . The scattered light was then imaged with a 1600 $\times$ 1200 pixel charge-coupled device (CCD) color camera (PCO1600, Cooke

Corp.) fitted with a 28 mm lens (AF Nikkor, Nikon) with an f-stop set at (plane 1) 5.6 and (plane 2) 16. The resulting nominal field of view (FOV) spanned $275 \text{ mm} \leq X \leq 435 \text{ mm}$ and $-59 \text{ mm} \leq Y \leq 65 \text{ mm}$. The images were spatially calibrated by imaging a three-dimensional calibration target aligned with the laser sheet. The target consisted of a $180 \times 180 \text{ mm}$ rectangular grid of dots spaced 10 mm apart and located in one of two planes spaced 1 mm apart. Only dots in one of the planes were used to calibrate the PIV images. For each test condition (tunnel velocity and phase position), 500 image pairs were acquired. These image pairs were then processed in the same commercial PIV software used to acquire the images (DaVis 8, LaVision). The processing applied the image calibration and computed the velocity vector field. The vectors were computed using standard cross-correlation methods with multiple passes. Each pass reduced the interrogation window, and the final interrogation window was 32×32 pixels with 50% overlap, which produces 1.44 mm vector spacing. The estimated PIV uncertainty, including calibration uncertainty and statistical uncertainty is approximately $\pm 2 \%$ of the mean value.

Table 2. Test condition, locations and phase averaging information for the standard PIV measurements acquired with the smooth cylinder. The “time delay range” is the span of time delays after the reference time, and the “delay increment” is the step size used to span the given range. The time delay of 0 ms had minor timing errors, which is the reason that subsequent measurements started with a minimum delay greater than 0 ms.

f_{imp} (rpm)	V_{ref} (m/s)	Time Delay Range	Delay Increment
Plane 1 ($Z = 11.5 \text{ cm}$)			
67	2.8	5 to 115 ms	5 ms
84	3.6	3 to 120 ms	3 ms
90	3.9	3 to 90 ms	3 ms
Plane 2 ($Z = 18.8 \text{ cm}$)			
67	2.8	0 to 150 ms	10 ms
82	3.5	0 to 120 ms	8 ms
89	3.9	3 to 87 ms	3 ms

3.1.3.3 Tunnel monitoring

The tunnel was regularly monitored during testing and the tunnel data were simultaneously acquired along with the cylinder monitoring data. Tunnel monitoring measurements included water temperature, total pressure, static pressure and impeller frequency. The tunnel temperature measurement was used to determine the water properties including density, viscosity and vapor pressure. The total pressure was measured with a Kiel probe mounted upstream of the test section contraction. The tunnel diameter at the position where the total pressure was measured was 0.914 m (36 in). In this section a single static pressure measurement was also acquired, which provided a measure of the total volumetric flow rate. This could be used to prescribe an equivalent inlet velocity to the cylinder (this velocity could not be directly measured due to the lack of optical access in this region of the tunnel). Additional static pressure ports were located along the length of the test section and used as real-time measurements of the tunnel velocity. Measurements were acquired at $X = 50, 121, 225, 329, 434, 538$ and 642 mm. The ports were located circumferentially 45 degrees from the axis of the cylinder. These measurements are subsequently compared with flow-field measurements. The total and static pressure measurements were acquired with the same pressure transducers (dxd-series, Heise) used for the cylinder static pressure measurements.

Similar to Part 1, the recorded pressure was determined from the difference between the output voltage and the no-flow voltage to minimize errors associated with zero velocity offsets between individual pressure transducers. Thus, at the start of every test a measurement of the tunnel pressure was acquired prior to starting the tunnel. The data acquisition system recorded the pressure in units of pounds per square inch (psi), which was converted to Pascals (Pa) using the conversion ($1 \text{ psi} = 6,894.76 \text{ Pa}$). The total pressure measurement was then combined with the local static pressure measurements to determine the local tunnel velocity using the relationship

$$U(X) = \sqrt{\frac{2(P_{total} - P_{static})}{\rho}}.$$

Here U is the local free-stream velocity at X where the static pressure measurement (P_{static}) was acquired, P_{total} is the total pressure and ρ is the water density. The tunnel reference velocity (V_{ref}) was then determined from the average of the measurements from $X = 225, 329$ and 538 mm.

3.1.4 Test matrix

During Part 2a of testing the tunnel water temperature ranged between 21.9 and 26.5 °C, and had an average temperature of 22.9 °C. Given the average temperature, the corresponding water density (ρ) and kinematic viscosity (ν) were estimated to be 997 kg/m³ and 9.4×10^{-7} m²/s, respectively. The tunnel pressure was set at 140 kPa throughout testing. The tunnel impeller frequency was operated between 0 and 155 rpm, but the majority of measurements were acquired at $57, 67, 78, 81, 84, 90$ and 115 rpm. Subsequently, it is shown that these impeller frequencies correspond to test section reference velocities of $2.3, 2.8, 3.3, 3.5, 3.6, 3.9$ and 5.2 m/s, respectively. The tunnel and cylinder monitoring measurements were acquired for all test conditions, but the flow-field measurements were acquired for only a subset of conditions. LDV measurements were acquired at impeller frequencies from 55 to 115 rpm at positions spanning $X = 172$ to 561 mm, $Y = -45$ to 55 mm and $Z = 0$ to 291 mm. The primary locations for LDV measurements were $X = 180, 186, 421$ and 529 mm, $Y = 0$ mm and $Z = 46, 115$ (mid-span) and 149 cm. PIV measurements were acquired at two Z -planes ($Z = 115$ and 188 mm). The plane at $Z = 115$ mm corresponds to the mid-span of the fin, and $Z = 188$ mm was the closest position to the fin tip possible for PIV (optical access for the laser sheet limited the maximum location). The nominal FOV for both planes was $X = 283$ to 429 mm and $Y = \pm 50$ mm. The FOV was selected to capture the flow-field at the fin location at the mid-span and as close to the fin tip as possible. For reference, the 50%-chord position at mid-span is $X = 392$ mm and the 50%-chord position at the fin tip

is $X = 317$ mm. Noting that the chord length is 50 mm, the PIV FOV captures the minimum and maximum fin positions.

3.2 Tunnel Velocity

Instead of using individual velocity measurements at multiple locations within the test section flow, an average tunnel velocity was determined.

3.2.1 Reference velocity

The section describes the reference velocity's dependence on impeller frequency and streamwise location.

3.2.1.1 Tunnel impeller frequency dependence

Throughout testing the average of three static pressure ports located at $X = 225, 329$ and 538 mm downstream of the test section inlet were used to estimate the reference tunnel velocity (V_{ref}). These transducers were chosen because they span the downstream location where the fin would eventually be installed. Figure 11 shows the velocities determined from each of these static pressure measurements as a function of the tunnel impeller frequency. This shows that there was minimal scatter between individual velocity measurements and the reference velocity is linearly related to the tunnel impeller frequency over the range tested. Note that during forced fin testing (Part 4) the velocity was below 4 m/s, but data was acquired over a wider range at this point because the final test velocity was not known. The linear fit to the reference velocity data acquired in Part 2a is

$$V_{ref} = m_{2A} f_{imp} + b_{2A},$$

$$m_{2A} = 0.0497 \text{ m/s/rev/min}$$

$$b_{2A} = -0.5509 \text{ m/s}.$$

For reference the linear fit from Part 1 is also included in Figure 11, which shows that the slope is nearly unchanged from Part 1 though the intercept has been shifted downward. This indicates that the

addition of the cylinder creates a significant tunnel blockage, which results in larger system losses and the need to operate at a higher tunnel impeller frequency to achieve a desired velocity. It is also apparent that the data does not as accurately follow the linear fit as accurately as the Part 1 data and that there is an increase in the amount of scatter when compared to the results of Part 1. The apparent nonlinearity is also the product of the additional blockage losses which have a velocity dependence, and the scatter is due in part to the measurements being acquired in the region of an oscillating wake rather than a steady, uniform flow. Additionally, the drag coefficient for a cylinder varies with Reynolds number.

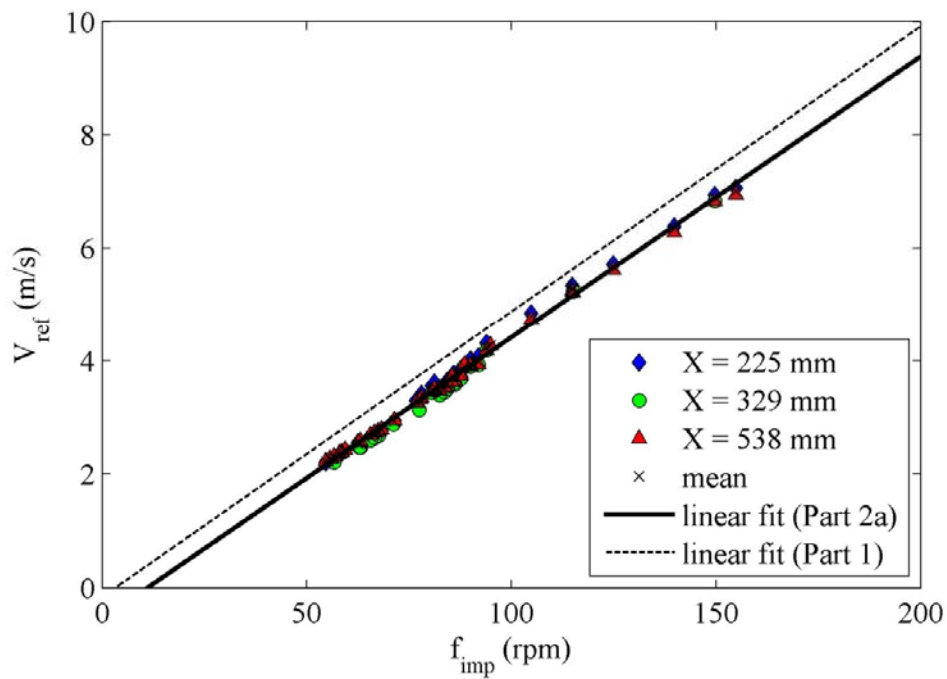


Figure 11. Tunnel free-stream velocity determined from static pressure measurements at $X = 225, 329$ and 538 mm plotted versus the tunnel impeller frequency (f_{imp}). The mean of these three measurement defines the ($\times$) reference velocity (V_{ref}) used throughout the experiment. Included are the linear fits to the Part 2a (smooth cylinder) data ($V_{ref} = 0.05 f_{imp} - 0.5716$) and the Part 1 (empty test section) data.

3.2.1.2 Streamwise dependence

Once again the relative velocity, $(V(X) - V_{ref})/V_{ref}$, is used to explore the streamwise variation in free-stream velocity determined from static pressure measurements. The relative velocity is plotted

versus the downstream distance scaled with the cylinder diameter ($D = 60$ mm) in Figure 12. Similar to Part 1 (Figure 3), an observed rise in velocity upstream and downstream of the region where the reference velocity was defined (i.e. region spanning the fin location). In Part 1 the increase in velocity was attributed to minor blockage effect created by the transition from the round test section to the flat optical windows. This effect will still be present, but the rise in Part 2a (smooth cylinder only) is greater than in Part 1 (empty test section). In Part 1 the elevated velocity upstream was between 5% and 10% of the reference velocity, but in Part 2a the elevation is about 15% above reference velocity. This is due to the presence of the cylinder in the inlet. The cylinder leading edge is located at $X = 19.5$ mm, and the trailing edge is located at $X = 79.5$ mm. Also as expected the relative rise in velocity downstream of the optical windows is comparable to that observed in Part 1, which is expected given that this section of the tunnel as not changed.

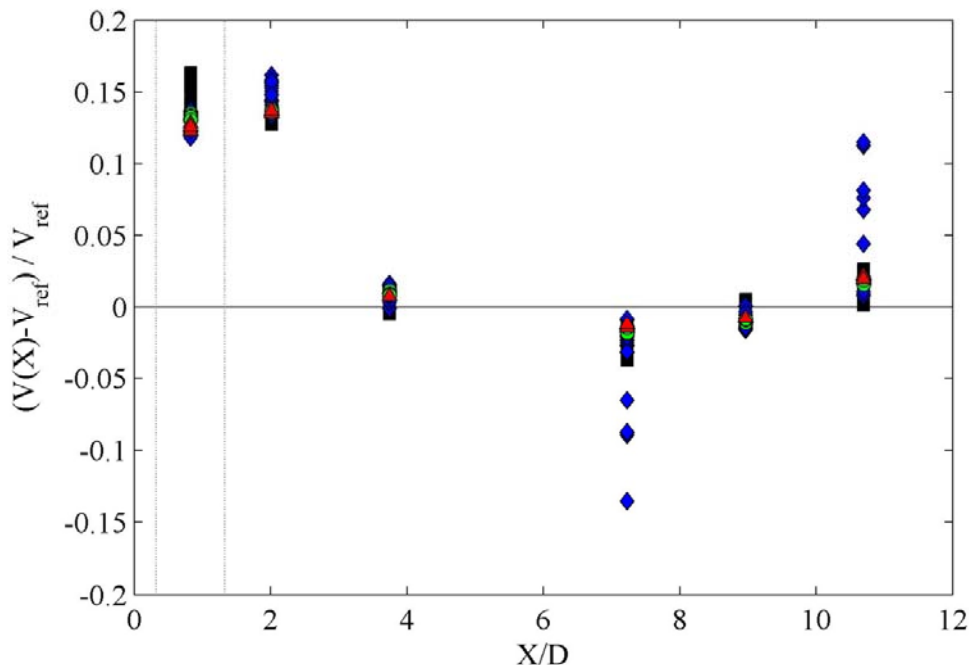


Figure 12. The relative velocity as a function of downstream distance from the test section inlet scaled with the cylinder diameter ($D = 60$ mm) for data acquired during Part 2a (smooth cylinder only). The dashed lines indicate the streamwise location of the leading and trailing edges of the cylinder. The symbol colors correspond to the tunnel reference velocity: (black) $V_{ref} < 2.9$ m/s, (blue) $2.9 \text{ m/s} \leq V_{ref} < 4.4$ m/s, (green) $4.4 \text{ m/s} \leq V_{ref} < 5.9$ m/s and (red) $V_{ref} \geq 5.9$ m/s.

3.2.2 Centerline velocity

The section describes the centerline velocity, defined as the fin mid-span height, and its dependence on impeller frequency and relationship to the reference velocity.

3.2.2.1 Tunnel impeller frequency dependence

Unlike the empty tunnel results, the centerline axial velocity measured with LDV is not expected to be nearly equivalent to the reference velocity. This is due to the fact that the centerline of the tunnel now corresponds to directly downstream of the cylinder. Furthermore, due to the cylinder wake the centerline velocity will also not be nearly constant through the test section. This is illustrated in Figure 13, which shows the average centerline velocity plotted versus the tunnel impeller frequency for various downstream positions. Note that the “centerline” velocity in Part 2a is actually located at $Z = 115$ mm (fin mid-span height) instead of the true tunnel center ($Z = 141$ mm). At a given tunnel impeller frequency there can be significant variation at a given downstream position, especially at the top speed tested (115 rpm).

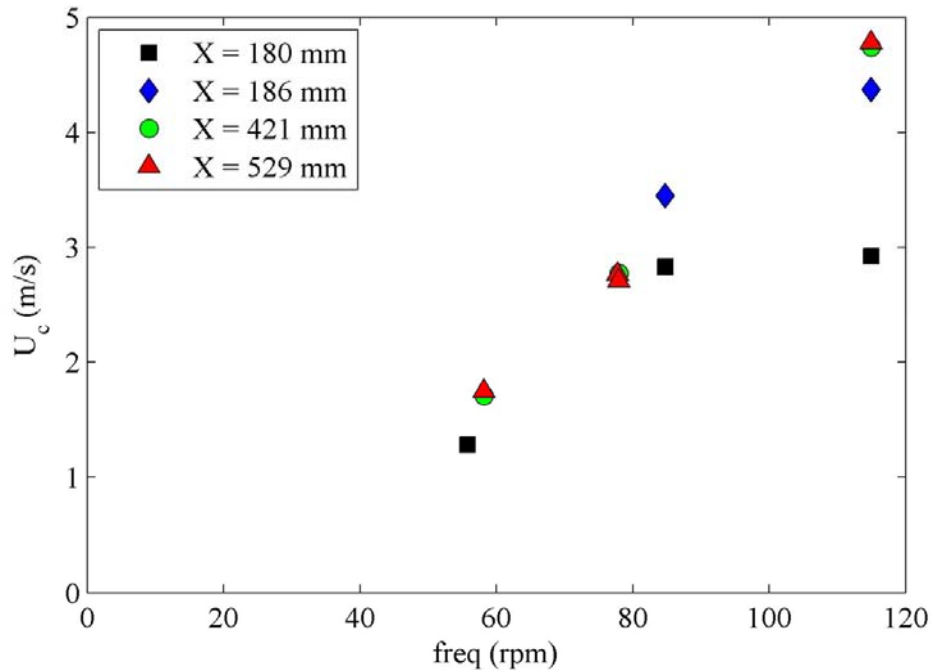


Figure 13. The average centerline velocity (U_c) measured with the LDV system plotted versus the tunnel impeller frequency, which was shown to be directly proportional to the reference velocity. Data from four separate downstream locations are shown, which illustrates the fact that the centerline velocity varies with downstream distance for Part 2a.

3.2.2.2 Comparison with the reference velocity

A more direct comparison between the centerline velocity and the reference velocity is provided in Figure 14, which shows the centerline velocity scaled with the reference velocity and plotted versus the tunnel impeller frequency. Here it is apparent that near the cylinder (i.e. $X = 180$ and 186 mm) the wake is not self-similar with the data scattered and a nonlinear trend. Note that the trailing edge of the cylinder is located at $X = 79.5$ mm and the cylinder diameter (D) is 60 mm, which makes those first measurements within two diameters downstream of the cylinder. Conversely, the far-wake measurements ($X = 421$ and 529 mm) correspond to 5.7 and 7.5 diameters downstream of the cylinder and exhibit self-similar behavior. Here we see that the scaling appears independent of downstream distance and the centerline velocity is approaching the reference velocity with increasing tunnel velocity. This wake deficit recovery will be further discussed subsequently.

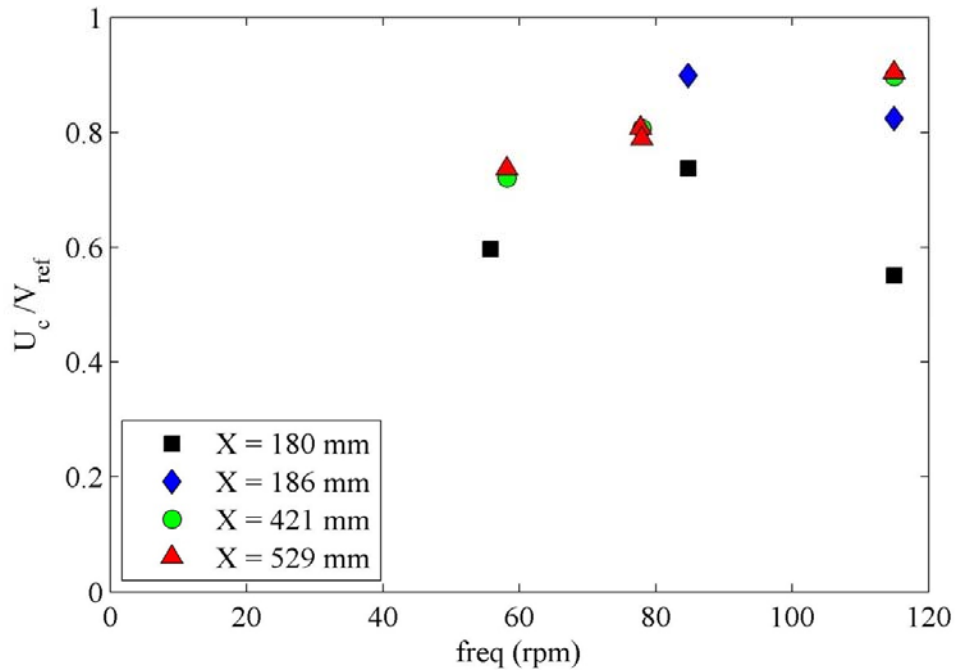


Figure 14. The centerline velocity measured with LDV scaled versus the reference velocity (V_{ref}) plotted versus the tunnel impeller frequency at various downstream distances.

Another way to illustrate this behavior is to plot the centerline velocity scaled with the reference velocity versus downstream distance. This is done in Figure 15, though the downstream distance is shown as the distance downstream of the cylinder ($X-X_c$) and scaled with the cylinder diameter (D). Here it is apparent that in the far wake (i.e. beyond six diameters downstream of the cylinder) the centerline velocity relative to the reference velocity increases with increasing speed. Conversely, in the near-wake region there is no obvious trend besides for a given tunnel velocity, the velocity ratio increases with increasing distance beyond ~ 2 diameters downstream. The unusual trends observed in the near-wake are due to the fact that these velocities are close to the critical Reynolds number for transition on a cylinder, which is the primary reason the smooth cylinder configuration was not used in the forced fin setup and will be further discussed when presenting cylinder pressure data.

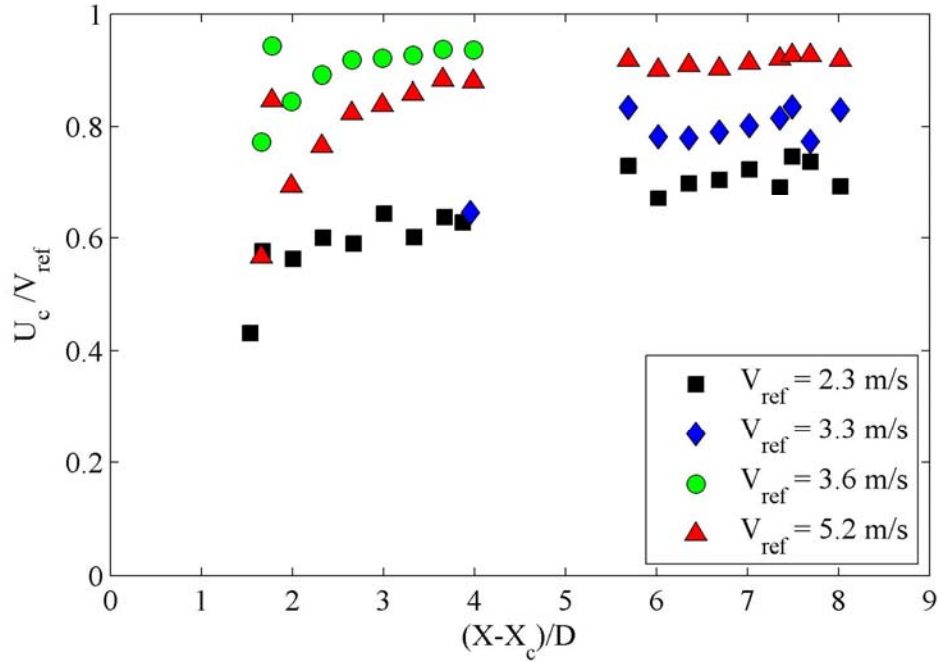


Figure 15. The tunnel centerline velocity scaled with the reference velocity and plotted versus $(X-X_c)/D$, where X_c is the trailing edge of the cylinder ($X_c = 79.5$ mm) and D is the cylinder diameter (60 mm). The data is grouped based on the given reference velocity.

3.3 Cylinder Pressure

It is important to know the characteristics of the steady and unsteady loads on the cylinder as the corresponding downstream flow fields will impact the fin. To do this, both steady and unsteady pressures were measured on the smooth cylinder. Additionally, the vibration of the cylinder was also measured.

3.3.1 Static base pressure coefficient

The static base pressure coefficient ($C_{pb} = \Delta P_b / 0.5 \rho U^2$) is a common parameter historically used to define the fin behavior because it is directly related to the drag on the cylinder, but significantly easier to measure than drag. Here ΔP_b is the difference between the pressure at $\theta = 180^\circ$ (i.e. the static base pressure) and the local static pressure, ρ is the fluid density and U is the local free-stream velocity.

The coefficient can be rewritten as the ratio of the difference in the base and static pressures to the difference in the total and static pressures. In the current study the static base pressure was measured at two spanwise positions on the cylinder ($Z = 115$ and 230 mm), which were selected because they correspond to the heights of the fin at the mid-span and the tip. These results are plotted in Figure 16 versus cylinder-diameter-based Reynolds number. Also included for comparison are smooth cylinder data from several sources available in the literature (Roshko, 1961; Bearman, 1969; Nakamura & Tomonari, 1982; Shih et al., 1993) as well as a representative smooth cylinder curve presented in Shih et al. (1993). The current experimental data follows these historical data and the representative curve within the scatter of the data. It should be noted that in calculating the Reynolds number the blockage effect had to be accounted for to match the data. Here the Reynolds number is defined as $Re_D = U_{cor}D/\nu$, where D is the cylinder diameter (60 mm), ν is the kinematic viscosity of water, U_{cor} is the reference velocity corrected for the blockage effect ($V_{ref} A_{ts}/(A_{ts}-A_B)$), A_{ts} is the test section cross sectional area and A_B is the projected area of the cylinder. In the current study the blockage effect results in an increase of 1.334 with respect to the reference velocity.

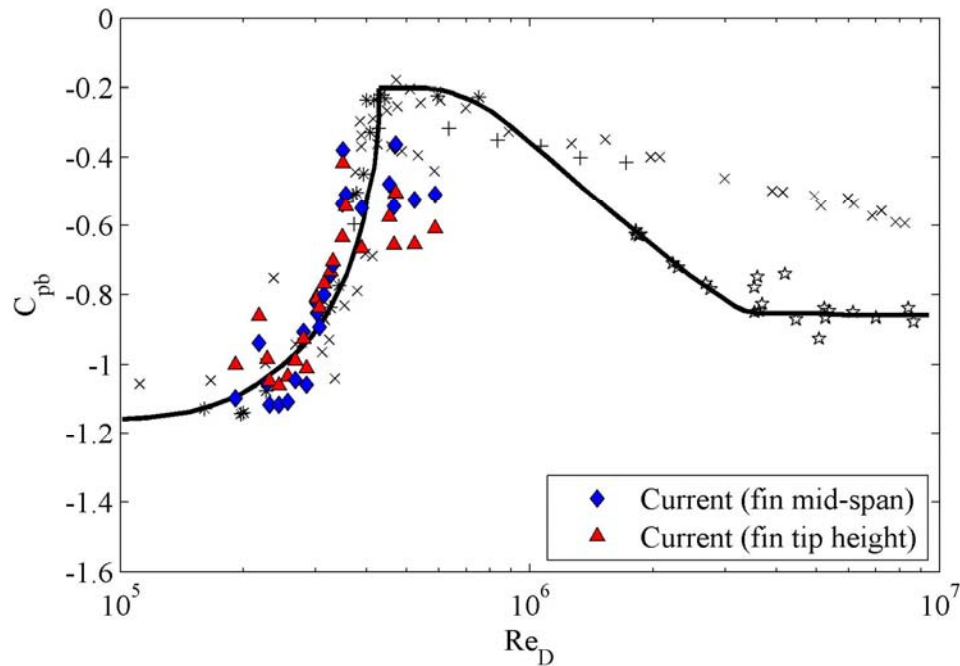


Figure 16. Static base pressure coefficient for Part 2a (smooth cylinder only) plotted versus the cylinder diameter based Reynolds number ($Re_D = U_{cor}D/\nu$). Current data was acquired at two spanwise locations on the cylinder, which corresponded to the fin mid-span ($Z = 115$ mm) and fin tip ($Z = 230$ mm) heights. Included in the plot for comparison are smooth cylinder data available in the literature; (*) Roshko (1961), (*) Bearman (1969), (+) Nakamura & Tomonari (1982) and (x) Shih et al. (1993). Also included is a representative smooth cylinder curve presented in Shih et al. (1993) that was accredited to Flachsbart. The current data follows the smooth curve data reasonably well.

As previously stated the static base pressure coefficient is directly related to the cylinder drag, and thus it is convenient to interpret the above results in light of a generic drag plot for a cylinder. Figure 17 is from Behara & Mittal (2011) and shows that in the subcritical regime (i.e. prior to transition) the drag coefficient is nearly constant. For the current study it was known that the required velocities would be approaching the critical stage, but it was hoped that we could achieve the needed fluctuations within the subcritical regime. While it has not been presented or discussed yet, the LDV measurement results indicated the required flow velocities achieve the designed flow-field fluctuations, which was how the range of speeds presented in the above plot were determined. Noting that the peak in the static base pressure curve corresponds to the minimum in the drag coefficient curve, it is apparent that using the smooth cylinder would place our final test condition in the critical regime. This

is not ideal due to issues related to modeling transition and increased sensitivity to the boundary conditions (i.e. reduced repeatability). Consequently, this motivated the change from the smooth cylinder to a cylinder with a roughened leading edge (Part 2b).

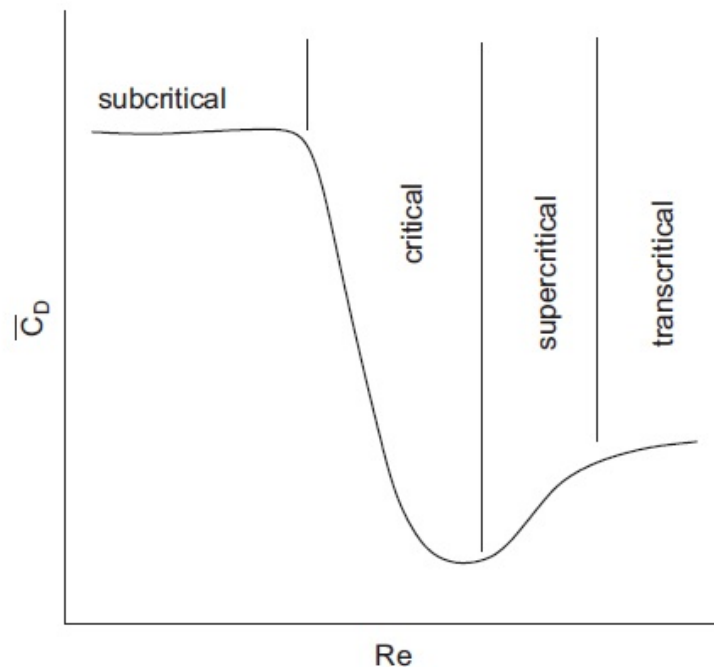


Figure 17. Figure from Behara & Mittal (2011) illustrating the various regimes associated with cylinder transition.

3.3.2 Dynamic pressure

The dynamic pressures were measured to quantify the correlated load along the span and to quantify its frequency content.

3.3.2.1 Comparison between sensors for a signal test

The vortex shedding generated by the flow over the smooth cylinder at various test conditions was quantified from fluctuating pressure measurements made on the aft side of the cylinder. The dynamic pressure measurements were made over the course of several days for a range of water tunnel speeds to capture the variation in shedding frequency dynamics at subcritical and critical Reynolds

numbers ($Re_D = V_{ref}D/\nu$), where V_{ref} is the measured reference velocity, D is the cylinder diameter and ν is the kinematic viscosity of water. Figure 18 shows the measured time signals for the four cylinder pressure transducers at 3 m/s during a single test (Test 2057). Here the time axis has been compressed to show the phase relationship between sensors and the shedding frequency dominance in the signals. Figure 19 and Figure 20 show the power spectral density functions from the cylinder dynamic pressures and accelerometer, respectively, at 3 m/s for the same test run (Test 2057). Both also include their electrical background spectra (i.e. spectra produced during no-flow tunnel condition) for reference. From these figures, it is apparent that the shedding frequency generated by the cylinder dominates the spectra as its peak is approximately 20 dB over the continuum level. All four of the fluctuating pressures in Figure 19 exhibit similar spectral levels and characteristic shape. Note that the dynamic pressures become background limited around 700 Hz, and the cylinder accelerometer is background limited starting around 30 Hz. The rapid roll-off above the shedding frequency for the accelerometer was the reason the signal was used for phase-averaged PIV results (i.e. the roll-off served as a natural low-pass filter).

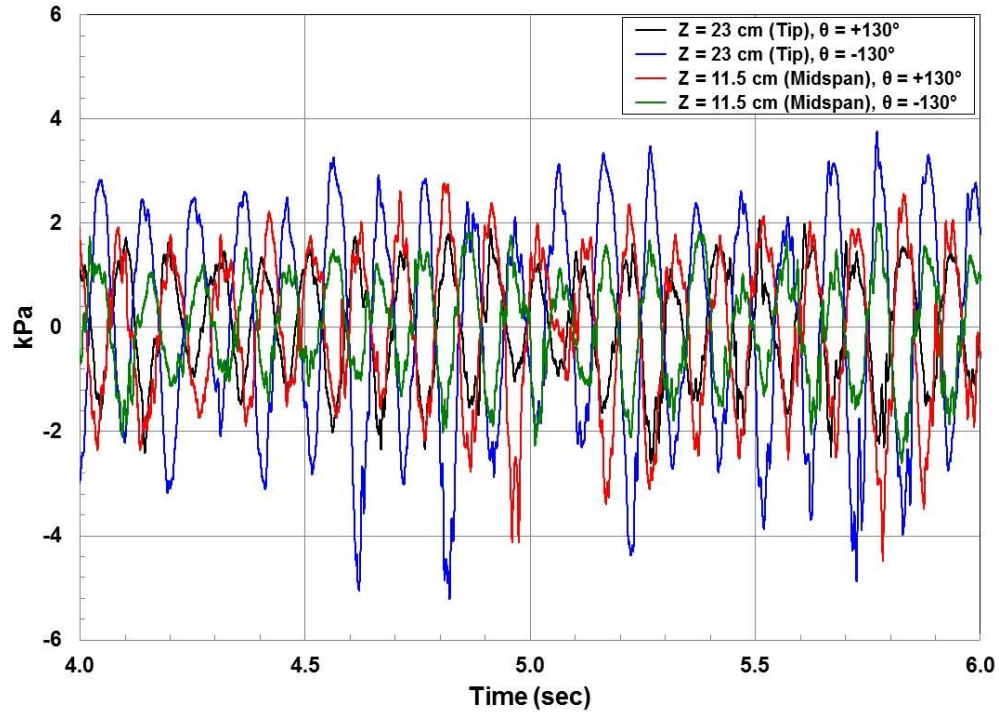


Figure 18. Cylinder dynamic pressure time traces over a two second period at a tunnel test section velocity of 3 m/s. All four signals were acquired during a single test run (Test 2057).

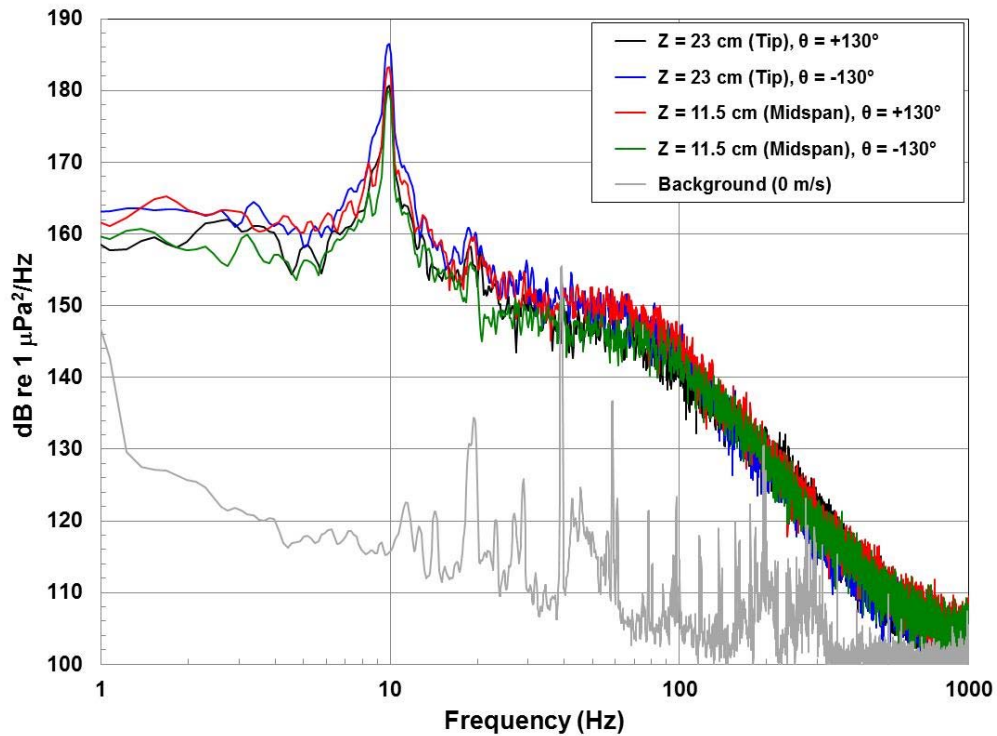


Figure 19. Cylinder dynamic pressure spectral levels at a test section velocity of 3 m/s during a single test (Test 2057). The electrical background spectra (i.e. no-flow condition) is also provided for reference.

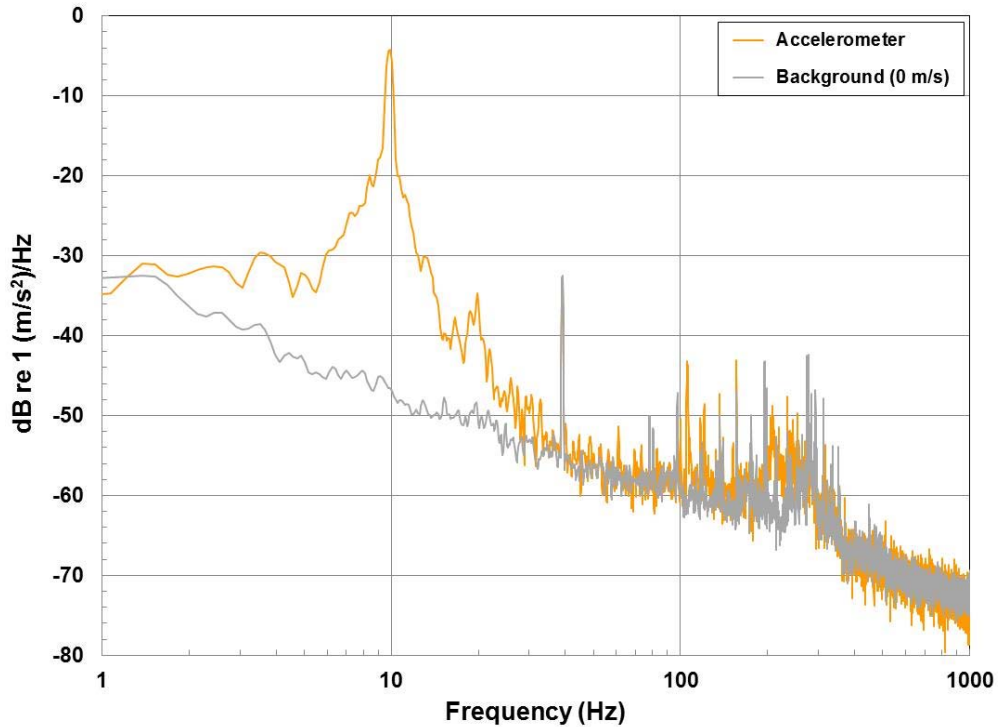


Figure 20. Cylinder accelerometer spectral levels at a tunnel test section velocity of 3 m/s from a signal run (Test 2057), along with the instrumentation electrical background (no-flow condition) spectral levels.

3.3.2.2 *Shedding frequency speed dependence*

Figure 21 shows the dynamic pressure power spectral density from the same test (Test 2057) at $Z = 115$ mm (fin mid-span height) over a range of water tunnel speeds. Note that the velocities shown in the legend correspond to the local test section velocities, which do not account for the blockage effects experienced by the cylinder. As the water tunnel speed increases up to the critical Re_D for a smooth cylinder, the shedding frequency dominates the dynamic pressure spectra, as the vortex shedding is well defined and periodic. Once the cylinder boundary layer begins to transition from laminar to turbulent (typically around $Re_D = 200,000$), the vortex shedding becomes less coherent and more random in the pressure data until the shedding frequency completely disappears from the spectra, as seen in velocities above 4 m/s.

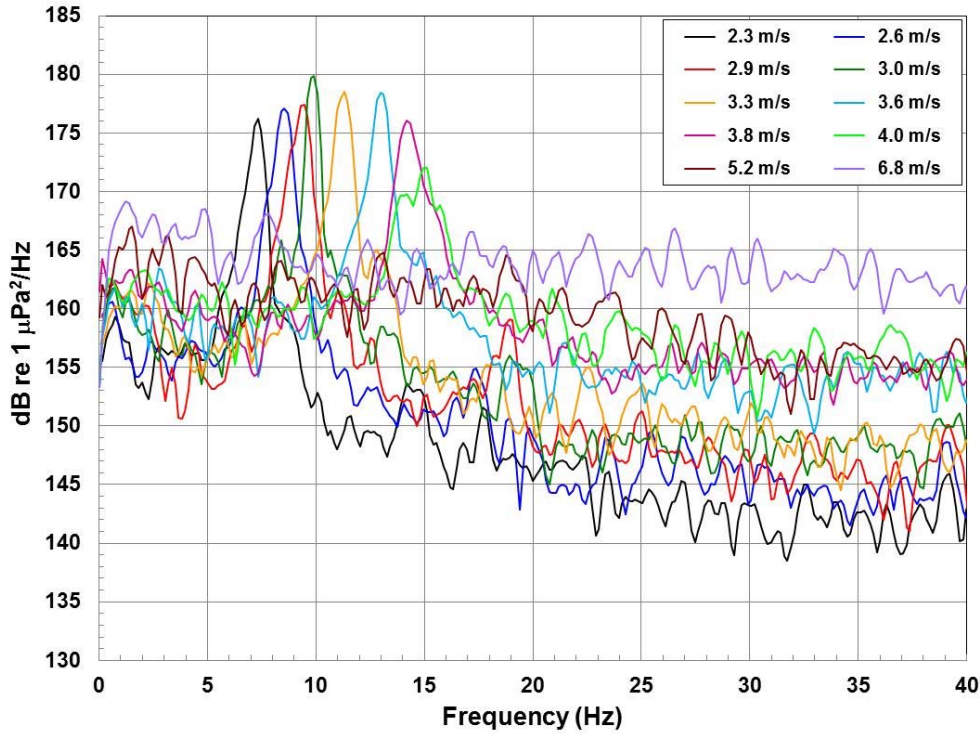


Figure 21. Cylinder dynamic pressure autospectra measured at $Z = 115\text{mm}$ (fin mid-span height) and $\theta = -130^\circ$. The reference velocities shown in the legend correspond to the local velocity measurements in the test section (i.e. V_{ref}), which is slightly lower than the velocity experienced by the cylinder when accounting for blockage effects.

Subsequent water tunnel tests provided similar results for the dynamic pressures. However, the critical Re_D and magnitude of the shedding frequency varied somewhat. This slight day-to-day variation is likely attributed to minor changes in the cylinder surface roughness, free-stream turbulence levels and/or the random nature of boundary layer transition. As a result of the observed variations, the fluctuating pressure data from four tests were compiled and compared. The dynamic pressures were converted to an equivalent lift force (L) by multiplying the pressure difference in the time domain by the cylinder's projected area (A_{cyl} = cylinder diameter multiplied by the cylinder span, equivalent to the blockage area),

$$L = (P_2 - P_1)A_{cyl}.$$

Here P_1 is the pressure at $\theta = -130^\circ$ and P_2 is the pressure at $\theta = +130^\circ$. It was desired to estimate the resulting lift because the lift induced on the cylinder will be proportional to the lift experienced by the fin during Part 4 of the experiment and these measurements were used to select the final test condition. This area definition assumes coherent shedding (i.e. pressure) at the shedding frequency along the entire cylinder span, which means this calculation serves as an upper bound on the lift. The assumption that there was strong spanwise coherence is supported by the results provided in Figure 22, which show the measured coherence level at the shedding frequency is greater than 0.9 at the two measured spanwise locations ($Z = 115$ and 230 mm) on both sides of the cylinder ($\theta = \pm 130^\circ$) at 3.2 m/s (Test 2070).

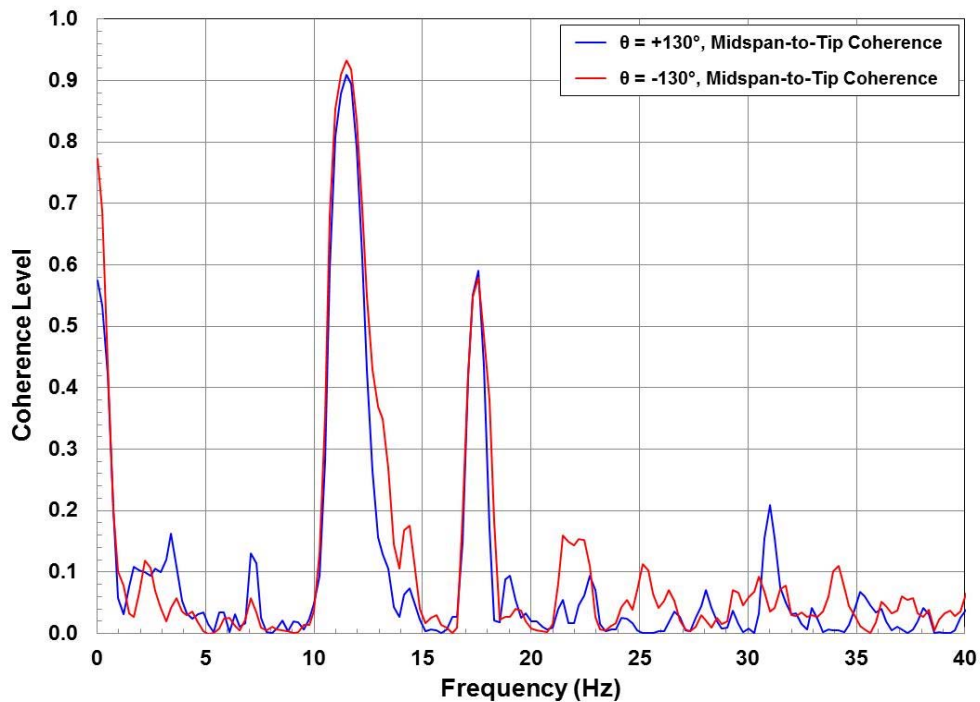


Figure 22. The coherence between the pressure signals at $Z = 115$ mm (fin mid-span height) and 230 mm (fin tip height) as a function of frequency. Data shown was for a single test (Test 2070) at 3.2 m/s. Results from both sides of the cylinder are shown ($\theta = \pm 130^\circ$). At the shedding frequency of ~ 12 Hz the coherence is ~ 0.9 on both sides of the cylinder.

3.3.2.3 Error analysis of the measured shedding frequency

Table 3 below compares the shedding frequencies calculated from the cylinder dynamic pressure transducers, cylinder accelerometer and LDV data. As shown in the table, there is minimal variation in shedding frequencies derived from the three independent measurement methods. This comparison across different measurement devices can be used to quantify the bias error of the reported shedding frequency values at each speed. At 95.4% confidence interval (i.e. twice the standard deviation), the estimated bias error is approximately 1.2% of the measured shedding frequency. In a similar manner, the random error can be quantified by investigating the variation in shedding frequency over multiple tests and measurements. Figure 23 shows the shedding frequency determined from the dynamic pressures from multiple tests (4 tests, each test had multiple runs at various speeds) spanning the range of speeds where coherent shedding was detected (i.e. below 4 m/s). The data indicates an estimated random error of ~2%.

Table 3. Shedding frequency measured with three independent measurement methods. This provides an estimate of the bias error associated with measuring the shedding frequency.

V_{ref} (m/s)	Measured Shedding Frequency (Hz)		
	Dynamic Pressures	Accelerometer	LDV Profiles
2.5	8.50 – 8.75	8.75	8.00
3.2	11.00 – 11.25	11.25	11.25
3.4	12.50 – 12.75	12.50-12.75	12.75
3.6	13.25 – 13.50	13.50	13.50

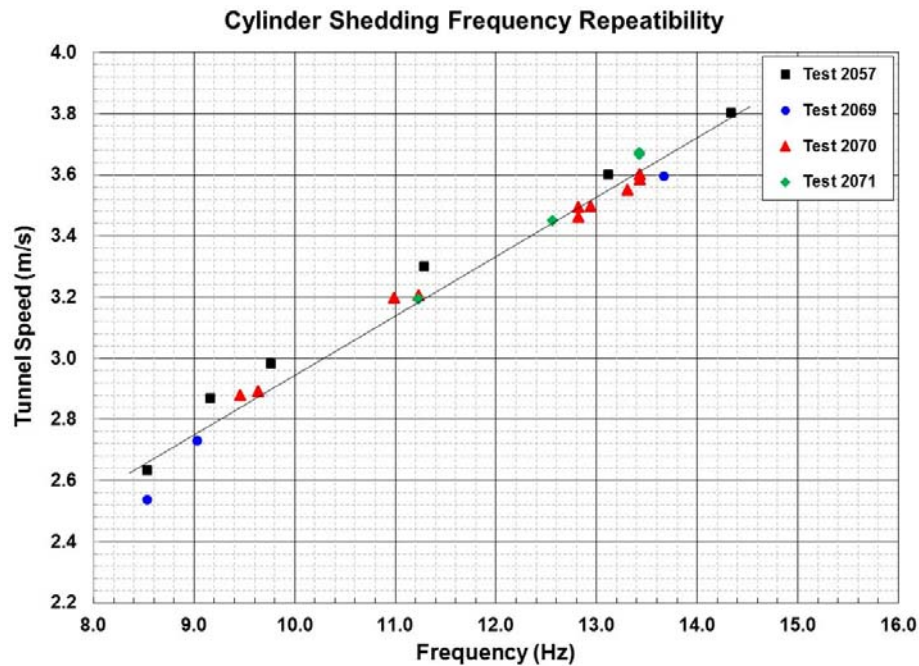


Figure 23. Tunnel velocity plotted versus the measured shedding frequency from the dynamic pressure measurements acquired from four tests spanning nearly four weeks of test time on the smooth cylinder only (Part 2a). This plot provides an estimate of the random error associated in measuring the shedding frequency with the dynamic pressure sensors.

3.3.2.4 Estimating shedding frequency RMS lift force

Power spectral densities (PSD's) of the cylinder lift were computed from the pressure difference time domain signals, and the root-mean-squared (RMS) fluctuating force levels were quantified by integrating over the bandwidth of the shedding frequency tone using the trapezoidal rule. This approach provided a more consistent measure of the fluctuating lift force associated with the shedding frequency independent of spectral processing parameters such as frequency resolution and sample rate. Figure 24 and Figure 25 show the cylinder shedding frequency RMS lift force levels computed from the fluctuating pressures at the fin tip ($Z = 230$ mm) and mid-span ($Z = 115$ mm) locations, respectively, plotted *versus* the tunnel test section velocity. These test runs span the entire duration of the smooth cylinder only part of the experiment (Part 2a), which was nearly four weeks long. The cylinder shedding frequency RMS lift levels produced consistent trends with respect to the tunnel velocity, but the computed levels at a given velocity had variation between tests.

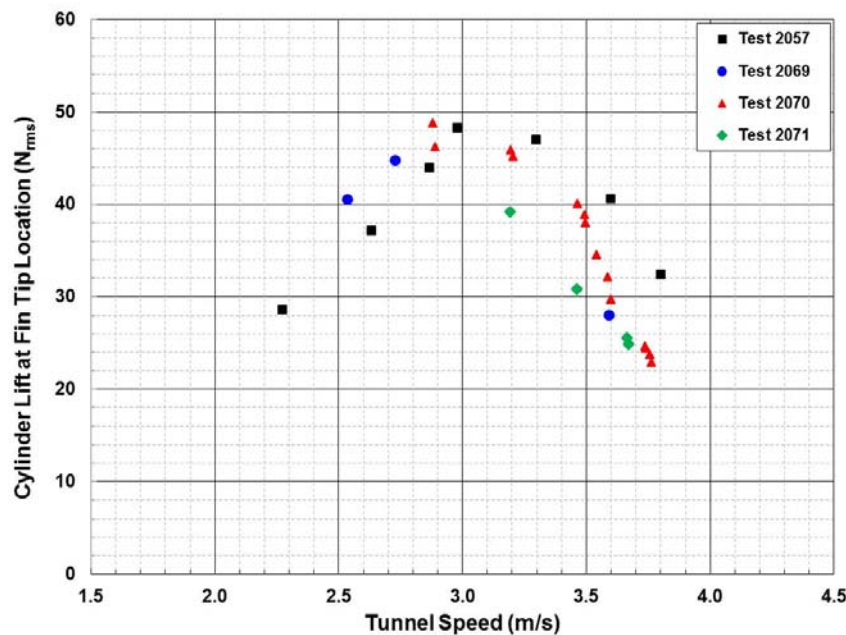


Figure 24. Cylinder shedding frequency computed RMS lift levels plotted versus test section tunnel velocity for the pressure transducer pair located at $Z = 230$ mm. The lift force was computed assuming perfect coherence along the entire cylinder span, and the tests shown span the entire smooth cylinder only part of the experiment (Part 2a).

Comparisons between the two figures suggests that the cylinder shedding lift force appears to reach its maximum level at ~ 3.0 m/s ($Re_D = 190,000$) and ~ 3.3 m/s ($Re_D = 210,000$) based on the results from the fin tip height ($Z = 230$ mm) and from the fin mid-span height ($Z = 115$ mm), respectively. In addition, the computed shedding frequency RMS lift force from the pressure pair located at the fin tip height measures up to 12 N_{rms} higher than the lift computed from the pressure pair at the fin mid-span height. However for velocities above the peak in RMS lift force, the RMS lift force decreases at a faster rate at the fin tip height than at the mid-span height. For all tests, the pressure measurements provided a generally consistent periodic vortex shedding tone for velocities up to ~ 3.6 m/s, indicative of the subcritical to critical Re_D regime. Above 3.6 m/s, the shedding frequency tone became increasingly intermittent and entirely disappeared for velocities above 4 m/s, which indicates that the cylinder was in the supercritical regime. Similar breakdown of the vortex shedding was observed in the LDV measurements (details of which are provided subsequently) at similar test section velocities (see Figure 31 and Figure 32 for spectra from the LDV measurements).

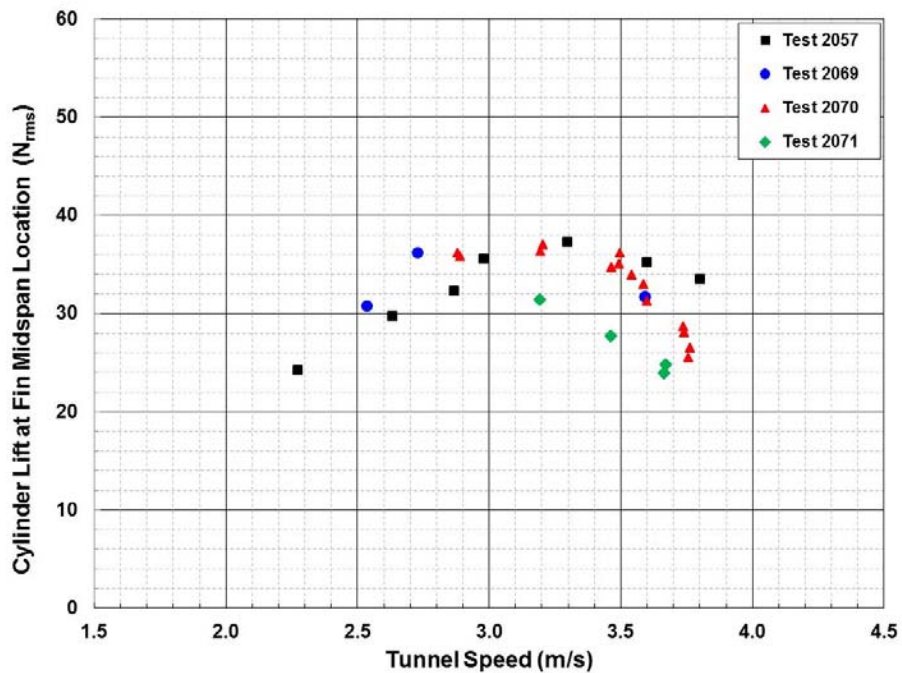


Figure 25. Same as shown in Figure 24 but with the pressure transducer pair located at $Z = 115$ mm (fin mid-span height).

Dynamic pressure data from the smooth cylinder only tests (Part 2a) shows that the cylinder produces a vortex sheet that could actively excite the fin to produce the desired maximum deflection. However, the data also indicates that the required velocity falls within the critical to supercritical flow regime. This is undesirable because the critical regime is characterized by reduced repeatability, and increasing velocity encounters the supercritical regime (likely around 4 m/s in the current study). In the supercritical regime the coherent shedding is completely dissipated, which means that if the desired forcing was not achieved below 3.6 m/s it would likely be impossible. Consequently, it was decided that the flow should be tripped at the cylinder leading edge to force the flow into the transcritical regime, where the flow is once again repeatable and provides greater control in setting the final forcing on the fin for the Part 4 experiment.

3.3.2.5 Shedding frequency scaling

The peak vortex shedding frequency is commonly scaled using the Strouhal number ($St = f_s D / U$), where f_s is the vortex shedding frequency, D is the diameter of the cylinder ($D = 60$ mm) and U is the characteristic velocity which for the current study is V_{ref} . Smooth cylinder Strouhal scaling results from the current study are plotted in Figure 26 versus the cylinder diameter based Reynolds number (Re_D). Here once again the Reynolds number velocity was corrected for blockage effects as was done for the scaling of the static base pressure coefficient results. Included for comparison in the figure are smooth cylinder data compiled in Roshko (1961), which spans the Reynolds number range tested in the current study. Also included is a composite curve for smooth cylinders, which was also presented in Roshko (1961). While the current results closely match the data presented it is important to note that in the current study vortex shedding was observed only between $1.9 \times 10^5 \leq Re_D \leq 3.3 \times 10^5$ even though testing was performed up to $Re_D = 5.7 \times 10^5$. This can be seen in Figure 21, which shows that the peak weakening at 4 m/s and no peak at velocities above 4 m/s. A similar phenomenon was observed in Roshko (1961), which acquired data spanning $0.9 \times 10^6 \leq Re_D \leq \sim 8 \times 10^6$ though shedding frequency was only observed for $Re_D \geq 3.5 \times 10^6$. This is unexpected given the data of Relf & Simmons (1924) and Delany & Sorensen (1953), which shows vortex shedding in the range between the maximum Reynolds number observed in the current study and the minimum observed in Roshko (1961). Roshko (1961) attributed the inability to observe coherent shedding within this range to transitional effects associated with experimental differences. This makes sense given the fact that the change is a transitional effect, which is highly sensitive to flow conditions. Thus in the current study it is unlikely that vortex shedding will not return until a Reynolds number of $\sim 3.5 \times 10^6$ is achieved, which corresponds to a water tunnel velocity of ~ 58 m/s. Since this is much higher than the maximum tunnel velocity, coherent vortex shedding was only going to be possible for the current setup at velocities below 4 m/s. Thus if the cylinder was not roughened there would be a fixed maximum tunnel velocity

that could possibly produce the desired fin deflections. Note that the fin fabrication for Part 4 was nearly complete at the time of this finding. The fin was designed such that an RMS force of approximately $\pm 3.5\%$ CoN was required to obtain the desired fin-deflection amplitude.

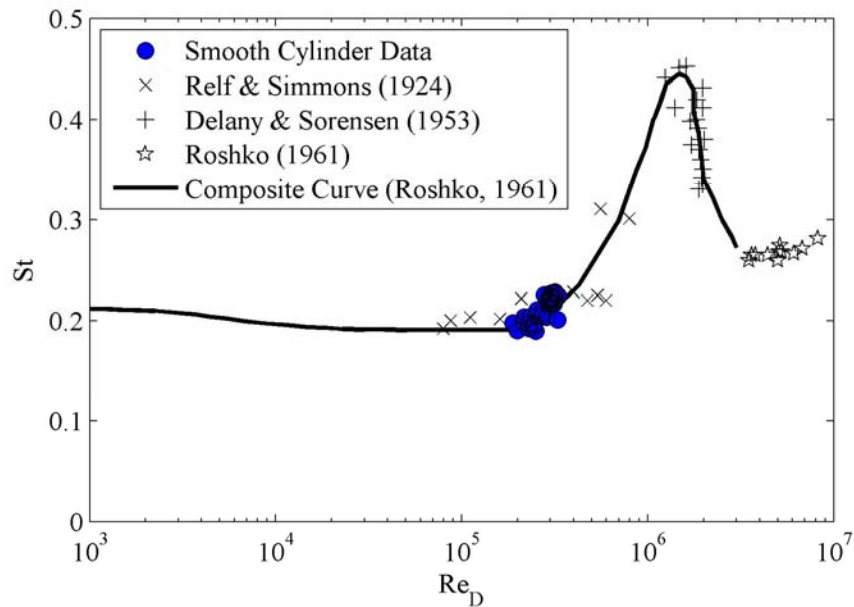


Figure 26. The smooth cylinder Strouhal number plotted versus the cylinder diameter based Reynolds number. Included for comparison are smooth cylinder results from Relf & Simmons (1924), Delany & Sorensen (1953) and Roshko (1961). Also included is a composite curve presented in Roshko (1961) representing the general Strouhal scaling trend for a smooth cylinder over a wide range of Reynolds numbers.

3.4 Cylinder Wake

In addition to the centerline velocity directly behind the cylinder, additional information can be gained by looking at the wake flow field time-averaged and RMS levels.

3.4.1 Profiles

The first level examination of the wake flow field is the mean and RMS velocity profiles.

3.4.1.1 Velocity Deficit

Mean velocity profiles within the wake of a cylinder are difficult to assess due to the fact that they do not scale well. This is illustrated in Figure 27, which plots the average streamwise velocity

component (U) scaled with the test section reference velocity (V_{ref}) versus the vertical direction (Z), which is parallel with the cylinder axis. Profiles were acquired at the tunnel centerline ($Y = 0$ mm), at several downstream locations ($X = 180, 186, 421$ or 529 mm) and at over a range of reference velocities. While this plot appears to have much scatter, it does show that the region where the wake will be impacting the fin ($0 \text{ mm} \leq Z \leq 230 \text{ mm}$) is nearly constant for a given velocity and downstream location (i.e. given color and marker combination). However, the boundary layer on the top of the wall nearly reaches the fin-tip height, which is denoted by the solid red line in the figure. The fin is influenced by the boundary layer forming at the tunnel floor ($Z < 50$ mm), but since this is at the base of the fin it has a weaker effect on the moment acting on the fin. Finally, the scatter from this figure is indicative of the fact that there is no simple scaling for a plane wake flow. The dashed lines in the figure denote locations where cross-stream velocity profiles were acquired, and these profiles are used to further explore the scaling of the cylinder wake.

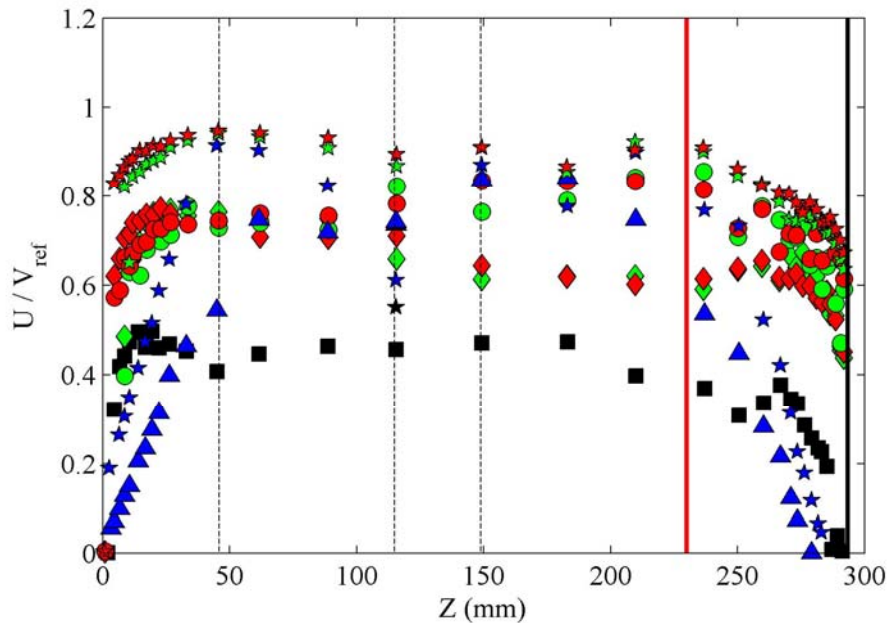


Figure 27. The streamwise velocity component (U) on the smooth cylinder scaled with the test section reference velocity (V_{ref}) plotted versus the direction parallel to the cylinder axis (Z). These measurements were acquired along transverse center of the tunnel ($Y = 0$ mm). The marker colors correspond to (black) $X = 180$ mm, (blue) $X = 186$ mm, (green) $X = 421$ mm and (red) $X = 529$ mm. The marker shapes denote the reference velocity for the given measurement; ($\square$) 2.2 m/s, ($\diamond$) 2.3 m/s, ($\circ$) 3.3 m/s, (Δ) 3.7 m/s and ($\star$) 5.2 m/s. The solid black lines denotes the top of the test section, the solid red line denotes the fin tip height ($Z = 230$ mm) and the dashed lines denote the locations that wake deficit profiles were acquired ($Z = 46, 115$ and 149 mm).

The inability to use such a simple scaling on the velocity profile within the smooth cylinder wake is not surprising. This is because there are two characteristic velocity scales associated with plane wakes, such as in the current study, which are the free-stream velocity (V_{ref} will be used in the current study) and the wake velocity deficit ($U_s \equiv V_{ref} - U(X,0,Z)$). Since the velocity at the center of the wake varies with downstream distance, as observed in Figure 15, it is apparent that the velocity deficit also will vary with downstream distance. The width of the wake is often characterized by the half-width ($Y_{1/2}$), which is defined such as

$$U(X, \pm Y_{1/2}, Z) = V_{ref} - 0.5U_s(X).$$

Since the velocity deficit varies with downstream distance, the half-width also varies with downstream distance. Consequently, the plane wake is not self-similar, but in the far wake as the ratio of U_s/V_{ref} approaches zero the wake becomes self-similar. Thus when the downstream distance becomes large compared to the cylinder diameter, the wake should asymptotically approach self-similar behavior with the cross-stream variable being $Y/Y_{1/2}$ and the self-similar velocity defect take the form of

$$\frac{V_{ref} - U}{U_s}.$$

Figure 28 applies this scaling to the profiles measured at various vertical positions ($Z = 46, 115$ or 149 mm), streamwise locations ($X = 180, 186, 421$ or 529 mm) and free-stream velocities ($V_{ref} = 2.2, 2.3, 3.3, 3.7$ or 5.2 m/s). The profiles shown were produced by averaging profiles from various velocities and binning them into $Y_{1/2}/10$ increments. Included in the figure for reference is the analytical solution from Pope (2000), which assumes a plane wake in the far-field with uniform-turbulent-viscosity,

$$\frac{V_{ref} - U}{U_s} = \exp\left(-\ln(2)\left(\frac{Y}{Y_{1/2}}\right)^2\right).$$

The current results follow this solution reasonably well, even at the closest profile measurement that is less than two cylinder diameters downstream of the cylinder. The scaling parameters used for each profile is provided in Table 4, which also shows that, as expected, with increasing downstream distance the wake spreads ($Y_{1/2}$ increases) and decays (U_s decreases). Note that the product of velocity deficit and the half-width are directly proportional to the momentum deficit flow rate, which is independent of downstream distance and equals the drag per unit span on the cylinder.

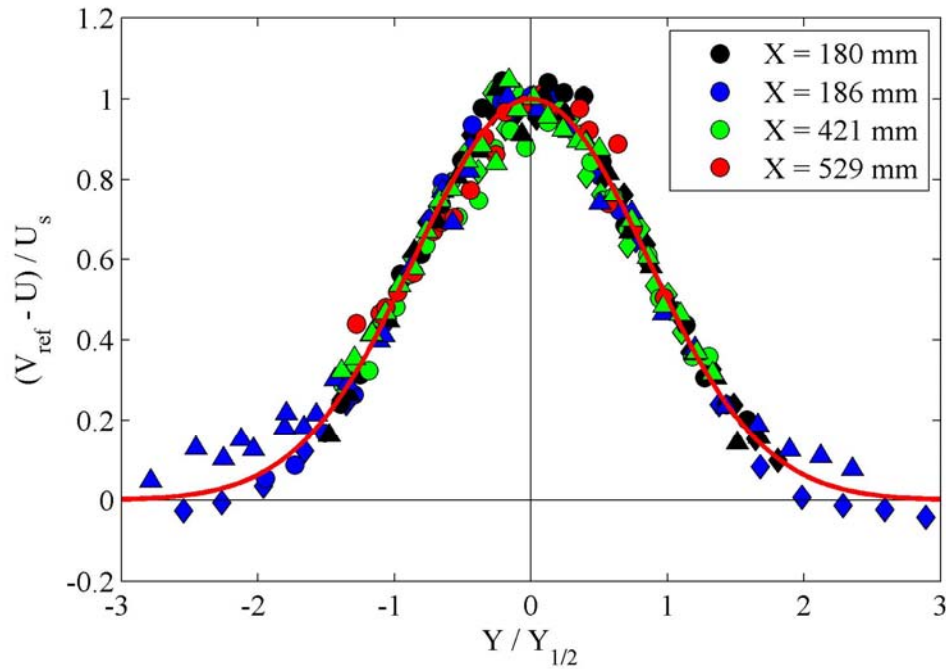


Figure 28. Wake deficit plot for the smooth cylinder only wake (Part 2a). Symbol colors specify the downstream position of the measurement as shown in the legend, and marker shapes provide the vertical location such that ($\diamond$) $Z = 46$ mm, ($\circ$) $Z = 115$ mm (fin mid-span) and (Δ) $Z = 149$ mm (tunnel centerline). The figure was produced by spatially averaging profiles from a range of velocities using the scaling shown. Here U_s is the velocity difference between the convection velocity (V_{ref} used as the estimated convection velocity), $Y_{1/2}$ is the Y -position where the wake has recovered 50% of the deficit ($U(X, \pm Y_{1/2}, Z) = V_{ref} - 0.5U_s$) and the velocity at the center of the wake ($U\{X, 0, Z\}$). Also included for reference is the analytical solution from Pope (2000) for a symmetric wake assuming uniform-turbulent-viscosity, which the current results follow reasonably well (shown with red curve.)

Table 4. Measured values of the velocity deficit (U_s) and the half width ($Y_{1/2}$) of the smooth cylinder wake. The results confirm that with increasing downstream distance the wake spreads (half width increases) and decays (velocity deficit decreases).

V_{ref} (m/s)	X (mm)	Z (mm)	U_s (m/s)	$Y_{1/2}$ (mm)
2.2	180	46	1.33	31.2
2.3	421	46	0.56	50.3
2.2	180	115	1.18	33.5
2.3	421	115	0.82	41.5
2.3	529	115	0.71	48.5
2.2	180	149	1.24	31.7
2.3	421	149	0.91	42.1
3.3	421	115	0.85	53.3
3.3	529	115	0.74	65.7
3.7	186	46	1.74	16.5
3.7	186	149	0.62	21.7
5.2	186	115	2.20	23.2
5.2	421	115	0.86	50.2
5.2	529	115	0.74	47.1
5.2	186	149	0.68	15.1
5.2	421	149	0.57	50.2

The evolution of the wake can also be investigated by investigating the average cross-stream velocity component (V). Figure 29 shows the average cross-stream velocity (V) scaled with the reference velocity (V_{ref}) for the smooth cylinder versus the cross-stream direction (Y) scaled with the cylinder diameter (D). The profiles at $X = 180$ and 186 mm correspond to 1.68 and 1.78 cylinder diameters downstream of the cylinder ($X-X_c$), respectively, where X_c is the downstream location of the cylinder trailing edge (79.5 mm). In this near-wake region, V achieves local extrema between Y/D of ± 0.25 and 0.5 . The peaks appear to decrease with increasing downstream distance, which supports the

previous observations that the wake is decaying with downstream distance. Profiles acquired in the far-wake region, $(X-X_c)/D = 5.69$ and 7.49 ($X = 421$ and 529 mm respectively), have a nearly constant profile at nominally 0 m/s. This does not mean that the velocity is not oscillating in the far wake, just that the oscillations across the tunnel width occur about zero. This makes sense as near the cylinder on the $+Y$ side of the cylinder the flow will either be straight ($V = 0$) or moving towards the trailing edge ($V < 0$), and the opposite on the $-Y$ side of the cylinder. Thus in the near-wake on average the $+Y$ side will have a negative V velocity while the $-Y$ side will have a positive V velocity, as seen in the figure.

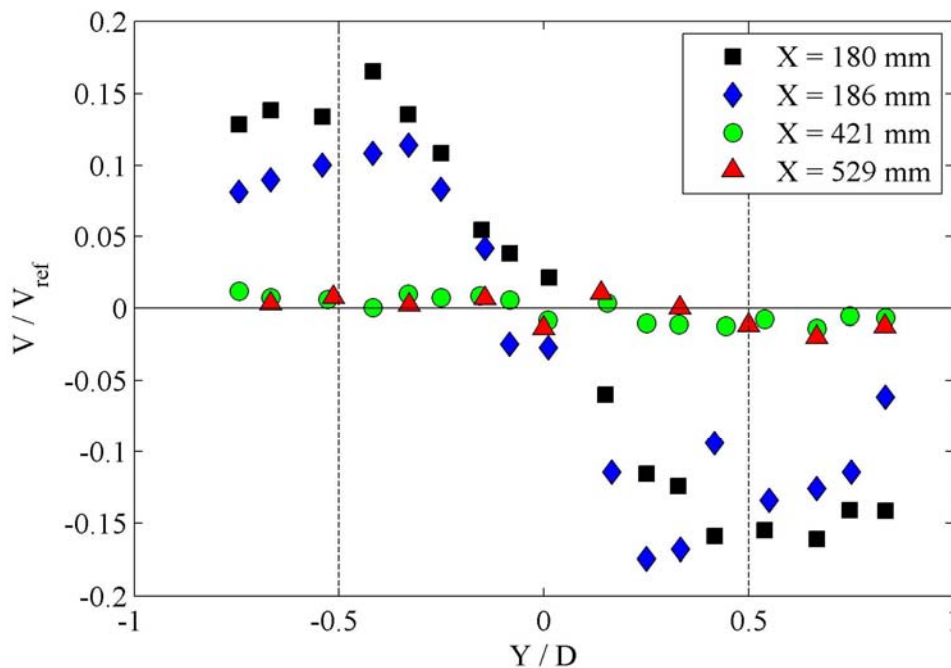


Figure 29. The average cross-stream velocity component (V) scaled with the reference velocity (V_{ref}) for the smooth cylinder and plotted versus the cross-stream direction scaled with the cylinder diameter. The dashed lines mark the corresponding edges of the cylinder.

3.4.1.2 Fluctuating cross-stream velocity

When investigating the cross-stream velocity component of a wake it is often more instructive to focus on the fluctuating velocity (V') rather than the mean velocity (V). This is apparent when viewing the far wake profiles in Figure 29, which shows a near zero mean velocity though the flow

still has significant oscillations at this location. Thus in Figure 30 the smooth cylinder fluctuating cross-stream velocity component (V') is scaled with the reference velocity (V_{ref}) and plotted versus the cross-stream direction (Y) scaled with the cylinder diameter ($D = 60$ mm). Here the peak in the fluctuating velocity occurs at the center of the tunnel ($Y = 0$ mm), where the mean cross-stream velocity was zero. The fluctuating velocity level then falls off symmetrically about the center peak for a given downstream location. The peak level appears to decrease with increasing downstream distance, which supports the idea that the wake is decaying with increasing downstream distance. Finally, in the far wake the fluctuating velocity towards the tunnel walls increases relative to the near-wake levels. This is the result of the wake spreading and influencing more of the free-stream than near the cylinder. Thus the strongest oscillations occur at the tunnel centerline near the cylinder, and the region influenced by the cylinder wake increases with increasing downstream distance.

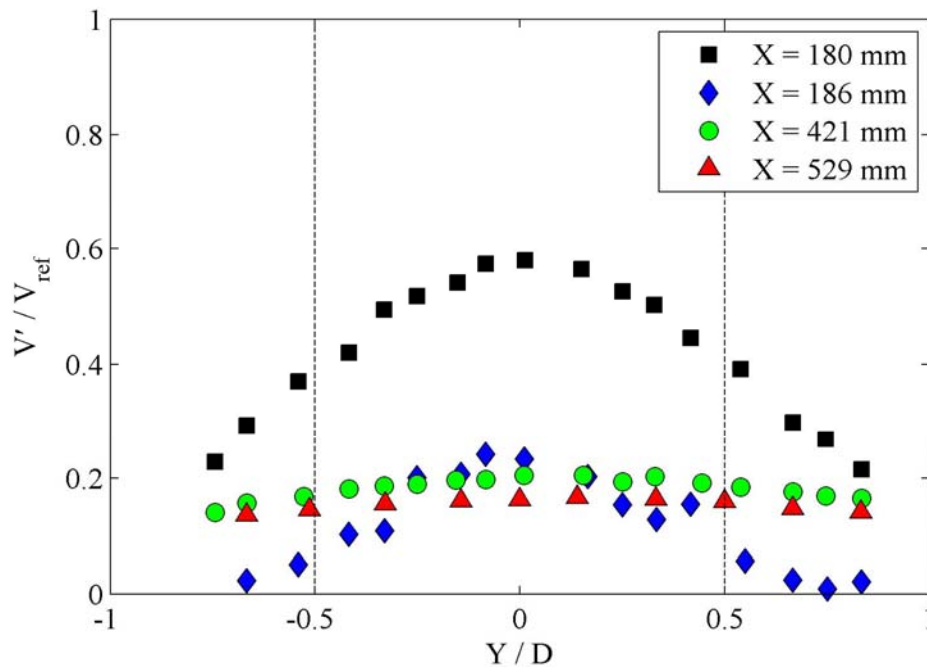


Figure 30. The fluctuating cross-stream velocity component (V') scaled with the reference velocity (V_{ref}) for the smooth cylinder and plotted versus the cross-stream direction (Y) scaled with the cylinder diameter ($D = 60$ mm). The dashed lines mark the edge of the cylinder.

The above fluctuating velocities are determined from the standard deviation of the time traces, which is a measure of all the fluctuating energy spread for all possible frequencies. Thus it is informative to look at the power spectrum for a given velocity measurement. Figure 31 and Figure 32 show the cross-stream velocity component spectrum at $Z = 230$ (fin tip height) and 115 mm (fin mid-span), respectively. Data was acquired over a range of velocities at the tunnel centerline ($Y = 0$ mm) and $X = 317$ mm. This downstream position is located between the fin leading edge at the tip ($X = 279$ mm) and the fin trailing edge at the base ($X = 404$ mm). The measurement was planned to be acquired at the 50% chord position of the fin tip ($X = 304$ mm), but a mistake in the setup put the final measurement position at $X = 317$ mm instead. The computed autospectra show a speed dependent tone corresponding to the shedding frequency, which was previously compared to other measurement methods in Table 3. Above 3.4 m/s the shedding frequency tone appears to weaken, and completely dissipates at 3.8 m/s at the fin tip height ($Z = 230$ mm). Conversely, at the fin mid-span height ($Z = 115$ mm) the shedding frequency has weakened at 3.8 m/s, but a tone is still present though broadened. This indicates that a decrease in spanwise uniformity exists in the far-field of the cylinder wake. This caused more concern since the fluctuating lift estimates from the dynamic pressure were assuming a high spanwise coherence. A decrease in coherence will result in reduced tip deflections of the fin during Part 4 testing. This was a concern since due to the flow being on the edge of supercritical flow regime, increasing velocity could not be used to increase the fluid loading. According to open literature data, this intermittency and breakdown in the vortex shedding is related to the boundary layer over the cylinder transitioning from laminar to turbulent flow and will typically reestablish in the transcritical (fully turbulent) Re_D regime around 4,600,000 (which would require a velocity increase larger than possible with the current tunnel). Consequently, these measurements supported the decision to roughen the cylinder leading edge, which will give us the ability to vary the fluid loading by varying velocity.

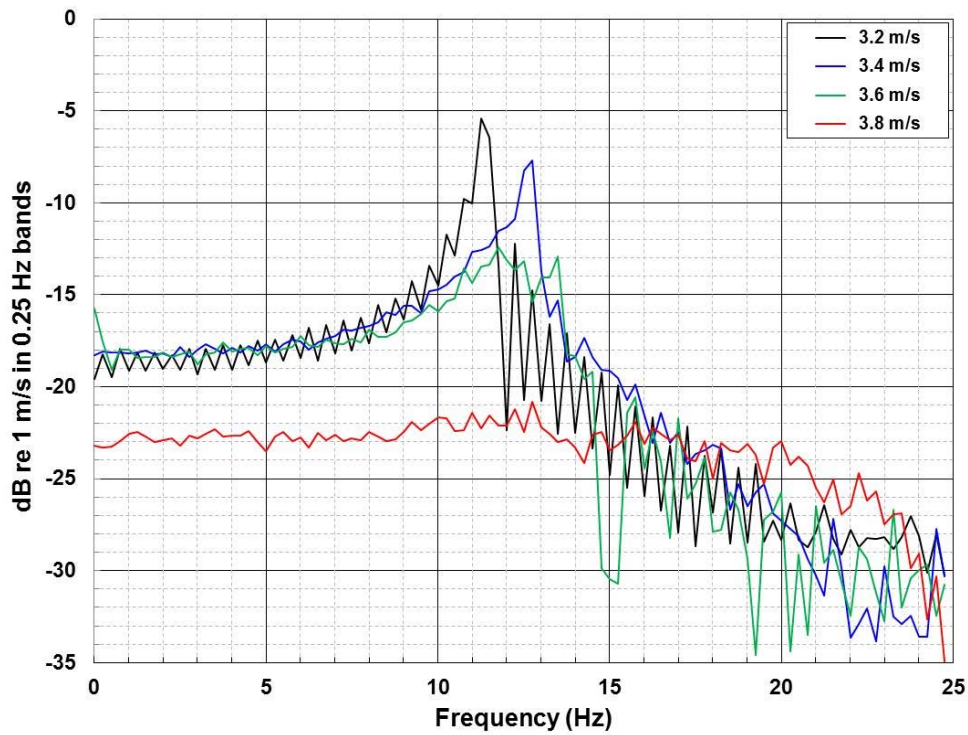


Figure 31. LDV cross-stream velocity (V) spectra measured at a single downstream location near the fin location ($X = 317$ mm), centered in the tunnel ($Y = 0$ mm) and at the fin tip height ($Z = 230$ mm). Data was acquired of a range of tunnel test section velocities.

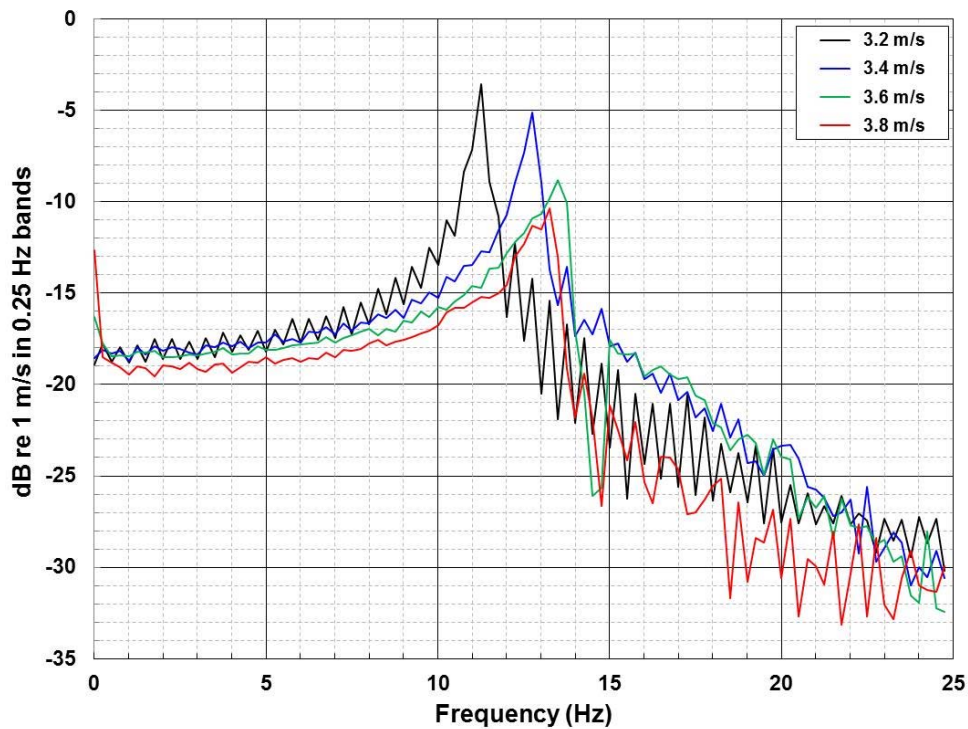


Figure 32. LDV cross-stream velocity (V) spectra measured at a single downstream location near the fin location ($X = 317$ mm), centered in the tunnel ($Y = 0$ mm) and at the fin tip height ($Z = 115$ mm). Data was acquired of a range of tunnel test section velocities.

3.4.2 Phase-averaged results

The flow-field was also characterized within the region where the fin would be mounted with the PIV system. Since Part 2a was performed prior to acquiring the high-speed PIV system, the results were phase averaged as described earlier. Several phase-averaged vector fields are shown in Figure 33, with each phase-average result being produced from 500 individual realizations at a given phase delay. These vector-fields show the phase-averaged velocity vectors (U_{ph} , V_{ph}) subtracted from the average velocity vectors (U , V), which this helps to identify the vortical structures passing through the field of view. All the measurements shown were acquired at the fin mid-span height ($Z = 115$ mm), though measurements were also acquired near the fin tip ($Z = 188$ mm; measurements of the fin tip height could not be performed due to optical access limitations). The background color in each image corresponds to the cross-stream velocity component, which illustrates that the resulting fluid loading if the fin were installed switches direction in a periodic fashion. For a reference in the upper left vector field, a sketch of the fin profile at the mid-span height is provided to help illustrate the FOV relative to where the fin was to be installed. Of note is that near the fin position the PIV results appear to be noisier in a circular region around the fin. This was due to the plug used to fill the hole for mounting the fin was extremely reflective and as a result reflected more undesirable light to the imager. The same problem was present even when the fin was installed, but some steps were taken to minimize the effect after seeing the results from this part of the experiment.

The left column in Figure 33 corresponds to measurements at $V_{ref} = 2.8$ m/s. Measurements were made with a delay time between 5 and 110 ms in 5 ms increments, though only a subset of these vector fields are shown. Shown is one full period for the 2.8 m/s velocity, which the estimated shedding frequency from the 110 ms period would be 9.1 Hz. The right column shows results from the same time delays but at a velocity of $V_{ref} = 3.6$ m/s. These measurements were acquired from 3 to 120 ms time delay in 3 ms increments. Consequently there was not a measurement at 110 ms for this

velocity, but 111 ms was included instead. Here it is obvious that the vortical structures at the higher velocity condition convect downstream more rapidly as each time step shown is nearly half a period (i.e. the red and blue structures switch sides in each step). Tracking of the vortical centers of the structures shows that the shedding frequency is ~ 13.8 Hz (period ~ 72.3 ms). This estimate closely matches the results from the accelerometer, dynamic pressure and LDV system provided in Table 3 for the same velocity. Results from the plane close to the fin tip ($Z = 188$ mm), show an oscillating flow pattern, but it is not nearly as coherent as the measurements acquired at the mid-span height. This is consistent with the spectral data acquired with the LDV system at the fin mid-span and fin height locations at higher velocities.

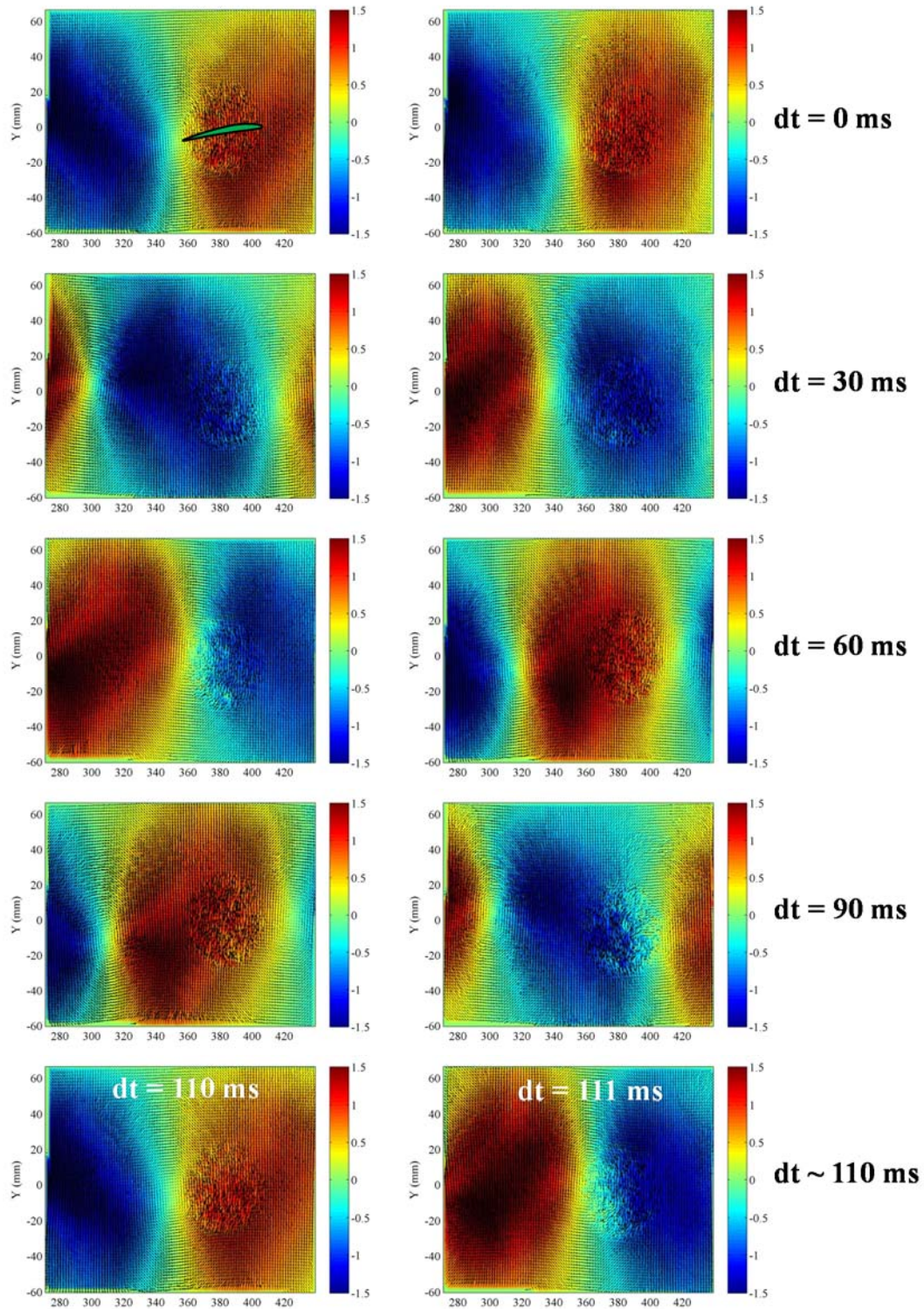


Figure 33. Phase-averaged velocity vector field minus the average velocity vector field for the smooth cylinder only (Part 2a) at the fin mid-span height ($Z = 115$ mm) with the flow from left to right in each field. The contour colors correspond to the average cross-stream velocity (V). Data was acquired at (left column) $V_{\text{ref}} = 2.8$ m/s and (right column) $V_{\text{ref}} = 3.6$ m/s, which have corresponding shedding frequencies of 9.1 Hz (period = 110 ms) and 13.8 Hz (period = 72.3 ms), respectively. The triggering delay times shown are only a subset of the total acquired. For reference a sketch of the fin profile is provided as a reference to where in the FOV it would be located during the forced fin testing.

A cross-stream profile was extracted from the acquired velocity fields at $X = 310$ mm to make a more detailed assessment of the resulting flow-field. The profiles were averaged over a 5 mm segment in the X-direction at the $V_{\text{ref}} = 3.6$ m/s velocity and at the mid-span height ($Z = 115$ mm). Figure 34 shows the cross-stream profile of the phase-averaged streamwise velocity (U_{ph}) minus the average streamwise velocity (U). The markers are colored based on the delay relative to the first row of images in Figure 33 (i.e., $dt = 0$ ms). Noting that at this test velocity the shedding frequency was estimated at 13.8 Hz, which gives a period time of ~ 72 ms, the color spectrum spans approximately one period. It shows that an increase above the mean on one side of the cylinder is accompanied by an equal decrease on the opposite side of the cylinder and vice versa.

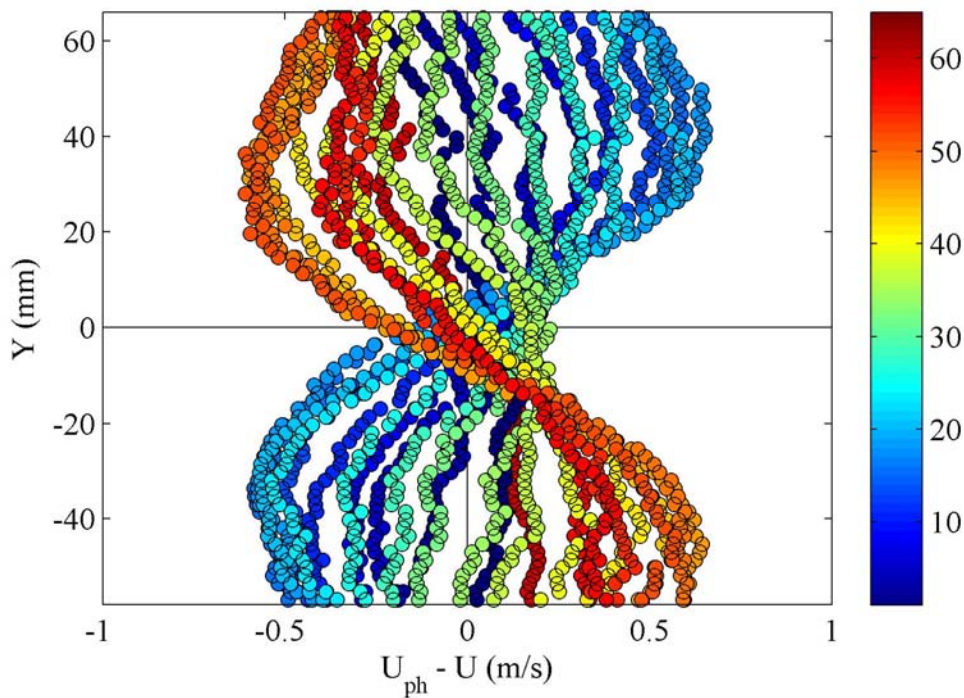


Figure 34. Phase-averaged streamwise velocity (U_{ph}) minus the average streamwise velocity (U) plotted versus the spanwise direction (Y). Profiles were acquired at the fin mid-span height ($Z = 115$ mm) and $X = 310$ mm with a tunnel test section velocity $V_{\text{ref}} = 3.6$ m/s. The marker colors denote the delay time in milliseconds, and the approximate period based on the shedding frequency for this velocity is ~ 72 ms.

Cross-stream profiles of the phase-averaged cross-stream velocity (V_{ph}) minus the average cross-stream velocity (V) are plotted in Figure 35. These profiles were acquired at the same tunnel

velocity ($V_{\text{ref}} = 3.6$ m/s) and extracted from the same location ($X = 310$ mm, $Z = 115$ mm). The marker colors once again show the delay time in milliseconds relative to the first row of images in Figure 33 (i.e. $dt = 0$ ms). Once again the period of ~ 72 ms is apparent from the figure as the (darkest blue) 0 ms data are nearly identical to the (darkest red) 72 ms data. These profiles show that the largest cross-stream velocity oscillation occurs at the tunnel center ($Y = 0$ mm), the majority of the time the velocity is at one of the extrema (rapidly passes through the zero condition) and the oscillations are in phase with the shedding frequency. Furthermore, the magnitude of the deviation from the mean velocity is greater for the cross-stream velocity component than for the streamwise component.

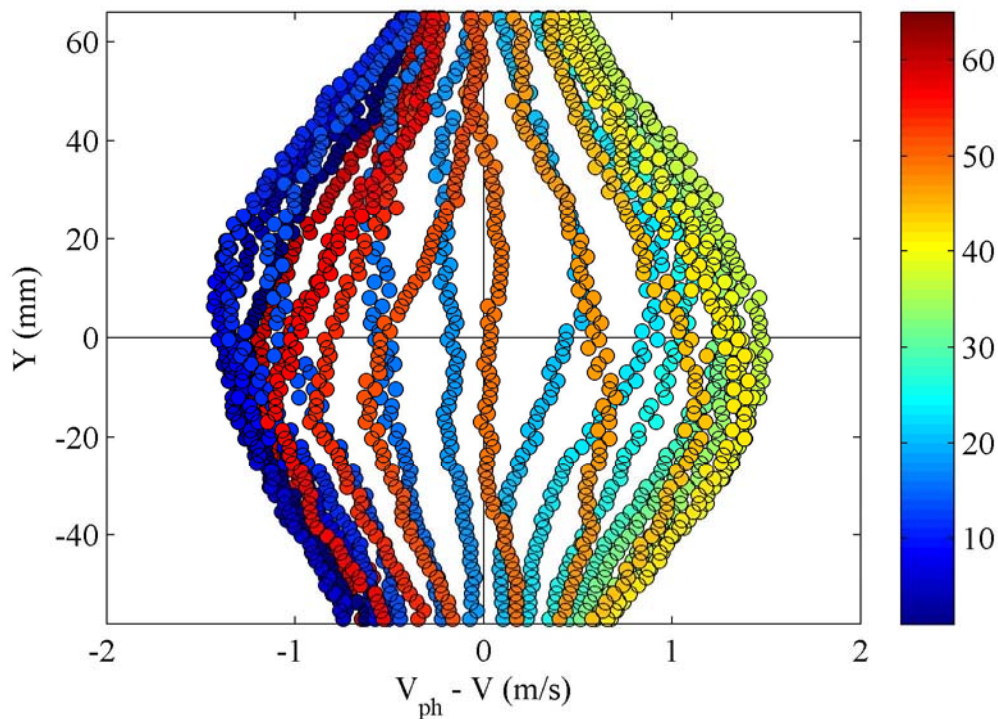


Figure 35. Phase-averaged cross-stream velocity (V_{ph}) minus the average cross-stream velocity (V) plotted versus the spanwise direction (Y), $V_{\text{ref}} = 3.6$ m/s. The test condition, measurement location and marker colors are identical to Figure 34. For this condition the shedding frequency was nominally 13.8 Hz, which gives a period time of ~ 72 ms.

Finally the results from Figure 34 and Figure 35 can be combined by looking at the phase-average effective angle-of-attack, which is defined as the angle determined from the arctangent of the cross-stream velocity component (V_{ph}) divided by the streamwise velocity component (V_{ph}). This

provides a measure of the change in the flow direction for a given phase within a period of oscillation. The resulting effective angle of attack determined from the profiles shown in Figure 34 and Figure 35 are provided in Figure 36, using the same marker color scheme. This shows that in the center of the tunnel ($Y = 0$ mm) the effective angle of attack varied between $\pm 30^\circ$ during a cycle. Noting that the fin was designed to be positioned at a -10° angle with respect to the streamwise direction, the instantaneous angle-of-attack experienced by the fin would be varying between -40° and $+20^\circ$ during each cycle.

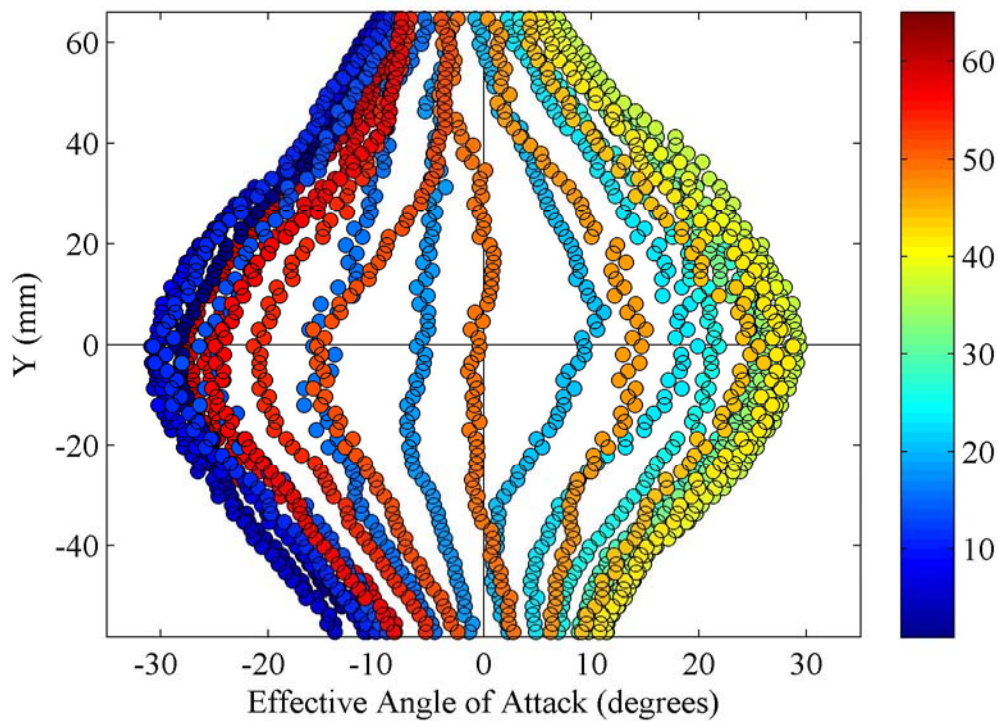


Figure 36. The effective angle of attack determined for the same conditions shown in Figure 34 and Figure 35. The effective angle of attack was determined from taking the arctangent of the cross-stream phase-averaged velocity component (V_{ph}) divided by the streamwise phase-averaged velocity component (U_{ph}), $V_{ref} = 3.5$ m/s.

4 Part 2b – Rough Cylinder Only

The second configuration considered is the flow generated by a roughened cylinder located upstream of the test section. The results from the smooth cylinder only test in Section 3 showed that the required tunnel velocity range fell within the critical Reynolds number regime of the cylinder, resulting in dissipated vortex shedding and significantly reduced lift forces at the fin tip location. Thus to achieve greater repeatability and control at the higher test velocities, it was decided to trip the cylinder boundary layer at the leading edge and force the flow into the transcritical regime, providing greater control over the fin forcing required to achieve maximum deflection at the tip region. Please note the rough cylinder only test was conducted after the forced fin test (Part 4) detailed in Section 5.

4.1 *Experimental methods*

This section describes details of the test facility, roughened cylinder geometry, measurement instrumentation and test matrix.

4.1.1 Test facility

The experiment was conducted in the 12-inch re-circulating water tunnel at the Pennsylvania State University Applied Research Laboratory, schematically shown in Figure 1. The tunnel is powered by a 112 kW motor and has either a cylindrical or rectangular test section. For the current study the cylindrical test section was used, which has an inlet diameter of 0.305 m (12-inch) and is 0.76 m long. The test section is designed such that the diameter gradually increases from the inlet to a maximum diameter of 307 mm at the test section outlet. This gradual increase in diameter is designed to minimize the influence that boundary layer growth on the tunnel walls has on the local free-stream velocity. Throughout testing the tunnel pressure was maintained at 138 kPa, though the absolute pressure can be varied from 20 to 414 kPa. The empty test section flow-field (Part 1) was measured at

velocities between 2.6 and 14.8 m/s, though higher velocities are possible with this facility. The empty test section measurements showed that the free-stream turbulence levels within the test section were below 1% (minimal measurable range for the acquisition system). Historical data acquired in this facility indicates that the empty test section free-stream turbulence level is below 0.3%. These measurements also confirmed that within the range of interest for the current study there was minimal increase in the free-stream velocity due to boundary layer growth on the tunnel walls. Additional tunnel details can be found in Madavan *et al.* (1984, used the rectangular test section), Deutsch & Castano (1986) and Fontaine & Deutsch (1992).

4.1.2 Test model (roughened cylinder)

The test model for Part 2b was the same 60 mm diameter cylinder used in Part 2a, which spanned the entire test section height. The cylinder's axis of rotation was located 49.5 mm downstream of the test section inlet ($X = 49.5$ mm) and centered in the cross-stream direction ($Y = 0$ mm). The same global coordinate systems used throughout the entire experiment was used (see Figure 10), which has X increasing in the streamwise direction with the origin at the test section inlet, Z aligned with the cylinder and increasing into the flow with the origin located at the fin base (11.4 mm inches above the tunnel floor) and Y completing the right-handed coordinate system with the origin located at the test section centerline. The only difference for the test model from Part 2a was that the leading edge of the cylinder was roughened, while the remainder of the cylinder surface remained hydraulically smooth. The cylinder leading edge was roughened between $\theta = \pm 50^\circ$ with 60-grit silicon carbide (Washington Mills), which has an average particle size of 254 μm . Here θ is the angle measured counterclockwise from the cylinder leading edge. The grit was attached to the cylinder surface with spar urethane (Helmsman, Miniwax). Images of the surface roughness as well as the smooth trailing edge of the cylinder are provided in Figure 37.

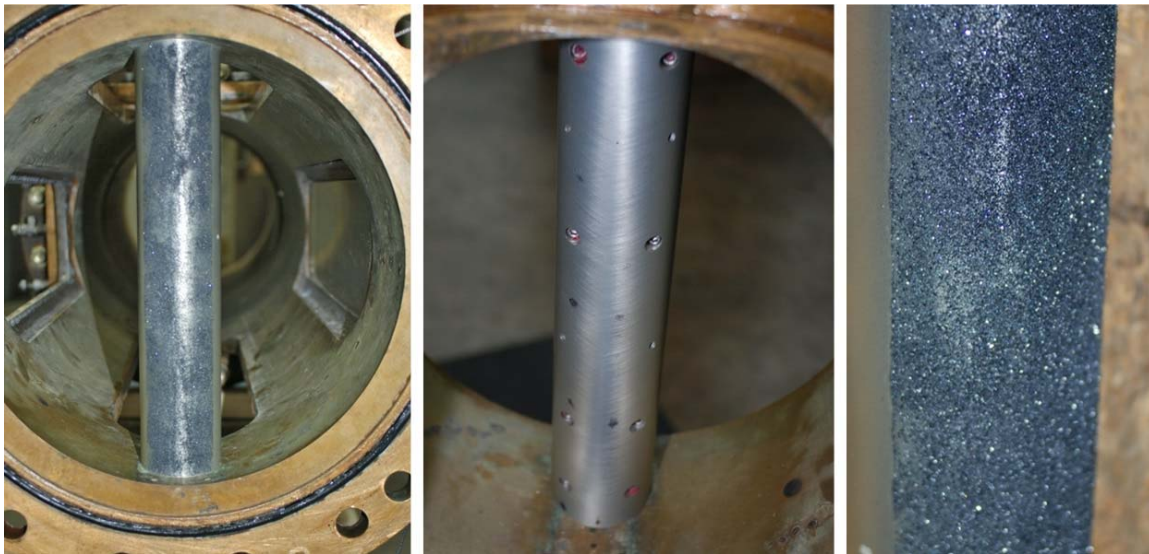


Figure 37. Images of the roughened cylinder used in Part 2b of the experiment. Shown is (left) the cylinder roughened leading edge while mounted in the tunnel, (center) the hydraulically smooth trailing edge of the cylinder while mounted in the tunnel and (right) a close up view of the surface roughness prior to installation in the tunnel.

The same instrumentation from Part 2a was mounted inside the roughened cylinder, though the cylinder was completely removed and disassembled between the two tests. The cylinder was instrumented with 4 dynamic pressure transducers, 2 static pressure ports and a single accelerometer mounted inside the cylinder. Unfortunately during the removal and reinstallation the accelerometer cable was damaged and no useful data was acquired from the accelerometer during this phase of testing. Figure 38 provides a picture of the cylinder opened exposing the inside, which houses the instrumentation. The dynamic pressure sensors were located at $\theta = \pm 130^\circ$ at either the fin tip height ($Z = 230$ mm) or the fin mid-span height (115 mm), and at each of these heights a single static pressure port was located at $\theta = 180^\circ$. As can be seen in the picture of the cylinder interior, the dynamic pressure sensors had to be inserted at an angle, which results in the sensor head being recessed within a small cavity on the aft cylinder surface rather than flush to the surface as preferred.

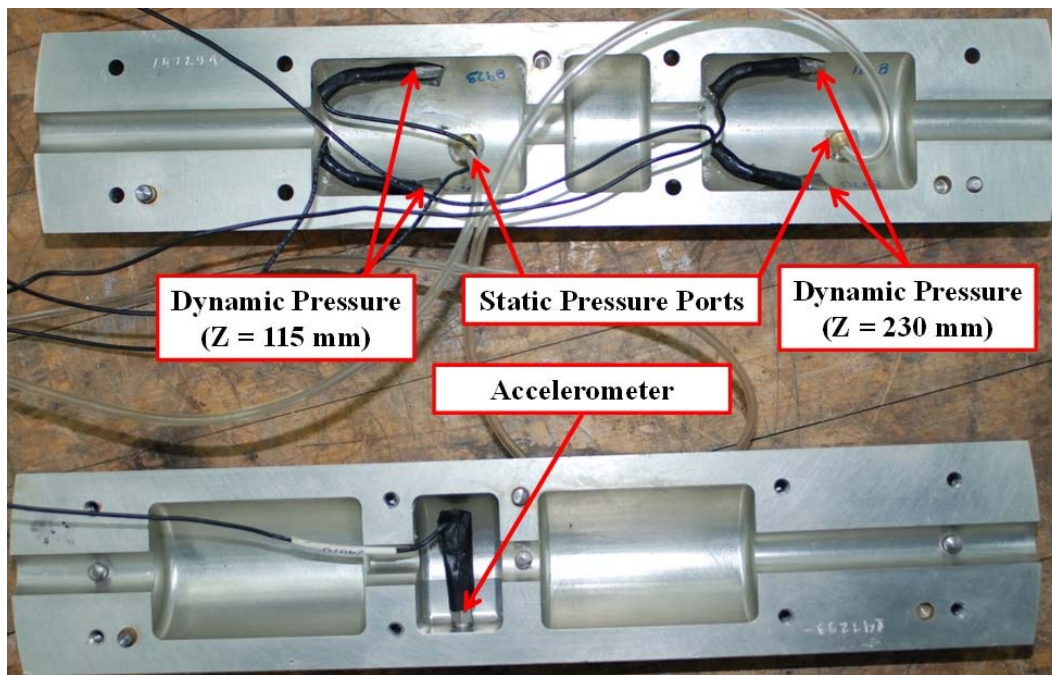


Figure 38. The inside of the cylinder showing the mounted instrumentation. The dynamic pressure sensors and static pressure ports are mounted in the (top) downstream half of the cylinder while the accelerometer was mounted in the (bottom) leading edge half.

4.1.3 Instrumentation

Sensors including pressure transducers and accelerometers were added to the cylinder to help characterize the source flow emanating downstream from the cylinder. This section describes the types and locations of the sensors. Additionally, PIV was also performed downstream of the cylinder.

4.1.3.1 *Cylinder instrumentation (dynamic pressure and static pressure)*

Four dynamic pressure transducers (105C02, PCB) were mounted in the cylinder. Two were positioned at the height corresponding to the fin tip ($Z = 230$ mm) and two at the height corresponding to the mid-span of the fin ($Z = 115$ mm). As shown in Figure 10, the dynamic pressure sensors were positioned at $\pm 50^\circ$ from the trailing edge of the cylinder ($\theta = \pm 130^\circ$). These sensors were used to measure the shedding frequency from the cylinder. Two static pressure ports were also mounted in the cylinder. Similar to the dynamic pressure transducers, the static pressure ports were positioned at the

fin tip height ($Z = 230$ mm) and fin mid-span height ($Z = 115$ mm). However, the azimuthal position was at the cylinder trailing edge ($\theta = 180^\circ$). The ports were plumbed to small tubing that was taken out of the tunnel with the use of a tee-junction box. The same tee-junction box was used to get the dynamic pressure transducer wires out of the tunnel. Each of the static pressure lines were then plumbed to a pressure transducer (dxd-series, Heise). The dynamic pressure transducers were powered with integrated circuit piezoelectric (ICP) power supplied either internally through the data acquisition system or externally with an ICP sensor signal conditioner (480B21, PCB Piezotronics). The outputted signals were then captured with a dynamic acquisition card (cDAQ-9178, National Instruments) and recorded with commercial acquisition software (LabView, National Instrumentation). The static pressure signals were recorded within the same acquisition program, but through a separate acquisition card (USB-6259, National Instruments).

4.1.3.2 High-speed PIV

High-speed particle image velocimetry (PIV) was acquired in the double-frame double-pulse mode, which requires the laser to be operated at the maximum laser power (diode current = 46 amps). Image pairs separated in time between 110 and 500 μ s were acquired at 1,000 Hz (i.e. a total of 2,000 images were acquired each second, which produced 1,000 vector fields). Table 5 provides a summary of the conditions tested and the total number of image pairs acquired. While the system is capable of acquiring 3D velocity measurements, optical access limited the arrangement to only acquiring two-components of velocity (X and Y velocity components) in a two-dimensional plane. The two-dimensional plane was located at $Z = 188$ mm with a field of view spanning $X = 145$ to 385 mm and $Y = -80$ to 85 mm. The same plane was used for acquisition with and without the fin installed in the tunnel. The plane was illuminated with a light sheet that entered the flow from the + Y side of the tunnel and was positioned at vertical position closest to the fin tip as optical access would allow ($Z = 188$ mm). The sheet was formed with the beam of a high-speed pulsed Nd:YLF diode pumped laser

(DM50-527, Photonics Industries) in the single head configuration. The laser is designed for a max energy per pulse at 1 kHz, but has a maximum repetition rate of 10 kHz. The energy per pulse at 1 kHz is 50 mJ with a pulse width of ~ 120 ns. The laser was mounted on the 3-axis linear traversing table used for LDV measurement, which had less than 50 μm (minimum measureable distance) relative motion between it and the test section. The green light beam (wave length = 527 nm) produced has a nominal diameter of 4.5 mm and a divergence of 8 mrad. The beam was then formed into a laser sheet with the use of an adjustable focus lens (KL-S0-277, LaVision) and a -10 mm focal length cylindrical lens. The pulse energy had to be adjusted to produce uniform light intensity in each acquired image, which the final setup had 70% energy in pulse 1 and 30% energy in pulse 2. The light was scattered in the flow with the use of hollow glass sphere particles (iM30K Glass Microspheres, 3M), which have an average diameter of 18 μm . The scattered light was then imaged with a 1280 $\times$ 800 pixel CMOS sensor high-speed camera (v1610, Phantom) fitted with a 28 mm lens (EF28mm f/1.8 USM, Canon). The images were spatially calibrated by imaging a 100 $\times$ 100 mm 3D PIV calibration target (106-10, LaVision) aligned with the laser sheet. The target consisted of a 100 $\times$ 100 mm rectangular grid of 2.2 mm diameter dots spaced 10 mm apart. The target has two planes separated by 2 mm for 3D calibrations, but this was not required for the current effort.

A minimum of 3,000 image pairs (3 seconds at 1 kHz) was acquired for each test condition measured. An average image produced from 99 images acquired close to the given image was subtracted from the raw PIV images, which significantly improved clarity of the PIV particles relative to the background. These average subtracted images were then processed using standard cross-correlation techniques (DaVis 8, LaVision) with multiple passes to produce an instantaneous velocity vector field. Each pass reduced the interrogation window, which had a final size of 24 $\times$ 24 pixels with 75% overlap. This produced a final vector spacing of 1.4 mm. The estimated PIV uncertainty, including calibration uncertainty and statistical uncertainty is approximately ± 2 % of the mean value.

Table 5. Tunnel impeller frequency, test section reference velocity, repeated conditions and the total number of image pairs (i.e. vector-fields) acquired during high-speed PIV acquisition during the rough cylinder only testing (Part2b). All the measurements were acquired in a single plane located at $Z = 188$ mm, which was the closest position to the fin tip that had sufficient optical access. The data rate for all the measurements was 1 kHz.

f_{imp} (rpm)	V_{ref} (m/s)	Test Runs	Total Image Pairs
58	2.5	test 79 (run 26, 38)	6,000
69	3.0	test 79 (run 11)	3,000
77	3.3	test 79 (run 44)	3,000
80	3.4	test 79 (run 17, 54)	6,000
84	3.6	test 79 (run 2, 34, 77)	21,000
140	6.0	test 79 (run 66)	3,000

4.1.3.3 Tunnel monitoring

The tunnel was regularly monitored during testing and the tunnel data were simultaneously acquired along with the cylinder monitoring data as well as the triggering time when high-speed PIV was being acquired. Tunnel monitoring measurements included water temperature, total pressure and static pressure. Unfortunately, the impeller frequency measurement stopped working during testing and it was not caught until after the experiment was completed. The tunnel temperature measurement was used to determine the water properties including density, viscosity and vapor pressure. The total pressure was measured with a Kiel probe mounted upstream of the test section contraction. The tunnel diameter at the position where the total pressure was measured was 0.914 m (36 in). In this section a single static pressure measurement was also acquired, which provided a measure of the total volumetric flow rate. Additional static pressure ports were located along the length of the test section and used as real-time measurements of the tunnel velocity. Measurements were acquired at $X = 225$, 329, 434 and 538 mm, though the pressure transducer at $X = 434$ mm appeared to have been damaged. The pressure transducers at $X = 50$, 121 and 642 mm had also appeared to be damaged during prior tests and therefore were not recorded. The ports were located circumferentially 45 degrees from the

axis of the cylinder. Thus the average from the other three static pressure measurements was used to define the reference velocity measurement. The total and static pressure measurements were acquired with the same pressure transducers (dxd-series, Heise) used for the cylinder static pressure measurements.

Similar to Part 1 and 2a, the recorded pressure was determined from the difference between the output voltage and the no-flow voltage to minimize errors associated with zero velocity offsets between individual pressure transducers. Thus, at the start of every test a measurement of the tunnel pressure was acquired prior to starting the tunnel. The data acquisition system recorded the pressure in units of pounds per square inch (psi), which was converted to Pascal (Pa) using the conversion (1 psi = 6,894.76 Pa). The total pressure measurement was then combined with the local static pressure measurements to determine the local tunnel velocity using the relationship

$$U(X) = \sqrt{\frac{2(P_{total} - P_{static})}{\rho}}.$$

Here U is the local free-stream velocity at X where the static pressure measurement (P_{static}) was acquired, P_{total} is the total pressure and ρ is the water density. The tunnel reference velocity (V_{ref}) was then determined from the average of the measurements from $X = 225, 329$ and 538 mm.

4.1.4 Test matrix

During the rough cylinder only testing (Part 2b) the only flow parameter varied was the tunnel impeller frequency, which was varied between 46 and 161 rpm (speeds below 58 rpm could not be regularly achieved). The corresponding tunnel test section velocities ranged from 2.0 to 6.9 m/s. The primary speeds where the majority of measurements were acquired were at 58, 69, 77, 80 and 84 rpm, which have a corresponding test section velocity of 2.5, 3.0, 3.3, 3.4 and 3.6 m/s. During Part 2b of testing the water temperature ranged from 20.1 to 21.0 °C, which results in a corresponding kinematic water viscosity (ν) of 9.8×10^{-7} to 10^{-6} m²/s, respectively. The average water temperature was 20.5 °C,

which results in a water kinematic viscosity and density of $9.9 \times 10^{-7} \text{ m}^2/\text{s}$ and 998 kg/m^3 , respectively. Continuous measurements acquired include the cylinder static and dynamic pressure, tunnel total and static pressure and water temperature. Due to an instrumentation malfunction that went undetected until after the conclusion of the experiment, the tunnel impeller frequency was not measured. For a subset of conditions high-speed PIV was acquired for the cylinder wake region extending from 65 to 305 m downstream from the trailing edge of the cylinder.

4.2 Tunnel Velocity

As was done in Parts 1 and 2a, the reference velocity (V_{ref}) was defined as the average velocity determined from static pressure measurements at $X = 225, 329$ and 538 mm . Consequently the reference velocity is a measure of the mean free-stream velocity within the tunnel test section. These transducers were chosen early during testing because they span the downstream location where the fin would eventually be installed. Figure 39 shows the reference velocity measurements as a function of tunnel impeller frequency (f_{imp}). Unfortunately due to an instrumentation malfunction prior to acquire the rough cylinder data (Part 2b), the tunnel impeller frequency was not properly recorded with the other acquired data, including the reference velocity. Consequently, the plot was produced by plotting the reference velocity versus the target impeller frequency, which was known from the experiment notebook. Since the rough cylinder data was acquired immediately after the forced fin testing (Part 4) was completed, a comparison was made between the target frequency (notebook) and the actual measured tunnel frequency for Part 4. The difference between the target and actual tunnel frequency was typically below 0.2 rpm , and the maximum observed was 0.4 rpm . Thus the target tunnel frequency is a reasonably accurate estimate of the actual tunnel frequency ($< 0.4\%$).

The data spans from 46 to 161 rpm and was linearly fitted to

$$V_{ref} = 0.0425 f_{imp} + 0.0411. \quad (\text{Part 2b})$$

For comparison the linear curve fitted data from the empty test section,

$$V_{ref} = 0.0504 f_{imp} - 0.1636, \quad (\text{Part 1})$$

and from the smooth cylinder only (Part 2a),

$$V_{ref} = 0.0497 f_{imp} - 0.5509, \quad (\text{Part 2a})$$

are also included. Relative to the empty test section data, the rough cylinder produces a lower reference velocity at a given tunnel impeller frequency. This shows that the introduction of the blockage due to the cylinder increases the overall system losses, which ultimately requires a higher impeller frequency to achieve a given test section velocity. However, unlike with the smooth cylinder, the slope had a significant change compared to the empty test section, which indicates that the dynamics with the rough cylinder are more complex. This is apparent when comparing the smooth and rough cylinder linear curve fits. As is typical with surface roughness, the losses generated at higher velocities increase relative to the smooth surface with increasing speed (i.e. the reference velocity decreases at a given impeller frequency). However, at the lowest speeds tested the losses are reduced relative to the smooth cylinder data. This is likely due to the boundary layer being turbulent on the rough cylinder, which allows a greater pressure recovery on the aft end of the cylinder. This advantage is lost as the speed increases because the smooth cylinder boundary transitions to turbulent and the surface roughness losses increase rapidly with velocity. The reference velocity measured during Part 2b at each of the primary test velocities used during force fin testing (Part 4) are provided in Table 6. The table includes the target tunnel impeller frequency, average reference velocity, standard deviation of the mean reference velocity and the number of samples used to determine the average and standard deviation. The standard deviation of the mean is relatively low compared to other parts of the experiment, which is due in part to acquiring data in a relatively short period of time (days compared to weeks).

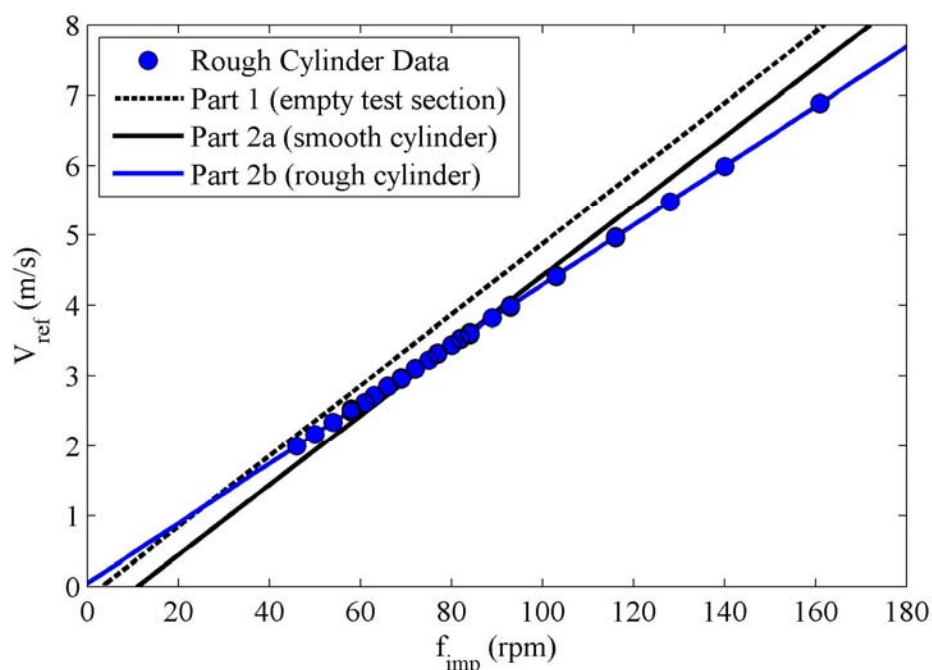


Figure 39. Tunnel test section reference velocity (V_{ref}) measured during Part 2b (rough cylinder only) plotted versus the tunnel impeller frequency (f_{imp}). The reference velocity was determined from the average of static pressure measurements at $X = 225, 329$ and 538 mm. The linear fit to data from the empty test section (Part 1), the smooth cylinder only (Part 2a) and the current rough cylinder only (Part 2b) are included for reference.

Table 6. During the rough cylinder only testing (Part 2b) the tunnel impeller frequency was varied between 46 and 161 rpm. Provided here are the average tunnel velocity, standard deviation of the average tunnel velocity and the number of repeated measurements for the primary tunnel velocities used during Part 2b. Due to an instrumentation malfunction the tunnel impeller frequency was not measured during this part of the experiment. The frequencies shown are based on the target frequency, which based on data acquired during the forced fin part of testing (Part 4) the difference between the target and the actual frequency was typically below 0.2 rpm.

f_{imp} (rpm)	V_{ref} (m/s)		Samples
	AVG	STD	
58	2.51	0.013	7
69	2.97	0.006	6
77	3.32	0.006	7
80	3.44	0.004	7
84	3.60	0.009	9

4.3 Cylinder Pressure

Applying roughness to the cylinder is expected to modify the flow field and delay separation around the cylinder. This modified flow will result in an adjusted static and dynamic pressure distribution. With the same sensors installed as with the smooth cylinder, the static base pressure and dynamic pressure measurements are compared to the smooth cylinder pressures.

4.3.1 Static base pressure

As stated in Part 2a, the static base pressure coefficient ($C_{pb} = \Delta P_b / 0.5\rho U^2$) is a common parameter historically used to define the cylinder behavior because it is directly related to the drag on the cylinder, but significantly easier to measure than drag. Here ΔP_b is the difference between the pressure at $\theta = 180^\circ$ (i.e. the static base pressure) and the local static pressure, ρ is the fluid density and U is the local free-stream velocity. The coefficient can be rewritten as the ratio of the difference in the base and static pressures to the difference in the total and static pressures. In the current study the static base pressure was measured at two vertical locations on the cylinder ($Z = 115$ and 230 mm), which were selected because they correspond to the heights of the fin at the mid-span and the tip. The static base pressure coefficient results with the roughened cylinder leading edge ($\theta = \pm 50^\circ$) are plotted in Figure 40 versus cylinder-diameter-based Reynolds number. As with the smooth cylinder results (Part 2a), the Reynolds number was computed with the blockage effect correction. Here the Reynolds number is defined as $Re_D = U_{cor}D/\nu$, where D is the cylinder diameter (60 mm), ν is the kinematic viscosity of water, U_{cor} is the reference velocity corrected for the blockage effect ($V_{ref} A_{ts}/(A_{ts}-A_B)$), A_{ts} is the test section cross sectional area and A_B is the projected area of the cylinder ($0.06\text{ m} \times 0.305\text{ m} = 1.83 \times 10^{-2}\text{ m}^2$). In the current study the blockage effect results in a velocity increase of 1.334 with respect to the measured reference velocity.

The current data shows minimal variation between spanwise locations except for at the lowest velocities tested. The figure also includes the representative smooth cylinder curve presented in Shih et

al. (1993), which there is an apparent difference in the trends between the smooth curve and the current data. The current results closely follow data presented in Nakamura & Tomonari (1982), which used a wire trip located at $\theta = 50^\circ$. The current ratio of particle size ($r = 254 \mu\text{m}$) to cylinder diameter ($D = 60 \text{ mm}$) is $r/D = 0.0042$, which is similar in range to the data from Nakamura & Tomonari (1982) that had $r/D = 0.0052$. However, the static base pressure sensitivity to surface roughness is more complicated than merely matching the particle to diameter ratio, which is illustrated in the figure by also plotting data from Nakamura & Tomonari (1982) with $r/D = 0.0052$ but with the entire surface roughened. This fully rough surface produced significantly different results relative to the current study and the wire tripped data of Nakamura & Tomonari (1982). The overall conclusions from Nakamura & Tomonari (1982) looking at numerous methods of roughening cylinders in the Reynolds number range of the current study, showed that tripping near $\theta = 50^\circ$ produced the most consistent and flat results. This was the reason it was decided to roughen only the leading edge up to $\theta = \pm 50^\circ$, and the particle size was selected to closely match the results from Nakamura & Tomonari (1982). These results confirm the ultimate goal of roughening the cylinder leading edge, which was to minimize the Reynolds number dependence.

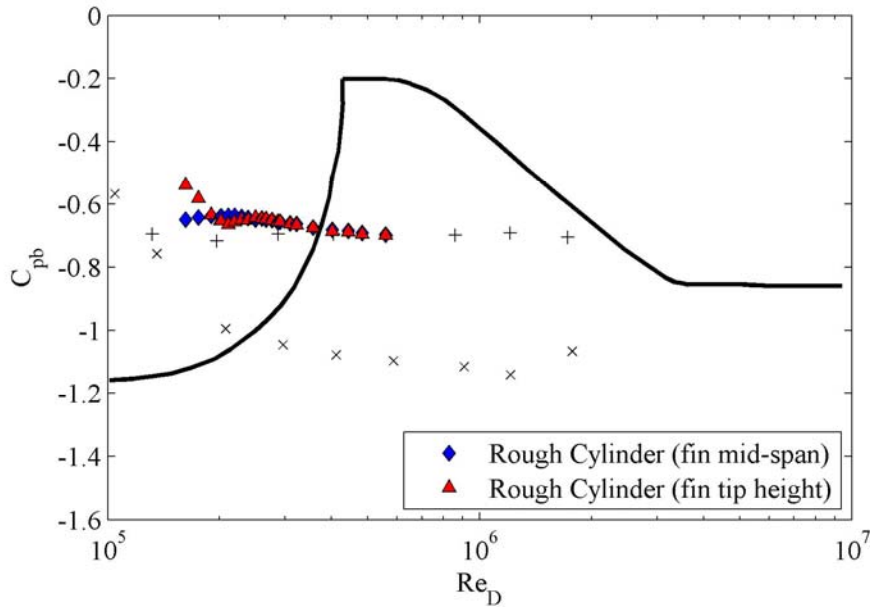


Figure 40. Static base pressure coefficient for the current cylinder with the leading edge ($\theta = \pm 50^\circ$) roughened with 254 μm grit particles plotted versus the cylinder diameter based Reynolds number corrected for blockage effects. Current data was acquired at two spanwise locations, fin mid-span ($Z = 115\text{ mm}$) and fin tip height ($Z = 230\text{ mm}$). Included for comparison is (solid curve) the representative smooth cylinder curve presented in Shih et al. (1993) and data at $r/D = 0.0052$ from Nakamura & Tomonari (1982); (+) wire trip located at $\theta = 50^\circ$ and (x) uniformly roughened over the entire surface.

4.3.2 Dynamic pressure

Similar to the smooth cylinder case, the dynamic pressure was measured on the roughened cylinder. In the following subsections, the sensors are compared to each other, the speed dependence is investigated and a comparison is made to the smooth cylinder data.

4.3.2.1 Cylinder pressure spectra

The cylinder dynamic pressure spectra from the rough cylinder at 2.95 m/s (Test 81) are shown in Figure 41. The figure includes spectra from the fin tip height ($Z = 230\text{ mm}$) and the fin mid-span height ($Z = 115\text{ mm}$) at $\theta = \pm 130^\circ$ as well as a representative electrical background spectrum from one of the sensors at 0 m/s. Similar to the smooth cylinder results, a peak is observed on the rough cylinder at the dominate shedding frequency (13 Hz), which is slightly higher for the rough cylinder than the smooth cylinder at the current test velocity. However, in addition to the shedding frequency peak there

are three additional peaks observed in all four pressure spectra at frequencies of 16, 17.1 and 18.6 Hz. Also, at the fin tip height ($Z = 230$ mm) the shedding frequency peak is barely above the broadband frequency content. Overall the amplitude associated with the shedding frequency is significantly reduced on the roughened cylinder compared to the smooth cylinder.

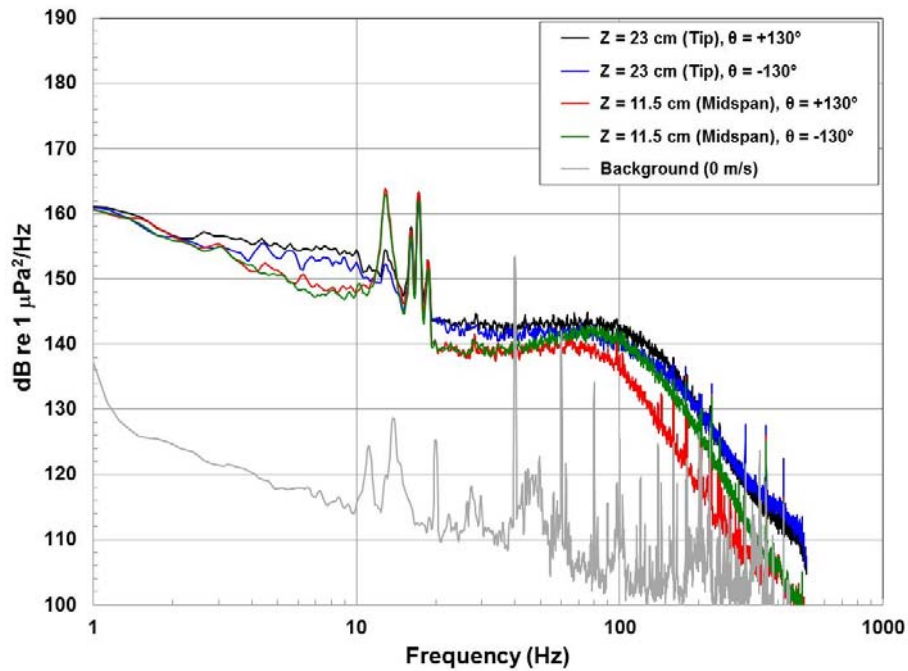


Figure 41. Pressure spectra from the cylinder with the roughened leading edge at 2.95 m/s test section velocity (Test 81). Spectra are shown from the fin tip height ($Z = 230$ mm) and the mid-span height ($Z = 115$ mm) at $\theta = \pm 130^\circ$. Also included for reference is the electrical background spectrum (0 m/s) from one of the sensors.

The three peaks are further investigated in

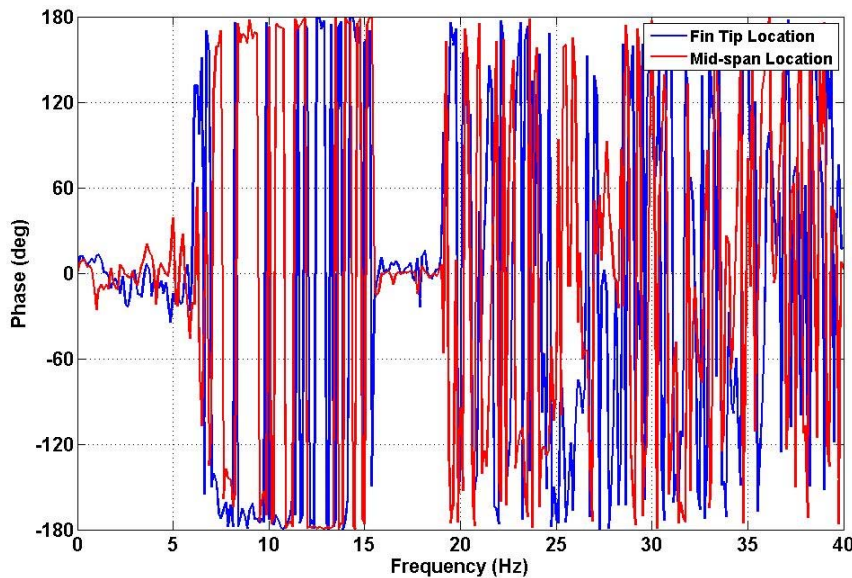


Figure 42, which (a) shows the computed cylinder lift and drag force components from the pressure measurements and (b) the cross-spectral phase between the cylinder pressures at the fin tip and mid-span locations. In Figure 42 (a) it is apparent that the three additional peaks only appear in the drag calculation and not in the lift, which is how the lower frequency peak was identified as the dominant shedding frequency. Figure 42 (b) shows that the cross-spectral phase is zero between the cylinder pressures at the higher three peak frequencies, also indicating that the force is a result of drag and not an out-of-phase fluctuating lift force. The peak frequency in the drag measurement is typically double that observed in the lift force, but the current results are not quite double and obviously more complex. Since the tunnel velocity was shown to be quite repeatability, the most likely cause of the observed complexity in the drag spectrum is spanwise variation. Fortunately, the fin loading is primarily dependent on the lift component, which does not exhibit the complex frequency content. It is also important to note here that the current shedding frequency peak is approximately 15 dB below those observed on the smooth cylinder. Careful inspection of the smooth cylinder results shows a noticeably reduced peak at close to double the dominant shedding frequency, which is associated with

the drag contribution. Those drag peaks are broad and noisy (some appear to have multiple peaks) and have levels comparable to those shown for the rough surface (~160 dB). Thus the primary question about the rough cylinder pressure spectra results is why the shedding frequency peak amplitude was so low. There are three likely possibilities; (1) reduced spanwise uniformity in the shedding separation point created by either local turbulence or non-uniformity of the surface roughness, (2) the transition to a turbulent boundary layer moves the separation point further downstream on the cylinder and potentially past the location of the dynamic pressure measurements and/or (3) the separation point moving downstream also narrows the vortex wake width and, consequently, a weaker periodic disturbance felt by the cylinder. It is difficult to separate these different phenomena without a detailed study of the flow around the cylinder, which was not done due to time limitations.

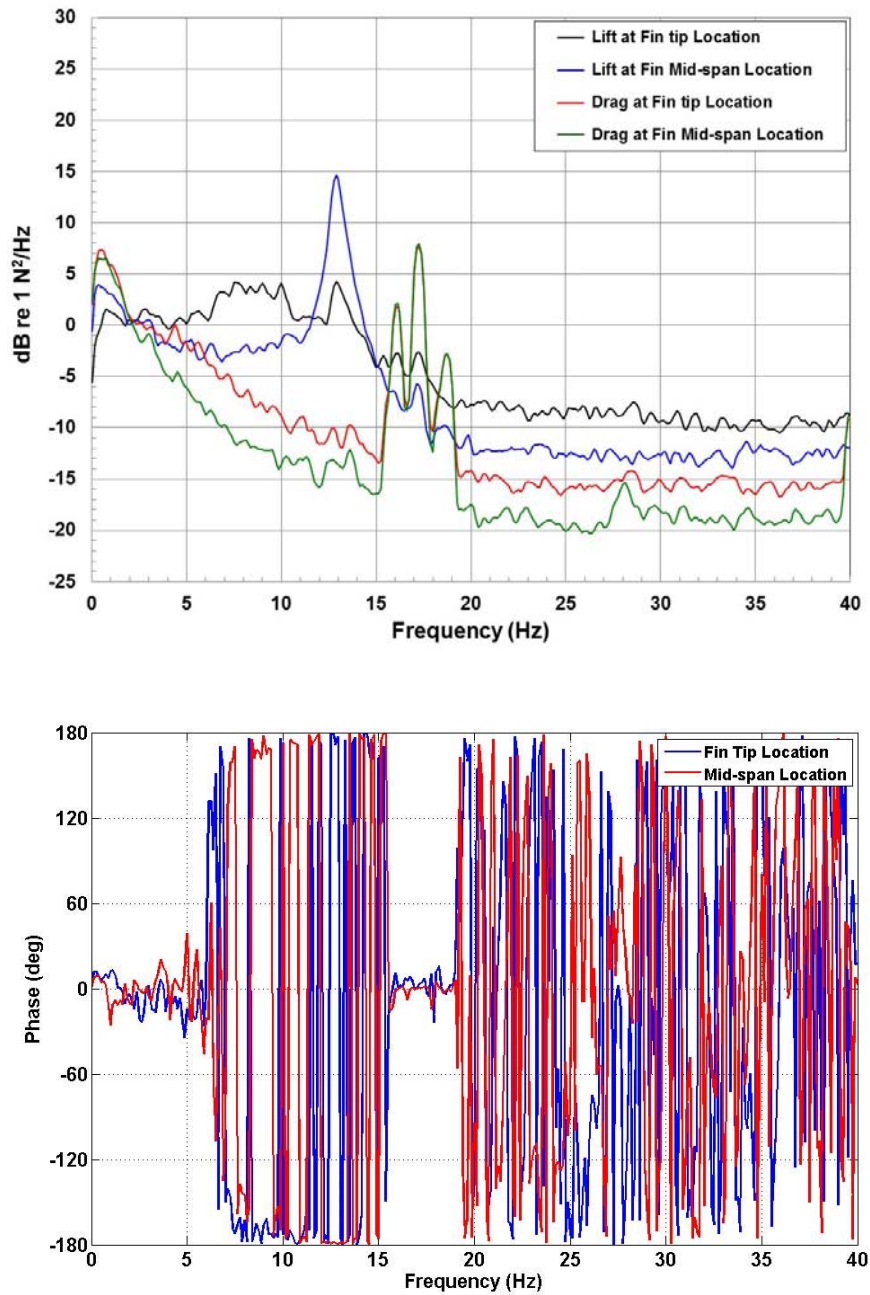


Figure 42. (a) Computed lift and drag force estimates on the rough cylinder from the pressure transducer measurements acquired at a test section velocity of 2.95 m/s (Test 81). (b) Cross-spectral phase of cylinder pressures at the fin tip and mid-span locations.

The possibility that spanwise non-uniformity was the cause for the multiple peaks observed in the drag measurement as well as the reduction in the shedding frequency amplitude can be inspected by looking at the coherence between the dynamic pressure measurements. Figure 43 shows the

coherence between the mid-span height and the tip height at $\theta = \pm 130^\circ$ as a function of frequency. Here the coherence at a given frequency is similar on each side of the cylinder (i.e. the curve for $\theta = 130^\circ$ is similar to the one for $\theta = -130^\circ$). The rough cylinder coherence associated with the fundamental shedding frequency at 2.95 m/s (13 Hz) is about 0.64 ($\theta = +130^\circ$) and 0.5 ($\theta = -130^\circ$), which is reduced compared to greater than 0.9 for the smooth cylinder. Conversely, the coherence associated with the drag force (peaks of 16, 17.1 and 18.6 Hz) is increased for the rough cylinder relative to the smooth cylinder. This suggests that the surface roughness reduces the spanwise coherence of the shedding vortices, which is expected as it is unlikely that with a rough turbulent boundary layer the separation point would be fixed along the entire cylinder span. This spanwise non-uniformity in the shedding apparently results in a semi-periodic loading of the cylinder in the flow direction. Only the decrease in the spanwise coherence should ultimately impact the fin loading.

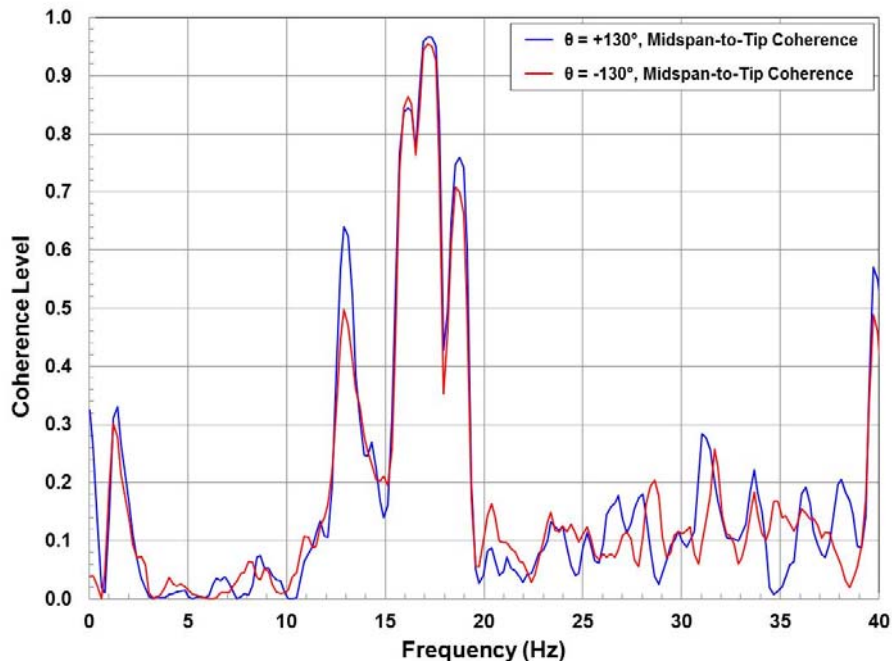


Figure 43. Spanwise coherence determined from the rough cylinder dynamic pressure sensors at 2.95 m/s. The coherence was determined between sensors at the fin tip height ($Z = 230$ mm) and the fin mid-span height ($Z = 115$ mm) at $\theta = \pm 130^\circ$.

4.3.2.2 Pressure spectra velocity dependence

Figure 44 shows the dynamic pressure power spectral density from several water tunnel velocities at the fin mid-span height ($Z = 115$ mm). These spectra were acquired during a single test run (Test 81). As with the smooth cylinder, the shedding frequency and level increases with increasing velocity. However, unlike the smooth cylinder pressure spectra that had the vortex shedding phenomenon dissipate near the critical Reynolds number, the rough cylinder pressure spectra continues to increase in the supercritical regime. This is illustrated with the measurement acquired at 6 m/s, which is significantly greater in velocity and resulted in a significant increase in shedding frequency and peak amplitude. However, the shedding frequency at this higher velocity is more broadband in nature, which is expected in the transcritical regime. In addition, the 6 m/s case does not appear to have the additional higher frequency peaks observed at the lower velocities. It is difficult to assess if this is due to the increased coherence of the shedding at the higher velocities or elevated fundamental frequency making the secondary peaks less pronounced.

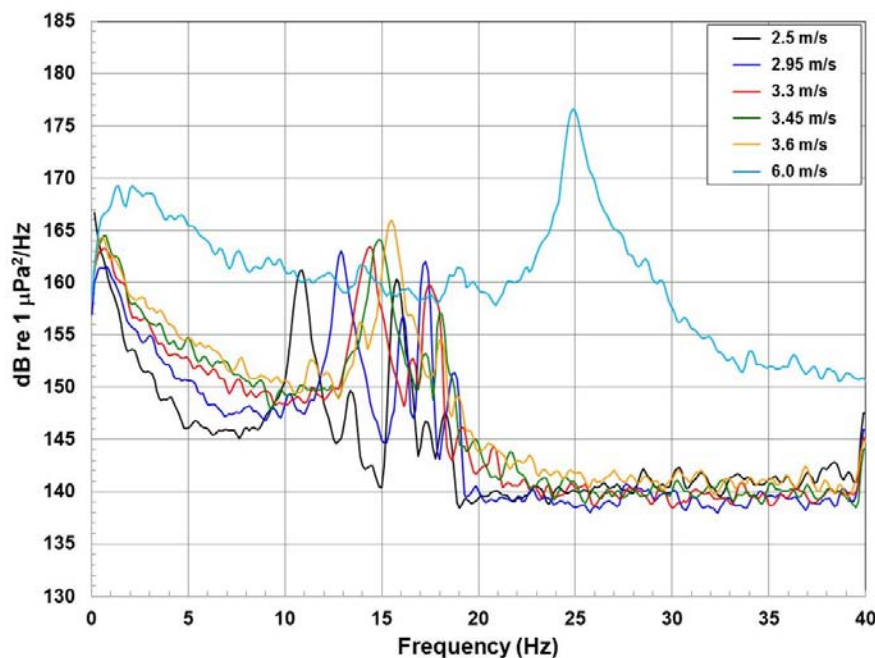


Figure 44. Pressure autospectra from the rough cylinder at the fin mid-span height ($Z = 115$ mm) and $\theta = -130^\circ$. The reference velocities shown in the legend correspond to the local velocity measurements within the test section.

4.3.2.3 *Comparison with smooth cylinder spectra*

The difference between the smooth cylinder and rough cylinder shedding frequency peak levels are compared in Figure 45. Here the computed shedding frequency rms lift force levels are plotted versus tunnel test section velocity from the dynamic pressure sensor pair located at the fin mid-span height ($Z = 115$ mm) for both the smooth (Test 2057) and rough cylinder (Test 81). As expected from the rough cylinder dynamic pressure spectra, a significant decrease in the roughened cylinder rms lift force levels relative to the smooth cylinder. As previously discussed, this decrease is due to either a decrease in the spanwise coherence or the boundary layer separation point moving further downstream (either beyond the dynamic pressure measurement location or enough to narrow the vortex wake and weaken the periodic disturbance). If it was due to a decrease in the spanwise coherence, then we would not have been able to produce the desired fin deflections at the expected velocity range. However at 6 m/s on the rough cylinder, the lift force is comparable to that observed on the smooth cylinder in the subcritical to critical regimes. Thus the surface roughness enables the vortex shedding to be present at higher velocities and if the forces on the fin were too weak to produce the desired deflections the tunnel velocity could simply be increased. As will be seen subsequently (Part 4), the desired deflections were achieved at the lower velocities, which indicate that this decrease is likely due to the boundary layer separation moving further downstream.

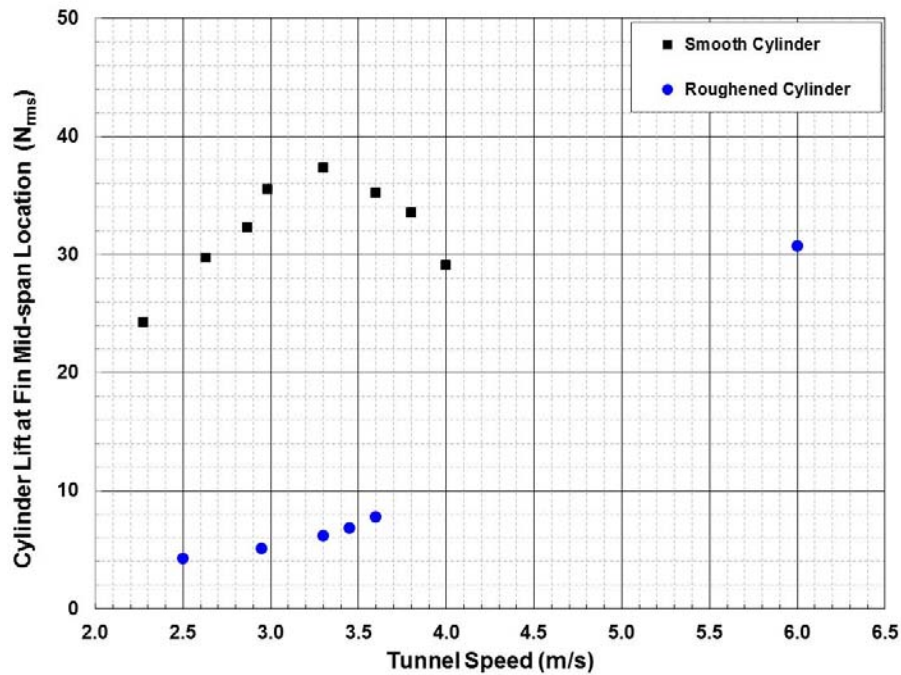


Figure 45. Shedding frequency rms lift force levels on the smooth and rough cylinder plotted versus the tunnel test section velocity. The lift force estimates were computed from the pressure transducer pair located at the fin mid-span height ($Z = 115$ mm).

4.3.2.4 Shedding frequency scaling

As in Part 2a, the peak vortex shedding frequency is scaled using the Strouhal number ($St = f_s D/U$), where f_s is the vortex shedding frequency, D is the diameter of the cylinder ($D = 60$ mm) and U is the characteristic velocity which for the current study is V_{ref} . The Strouhal scaling results for the cylinder with the leading edge ($\theta = \pm 50^\circ$) roughened with 254 μm grit particles are plotted versus the cylinder diameter based Reynolds (Re_D) in Figure 46. Here once again the Reynolds number velocity was corrected for blockage effects as was done for the scaling of the static base pressure coefficient results. The composite curve presented in Roshko (1961) for smooth cylinders is included for comparison, noting that in the current study no vortex shedding was observed for $Re_D \geq 3.3 \times 10^5$. The current results show significantly different behavior. The roughened cylinder data are nearly constant, as observed for smooth cylinder data in either the subcritical or transcritical regimes, and vortex shedding was observed at higher Reynolds number than possible without the trip. Also included in the

figure are Strouhal scaling data for the same data from Nakamura & Tomonari (1982) included in the rough cylinder static base pressure coefficient plot. The Nakamura & Tomonari (1982) data tripped the cylinder flow with either a 3.2 mm diameter wire at $\theta = 50^\circ$ or had uniformly distributed roughness over the entire cylinder surface, which both conditions result in $r/D = 0.0052$. Here r is the characteristic length associated with the roughness (particle size) or trip, and D is the diameter of the cylinder. For the current study the ratio of roughness size ($r = 254 \mu\text{m}$) to cylinder diameter ($D = 60 \text{ mm}$) is $r/D = 0.0042$, and the Strouhal scaling of the current data falls between the two Nakamura & Tomonari (1982) conditions. Overall this scaling further confirms the design choice of roughening the cylinder as it (1) is nearly Reynolds number independent and (2) vortex shedding can be achieved at higher velocities than possible on the smooth cylinder.

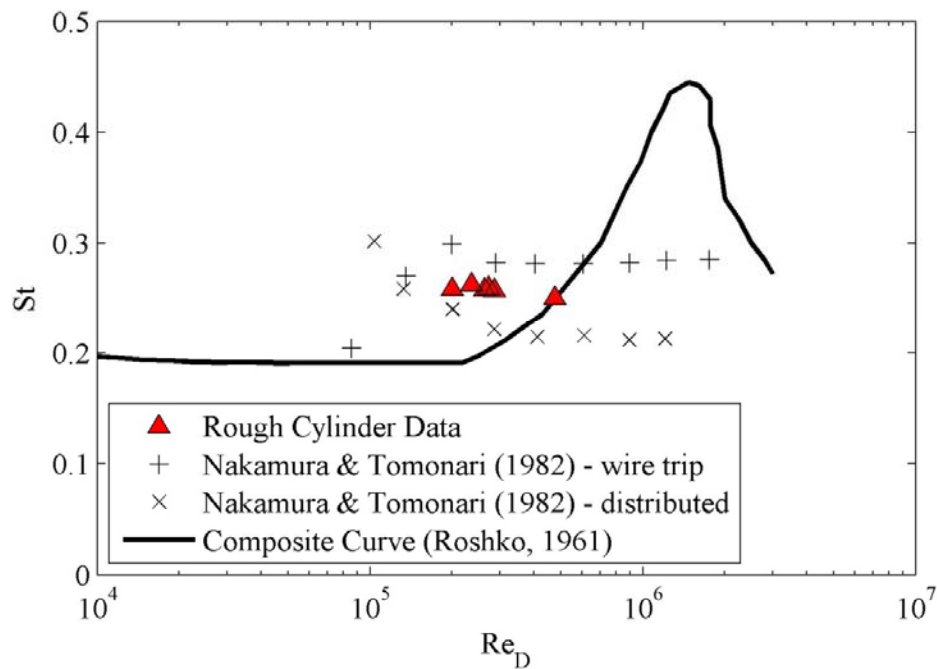


Figure 46. Strouhal scaling results for the cylinder with the leading edge ($\theta = \pm 50^\circ$) roughened with $254 \mu\text{m}$ grit particles. Included for comparison are data at $r/D = 0.0052$ from Nakamura & Tomonari (1982) with (+) a wire trip located at $\theta = 50^\circ$ and (×) uniform roughness distributed over the entire surface. Also included is the composite curve from Roshko (1961) showing the general trend of smooth cylinders.

4.4 Cylinder Wake

With a roughened cylinder, the flow field is expected to change from that of a smooth cylinder. To better understand the flow field, PIV measurements were measured behind the cylinder. The velocity field is measured in a region where the fin will eventually be positioned. In Section 5, similar measurements will be made with the fin present.

4.4.1 Field of view

The high-speed PIV measured the streamwise (U) and cross-stream (V) velocities within a 2D plane at $Z = 188$ mm with a 1 kHz data rate. Figure 47 shows a top view schematic of the water tunnel test section layout including the cylinder, fin and tunnel walls. Also shown is the nominal field-of-view (FOV) for the high-speed PIV measurements. Within this FOV there are 12 red dots, which illustrate the nominal locations where the time histories were extracted. Each probe location was averaged from the three closest vectors to the location of interest. The averaging was done to minimize potential random noise from an individual vector, but inspection with and without averaging showed minimal variation. These points were used to produce a profile in the streamwise direction ($X = 160, 200, 240$ and 280 mm) along the test section centerline ($Y = 0$ mm) and cross-stream profiles ($Y = 0, \pm 30$ and ± 80 mm) in the near wake region ($X = 160$ mm) and the far wake near where the fin tip leading edge would be located ($X = 280$ mm). The streamwise positions correspond to 1.3, 2.0, 2.7 and 3.3 diameters downstream of the cylinder trailing edge. The cross-stream locations correspond to 0, ± 0.5 and ± 1.3 cylinder diameters from the tunnel centerline.

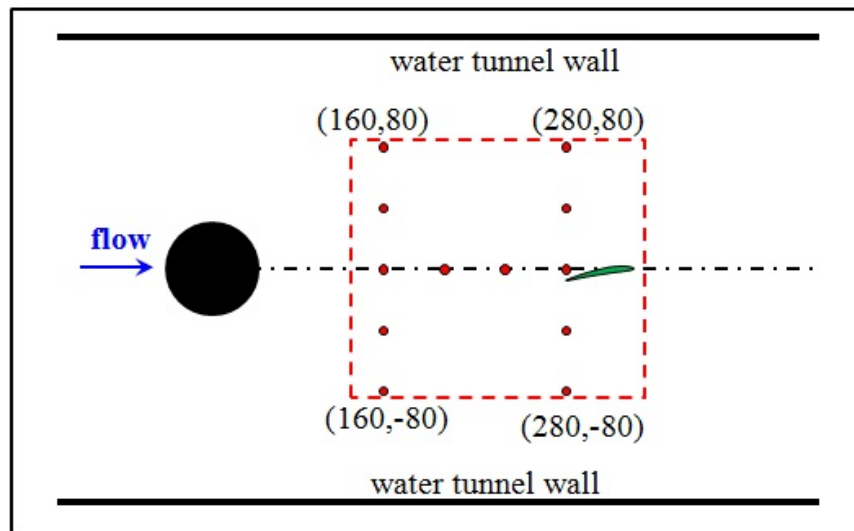


Figure 47. Top view schematic showing the layout of the water tunnel testing including the (large black circle) cylinder, (thick black lines) tunnel walls and (green object) fin location at the tip height ($Z = 230$ mm). Note that the current results are without the fin installed, but it is shown in the figure for reference. Also shown is the (red dashed line box) nominal location of the high-speed PIV FOV and (red dots) the locations within the FOV where velocity time traces were extracted from the 1 kHz PIV results. The coordinates shown are in millimeters and measured from the test section inlet (X) and the tunnel centerline (Y). All high-speed PIV measurements were acquired at $Z = 188$ mm.

4.4.2 Mean contour plots

Figure 48 shows the mean and fluctuating contour plots for the streamwise velocity component (U) scaled with the reference velocity from a single test run (Test 79 – Run 2) at $V_{ref} = 3.6$ m/s. Similarly, Figure 49 shows the mean and fluctuating contour plots for the cross-stream velocity component (V) scaled with the reference velocity from the same test run (Test 79 – Run 2). Contour plots for all the conditions tested with only the roughened cylinder (Part 2b) are provided in Appendix B.1. These contour plots illustrate that there was a problem with the streamwise velocity measurement when $Y/D < 0$, especially in the near wake region. This is made apparent by the lack of symmetry in the contour plot between the top and bottom of the images and the very large streamwise velocity fluctuations at the left bottom of the image where the fluctuations should be low. Inspection of the raw images indicate that there were significant particle drop outs in this part of the image leading to erroneous vectors. Since this was observed in the rough cylinder only testing (Part 2b) it was

determined that the laser sheet must have been slightly bumped between the forced fin testing and the rough cylinder only testing (note that Part 4 was performed before Part 2b) leading to a slight misalignment on the opposite side where the laser sheet enters the tunnel. In spite of this issue with the streamwise velocity component, the cross-stream velocity measurement does not appear to be affected. This combined with the fact that the most significant errors in the streamwise velocity occurred in the near-wake region on the $Y < 0$ side, suggests that the laser sheet was not parallel with the X-Y plane. In addition, the misalignment was such that the particles in the laser sheet upstream of $(X-X_c)/D \sim 1.5$ are separate particles from downstream of that point. However, the misalignment is such that the point where this would take place for the Y-direction is out of view and thus does not significantly impact the Y-velocity component. Similar results are produced from the other test runs independent of the test section velocity.

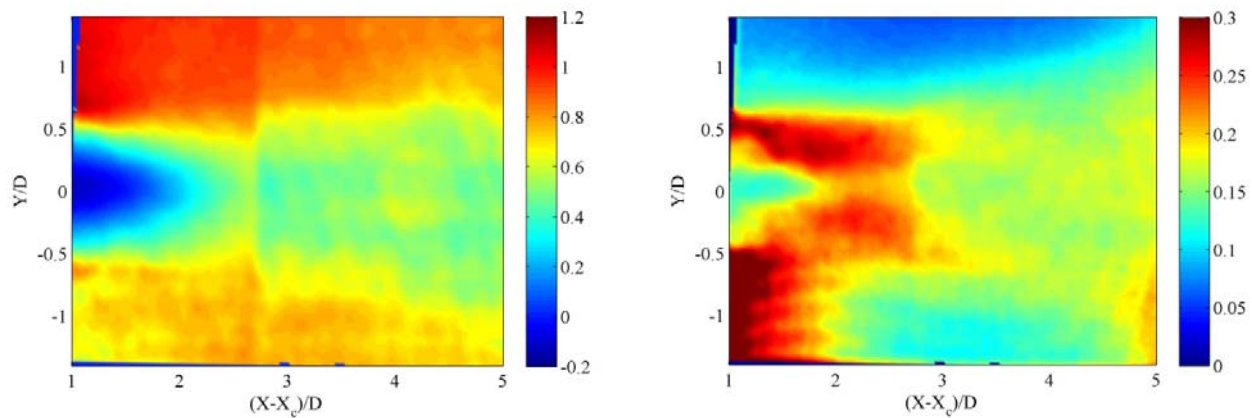


Figure 48. Contour plots of the streamwise velocity (left – mean component; right – fluctuating component) scaled with the reference velocity (U/V_{ref}) from a single test condition (Test 79 – Run 2).

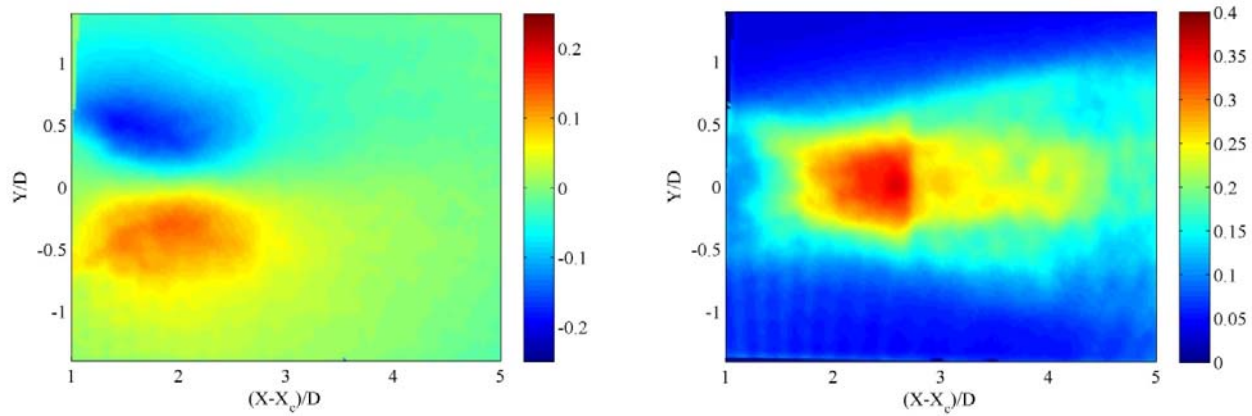


Figure 49. Contour plots of the cross-stream velocity component (left – mean component; right – fluctuating component) scaled with the reference velocity (V/V_{ref}) from a single test condition (Test 79 – Run 2).

4.4.3 Flow-field angle-of-attack profiles

Now that a global picture of the mean flow-field is established, it is useful to take some representative profiles through the FOV to better quantify the trends in the data. Prior to looking at the mean and fluctuating velocity profiles, it is informative to view the mean flow-field angle-of-attack measured relative to the streamwise direction, $\alpha_{flow} = \tan^{-1}(V/U)$. This is similar to the results from the smooth cylinder only testing (Part 2a), but here V and U are the average velocity instead of the phase-averaged. This is not quite as informative as the angle-of-attack determined from the phase-averaged flow-field, but it is helpful in identifying key features of the flow. Figure 50 shows the mean flow-field angle-of-attack versus the downstream distance (X) from the cylinder trailing edge (X_c) scaled with the cylinder diameter (D). The profiles were acquired at either $Y/D = 0$ or ± 0.5 . In the figure there are results from six separate test section velocities ($V_{ref} = 2.5, 3.0, 3.3, 3.4, 3.6$ and 6.0 m/s), which shows excellent collapse of the data except for results from the centerline ($Y/D = 0$) near the solid black line located at $(X-X_c)/D = 1.48$. The line nominally corresponds to the end of the recirculation zone, which the streamwise velocity approaches zero and consequently the angle rapidly increases toward 90° . The results from $Y/D = \pm 0.5$ show that the flow on average has a positive flow-field angle-of-attack for $Y <$

0 and a negative flow-field angle-of-attack when $Y > 0$. As will be seen subsequently, this is due to the mean V velocity having an opposite sign of the Y -location in the near-wake region.

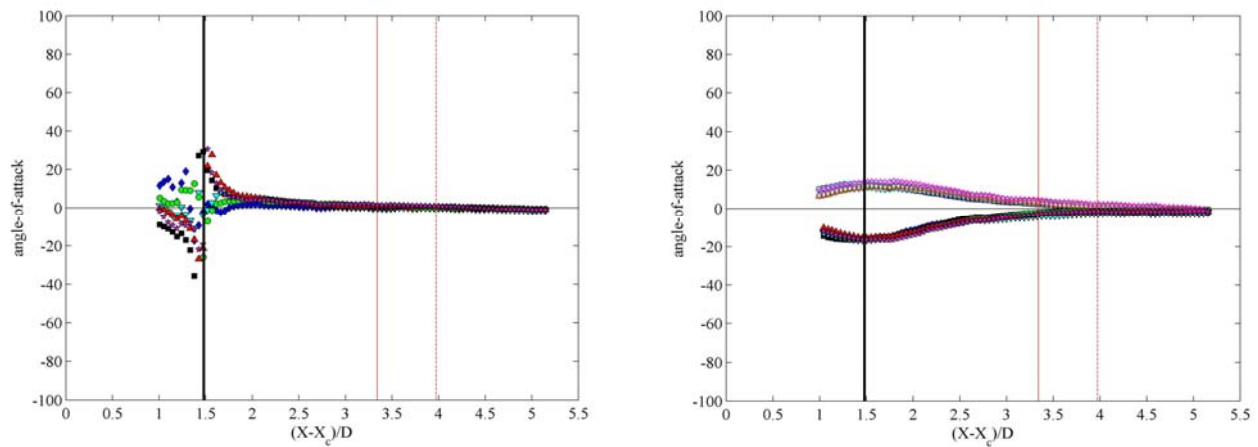


Figure 50. Mean flow-field angle-of-attack measured relative to the streamwise direction, $\alpha_{flow} = \tan^{-1}(V/U)$, plotted versus the scaled downstream distance from the cylinder trailing edge, $(X-X_c)/D$. The symbol colors correspond to $V_{ref} =$ (black) 2.5, (blue) 3.0, (cyan) 3.3, (green) 3.4, (red) 3.6 and (magenta) 6.0 m/s. The data shown are the average results from a given velocity at (left) $Y/D = 0$ and (right) $Y/D = \pm 0.5$. In the right image, the closed symbols were acquired from $Y/D = +0.5$ and open symbols from $Y/D = -0.5$. The solid black line represents the nominal location of the end of the recirculation region. The two thin red lines downstream show the nominal locations of the fin tip leading edge and the leading edge at the PIV plane ($Z = 188$ mm).

Cross-stream mean flow-field angle-of-attack profiles are provided in Figure 51, which the cross-stream direction (Y) is scaled with the cylinder diameter (D). These profiles were acquired in the near or far wake regions, which correspond to $(X-X_c)/D = 1.3$ or 3.3 , respectively. Each profile was produced by averaging the repeated conditions from a given velocity, and the symbol colors denote the given test section velocity ($V_{ref} = 2.5, 3.0, 3.3, 3.4, 3.6$ and 6.0 m/s). Once again excellent collapse of the data at all velocities is evident. The only significant scatter in the results is for data between nominally $Y/D = \pm 0.2$. The width of this region indicates the cross-stream width of the recirculation zone at this location. Note that the near-wake location shown ($(X-X_c)/D = 1.3$) is less than the location of the end of the recirculation zone ($(X-X_c)/D \sim 1.5$). Thus the cross-stream profile will cross through two locations where the streamwise velocity is approaching zero, with the negative- Y location having a positive V component and the positive- Y having a negative V component. The sign of the angle will

correspond to the sign of the V component, which is why the positive-Y edge of the recirculation zone approaches -90° and the negative-Y edge of the recirculation zone approaches $+90^\circ$. In the far wake the mean flow-field angle-of-attack approaches zero across the entire profile. This does not mean there is not large fluctuations, which can be observed in the time-trace signals, but that the fluctuations in the angle-of-attack are about zero degrees in the far-wake.

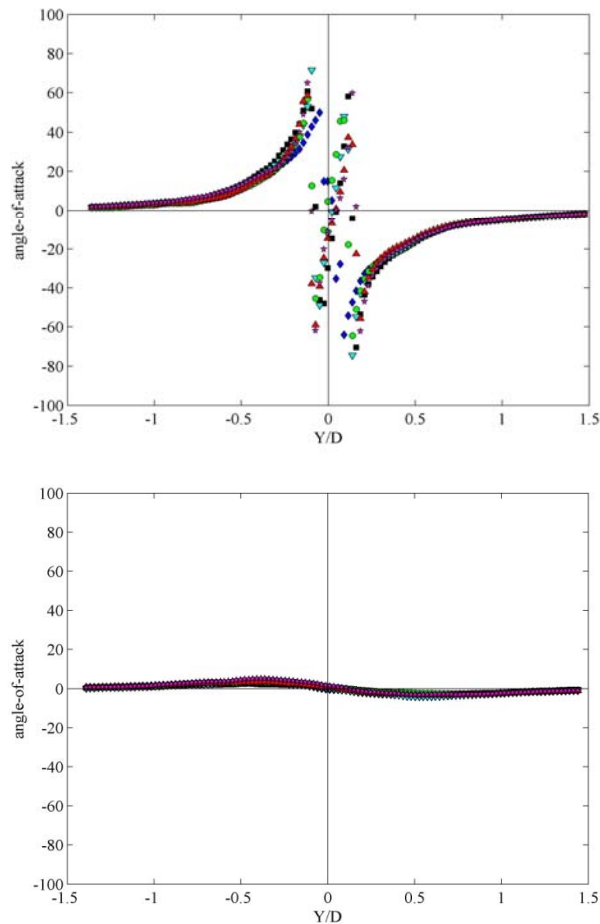


Figure 51. Mean flow-field angle-of-attack measured relative to the streamwise direction, $\alpha_{\text{now}} = \tan^{-1}(V/U)$, plotted versus the cross-stream direction (Y) scaled with the cylinder diameter. The data shown are the average results from a given velocity in the (left) near-wake region at $X = 160$ mm and (right) far wake at $X = 280$ mm. The symbol colors correspond to $V_{\text{ref}} =$ (black) 2.5, (blue) 3.0, (cyan) 3.3, (green) 3.4, (red) 3.6 and (magenta) 6.0 m/s.

The above plots demonstrate that the acquired data collapses reasonably well independent of the given test section velocity, thus in Figure 52 the results for the streamwise and cross-stream

profiles are shown with the mean flow-field angle-of-attack determined from the mean of all the conditions tested independent of the test section velocity. These two plots help show the spatial trends in the cylinder wake results. The streamwise profiles show the nominal location of the end of the recirculation zone (i.e. centerline location where the streamwise velocity goes to zero and consequently the angle-of-attack rapidly approaches $\pm 90^\circ$). The symmetry between the $\pm Y$ locations can be observed as well as the dissipation of the fluctuations when moving away from the centerline. The cross-stream profile shows that for locations prior to the end of the recirculation zone the edges are noted by the angle of attack approaching $\pm 90^\circ$. Beyond the recirculation zone there is a smooth continuous curve with an extrema nominally at $Y/D = \pm 0.25$. This peak dissipates with increasing downstream distance.

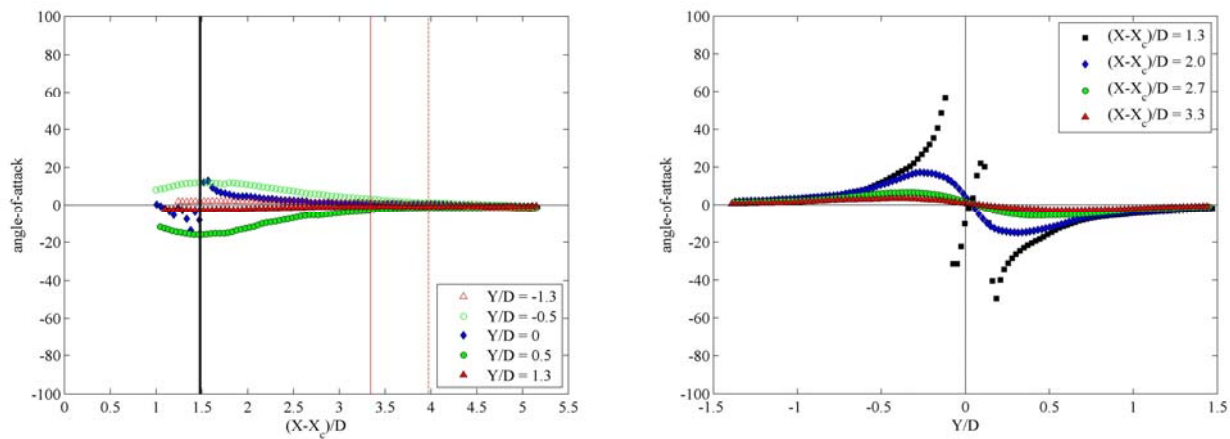


Figure 52. Mean flow-field angle-of-attack measured relative to the streamwise direction, $\alpha_{flow} = \tan^{-1}(V/U)$, plotted versus (left) scaled distance downstream of the cylinder trailing edge or (right) the scaled cross-stream direction. The data shown are the average results from all conditions independent of the test section velocity. The solid black line in the left image denotes the end of the recirculation zone.

4.4.4 Streamwise velocity

The PIV provides velocity data for both the streamwise and transverse components. This section discusses characteristics of the mean and fluctuation velocity components of the streamwise velocity.

4.4.4.1 Mean velocity

While there was some variation in the results when comparing scaled results between velocities, it is apparent from the time trace data and the mean angle-of-attack data that the results scale reasonably well independent of velocity when scaled with the reference velocity. Thus in the discussion of the streamwise and cross-stream velocity results will be shown from the scaled average from all velocities tested. All the results averaged at a given velocity are provided in Appendix B.3, which shows that there is scatter but the scatter appears independent of velocity. Figure 53 shows the mean streamwise velocity scaled with the test section reference velocity (U/V_{ref}) plotted versus the downstream distance from the cylinder trailing edge scaled with the cylinder diameter ($(X-X_c)/D$). The results are from a given Y-location and the average from all velocities tested. Five separate profiles spanning $Y/D = \pm 1.3$ are shown. The centerline profile ($Y/D = 0$) shows the streamwise velocity initially negative and increasing with downstream distance until approximately $2.5D$ downstream from the cylinder trailing edge. The mean streamwise velocity passes through zero at the point previously noted as the end of the recirculation zone (i.e. $\sim 1.5D$ downstream of the cylinder trailing edge). Beyond $2.5D$ downstream of the cylinder trailing edge, the mean velocity appears less smooth but nearly constant. It is unclear if the lack of smoothness is due to insufficient duration of the acquired sample or some other phenomenon. It should be noted that this was also observed with the fin installed in the tunnel. Noting that the structures were not as coherent at this spanwise location on the smooth cylinder compared to the mid-span height, a possible explanation is that at this downstream position three-dimensionality generated by edge effects begins to impact the flow-field at this spanwise location. The results at $Y/D = \pm 0.5$ are similar to each other and two distinct behaviors can be observed upstream and downstream of $(X-X_c)/D \sim 2.5$. This suggests that the error with the laser alignment does not significantly impact the results for $Y/D \geq -0.5$. Finally the results from $Y/D = \pm 1.3$ shows that there is a significant deviation between the two profiles, especially in the near-wake region. This is an

indication that the data for $Y/D < -0.5$ is erroneous, especially in the near wake region. The results from $Y/D = +1.3$ shows that the mean streamwise velocity exceeds the reference velocity in the near-wake region, which is the result of the blockage effect generated by the cylinder. Several cross-stream profiles of the scaled streamwise velocity (U/V_{ref}) are shown in Figure 54. This makes the issue with the streamwise velocity for $Y/D < -0.5$ even more apparent, with the lack of symmetry about $Y/D = 0$. In spite of this limitation with the data, these plots clearly illustrate that the wake is decaying and widening with increasing downstream distance.

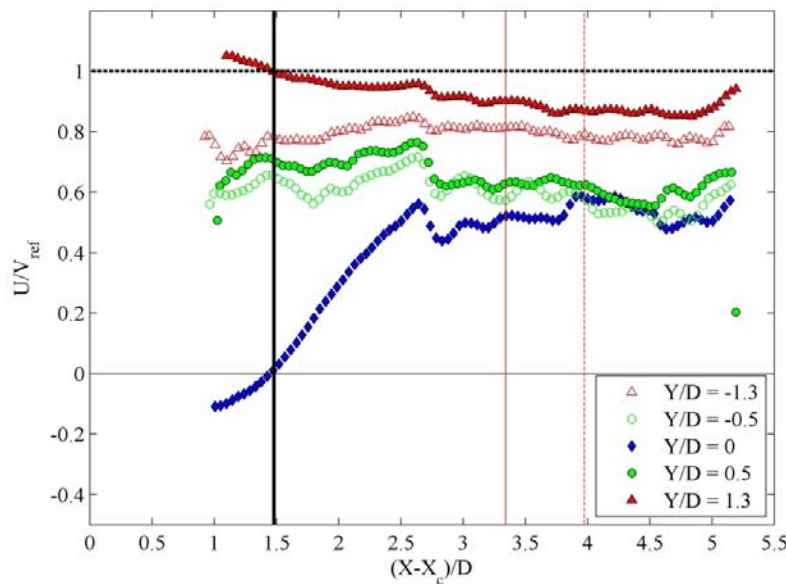


Figure 53. Mean streamwise velocity (U) scaled with the test section reference velocity (V_{ref}) plotted versus the downstream distance (X) from the cylinder trailing edge (X_c) scaled with the cylinder diameter (D). The data shown are the average results from all conditions with the rough cylinder only (Part 2b). The solid black line represents the nominal location where the recirculation zone ends, $(X-X_c)/D = 1.48$. The two thin red lines downstream show the nominal locations of the fin tip leading edge and the leading edge at the PIV plane ($Z = 188$ mm) when installed.

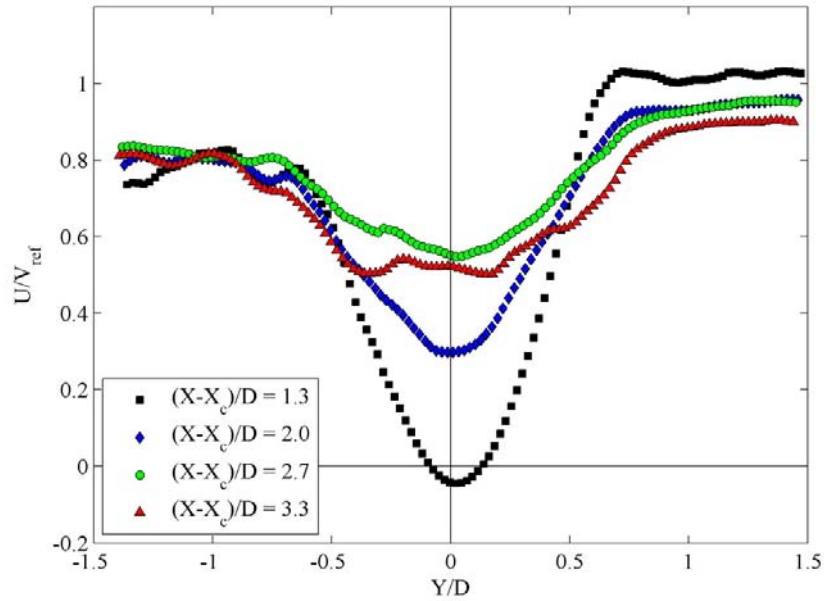


Figure 54. Scaled mean streamwise velocity (U/V_{ref}) plotted versus the scaled cross-stream location (Y/D). The data shown are the average results from all conditions acquired with the rough cylinder only (Part 2b).

4.4.4.2 *Fluctuating velocity*

Figure 55 shows the fluctuating streamwise velocity scaled with the test section reference velocity (u'/V_{ref}) plotted versus the distance downstream from the cylinder trailing edge scaled with the cylinder diameter ($(X-X_c)/D$). These results are from the same Y -locations as was shown for the mean velocity profiles. The profiles at $Y/D = \pm 1.3$ are significantly different and confirm that the data at $Y/D = -1.3$ was erroneous. Unless a significant change occurred upstream of the cylinder, there is no physical rationale to explain a significant increase in streamwise fluctuations in the test section inlet on one side and not the other. In fact the blockage effect that causes the flow to accelerate in this region will also suppress any turbulent fluctuations, which is seen in the $Y/D = +1.3$ results with the minimum value being achieved upstream in the profile. The results at $Y/D = \pm 0.5$ are in agreement indicating once again that the data was valid at this point in the flow, and both show that the fluctuations decay with downstream distance. Finally the results from $Y/D = 0$ has the fluctuations increasing with increasing downstream distance until a peak is achieved near $(X-X_c)/D \sim 2.2$. This peak is close to the location where the centerline mean velocity ceases to increase and becomes nearly constant.

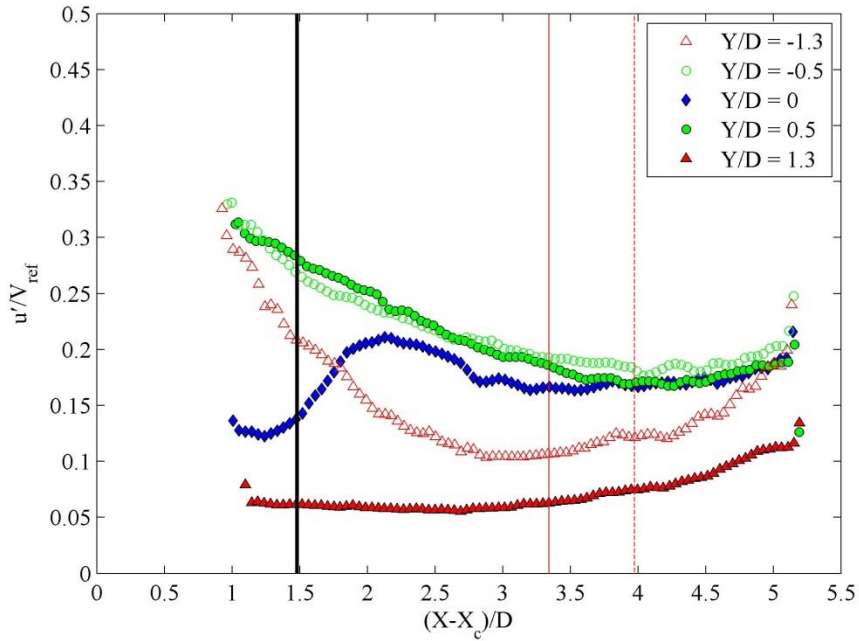


Figure 55. Fluctuating streamwise velocity (u') scaled with the test section reference velocity (V_{ref}) plotted versus the downstream distance (X) from the cylinder trailing edge (X_c) scaled with the cylinder diameter (D). The data shown are the average results from all conditions with the rough cylinder only (Part 2b). The solid black line represents the nominal location where the recirculation zone ends, $(X-X_c)/D = 1.48$. The two thin red lines downstream show the nominal locations of the fin tip leading edge and the leading edge at the PIV plane ($Z = 188$ mm) when installed.

Cross-stream profiles of the scaled fluctuating velocity (u'/V_{ref}) from the same streamwise locations as shown for the mean streamwise locations as was shown for the mean velocity profiles is provided in Figure 56. The results from the near-wake region at $(X-X_c)/D = 1.3$ show that the misalignment had a greater impact on the near-wake data than the far wake. However, there are insights that can be had if data from $Y/D \geq -0.5$ is inspected. These data indicates that there are peaks in the streamwise velocity fluctuations at $Y/D \sim 0.5$ and the fluctuations within the wake decay with downstream distance (i.e. u' decreases with increasing X in the center region). However, the wake grows with increasing downstream distance, which is apparent by the increase in u' with increasing distance for $Y/D > \sim 0.7$.

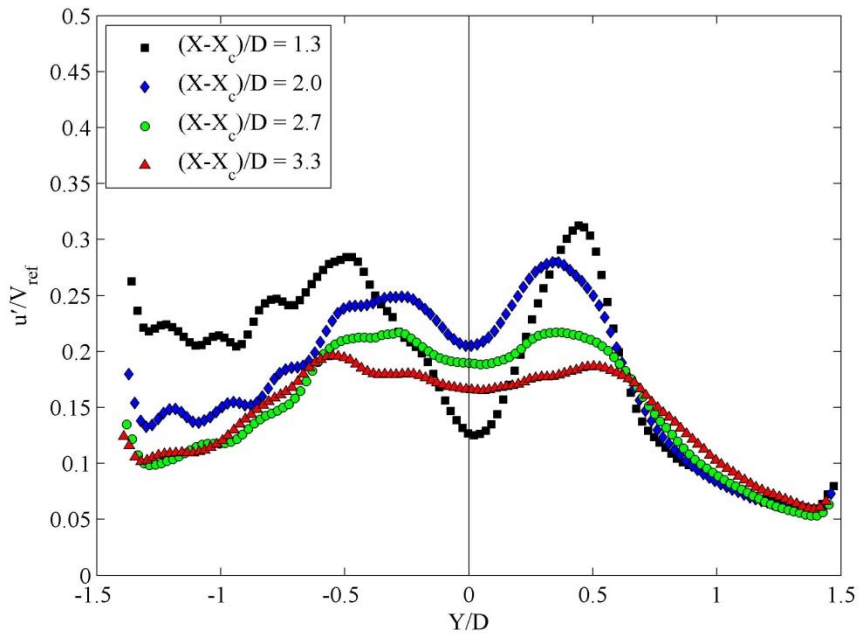


Figure 56. Scaled fluctuating streamwise velocity (u'/V_{ref}) plotted versus the scaled cross-stream location (Y/D). The data shown are the average results from all conditions acquired with the rough cylinder only (Part 2b).

4.4.5 Cross-stream velocity

The PIV provides velocity data for both the streamwise and transverse components. This section discusses characteristics of the mean and fluctuation velocity components of the transverse velocity.

4.4.5.1 Mean velocity

Once again the cross-stream velocity profiles are shown as average profiles from all velocities tested, but the average from a given velocity can be viewed in Appendix B.3. Figure 57 shows the mean cross-stream velocity scaled with the test section reference velocity (V/V_{ref}) plotted versus the downstream distance from the cylinder trailing edge scaled with the cylinder diameter ($(X-X_c)/D$). The centerline profile shows that the mean cross-stream velocity is within 5% of the reference velocity, but the results appear biased towards the positive- V values, which suggests that the $Y/D = 0$ position was

not exactly zero but slightly negative. The data from $Y/D = \pm 1.3$ shows that there is peak in the magnitude of the cross-stream velocity at the end of the recirculation zone, which the average then decays with increasing downstream distance beyond that point. Finally, the data from $Y/D = \pm 1.3$ appears to be symmetric, which supports the observation from the contour plots that the cross-stream velocity component is not significantly impacted by the laser misalignment.

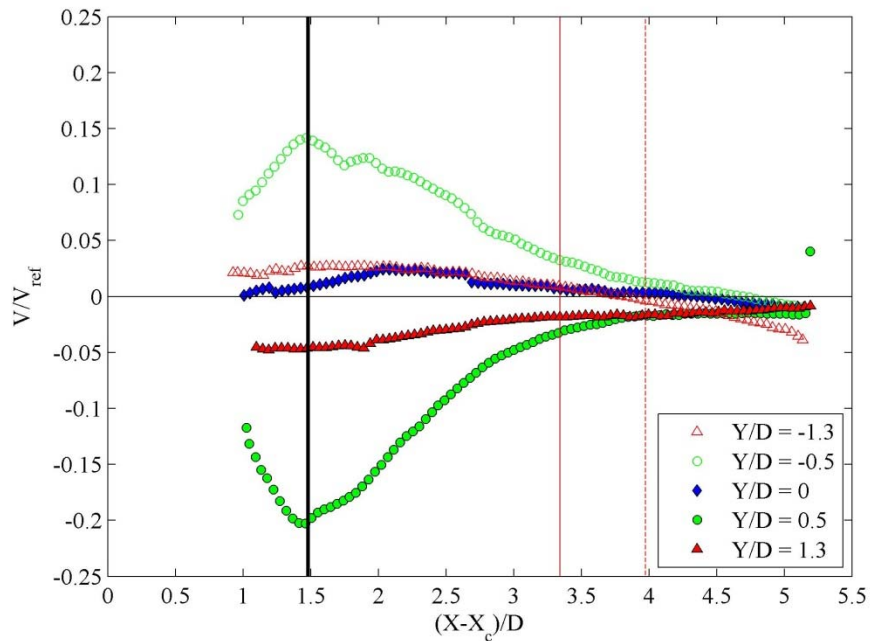


Figure 57. Mean cross-stream velocity (V) scaled with the test section reference velocity (V_{ref}) plotted versus the downstream distance (X) from the cylinder trailing edge (X_c) scaled with the cylinder diameter (D). The data shown are the average results from all conditions with the rough cylinder only (Part 2b). Open symbols are from $Y/D < 0$ and closed symbols are from $Y/D \geq 0$. The solid black line represents the nominal location where the recirculation zone ends, $(X-X_c)/D = 1.48$. The two thin red lines downstream show the nominal locations of the fin (when installed) leading edge at the tip and the PIV plane ($Z = 188$ mm).

Figure 58 shows cross-stream profiles of the scaled cross-stream velocity component (V/V_{ref}) at several downstream locations. Overall these results show reasonable anti-symmetry about $Y/D = 0$, which further supports the observation from the contour plots that the cross-stream velocity component was not significantly impacted by the laser alignment issue. These results show that there is a peak in the magnitude of the cross-stream velocity at nominally $Y/D = 0.5$, which decays with increasing

downstream distance. Unlike the streamwise velocity component, the mean cross-stream velocity component appears to decay with increasing downstream distance even beyond $Y/D = 1$.

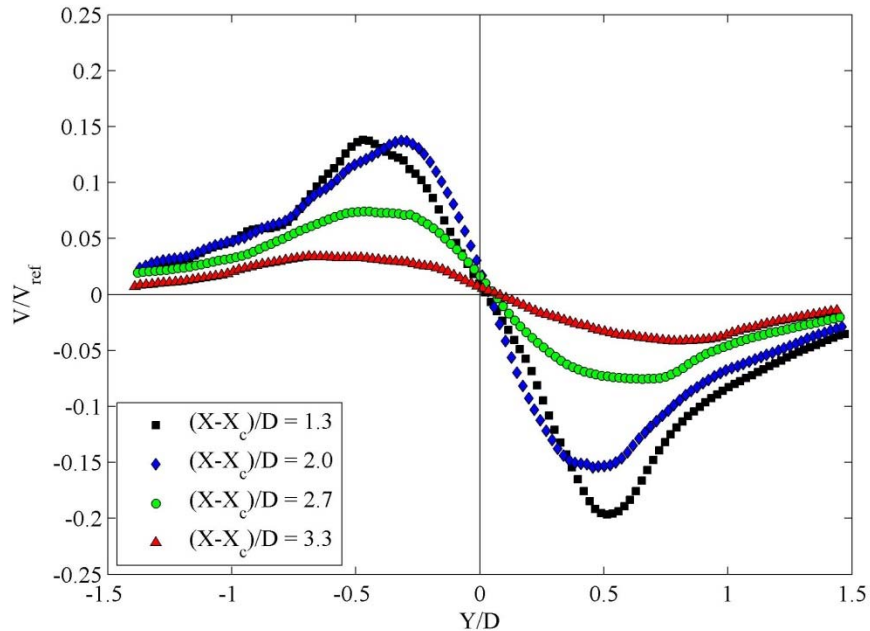


Figure 58. Scaled mean cross-stream velocity (V/V_{ref}) plotted versus the scaled cross-stream location (Y/D). The data shown are the average results from all conditions acquired with the rough cylinder only (Part 2b).

4.4.5.2 *Fluctuating velocity*

Figure 59 shows the fluctuating cross-stream velocity scaled with the test section reference velocity (v'/V_{ref}) plotted versus the distance downstream from the cylinder trailing edge scaled with the cylinder diameter ($(X-X_c)/D$). These results are from the same Y -locations as was shown for the mean velocity profiles. The centerline profile ($Y/D = 0$) shows the fluctuating velocity increasing with increasing downstream distance until between $2.0 D$ and $2.5 D$ downstream of the cylinder trailing edge, which nominally corresponds to the location of the peak in the streamwise velocity fluctuations along the tunnel centerline and the point when U ceases to increase with increasing downstream distance. Beyond this point the fluctuations decay with increasing downstream distance. The data from

$Y/D = \pm 0.5$ are not identical in magnitude, but there is minimal deviation in their trend. Both have a minor peak at the same location as the centerline peak, though significantly reduced, and there is minimal variation in magnitude upstream or downstream of the peak. Finally the results from $Y/D = \pm 1.3$ indicate that the cross-stream velocity might be impacted in the near-wake region for $Y/D < 0.5$ where the fluctuations increase relative to the data at $Y/D = 1.3$. However, downstream the two profiles merge and are in excellent agreement. The overall trend at this position is that v' gradually increases with increasing downstream distance from about 2.5% of V_{ref} in the near-wake to ~6% of V_{ref} in the far wake.

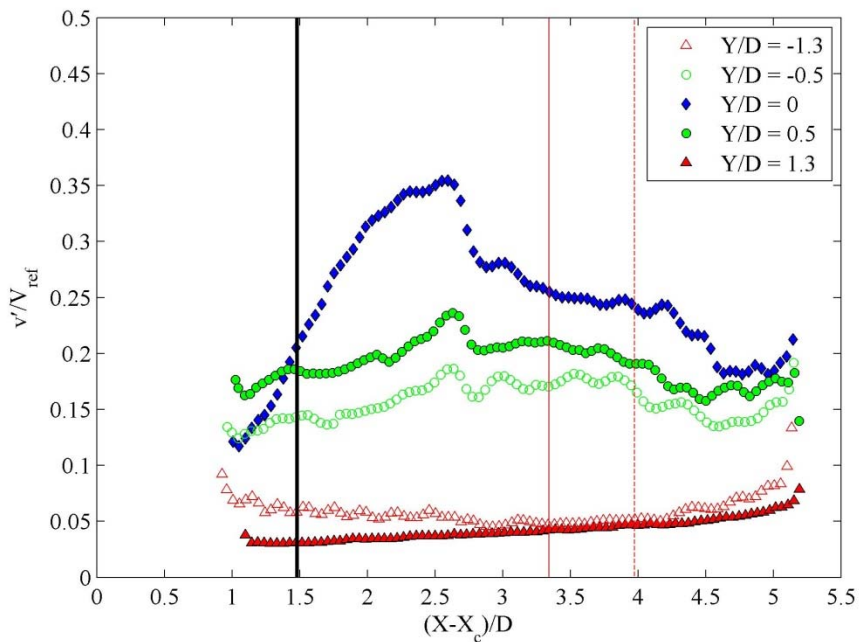


Figure 59. Fluctuating cross-stream velocity (v') scaled with the test section reference velocity (V_{ref}) plotted versus the downstream distance (X) from the cylinder trailing edge (X_c) scaled with the cylinder diameter (D). The data shown are the average results from all conditions with the rough cylinder only (Part 2b). The solid black line represents the nominal location where the recirculation zone ends, $(X-X_c)/D = 1.48$. The two thin red lines downstream show the nominal locations of the fin leading edge at the tip and the PIV plane height ($Z = 188$ mm) when installed.

Figure 60 provides the cross-stream profiles of the scaled fluctuating velocity (v'/V_{ref}) from the same streamwise locations as shown for the mean cross-stream velocity results. The peak fluctuations are observed on the centerline, except for the profile acquired in the near-wake region, which has a

nearly flat value across the wake. The peak initially increases with increased downstream distance until 2-2.5D downstream of the cylinder trailing edge, which beyond that location the velocity fluctuations decrease with increased downstream distance. In addition, it can be seen that the wake widens with increasing downstream distance.

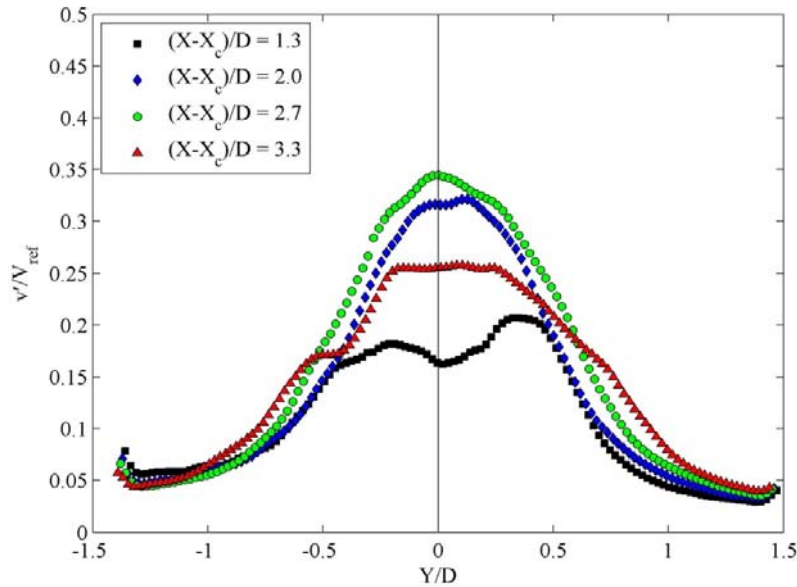


Figure 60. Scaled fluctuating cross-stream velocity (v'/V_{ref}) plotted versus the scaled cross-stream location (Y/D). The data shown are the average results from all conditions acquired with the rough cylinder only (Part 2b).

4.4.6 Spectral results

This section provides spatial correlations and wavenumber spectra for PIV measurements. The definition of a spatial autocorrelation for a homogeneous velocity component u is

$$R_{uu}(\xi, \eta) = E[u(x, y)u(x + \xi, y + \eta)],$$

where $E[\]$ is the expected value and ξ and η are relative distances in the x and y directions, respectively. The units of R_{uu} are $(\text{m/s})^2$. The spatial autocorrelation is even (symmetric), thus all spatial autocorrelations presented here are shown for positive separation distance only.

The corresponding wavenumber spectrum is simply the Fourier transform of the autocorrelation in both x and y directions.

$$S_{uu}(k_x, k_y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} R(\xi, \eta) \exp[-i(k_x \xi + k_y \eta)] d\xi d\eta.$$

Notice that the units for this double two-sided autospectrum is (m/s)²m². Since the spatial autocorrelation is even along both axes, the autospectrum is real and also even (symmetric). Thus, the wavenumber autospectrum is only shown for positive k_x and k_y .

The velocity data from the PIV plane were masked into a rectangle 178.2 mm long in the streamwise (x) direction and 164.2 mm wide in the transverse (y) direction. The velocity vectors were computed for increments of 1.403 mm.

To compute these quantities the wave number spectrum was computed first and the inverse Fourier transform method was used (Bendat & Piersol, 1986) p. 386-391. In the method since the data is evenly spaced, the FFT of the velocity is obtained and the square of the magnitude square is computed. The autocorrelation is then obtained by taking the inverse FFT. As far as particulars, the velocity components are padded with zeros to extend the spatial range of the data. A Hanning window is applied to the spatial data.

Analogous to time series data, the sampling increment was 712.75 samples/m. The maximum wavenumber reported here is 2250 m⁻¹ which is below the Nyquist wavenumber. The bandwidth is 35.3 m⁻¹. The ensemble length is approximately 0.180 m. Three thousand frames were taken in 1 ms intervals. For the lowest tunnel velocity 2.51 m/s, there is 98.6% overlap between succeeding frames. The amount of independent ensembles drops to 42. Assuming a coherence of 1.00, the normalized random error for the autospectrum is 0.1543 or about 0.6 decibels.

Spatial autocorrelations were obtained without the fin installed for three tunnel velocities (2.51, 2.97 and 3.61) m/s and are displayed as two contour plots in Figure 61, Figure 62 and Figure 63. The general shape is similar between the velocities although the levels increase with velocity squared as expected.

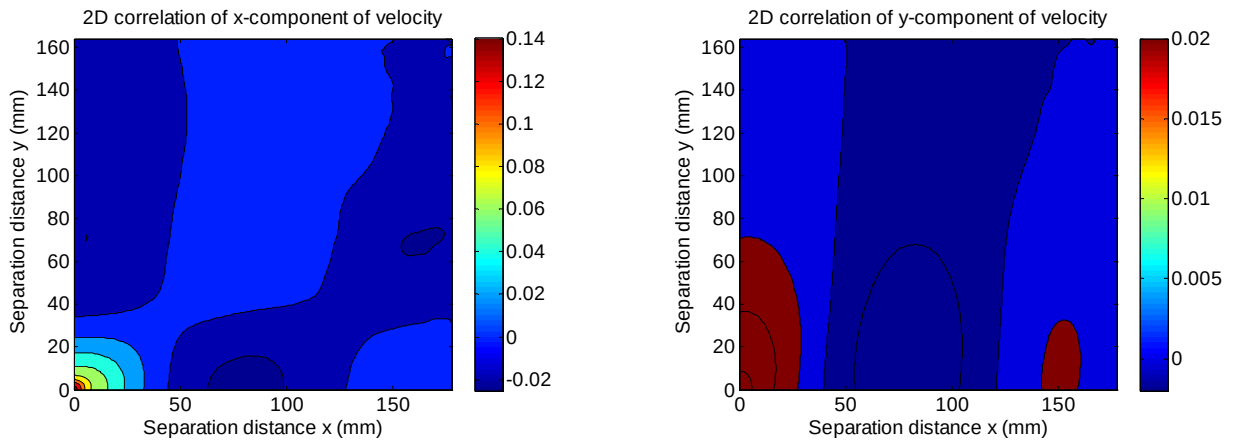


Figure 61. Spatial Auto Correlation for x- and y- components of velocity without fin, $V_{ref}=2.51$ m/s. (Run 79-26) The units of the contours are $(m/s)^2$.

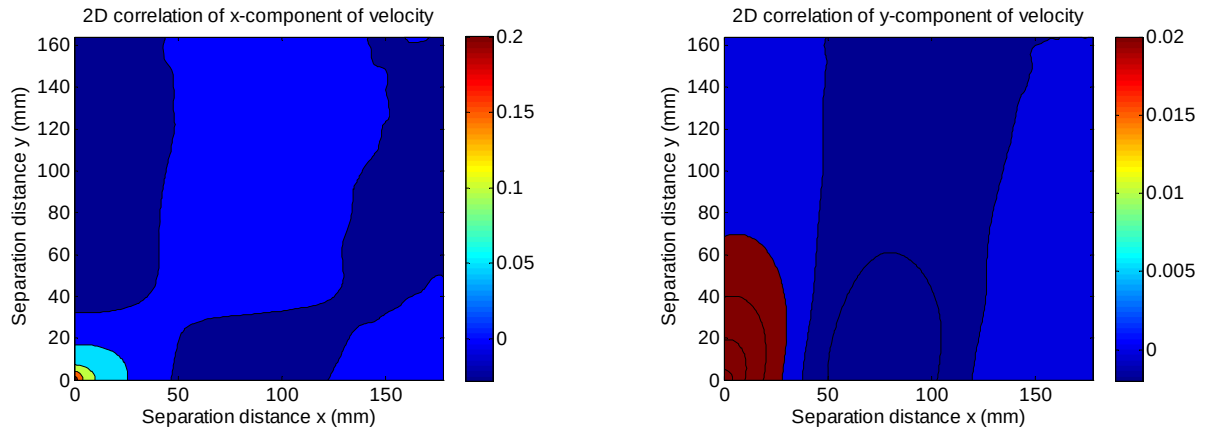


Figure 62 Spatial Auto Correlation for x- and y- components of velocity without fin, $V_{ref}=2.97$ m/s. (Run 79-11) The units of the contours are $(m/s)^2$.

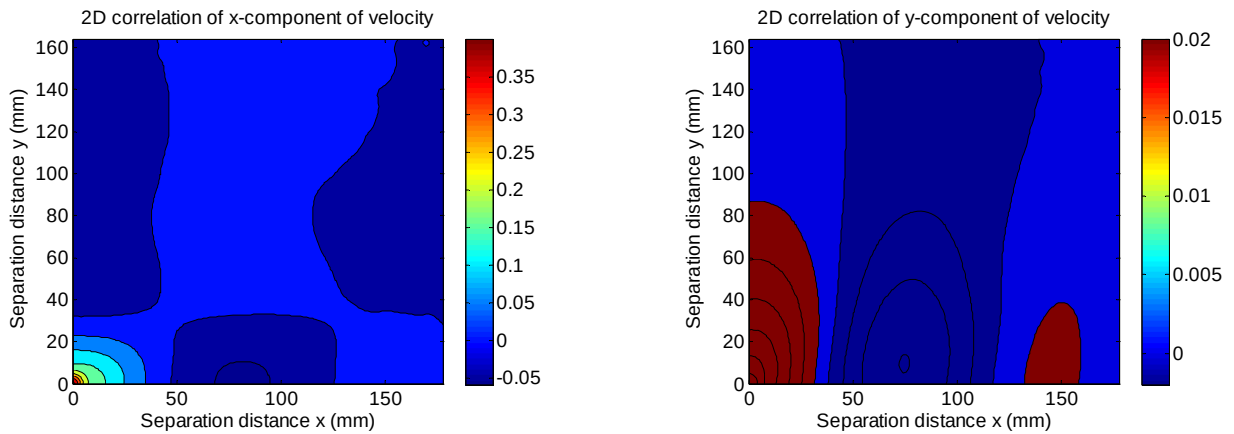


Figure 63. Spatial Auto Correlation for x- and y- components of velocity without fin, $V_{ref}=3.61$ m/s. (Run 79-2) The units of the contours are $(m/s)^2$.

Figure 64 shows normalized autocorrelation cuts along the x - and y - axes. The plots on the left-hand side are the x - and y - components of velocity as a function of x -direction separation distance. The plots on the right-hand side are the x - and y - components of velocity as a function of y -direction separation distance. For three of the curves within Figure 64 the correlations have an oscillating character typical of the shedding of the cylinder, however the variation of the y -component of velocity in the y -direction shows a monotonically decreasing trend with no oscillation. Because the ordinate is normalized by the variance of the velocity and the predominant flow structure is based on a 60 mm diameter cylinder, it is not surprising that the all four plots in Figure 64 collapse.

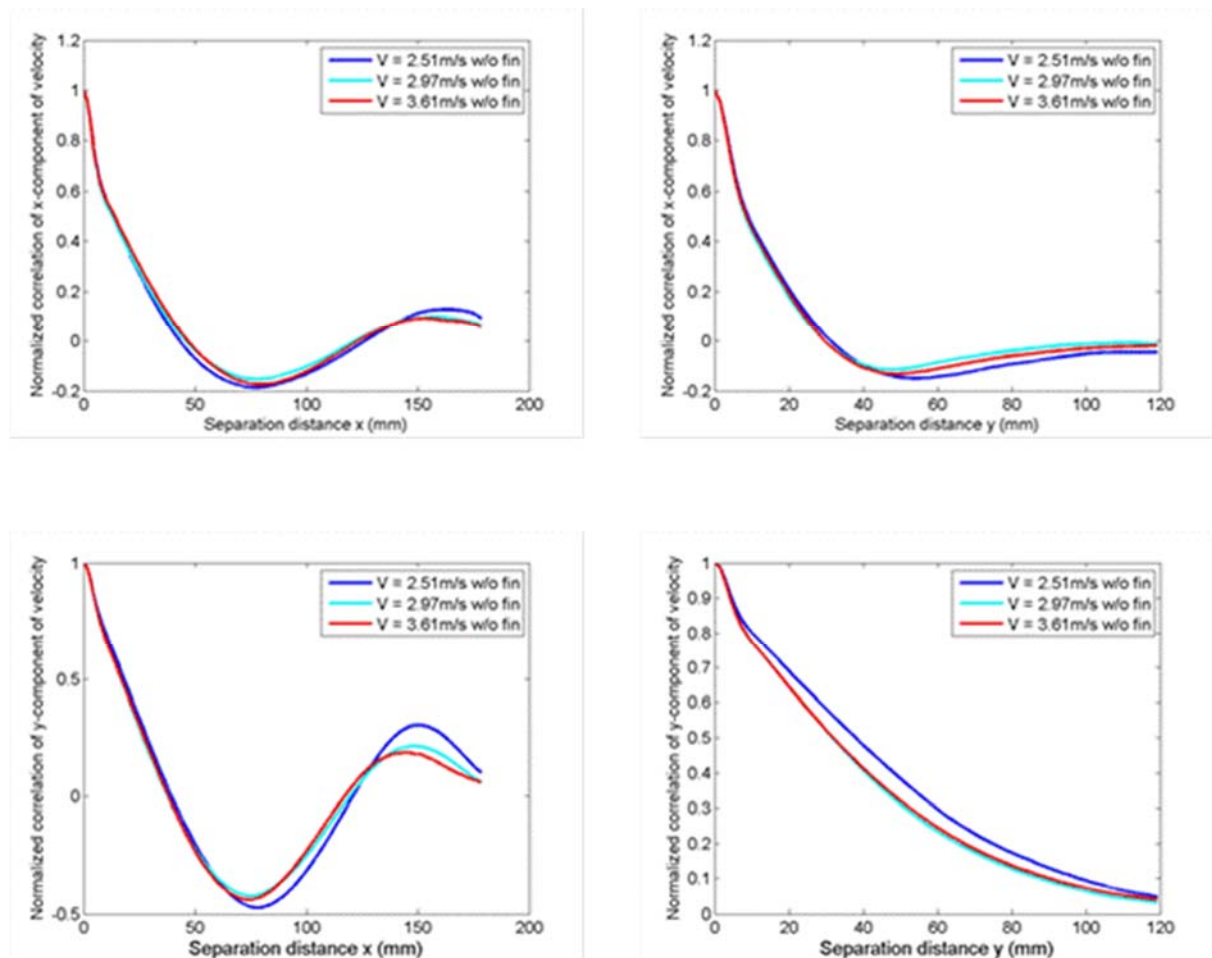


Figure 64. Comparison of velocity correlations without fin along x - and y - axis for x - and y - components of velocity.

Figure 65, Figure 66 and Figure 67 show the corresponding wavenumber spectra for the x - and y - component of velocity for the three reference velocities. The cylinder wake contains a mean deficit due to the cylinder drag and fluctuations due to the shedding from both sides of the cylinder. For the shedding, the flow becomes non-uniform and nearly periodic both spatially and temporally. In past sections the temporal aspect was analyzed by showing typical flow velocity, cylinder vibration and pressures levels as a function of time. The plots in this section show the spatial variation of the flow. For the streamwise and transverse velocities components we can show how these quantities in an average sense vary in the streamwise direction (separation distance x) and the corresponding variation in the transvers direction (separation distance y). Analogous the frequency spectrum, the wavenumber is computed both in the streamwise direction (k_x) and the transverse direction (k_y). We can see from the wave number plots, that the streamwise velocity component has wavenumber peak $k_{x\text{peak}}$ and $k_{y\text{peak}}$ associated with the wavelength of the cylinder shedding. We can see this by examining the red blob is centered 45 degrees from the k_x axis. In hindsight it would have been good to resolve the actual $k_{x\text{peak}}$ and $k_{y\text{peak}}$ better. To do this, the PIV window would need to be much larger so several wavelength could be captured. In contrast, the wavenumber spectrum of the transverse velocity component is has only $k_{x\text{peak}}$ and no $k_{y\text{peak}}$. An inkling of fact is evidence from contrasting the sinusoidal nature of the velocity correlations shown in left versus right figures in Figure 64.

The corresponding wavenumber level for the y -component of velocity is on the k_x axis. This explains the monotonically decreasing trend for the bottom right curve in Figure 64. To add additional quantitative detail, the line curves are provided below the contour plots to show the spectral levels along the k_x axis for various constant k_y values.

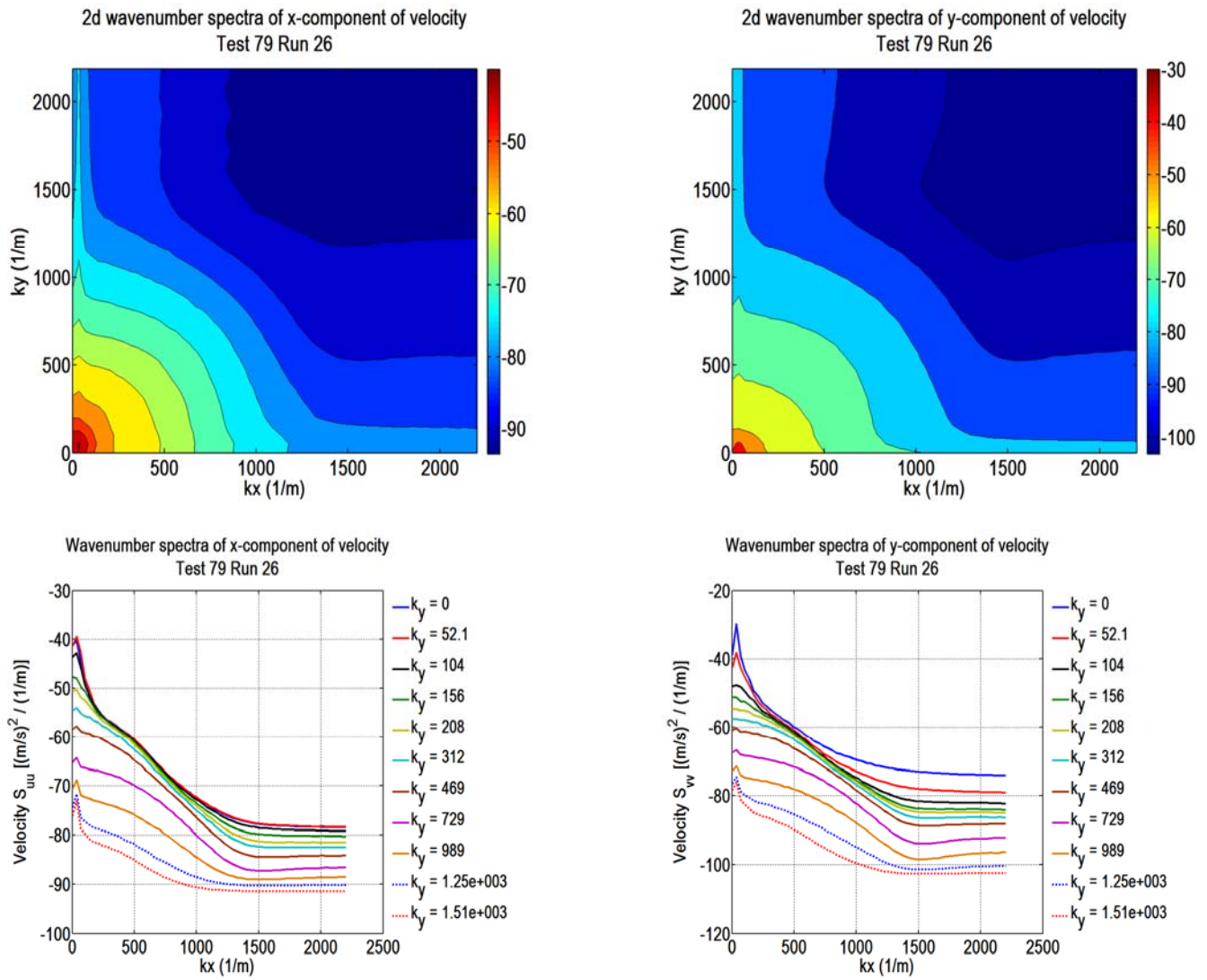


Figure 65. Wavenumber spectra for no fin for $V_{ref}=2.51$ m/s (Run 79-26). The bandwidth along k_x is 35.1 m^{-1}

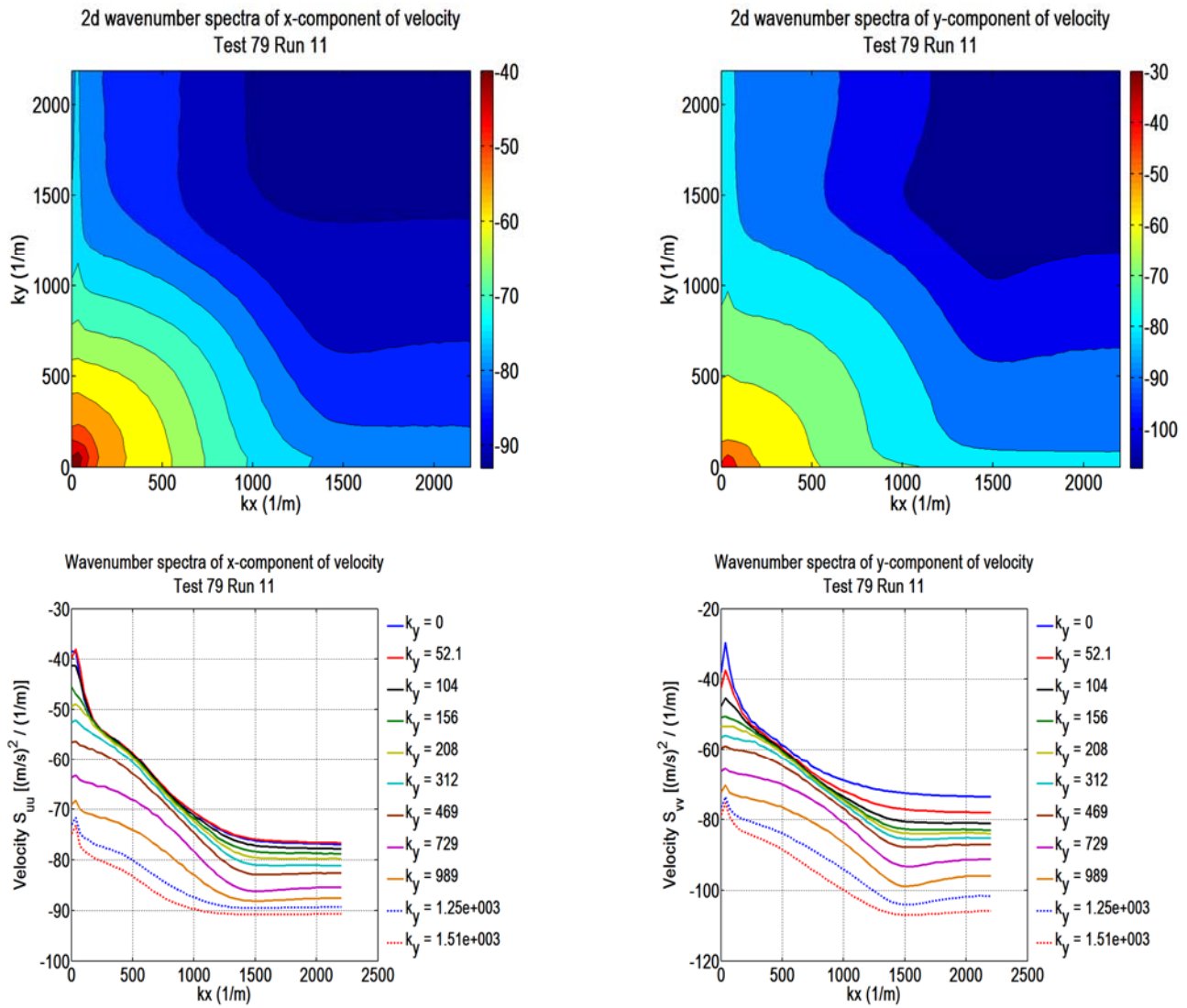


Figure 66. Wavenumber spectra for no fin for $V_{ref}=2.97$ m/s (Run 79-11). The bandwidth along k_x is 35.1 m^{-1}

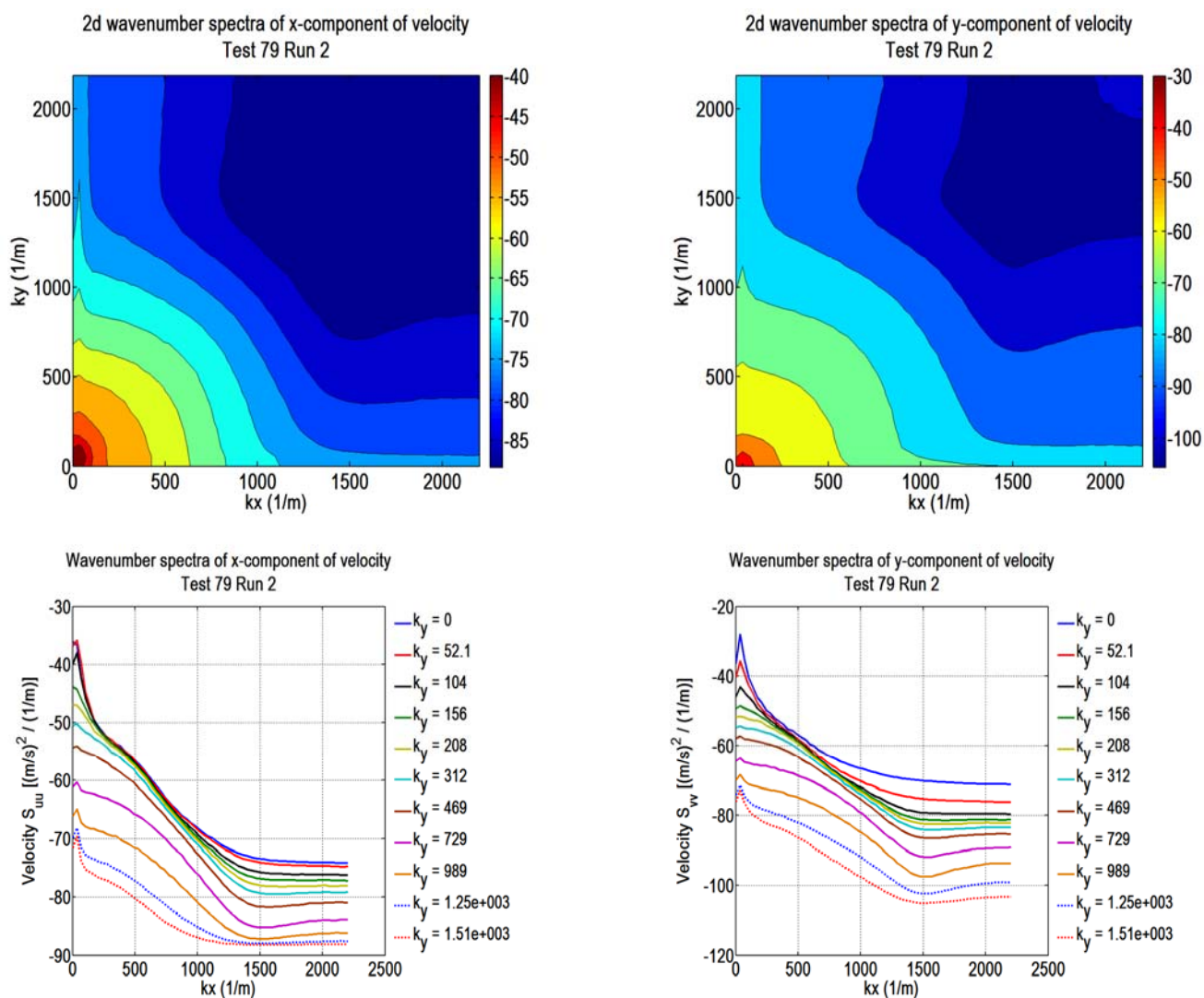


Figure 67. Wavenumber spectra for no fin for $V_{ref}=3.61$ m/s (Run 79-2). The bandwidth is along k_x is 35.1 m^{-1}

5 Part 4 – Forced Fin

The final configuration being considered contains the roughened cylinder and the fin installed in the water tunnel. Here the cylinder wake is used to generate a wake designed to excite the fin into bending. This section includes a complete definition of the water tunnel configuration, repeated baseline measurements similar to previous sections, and finally measurements on the fin itself.

5.1 *Experimental methods*

This section describes the experimental configuration where the fin is added to water tunnel test section behind the roughened cylinder. Both the details of the fin are explained plus the associated instrumentation including a load cell and the use of a laser vibrometer system to measure its vibration.

5.1.1 Test section configuration

This section discusses the cylinder and fin installation, as well as the fin load cell.

5.1.1.1 Water tunnel specifications

The experiment was conducted in the 12-inch re-circulating water tunnel at the Pennsylvania State University Applied Research Laboratory. The tunnel is schematically shown in Figure 1 and Figure 68 provides a picture of the experimental setup during testing. The tunnel is powered by a 112 kW motor and has either a cylindrical or rectangular test section. For the current study the cylindrical test section was used, which has an inlet diameter of 0.305 m (12-inch) and is 0.76 m long. The test section is designed such that the diameter gradually increases from the inlet to a maximum diameter of 307 mm at the test section outlet. This gradual increase in diameter is designed to minimize the influence that boundary layer growth on the tunnel walls has on the local free-stream velocity. Throughout testing the tunnel pressure was maintained at 138 kPa, though the absolute pressure can be varied from 20 to 414 kPa. In the current experiment the empty test section flow-field was measured at

velocities between 2.6 and 14.8 m/s, though higher velocities are possible with this facility. These empty test section measurements showed that the free-stream turbulence levels within the test section were below 1% (minimal measurable range for the acquisition system used). Historical data acquired in this facility indicates that the empty test section free-stream turbulence level is below 0.3%. These measurements also confirmed that within the range of interest for the current study there was minimal increase in the free-stream velocity due to boundary layer growth on the tunnel walls. Additional tunnel details can be found in Madavan *et al.* (1984, used the rectangular test section), Deutsch & Castano (1986) and Fontaine & Deutsch (1992).

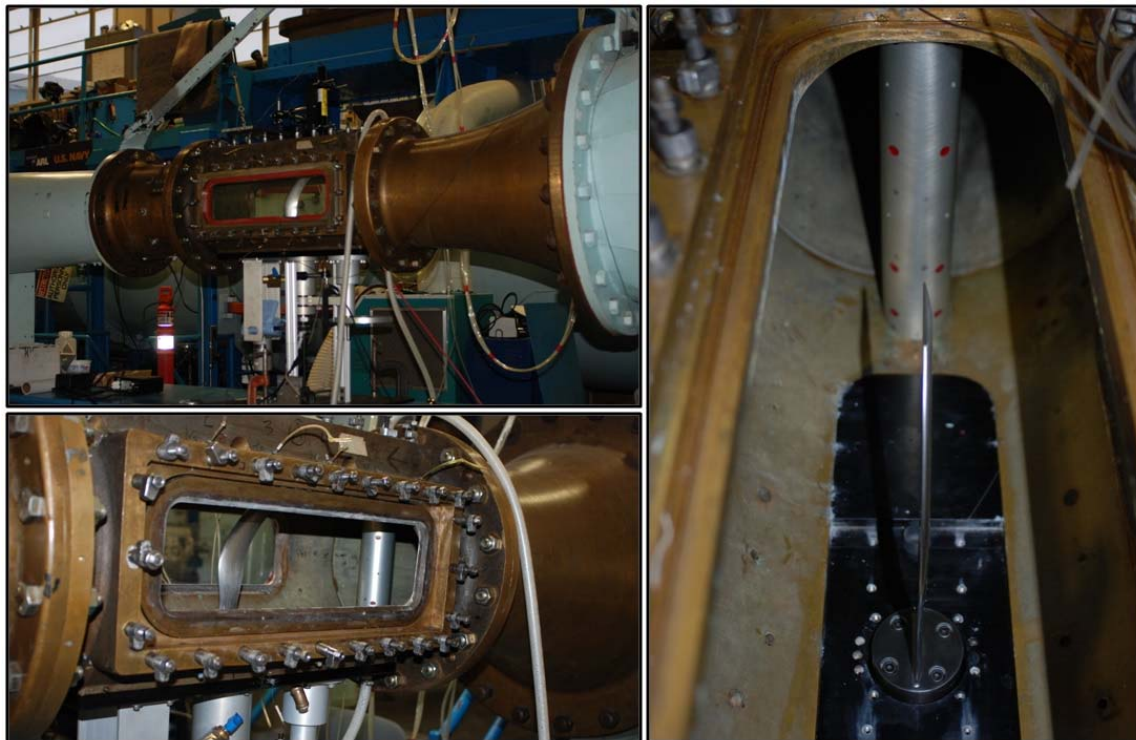


Figure 68. Pictures of the ARL 12-inch water tunnel test section during the HMMR forced fin testing (Part 4). (upper left) Shows the entire test section including the upstream contraction on the right edge, and the fin can be seen installed in the test section. (right) Shows a top view of the fin mounted in the tunnel downstream of the cylinder. This picture was taken prior to finishing the installation, which can be seen because the plates used to make the fin base flush with the tunnel bottom are not installed. (lower left) Shows a close up view of the test section from the opposite view of the upper right image, which allows the cylinder to be seen mounted in the test section inlet.

5.1.1.2 Test section layout

The overall test section configuration consisted of a roughened circular cylinder mounted in the test section inlet and a fin mounted to a six degree-of-freedom load cell located downstream in the cylinder wake, as schematically shown in Figure 69. The fin mounted to the load cell is referred to herein as the fin assembly. The coordinate system used throughout the experiment has the X coordinate increasing in the streamwise direction with its origin at the test section inlet, which was selected because it was a reference location available during every part of the experiment. The Z coordinate increasing vertically upward with the origin at the fin base height, which is 11.43 mm (0.45 in) above the bottom of the test section at the inlet due to a small ramp to create the flat surface at the bottom of the round test section. Finally, the Y coordinate completes a right-handed coordinate system with the origin at the tunnel centerline. The fin was positioned directly downstream from the cylinder, which places the fin in the oscillating cylinder wake. This was done intentionally to subject the fin to fluid-flow induced oscillating loading, which will result in the fin structure being deformed by the resulting forces. The altered fin structure results in changes to the flow pattern, and thus this is a fluid-structure interaction experiment. Specifics of the fin and cylinder design are provided subsequently.

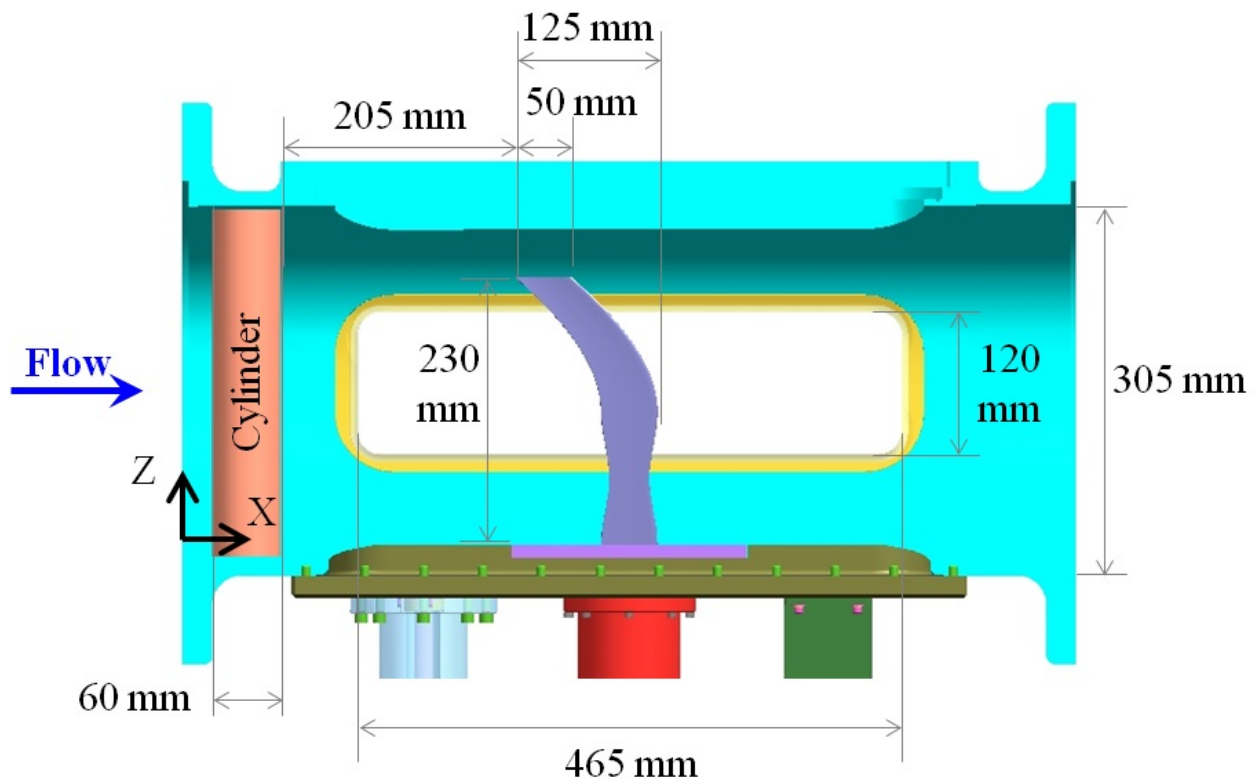


Figure 69. Schematic of the ARL 12-in water tunnel test section during the forced fin testing (Part 4). Here the fin is located directly downstream in the cylinder wake. Included in the schematic is the coordinate system used throughout the entire experiment. The out of plane direction (Y) completes a right-handed coordinate system, which would be out of the page in the figure.

5.1.2 Test model

This section describes the roughened cylinder and fin assembly for the forced fin test.

5.1.2.1 Cylinder

The roughened cylinder mounted in the test section inlet had a 60 mm diameter, spanned the entire test section height and was centered in the cross-stream direction (i.e., center of the cylinder was at $Y = 0$ mm). The cylinder was centered 49.5 mm downstream of the test section inlet, which places the cylinder trailing edge at $X = 79.5$ mm. The cylinder leading edge was roughened between $\theta = \pm 50^\circ$ with 60-grit silicon carbide (Washington Mills), which has an average particle size of 254 μm . Here θ is the angle measured counterclockwise from the cylinder leading edge (see Figure 10). The grit was

attached to the cylinder leading edge with spar urethane (Helmsman, Miniwax). The remainder of the cylinder was hydraulically smooth, as shown in Figure 37. The cylinder was instrumented with four dynamic pressure transducers and two static pressure ports (see Figure 38). A single accelerometer was also mounted inside the cylinder but it was damaged during the installation for Part 4 resulting in no useful accelerometer data for Part 4 and 2b. The dynamic pressure sensors were located at $\theta = \pm 130^\circ$ at either the fin tip height ($Z = 230$ mm) or the fin mid-span height (115 mm), and at each of these heights a single static pressure port was located at $\theta = 180^\circ$. Forced fin testing (Part 4) was conducted prior to the rough cylinder only testing (Part 2b), and the cylinder was not altered between these two parts of testing (unlike between Part 2a and Part 4, which had the entire test section disassembled and then reassembled).

5.1.2.2 Fin assembly

The fin assembly was designed to be compliant and allow for large fluid-induced motions. The fin was fabricated from Inconel 718 and had a chord length of 50 mm, a span of 230 mm and was swept forward 75 mm, as schematically shown in Figure 70. While able to change the angle-of-attack, the final test condition was fixed at -10° . The fin's span had a swept profile, but is oriented such that the sweep is into the flow (opposite typical operation) to simulate a propeller crashback type event. As shown in the figure, the first 115 mm of the span is straight, and then from the mid-span to the tip the profile is swept forward 75 mm. On the straight section of the fin span, the fin cross section (NACA 4408 profile) is necked down with a constant 8% thickness from a chord length of 50 mm to a minimum of 35 mm at about 57.5 mm from the fin base. This was done to reduce the stiffness of the fin near the base to promote larger tip deflections. Additional fin design details are provided in Appendix A. Due to the swept forward fin shape there are several relevant downstream positions for the fin. With the fin at -10° angle-of-attack, at the fin base the leading edge, 50% chord and trailing edge were located at $X = 354.4$, 379 and 403.6 mm, respectively. Similarly at the fin tip, the leading

edge, 50% chord and trailing edge were located at $X = 279.4$, 304 and 328.6 mm, respectively. The angle of attack also results in the tip leading edge ($X = 279.4$ mm) being located at $Y = -17.4$ mm and the base trailing edge ($X = 403.6$ mm) being located at $Y = 4.3$ mm.

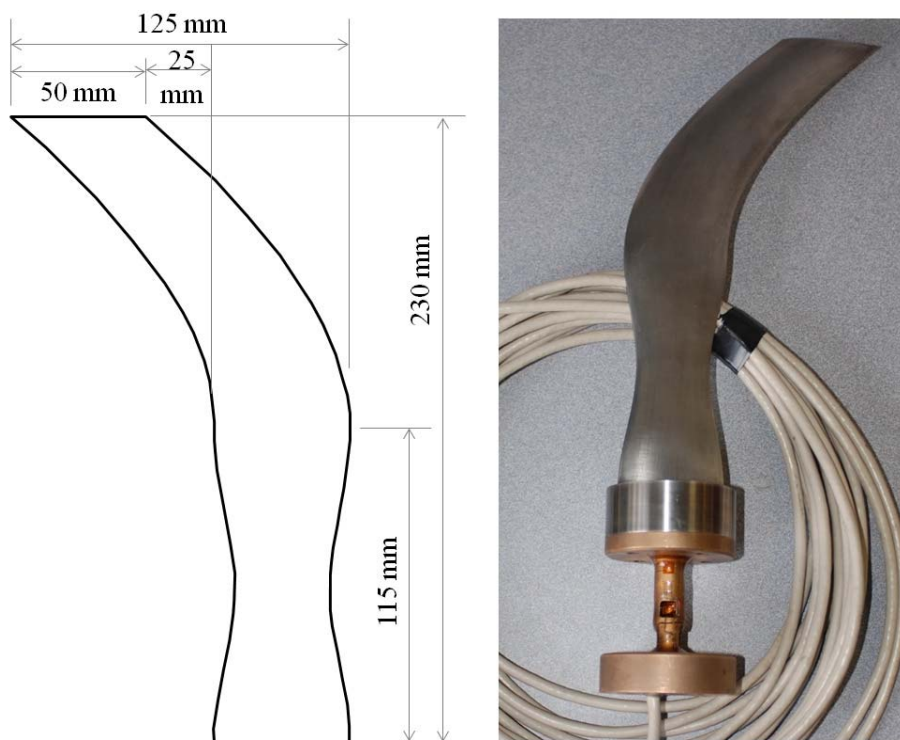


Figure 70. On the left is a schematic of the fin shape showing the span and chord directions along with the overall dimensions. The right image shows a picture of the fin mounted to the load cell. Note that the schematic does not include the fin base; the entire fin and base was machined from a single piece of Inconel 718.

The load cell is described in greater detail subsequently in the instrumentation section, but a brief description of the overall geometry is provided here. The four-component load cell shown in Figure 71 consists of a beryllium copper 69.9 mm long by 60.3 mm diameter cylinder that has a pocketed reduced-diameter center section that is strain gaged to measure fin assembly forces and moments. This instrumented section had an outer diameter of 12.7 mm and was 44.5 mm long. The four 7.62 mm by 7.62 mm pockets cut into the 12.7 mm diameter cylinder at various locations are shown in Figure 71. A 12.0 mm diameter hole was bored down the center of the load cell, 22.2 mm

from the end that attaches to the fin. This created a section of the instrumented cylinder that had a wall thickness of only 0.71 mm, which was required to facilitate the torque measurements. These load cell features required for the force and moment measurements significantly reduced the stiffness of the fin assembly and consequently must be considered in any model attempting to predict the structural motion of the fluid loaded fin assembly. Specific geometry and instrumentation layout of the load cell are also provided in Appendix A.

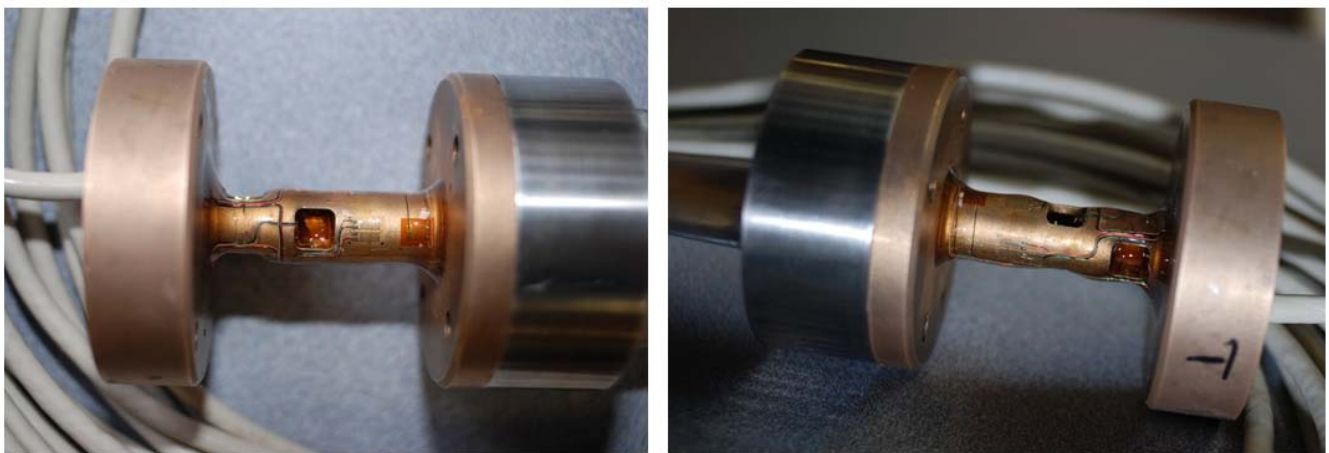


Figure 71. Pictures of the load cell from different angles to show the 7.62 mm × 7.62 mm pockets that have been cut out of the instrumented center shaft. The lift cell pocket is located closer to the thicker beryllium copper base, while the drag cell pocket is farther from the thick base.

5.1.3 Instrumentation

This section describes the instrumentation used for measurements of fin angle of attack and maximum tip deflection limits, cylinder dynamic pressures, two-component velocity flow field (high-speed PIV), fin forces and moments (fin load cell), fin surface normal displacement (laser vibrometry), fin tip motion (high-speed video) and tunnel operating conditions.

5.1.3.1 *Fin assembly monitoring*

The fin assembly was continuously monitored throughout Part 4 testing. Discussion of the fin assembly force and moment measurements with a four-component load cell is provided subsequently. The base angle of attack was precisely controlled and measured with the use of a rotary positioning assembly attached to the fin assembly. A picture of the overall arrangement is provided in Figure 72. The fin was rigidly attached to the instrumented load cell. The opposite end of the load cell was rigidly fixed to the load cell shaft, which was connected to the load cell housing through a pair of tapered roller bearings and a lip seal. The load cell housing was flooded through the gap between the fin base and the surrounding tunnel window. External to the tunnel the load cell shaft was clamped to the cam follower arm, which was pinned to a cam plate. The plate could be rotated about an off-center cam shaft. The load cell was also secured to a timing belt assembly with the opposite end of the belt fixed to a rotary encoder (M25D-X-H3600B3-XD5-X-E-C14-X-5, BEI Motion Systems). The output signal from the rotary encoder was sent to an absolute encoder resolver, which had an output of 10 mV per degree. This output signal was acquired through a data acquisition card (USB-6259, National Instruments) and recorded with commercial acquisition software (LabView, National Instrumentation). A calibration was performed in-situ on the rotary encoder and determined that $\alpha = -100V_\alpha + 171$, where α is the no-flow angle of attack in degrees and V_α is the outputted voltage from the absolute encoder resolver. Preliminary Part 4 tests were performed at lower angles of attack, but the final test configuration had a fixed $\alpha = -10^\circ$. To ensure that the fin assembly was secure during testing, an additional clamp was used to fix the cam follower arm to the tunnel support structure.

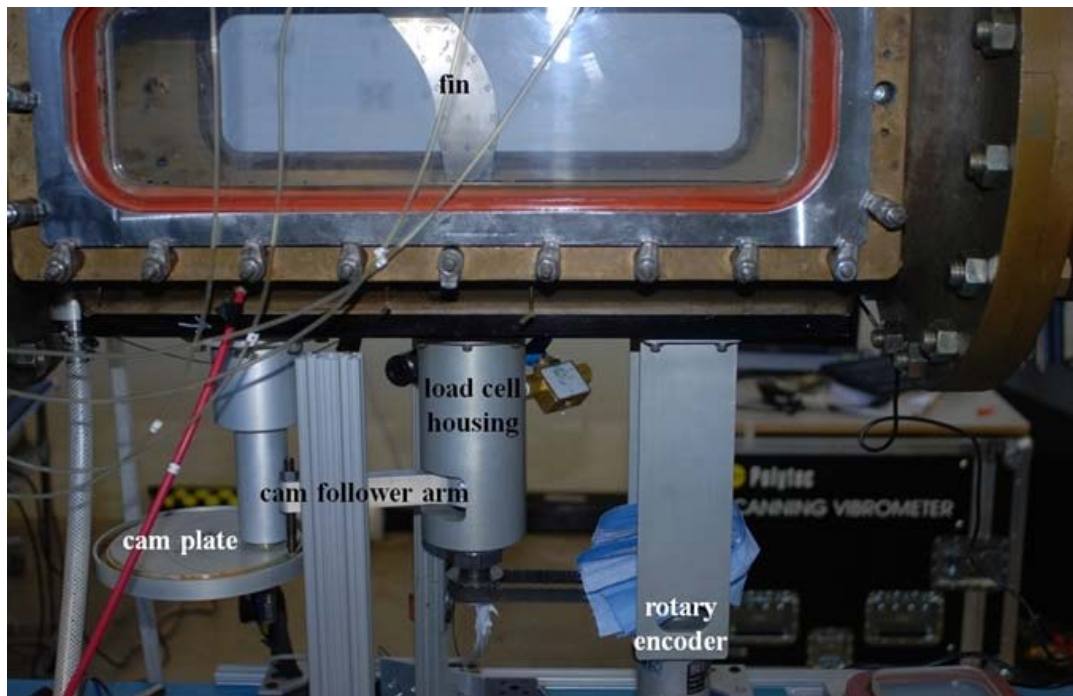


Figure 72. The angle of attack control and measurement assembly. Shown is the fin mounted within the test section, the load cell housing, the cam follower arm, the cam plate with the off-center cam shaft and the rotary encoder with the pulley assembly.

An optical switch was used throughout forced fin testing (Part 4) in order to detect if the fin deflected beyond the design limits. The optical setup consisted of a 1.5 mW random recertified (05-N) HeNe laser (NT62-718-RCD-05N, Edmund Optics) mounted on the top of the test section and a photodiode (PDA55, Thorlabs) positioned below the test section. The laser, pictured in Figure 73, had a 110 V power supply (NT62-733 Edmund Optics) and the red beam entered the test section through the optically transparent window on the top of the test section. The beam was carefully positioned such that it passed through the test section near the fin tip and exited through a small optically transparent plug in the bottom of the test section. The distance between the fin tip and the beam was adjusted such that a tip deflection of $\sim 3.5\%$ of the span (8.1 mm) would break the beam path. This distance was selected to limit deflections of the fin to preclude adversely affecting the structural integrity of the Inconel 718 fin. Due to optical access limitations when acquiring high-speed video and PIV the beam could not be positioned directly above the fin. Thus the beam path had to pass through a position lower

on fin span, but the offset was adjusted so the beam would still be broken when a tip deflection of $\sim 3.5\%$ was achieved. When the beam path was broken the output from the photodiode would drop from 5 V to zero. The photodiode signal was acquired through a data acquisition card (USB-6259, National Instruments), which also acquired the load cell signals, the water temperature, tunnel impeller frequency and a trigger signal used to synchronize these measurements with high-speed video and PIV data. In addition to the optical stop, a mechanical stop, shown in Figure 73, was initially used during forced fin testing. The mechanical stop was fixed to the test section top window and had adjustable set screws to precisely position their nylon tipped ends relative to the fin. Initial testing of the fin with the mechanical stop was performed at $\alpha = 0^\circ$, -5° and -10° . The nylon tip set screws were adjusted for each angle-of-attack such that the fin tip could not deflect more than 3.9% of the fin span (8.9 mm), which was selected to ensure that the fin would not experience fatigue failure during the initial shakedown. Once the angle-of-attack was increased to the design angle (-10°) and the velocity required to achieve tip deflection in excess of 3% was determined, the mechanical stop was removed from the test section and never used again during the forced fin testing. Comparisons between data acquired with and without the mechanical stop are in excellent agreement; however, unless stated otherwise, all measurement results provided herein are without the stop installed.

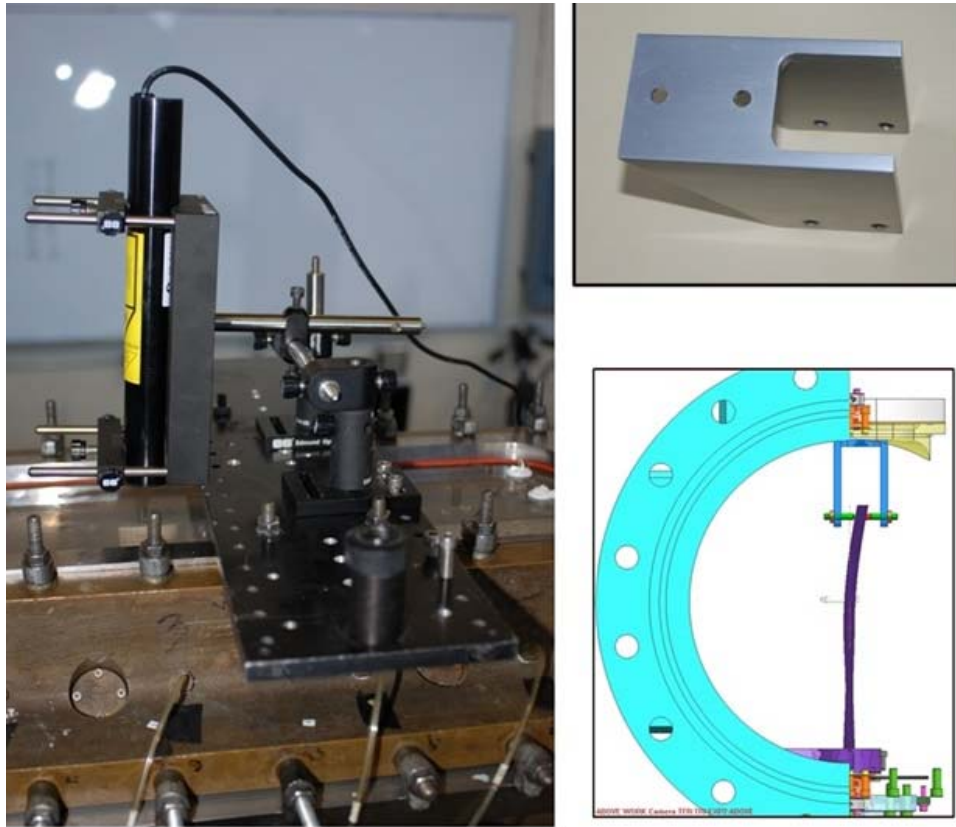


Figure 73. Shown (left) is the HeNe laser for the optical stop mounted on the top of the test section, (upper right) a picture of the mechanical stop and (lower right) a schematic of the mechanical stop installed with the fin. The mechanical stop was only used during the initial testing until the final target test condition was established.

5.1.3.2 Cylinder monitoring

The cylinder performance was monitored with two static pressure ports and four dynamic pressure sensors (105C02, PCB) on the aft end of the cylinder. The accelerometer used during testing with the smooth cylinder (Part 2a) was damaged during the reinstallation of the roughened cylinder, which prevented its use during Parts 2b and 4 testing. The mounting of the instrumentation inside of the cylinder is shown in Figure 38. Two of the dynamic pressure sensors were mounted at the fin tip height ($Z = 230$ mm) and the other two were mounted at the fin mid-span height ($Z = 115$ mm). As shown in Figure 10, at each height one sensor was positioned $\theta = +130^\circ$ and the other at $\theta = -130^\circ$ (i.e. $\pm 50^\circ$ from the cylinder trailing edge). These sensors were used to measure the cylinder shedding frequency and the relative strength of the shed vortices. A static pressure port was positioned at $\theta =$

180° at the fin mid-span ($Z = 115$ mm) and tip ($Z = 230$ mm) heights. Each port was plumbed to a small tube (see Figure 10), which exited the tunnel through a tee-junction box. The same tee-junction box was used to get the dynamic pressure transducer wires out of the tunnel. Each of the static pressure lines were then plumbed to a pressure transducer (dxd-series, Heise). The dynamic pressure transducers were powered with integrated circuit piezoelectric (ICP) power supplied either internally through the data acquisition system or externally with an ICP sensor signal conditioner (480B21, PCB Piezotronics). The outputted signals were then captured with a dynamic acquisition card (cDAQ-9178, National Instruments) and recorded with commercial acquisition software (LabView, National Instrumentation). The static pressure signals were recorded within the same acquisition program, but through a separate acquisition card (USB-6259, National Instruments).

5.1.3.3 High-speed PIV

High-speed PIV was acquired in the double-frame double-pulse mode, which requires the laser to be operated at the maximum laser power (diode current = 46 amps). Image pairs separated in time between 110 and 500 μ s were acquired at 1,000 Hz (i.e. a total of 2,000 images were acquired each second, which produced 1,000 vector fields), and Table 7 provides a summary of all the conditions acquired with high-speed PIV during Part 4. While the system is capable of acquiring 3D velocity measurements, optical access limited the arrangement to only acquiring two-components of velocity (X and Y velocity components) in a 2D plane. The 2D plane was located at $Z = 188$ mm with a field of view spanning $X = 145$ to 385 mm and $Y = -80$ to 85 mm. This plane was used for acquisition with and without the fin installed in the tunnel. The plane was illuminated with a light sheet that entered the flow from the + Y side of the tunnel and was positioned as close to the fin tip as optical access would allow ($Z = 188$ mm). The sheet was formed with the beam of a high-speed pulsed Nd:YLF diode pumped laser (DM50-527, Photonics Industries) in the single head configuration. The laser is designed

for a maximum energy per pulse at 1 kHz, but has a maximum repetition rate of 10 kHz. The energy per pulse at 1 kHz is 50 mJ with a pulse width of ~ 120 ns. The laser was mounted on the three-axis linear traversing table used for LDV measurement, which had less than 50 μm (minimum measureable distance) relative motion between it and the test section. The green light beam (wave length = 527 nm) produced has a nominal diameter of 4.5 mm and a divergence of 8 mrad. The beam was then formed into a laser sheet with the use of an adjustable focus lens (KL-S0-277, LaVision) and a -10 mm focal length cylindrical lens. The pulse energy had to be adjusted to produce uniform light intensity in each acquired image, which the final setup had 70% energy in pulse 1 and 30% energy in pulse 2. The light was scattered in the flow with the use of hollow glass sphere particles (iM30K Glass Microspheres, 3M), which have an average diameter of 18 μm . The scattered light was then imaged with a 1280 $\times$ 800 pixel CMOS sensor high-speed camera (v1610, Phantom) fitted with a 28 mm lens (EF28mm f/1.8 USM, Canon). The images were spatially calibrated by imaging a 100 mm $\times$ 100 mm 3D PIV calibration target (106-10, LaVision) aligned with the laser sheet. The target consisted of a 100 mm $\times$ 100 mm rectangular grid of 2.2 mm diameter dots spaced 10 mm apart. The target has two planes separated by 2 mm for 3D calibrations, but this was not required for the current effort.

A minimum of 3,000 image pairs (3 seconds at 1 kHz) were acquired for each test condition measured. Prior to computing the vector-field from the image pairs, the average from 99 adjacent images was subtracted from each raw PIV image. This significantly improved clarity of the tracer particles relative to the background in each image. These average subtracted image pairs were then processed using standard cross-correlation techniques (DaVis 8, LaVision) with multiple passes to produce an instantaneous velocity vector field. Each pass reduced the interrogation window, which had a final size of 24 $\times$ 24 pixels with 75% overlap. This produced a final vector spacing of 1.4 mm.

Table 7. Tunnel impeller frequency, test section reference velocity, repeated conditions and the total number of image pairs (i.e. vector-fields) acquired during high-speed PIV acquisition during the forced fin testing (Part 4). All the measurements were acquired in a single plane located at $Z = 188$ mm, which was the closest position to the fin tip that had sufficient optical access. The data rate for all the measurements was 1 kHz.

f_{imp} (rpm)	V_{ref} (m/s)	Test Runs	Total Image Pairs
58	2.5	test 42 (run 2, 4)	6,000
69	3.0	test 42 (run 7); test 75 (run 48)	6,000
77	3.3	test 42 (run 10)	3,000
80	3.4	test 42 (run 13); test 75 (run 4)	6,000
84	3.6	test 75 (run 14, 27, 36)	9,000

5.1.3.4 Load cell

The following sections describe the load cell design, calibration and measurement error estimates.

Structure/Geometry

The load cell was briefly described previously and the mechanical drawings are provided in Appendix A, but a description of the overall load cell geometry is provided here as well for completeness. The beryllium copper load cell is a 69.9 mm long, 60.3 mm diameter cylinder that is rigidly fixed to the 60.3 mm diameter fin base with four screws and 4 locating pins. The opposite end of the load cell is fixed to the load cell shaft, which is rigidly fixed to the angle of attack positioning and measurement assembly described in the fin monitoring section. The diameter of the cylinder is reduced to 12.7 mm for a 44.5 mm long section in the middle of the load cell (see Figure 71). This section of the load cell is instrumented with the strain gauges at various locations required to measure fin assembly forces and moments. To measure the strains created by the lift and drag forces, 7.62 mm by 7.62 mm pockets were cut out of each side of the center section leaving only a thin membrane aligned in either the lift or drag directions at the center of the cylinder. The thin membrane was

centered 31.9 mm below the fin attachment location for the drag force measurement. The lift force membrane was centered 45.4 mm below the fin attachment location and rotated 90° relative to the drag cell membrane. The cylinder was also weakened to facilitate the torque measurement by boring a 12.0 mm diameter hole, 22.2 mm deep down the center of the cylinder from the fin attachment side. This resulted in a section of the instrumented center that had a wall thickness of only 0.71 mm, which results in significant strains in the material for the given torque. The drag moment bridges were attached to the outside of the reduced diameter cylinder 19.8 mm below the fin attachment end, and the torque cell bridges were affixed to the outside of the reduced diameter cylinder 12.1 mm below the fin attachment location on the same side as the drag force pockets (see Appendix A for complete instrumentation layout drawing). The final load cell wall thicknesses where the Wheatstone bridges were affixed were sized to produce a desired dynamic strain measurement range. The lift-force cell, drag-force cell, drag-moment cell and torque-moment cell were designed for a maximum load of 110 N, 22 N, 5.0 Nm and 5.5 Nm, respectively.

Wiring and Gauging

The load cell was designed to measure the lift force, drag force, *Y*-axis moment (drag moment) and the *Z*-axis moment (torque) when at $\alpha = 0^\circ$. An attempt was made to also measure the *X*-axis moment (lift moment), but the cell could not be optimized to accommodate this measurement. For each measured component a separate Wheatstone bridge of strain gauges (lift, drag and torque – sk-06-062TW-350, Vishay; *Y*-moment – TK-06-092P-10C/DP, Vishay) was affixed (M-Bond AE-10, Vishay) to the beryllium copper pocketed cylinder. The wiring diagram for the load cell including the lift moment is provided in Figure 74. All the bridges were supplied with a 10V excitation from a single DC power supply (Harrison 6200B, Hewlett Packard). The output signal from each bridge was then acquired with a data acquisition card (USB-6259, National Instruments) and commercial acquisition software (LabView, National Instruments) at 1 kHz sample rate.

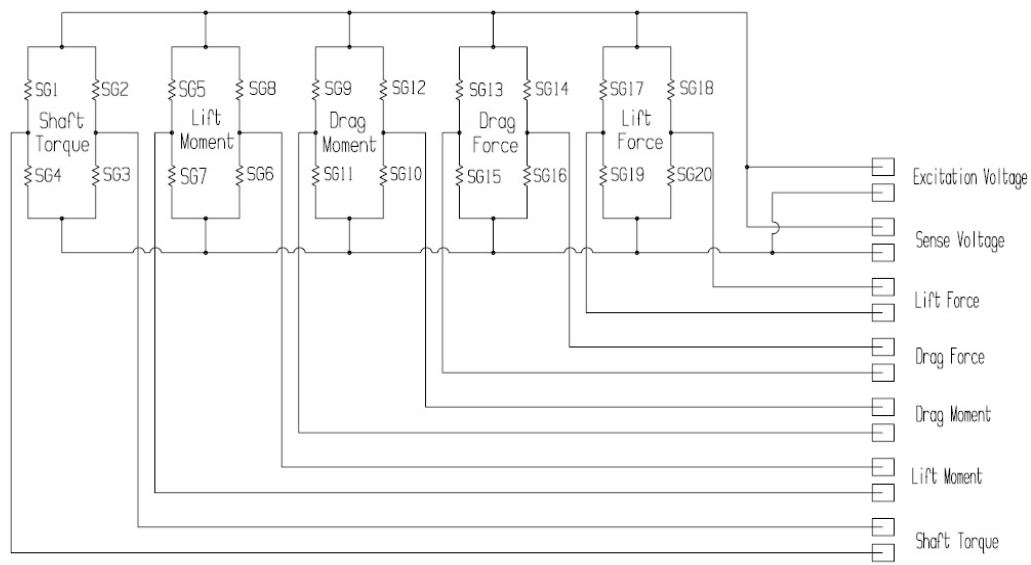


Figure 74. The load cell wiring diagram showing the force and moment components. Each of the outputs, as well as the excitation voltage (sense voltage), were recorded along with the cylinder and tunnel monitoring data.

Calibration

The load cell was calibrated prior to testing following ARL established calibration procedures for multi-component load cells (procedure GTWT-R0). Here the fin, load cell and the load cell shaft were assembled and rigidly mounted in the GTWT calibration laboratory (separate from the water tunnel). There were a total of 36 separate conditions tested to produce the final calibration matrix. For each condition the output signals were recorded while a 53.4 N (12 lb) force was hung from the load cell and then removed. The cell was oriented during the calibration such that the axis of rotation was horizontal and at an angle of 0° so that the applied calibration load corresponded to the drag force when installed in the tunnel (i.e. 90° corresponds to the lift force). During the calibration the angle was rotated from 0° to 315° , the lift and drag moment arms were varied (76, 152 or 229 mm) and the torque moment was either 0 or ± 25.3 mm. The lift and drag moment arms were measured relative to the load cell face that attaches to the fin. The final calibration matrix after the lift moment was removed was

$$\begin{bmatrix} L \\ D \\ Tq \\ DM \end{bmatrix} = \begin{bmatrix} -8203.014 & -142.8556 & -11.36067 & 86.8379 \\ -68.0666 & 7491.664 & 35.99477 & 297.1874 \\ 206.4989 & -495.471 & 3050.562 & -75.4253 \\ 111.01 & -6888.289 & -2.33992 & 3525.451 \end{bmatrix} \begin{bmatrix} V_L \\ V_D \\ V_{Tq} \\ V_{DM} \end{bmatrix}.$$

Here L is the lift force in pounds, D is the drag force in pounds, Tq is the torque in inch-pounds, DM is the drag moment in inch-pounds, V_L is the voltage from the lift cell, V_D is the voltage from the drag cell, V_{Tq} is the voltage from the torque cell and V_{DM} is the voltage from the drag moment cell. This calibration matrix was then confirmed with a crude in-situ calibration using a mechanical force gauge (Chatillon LG-100, Ametek) to apply loads to the installed fin assembly at various locations on the fin.

Error Propagation/Analysis

Uncertainties in load cell measurements are broadly divided into errors generated by the calibration procedure and all other errors associated with the instrument and measurement equipment. Uncertainties are divided in this manner because the load measurement involves so many potential sources of error that traditional propagation of error techniques would be challenging and potentially inaccurate due to each custom sensor having unique behaviors. Consequently, the difference between the back-calculated loads and known applied calibration loads are considered the measurement uncertainty. This difference is typically termed the residual load, which provides a measure of both the random and bias errors in the measurement device. The primary limitation with this approach is that it does not account for error in the calibration procedure (e.g. accuracy of alignment). However, these alignment uncertainties are typically an order of magnitude less than the other measurement uncertainties. The typical measured residual loads from the load cell calibration are provided in Table 8. Given the mean values of these measurements from the experiment, the typical accuracy of the measurement is 4% to 5% of the measurement for the lift force and drag moment, but between 7% and 10% of the measurement for the drag and torque. The target accuracy for the lift, drag and torque measurements was 4%, but these final numbers are slightly higher primarily because the final

maximum loading was slightly lower than assumed during the design phase. Note also, that the uncertainty increased during the end of the testing because the load cell (particularly the lift and drag moment cells) were going bad, and due to the cross-talk components, this introduces additional error into all the measurements. In spite of these limitations and the resulting scatter, the velocity dependence in the results is still apparent in spite of the narrow velocity range. These calibrations were only performed under static conditions, but an experimental modal analysis (see Section 5.2) was performed to confirm that the load cell resonant frequency was at least an order of magnitude higher than the forcing frequency of interest in the current study (~200 Hz minimum frequency).

Table 8. Summary of the residual load estimates from the load cell calibration and the resulting uncertainty range for each measured component.

Component	Mean Residual Load	Full Scale	Typical Uncertainty
Lift Force	±0.3% f.s.	110 N	±0.3 N
Drag Force	±2.0% f.s.	20 N	±0.4 N
Torque	±1.0% f.s.	5.4 Nm	±0.05 Nm
Drag Moment	±0.5% f.s.	4.7 Nm	±0.02 Nm

Mounting/Gap Control

There is an additional bias error that is unaccounted for in the residual load estimates. This potential additional uncertainty is related to misalignment between the floating element (fin base) and the surrounding tunnel wall as well as flow through the gap. Figure 75 shows two figures from Klewicki (2007), which discusses the influence of misalignment and gap errors on shear stress measurements acquired with floating-element sensors. The current experiment is not as sensitive because the loading on the fin is much greater than the skin-friction generated on the flush mounted floating plate (i.e. fin base). However, it is instructional to use these figures to highlight how these errors impact the measurements. The upper schematic in Figure 75 shows the various undesirable flow

patterns that are generated due to misalignment and the resulting pressure and forces that act on the floating element. When only measuring the skin-friction these errors can quickly become comparable (or even larger) than the desired measurement. In the current study this is not the case because the fin has normal surfaces in the flow that will generate similar pressures and the surface area intentionally exposed to the flow is much larger than any unintended area exposed at the fin base.

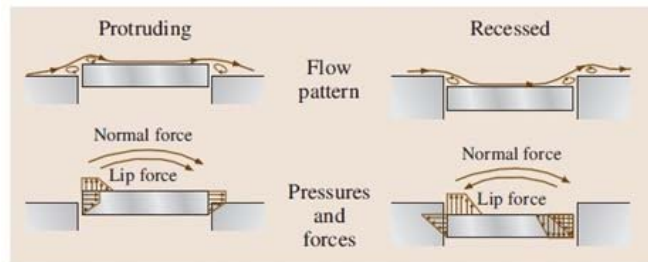


Fig. 12.8 Schematic representation of detrimental floating element misalignment errors (after [12.58])

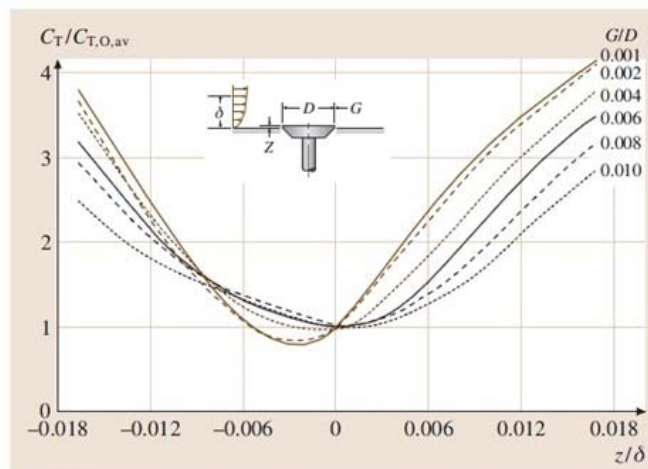


Fig. 12.9 Effects of nondimensional gap and step size on floating element drag measurements (after [12.58])

Figure 75. Figures reprinted from Klewicki (2007) showing the influence that the gap and misalignment have on the accuracy of floating-element type force sensors.

However, the gap flow error is of particular concern for the current study because the gap had to be relatively large to accommodate the large motions designed into the test model. This large gap (0.3 mm) was required because if the fin base touches any of the surrounding tunnel walls then the load measurements will be clipped. The lower plot in Figure 75 shows that the gap size is not critical if the floating element misalignment height is much smaller than the boundary layer thickness. Though

the boundary layer thickness was not specifically defined due to the oscillating free-stream velocity at the fin location, from Figure 27 it is apparent that the nominal boundary layer thickness is approximately 50 mm. A realistic estimate for the plate misalignment would be 250 μm , which gives a misalignment to boundary layer thickness ratio of 0.005. This results in the error generated by the gap being of the same order of magnitude as the skin-friction generated on the circular fin base. This level of precision would be insufficient if the current study was measuring the skin-friction generated from the developing boundary layer. However, in the current study the desired forces are significantly larger than the skin-friction. Hence the gap error is expected to have minimal influence on the final results.

5.1.3.5 Fin motion (laser vibrometry)

A Polytec PSV-400-3D scanning vibrometer was used to quantify the surface displacement of the forced fin for several operating conditions. The vibrometer uses a helium-neon laser (633 nm wavelength) and has sensitivity for frequencies near DC to 1 MHz. It is capable of measuring surface vibration up to 10 m/s (velocity). The PSV-400-3D is capable of scanning up to 30 surface locations per second.

The scanning vibrometer was focused on the pressure side of the fin from outside the water tunnel. Due to visual access limitations associated with the test section windows, it was known a priori that surface measurements at the fin tip and below 40% span would likely not be obtained. As such, a 7 $\times$ 3 grid of points was chosen for the vibrometry measurements. These 27 locations on the pressure side of the fin correspond to 40, 50, 60, 70, 80, 90 and 98 percent span and 10, 50 and 90 percent chord at each spanwise location. These surface measurement locations were located on the fin with 3 mm diameter black circles during the manufacturing inspection process. In order to achieve vibrometry measurements closest to the fin tip, the vibrometer head was positioned at the 50% fin span location with the laser beam parallel to the floor. The vibrometer standoff distance from the fin surface was

optimized for maximum signal return with the long range lens installed at 507 mm. At this distance, however, the maximum spanwise location that could be obtained was 95% span. As a result, the fin tip displacement was measured at this location instead of 98% span.

To obtain phase information from a reference channel for the scanning laser vibrometry measurements, a second laser vibrometer head and controller (Polytec OFV-505 and OFV-5000, respectively) was set up and permanently fixed at the 80% span, 90% chord fin location. Figure 76 shows the two vibrometers focused at different locations on the fin surface. Both vibrometers were positioned normal to the fin surface, with the stationary fin angle-of-attack at approximately -9.7° , using a mirror at the 90% chord location to direct the beam reflections back into the laser head optics. The beams from the vibrometer heads were approximately normal to the fin surface at the 90% chord locations. The surface angle at the 90% fin chord position only varied by 0.2° for all 7 vibrometer span locations and by up to 3.4° compared to the 10% chord locations. Assuming the vibration of the fin is purely normal to the surface, the laser vibrometry data was corrected for changes in surface angle before being processed by dividing by the direction cosine.

The scanning laser vibrometry data was acquired on both the PSV-400-3D system analyzer and a National Instruments (NI) PXI 4496 Data Acquisition (DA) card. The single-point OFV-505 vibrometry data was acquired solely on the NI system. Both vibrometers used a tracking filter (set to slow) to minimize signal drop-outs and internal low pass filters (set to 5 kHz). The sampling rate for both data acquisition systems was 512 Hz. The maximum frequency bandwidth was 200 Hz, which is below the Nyquist frequency. The frequency resolution was set to 0.125 Hz providing an ensemble period of 8.00 seconds. The scanning vibrometer was set up to acquire 16 complex ensembles at each measurement location using 50% overlap processing, resulting in a total acquisition time of at least 64 seconds per point. If any overloads in the vibrometry signal or poor signal-to-noise conditions occurred during the scanning measurement, that particular ensemble was omitted from the averaging; thus the acquisition time at each point would often exceed the 128 seconds in order to get the proper number of

averages for processing. Total acquisition time for all 21 measurement points was typically on the order of 30 minutes. The random error can be quantified using equations provided by Bendat & Piersol (1980). Assuming a coherence of 0.9000, the normalized random errors for the autospectrum, cross spectrum, coherence, coherent output power (COP) and transfer function are 0.2500, 0.2635, 0.0373, 0.2764 and 0.0589, respectively.

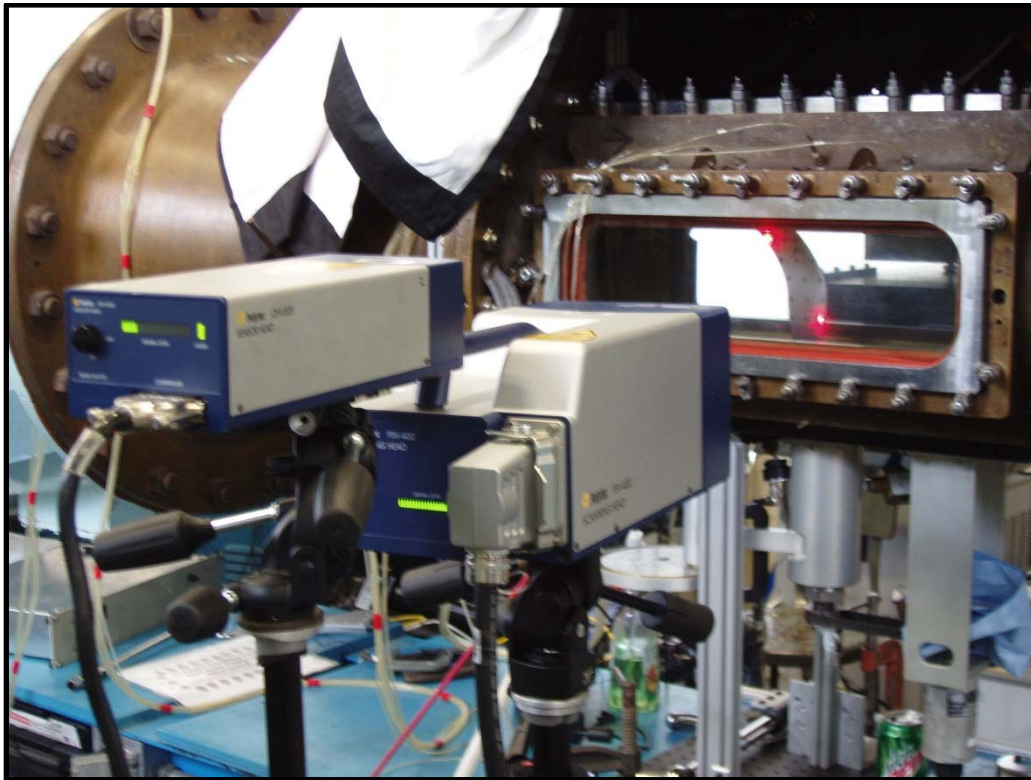


Figure 76. Both laser vibrometer heads focused on two separate fin locations.

5.1.3.6 Fin tip motion (high-speed video)

High-speed video was used to track the motion of the fin tip ($Z = 230$ mm). The camera used was the same one used for high-speed PIV (v1610, Phantom) fitted with the 28 mm lens. In fact, the PIV images were also used to measure the tip deflection in addition to the velocity field, but the accuracy was reduced due to the lighting not being optimized for the tip motion. Thus there was a subset of measurements acquired specifically focused on the fin tip motion in addition to the high-

speed PIV measurements. Sample images from both measurements are provided in Figure 77. When only acquiring fin motion measurements the fin was illuminated with halogen lights and the frames were synchronized with the load cell by sending the camera trigger source (manual switch) to the load cell acquisition system. Control, recording and initial filtering of these images were performed in the camera software package (PCC 2.14, Phantom). As can be seen from Figure 77, the camera focus and lighting for these measurements creates a much sharper edge and consequently less noise in the final results than the PIV images. While the PIV images are obviously noisier, the PIV images have two images spaced $\sim 100 \mu s$ between each other. Using the average deflection between the two measurements helped reduced the noise and consequently for at least the translational motion the accuracy is comparable to the tip motion only measurements. The primary difference when using the PIV images for fin tip motion is that the lighting source is now the Nd:YLF diode pumped PIV laser. The only issue with this is that now the light source enters the tunnel from the side, which prevents the opposite fin tip edge from getting much illumination. However, the side facing the laser is very bright and provides a clear edge to locate during processing. The other difference is that the load cell data is now synchronized with the imaging data by recording the camera trigger signal from the PIV controller unit and the acquisition is done through the PIV software (DaVis 8, LaVision).

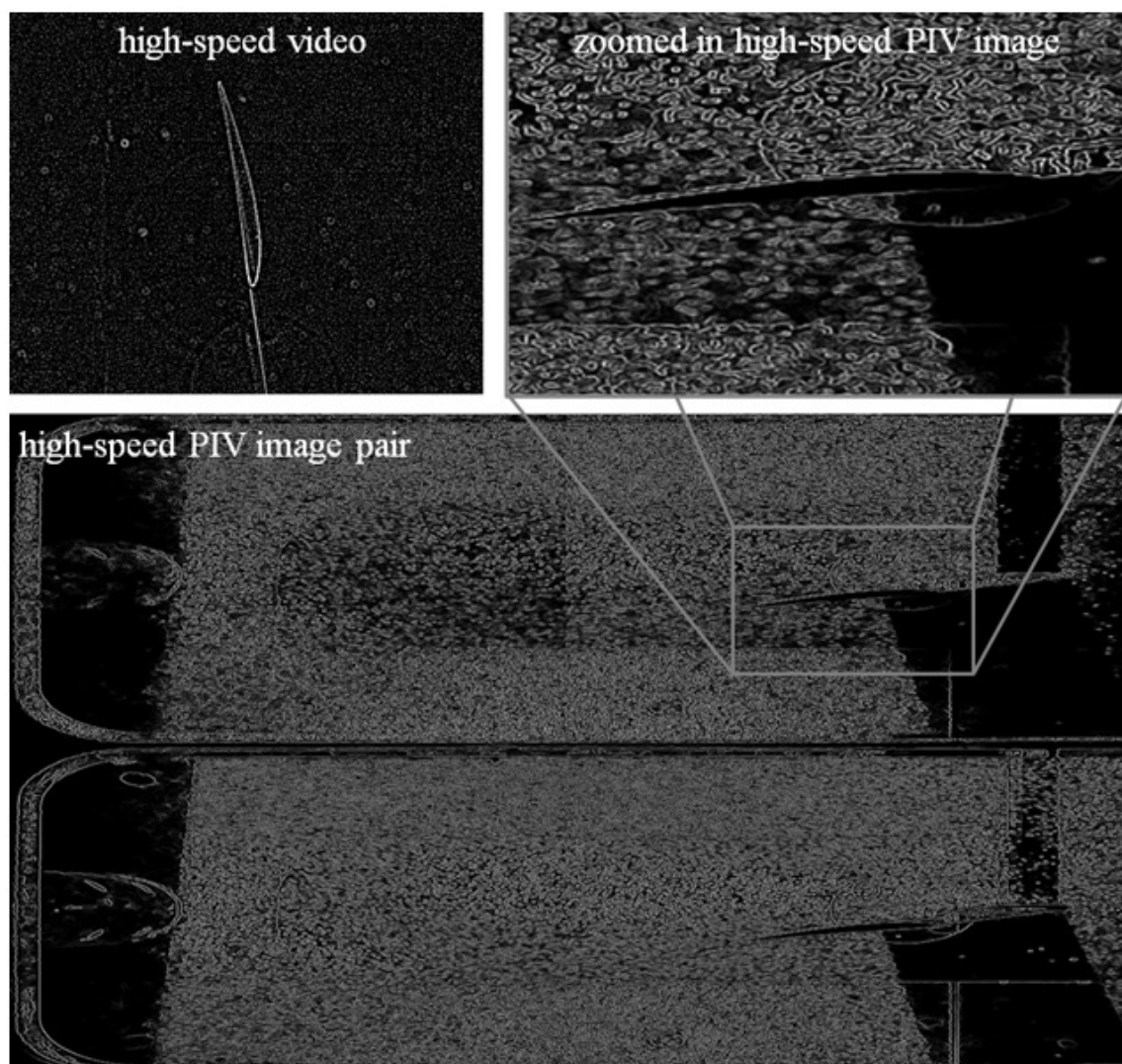


Figure 77. Edge filtered sample images used to measure the deflection and twist of the fin tip. In the upper left corner is an image from the high-speed-video focused specifically on the fin tip. Here the flow is from top to bottom in the image. These images produced accurate measurements of deflection and twist due to the sharp outline of the fin tip. The bottom image shows an image pair produced from PIV measurements, which has two independent images of the fin tip. The flow in the PIV images is from left to right. In the upper right corner is a zoomed in view of just the fin tip in the first (top) image from the PIV pair. These images do not produce as sharp of an edge, but the results from the two images are averaged to determine the tip deflection. This accurately measures the deflection, but obscures the twist measurement due the twist magnitude being small ($<0.4^\circ$).

The fin tip deflections were processed using a cross-correlation processing scheme. If the images were also used to acquire PIV measurements, the raw images were bandwidth filtered and then smoothed over a 3×3 pixel window to minimize the influence of the seed particles. Then all the images were passed through an edge filter using the Canny method to make the fin tip more apparent. A custom image processing code was written to compare each image with a single reference image. The

reference image was produced from the average of 100 images from a single no-flow condition. This reference image was used to process all the images acquired, which also allows for a measure of any warping of the fin over the course of the experiment. Comparison between the reference image and no-flow conditions acquired throughout testing showed the no-flow fin tip position varied less than 0.01 mm (less than a single pixel). The reference image was then segmented into 5 chord-wise pieces and a mask was applied to the image that set everything to zero besides the outline of the fin tip. Then the correlation coefficient,

$$R(dx, dy) = \frac{\sum_{i=1}^N \sum_{j=1}^M (A_{i,j} - \bar{A})(B_{i,j}(dx, dy) - \bar{B})}{\sqrt{\sum_{i=1}^N \sum_{j=1}^M (A_{i,j} - \bar{A})^2} * \sqrt{\sum_{i=1}^N \sum_{j=1}^M (B_{i,j}(dx, dy) - \bar{B})^2}}$$

where $\bar{A} = \frac{1}{NM} \sum_{i=1}^N \sum_{j=1}^M A_{i,j}$ and $\bar{B} = \frac{1}{NM} \sum_{i=1}^N \sum_{j=1}^M B_{i,j}$,

was computed between a given fin-deflected image and the un-deflected reference image. Here A is the reference image and B is the deflected image, which are each $M \times N$ pixels. Then the reference image would be reconstructed by shifting the image vertically (dy) and/or horizontally (dx) in one pixel increments. Then the correlation coefficient would be recomputed at the new shifted position. The maximum correlation coefficient for a given segment defined the deflection relative to the no-flow, un-deflected condition. This processing scheme was compared against over 400 manually calculated images and showed excellent agreement. If the images being used were PIV images then this processing was performed on each of the two images for a given time step and the deflection determined from the average of the two images. The spacing between the two PIV images was on the order of 100 μs , which is an order of magnitude smaller than the sample rate. The five segments of the fin now each have a measured deflection at a given chord-wise position. To achieve sub-pixel resolution, the data was linearly curve fitted, which the average offset is the fin tip translation (or deflection) and the slope is a measure of the fin tip twist (twist = $\tan^{-1}(\text{slope})$). The translation was

converted from pixels to physical units by applying a linear spatial calibration. This was done for each image producing a time trace of deflection and twist at 1 kHz temporal resolution. Estimated uncertainty in fin tip deflection and twist was ± 0.02 mm and ± 0.06 degrees respectively.

5.1.3.7 Tunnel monitoring

The tunnel conditions were monitored throughout testing with measurements of the water temperature and tunnel pressure (total and static). The water tunnel impeller frequency was initially recorded, but an undetected malfunction prevented the impeller frequency from being recorded during the second half of testing. However, the nominal impeller frequency was monitored and recorded in a notebook throughout testing. The signals were sampled at 1 kHz. The tunnel water temperature was measured with a RTD sensor (911PL, Stow Laboratories), which had a nominal output of 10 mV/°F. The probe was located in the upstream contraction. The tunnel temperature measurement was used to determine the water properties including density and kinematic viscosity.

The total pressure was measured with a Kiel probe mounted upstream of the test section contraction. The tunnel diameter at the Kiel probe location was 0.914 m, which also had a single static pressure port to provide a crude measure of the total volumetric flow rate into the test section. Additional flush-mounted static pressure ports were located along the length of the test section and used as real-time measurements of the tunnel velocity. Measurements were acquired at $X = 225, 329, 434$ and 538 mm, though the pressure transducer at $X = 434$ mm appeared to have been damaged. The pressure transducers at $X = 50, 121$ and 642 mm had also appeared to be damaged during prior tests and therefore were not recorded. The ports were located circumferentially 45 degrees from the axis of the cylinder. The total and static pressure measurements were acquired with the same pressure transducers (dxd-series, Heise) used for the cylinder static pressure measurements. All the tunnel monitoring measurements were recorded with a standard computer with a commercial data acquisition software package (LabView, National Instruments). The tunnel impeller frequency and water

temperature were acquired with the same acquisition card (USB-6259, National Instruments) used to acquire the load cell signals.

The difference between the total and static pressure measurements were used to provide a real-time measure of the local free-stream velocity. To minimize error associated with zero velocity offset between individual pressure transducers, prior to every test the pressure was acquired under no-flow conditions and that voltage was subtracted from the measurements at a given tunnel velocity. The data acquisition system recorded the pressure in units of pounds per square inch (psi), which was converted to Pascals (Pa) using the conversion the standard conversion (1 psi = 6,894.76 Pa). The total pressure measurement was then combined with the local static pressure measurements to determine the local tunnel velocity by applying the Bernoulli equation between the total pressure and static pressure locations,

$$U(X) = \sqrt{\frac{2(P_{total} - P_{static})}{\rho}}.$$

Here U is the local free-stream velocity at X where the static pressure measurement (P_{static}) was acquired, P_{total} is the total pressure and ρ is the water density. Throughout testing the average of the three velocity measurements was used to define the test section reference velocity (V_{ref}).

5.1.4 Test matrix

During the forced fin testing (Part 4) the tunnel impeller frequency and fin angle-of-attack could be varied. However, the angle-of-attack was fixed at -10° once a protective mechanical stop was removed from the tunnel. The nominal tunnel pressure was set at 140 kPa throughout testing. Thus the only flow parameter varied in the final forced fin dataset was the tunnel impeller frequency, which was varied between 50 and 84 rpm (though speeds below 58 rpm could not be regularly achieved). The corresponding tunnel test section reference velocity range was 2.1 to 3.6 m/s. The primary speeds where the majority of measurements were acquired were at 58, 69, 77, 80 and 84 rpm, which have a

corresponding test section velocity of 2.5, 3.0, 3.3, 3.4 and 3.6 m/s, respectively. The water temperature ranged during Part 4 from 19.7 to 21.5 °C, which results in a corresponding kinematic water viscosity (ν) of 9.7×10^{-7} to 1.0×10^{-6} m²/s, respectively. The average water temperature was 20.4 °C, which corresponds to a water kinematic viscosity and density (ρ) of 1.0×10^{-6} m²/s and 998 kg/m³, respectively. Continuous acquired measurements included the cylinder static and dynamic pressure, tunnel total and static pressure, tunnel impeller frequency, water temperature, fin angle-of-attack, fin forces and moments, and a binary indicator of the fin tip position. In addition, high speed video of the fin tip, high-speed PIV of the cylinder wake and laser vibrometry on the fin surface were acquired for a subset of conditions.

5.2 Fin and Load Cell Modal Analysis

In-air and in-water experimental modal analyses were performed to determine mode shapes and loss factors of the fin mounted on the load cell. Modal tests were conducted using a roving hammer and accelerometers while the fin was fully installed in the water tunnel, as shown in the left image in Figure 78, both in air and fully submerged in water. The hit points used are illustrated in the schematic on the right of Figure 78. Rows of hit points were located at nominally 10, 25, 40, 50, 60, 70, 80, 90 and 98% span and 10, 50 and 90% chord. Accelerometers were fixed at points 15 (60% span, near trailing edge) and 19 (40% span, near leading edge) and positioned to measure the cross-stream direction (Y). These two accelerometers were placed on the opposite side of the fin from the hit points. A third accelerometer was attached to the fin base via a mounting block and oriented to measure in the streamwise direction, as shown in the left image in Figure 79. Five streamwise oriented hits were made on the fin trailing edge, approximately normal to the surface, as illustrated in the schematic on the right of Figure 79. Hits were made near points 3, 9, 15, 21 and 27. A sixth hit was made on the fin base block, which had the third accelerometer mounted to it.

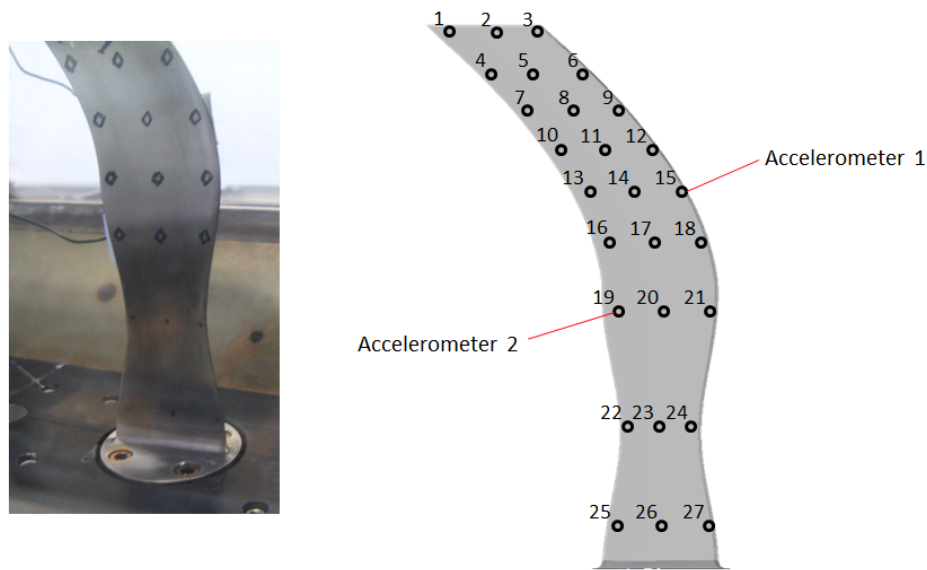


Figure 78. (left) Picture of the fin installed in the water tunnel, which shows the markings for the modal hit points. (right) A schematic diagram of the fin with the hit points numbered and locations of the fin mounted accelerometers noted.

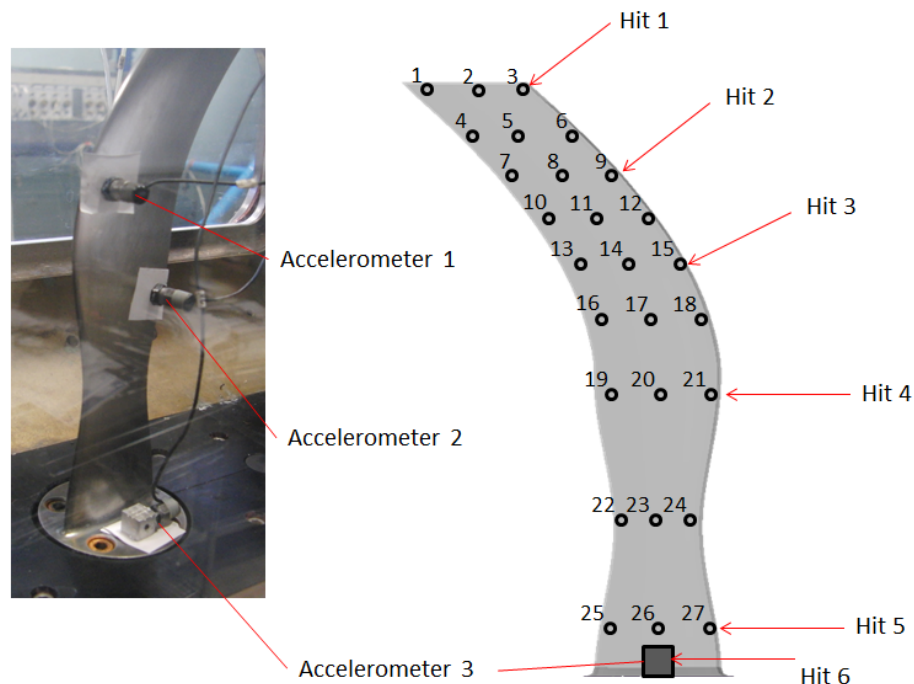


Figure 79. (left) Picture of the opposite side of the fin where the hits were made. This shows the mounting locations of the three accelerometers used to do the modal analysis. (right) A schematic diagram of the fin with the hit points numbered and streamwise oriented hit locations noted.

Three hits were made at each hit point. The outputs from the accelerometers were acquired at a sample rate of 3200 Hz for a duration of 5.12 seconds, which gives a usable bandwidth of 1250 Hz.

The duration was selected such that the fin vibrations decayed within the selected time window. The acquired data were processed using a singular value decomposition approach combined with rational fraction polynomial curve fitting to identify mode shapes, resonance frequencies and loss factors (Fahnline, Campbell and Hambric, 2004.) The frequency and loss factor of the first seven modes for the in-air and in-water cases are provided in Table 9. The in-water resonant frequencies were lower than the corresponding in-air frequencies for all seven modes. In-water loss factors were higher than in-air for all but the first torsion mode.

Table 9. Frequency and loss factors for in-air and in-water modal testing of the fin and load cell assembly mounted in the water tunnel. Provided are results for the first seven mode numbers.

Mode Number	Description	Frequency (Hz)		Loss Factor	
		In-Air	In-Water	In-Air	In-Water
1	First cross-stream bending	32.7	23.2	0.00250	0.01120
2	First streamwise bending	44.7	43.9	0.00518	0.00911
3	Second cross-stream bending	132.0	102.7	0.00444	0.00694
4	First torsion	212.9	185.4	0.01540	0.00916
5	Third cross-stream bending	318.1	285.1	0.00174	0.00489
6	Second streamwise bending	371.0	341.2	0.03560	0.05870
7	Second torsion	586.9	462.4	0.01230	0.02050

5.3 Tunnel Velocity

As was done in Parts 1 and 2, the reference velocity (V_{ref}) was defined as the average velocity from the static pressure measurements at $X = 225, 329$ and 538 mm. The reference velocity is a measure of the mean free-stream velocity within the tunnel test section. These transducers were chosen because they span the downstream location where the fin was located and the flow-field measurements were acquired. Figure 80 shows the reference velocity measurements as a function of tunnel impeller frequency (f_{imp}), which was acquired at tunnel speeds between 57 and 84 rpm. The frequency range is noticeably reduced compared to other parts of the experiment due to limit deflections of the fin

assembly. The tunnel impeller frequency measurement was lost in the middle of Part 4 testing due to an undetected instrumentation malfunction. Since it occurred in the middle of testing the measurements acquired prior to the malfunction were used to assess the difference between hand written notes and the actual measured frequency. It should be noted that the notebook values were taken from a digital display of the signal that was supposed to be recorded. This inspection showed that the average deviation between the notebook and the measured frequency was typically within 0.2 rpm. The maximum deviation observed (excluding the initial test without the mechanical stop) was 0.4 rpm, which results in a relative deviation in tunnel frequency of less than 0.9% (typically below 0.4%). Consequently, the plot was produced from a combination of notebook records and actual tunnel impeller frequency measurements. To show the difference solid symbols in the figure correspond to average results from actual measurements while the open symbols correspond to notebook estimates. It is apparent that the two are in excellent agreement. Also included in the figure are the linear curve fits from the empty test section

$$V_{ref} = 0.0504 f_{imp} - 0.1636 , \quad (\text{Part 1})$$

rough cylinder only

$$V_{ref} = 0.0425 f_{imp} + 0.0411 , \quad (\text{Part 2b})$$

and the rough cylinder with the fin

$$V_{ref} = 0.0436 f_{imp} - 0.0495 . \quad (\text{Part 4})$$

As expected, the current reference velocity curve fit is nearly identical to the fit from Part 2b, which the only difference in test configuration is the addition of the fin. This is expected because the blockage created by the fin is much smaller than that of the cylinder, and the fin is located in the cylinder wake (i.e. the cylinder generated momentum deficit). Comparing the current results to the empty test section linear curve fit shows that the rough cylinder (with or without the fin) produces a lower reference velocity at a given tunnel impeller frequency. This indicates that the blockage created

by the cylinder has a measurable impact on the overall system losses, which ultimately requires a higher impeller frequency to achieve a given test section velocity. The change in the slope, which was not observed with the smooth cylinder (Part 2a) data, indicates that the generated losses are velocity dependent. This likely will result in the curve fit being nonlinear, but over the range of interest the linear fit is appropriate (deviation between fit and measurement is below 0.4%). The measured reference velocities at the primary test conditions are provided in Table 10. The table includes the target tunnel impeller frequency, average reference velocity, standard deviation of the mean reference velocity and the number of samples acquired. The standard deviation of the mean is higher than during the rough cylinder only (Part 2b). This is due to the fact that the forced fin data was acquired over a seven-week period compared to the rough cylinder only data that was acquired in two days.

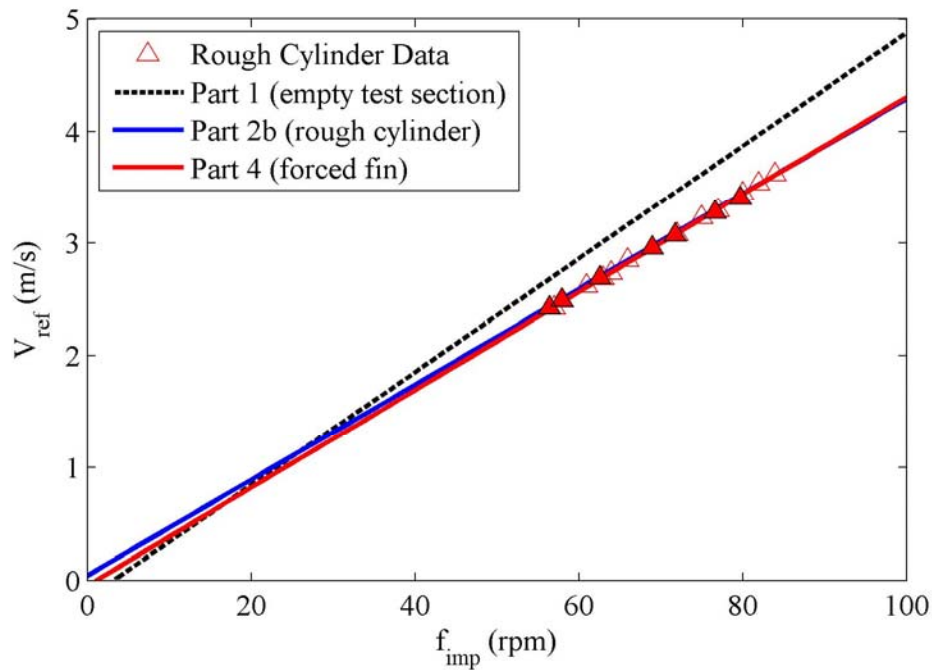


Figure 80. Test section reference velocity (V_{ref}) measured with the rough cylinder and fin installed (Part 4) plotted versus the tunnel impeller frequency (f_{imp}). During Part 4 the tunnel impeller frequency measurement was lost due to a malfunction resulting in the need to use the experiment notebook as an estimate of the tunnel impeller frequency. Thus the solid symbols denote the average from actual measurements while the open symbols are estimates from the notebook. Also included for reference are the linear fits for the empty test section (Part 1), the rough cylinder only (Part 2b) and the current forced fin data (Part 4).

Table 10. During the forced fin testing (Part 4) the tunnel impeller frequency was varied between 57 and 84 rpm. Provided here are the average tunnel velocity, standard deviation of the average tunnel velocity and the number of repeated measurements for the primary tunnel velocities used during Part 4. Due to an instrumentation malfunction the tunnel impeller frequency was only acquired for a subset of test runs. Inspection of data prior to the malfunction showed that the average deviation of the actual average tunnel velocity from the target tunnel speed was within 0.2 rpm, and the maximum observed deviation was 0.4 rpm (except for the first couple runs without the mechanical stop, which saw deviations as high as 0.6 rpm).

f_{imp} (rpm)	V_{ref} (m/s)		Samples
	AVG	STD	
58	2.49	0.043	23
63	2.69	0.070	9
69	2.96	0.065	15
72	3.08	0.049	7
77	3.29	0.062	11
80	3.44	0.020	12
84	3.62	0.004	6

5.4 Cylinder Pressure

As discussed in Section 4.3, applying roughness to the cylinder is expected to modify the flow field and delay separation around the cylinder. This modified flow will result in an adjusted static and dynamic pressure distribution. Because the instrumentation is exactly the same as the smooth cylinder case, the static base pressure and dynamic pressure is presented. The measurements discussed in Section 4 are repeated here to make sure the cylinder flow field is not modified by the presence of the downstream fin.

5.4.1 Static base pressure

As stated in Part 2 (smooth and rough cylinder only), the static base pressure coefficient ($C_{pb} = \Delta P_b / 0.5\rho U^2$) is a common parameter historically used to define the cylinder behavior because it is directly related to the drag on the cylinder, but significantly easier to measure than drag. Here ΔP_b is the difference between the pressure at $\theta = 180^\circ$ (i.e. the static base pressure) and the local static pressure, ρ is the fluid density and U is the local free-stream velocity. The coefficient can be rewritten

as the ratio of the difference in the base and static pressures to the difference in the total and static pressures. In the current study the static base pressure was measured at two axial locations on the cylinder ($Z = 115$ and 230 mm), which correspond to the fin mid-span and tip heights, respectively. The static base pressure coefficient results with the roughened cylinder leading edge ($\theta = \pm 50^\circ$) with and without the fin installed in the cylinder wake are plotted in Figure 81 versus cylinder-diameter-based Reynolds number ($Re_D = U_{cor}D/\nu$). Here D is the cylinder diameter (60 mm), ν is the kinematic viscosity of water, U_{cor} is the reference velocity corrected for the blockage effect ($V_{ref} A_{ts}/(A_{ts}-A_B)$), A_{ts} is the cross sectional area of the test section and A_B is the projected area of the cylinder ($0.06 \text{ m} \times 0.305 \text{ m} = 1.83 \times 10^{-2} \text{ m}^2$). In the current study the blockage effect results in an increase in velocity by a factor of 1.334 with respect to the measured reference velocity.

The representative curve for smooth cylinders from Shih et al. (1993) is included for comparison. The rough cylinder results, with and without the fin installed, have an apparent difference in trends from the smooth cylinder data. This is due to the fact that for a smooth cylinder this Reynolds number range corresponds to the subcritical to supercritical regimes where the boundary layer on the cylinder is transitioning from laminar to turbulent. Conversely, roughening the leading edge trips the boundary layer immediately to the turbulent regime and as a result they are nearly Reynolds number independent. Comparing the results with and without the fin installed in the cylinder wake shows a small but measurable shift in the cylinder performance. This slight shift is likely a combination of the local blockage effect on the velocity measurement, which was acquired in the cylinder wake region, and potentially the fin blockage impacting the pressure recovery on the backside of the cylinder. Finally comparing the measurements with the fin installed from the two spanwise positions ($Z = 115$ and 230 mm) shows that there was minimal spanwise variation between spanwise locations. However, there is more scatter than without the fin installed, which is likely due to (i) the data being acquired over a significantly longer period of time and (ii) the blockage effect created by the fin would be unsteady due to the fin oscillations. In spite of the variation with and without the fin and the increased

scatter, it is apparent that with the fin installed there still was minimal spanwise variation and the behavior is nearly Reynolds number independent over the range of velocities tested.

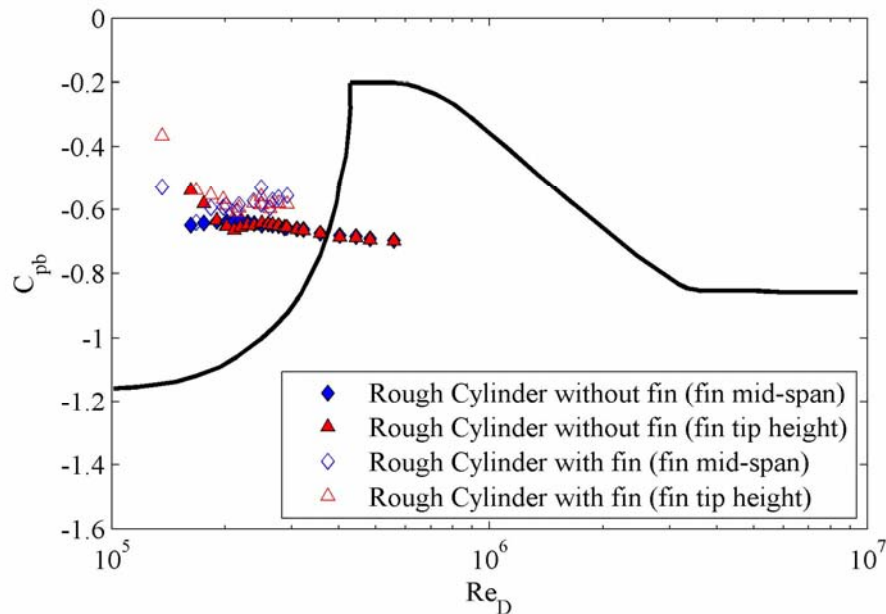


Figure 81. Static base pressure coefficient results from the cylinder with the leading edge ($\theta = \pm 50^\circ$) roughened with 254 μm grit particles plotted versus the cylinder diameter based Reynolds number corrected for blockage effects. Included are data with and without the fin installed in the cylinder wake. Measurements were acquired at either the fin mid-span height ($Z = 115\text{ mm}$) or the fin tip height ($Z = 230\text{ mm}$). Included for comparison is the solid curve, which is a representative curve for smooth cylinders presented in Shih et al. (1993).

5.4.2 Dynamic pressure

As stated in Sections 3 and 4, static and dynamic pressure measurements were measured on the cylinder. These measurements assure that the cylinder pressure distributions were not modified by the presence of the downstream fin.

5.4.2.1 Cylinder pressure spectra

Measurements of the fluctuating pressure on the roughened cylinder with the fin installed (Part 4) were performed and comparisons with the rough cylinder only testing (Part 2b) were investigated. Once again the cylinder accelerometer was not functional for these tests and thus has been excluded from the results. Figure 82 shows the dynamic pressure power spectral density from a single test

condition (Test 20) at the fin mid-span height ($Z = 115$ mm) over a range of water tunnel test section velocities. As with previous cylinder pressure data, the shedding increases in frequency and level with increasing water tunnel velocity. The measured shedding frequencies and levels are very comparable to the dynamic pressures measured with the roughened cylinder only (Figure 44), suggesting that the fin installation and presence had no significant effect on the cylinder fluctuating pressures in spite of the slight change in the base static pressure measurements.

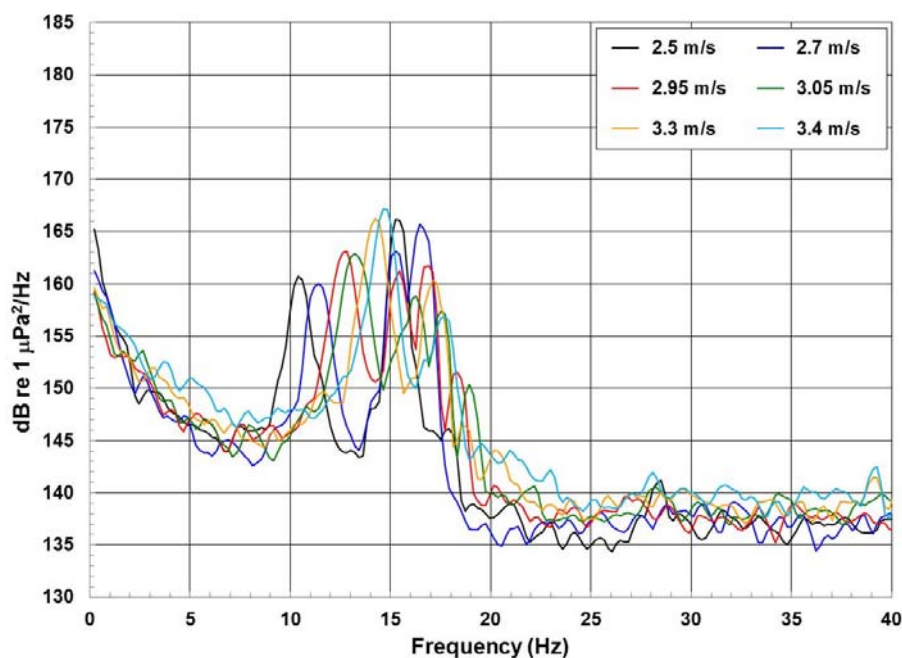


Figure 82. Roughened cylinder dynamic pressure autospectra with the fin installed (Part 4). Measurements were acquired at the fin mid-span height ($Z = 115$ mm) and at $\theta = -130^\circ$. The reference velocities shown in the legend correspond to the test section velocity determined from the static pressure measurements.

Figure 83 and Figure 84 show the computed shedding frequency RMS lift force levels versus tunnel test section velocity and frequency, respectively. The shedding frequency RMS lift force levels were computed at the fin mid-span height. Included in the figures are results from the smooth cylinder only test (Part 2a – Test 2057), rough cylinder only test (Part 2b – Test 81) and the rough cylinder with the fin installed (Part 4 – test 20). As previously discussed, the rough cylinder results are significantly lower than the smooth cylinder results. However, the rough cylinder with and without the fin installed

are nearly identical. This indicates that the addition of the fin has a negligible impact on the cylinder induced fluctuations, at least in the near-wake region.

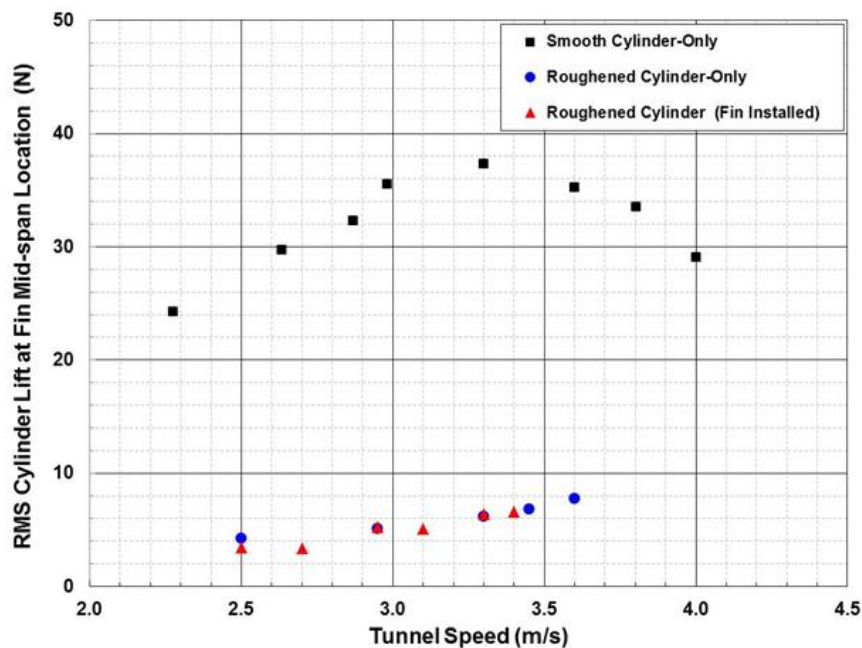


Figure 83. Computed shedding frequency RMS lift levels plotted versus the tunnel test section velocity from the pressure transducer pair located at the fin mid-span height ($Z = 115$ mm). Included are results from the smooth cylinder only (Part 2a), the rough cylinder only (Part 2b) and the rough cylinder with the fin installed (Part 4).

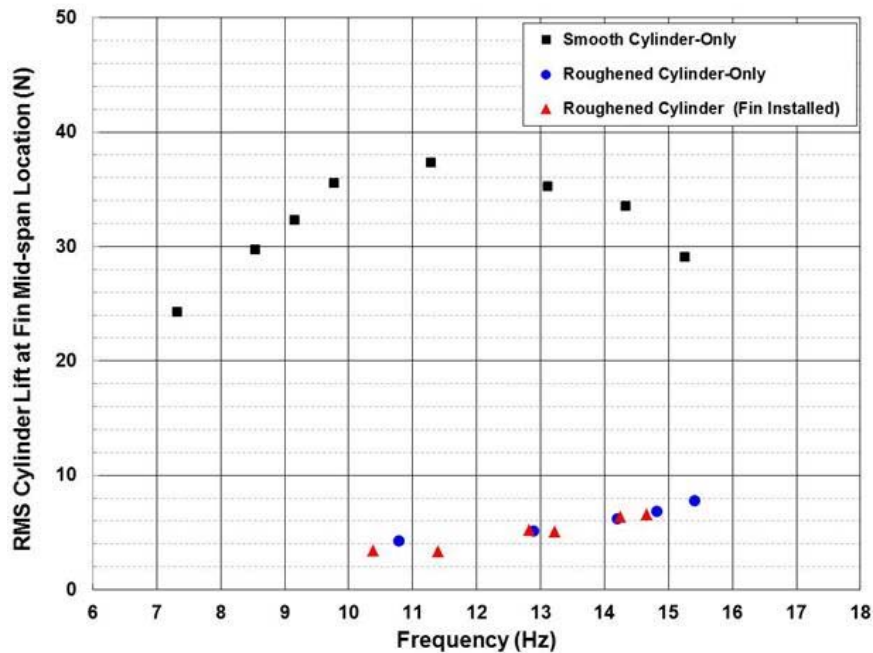


Figure 84. Computed shedding frequency RMS lift levels plotted versus frequency from the pressure transducer pair located at the fin mid-span height ($Z = 115$ mm). Included are results from the smooth cylinder only (Part 2a), the rough cylinder only (Part 2b) and the rough cylinder with the fin installed (Part 4).

5.4.2.2 *Cylinder shedding frequency scaling*

As with the cylinder only measurements (smooth and roughened), the peak vortex shedding frequency is scaled using the Strouhal number ($St = f_s D / U$), where f_s is the vortex shedding frequency, D is the diameter of the cylinder ($D = 60$ mm) and U is the characteristic velocity which for the current study is V_{ref} . The Strouhal scaling results for the cylinder with the leading edge ($\theta = \pm 50^\circ$) roughened with 254 μm grit particles are plotted versus the cylinder diameter based Reynolds (Re_D) in Figure 85. These results include data with and without the fin installed in the cylinder wake. Once again the Reynolds number velocity was corrected for blockage effects as was done for the static base pressure scaling, and the composite curve presented in Roshko (1961) for smooth cylinders is included for comparison. Note that in the current study on the smooth cylinder no vortex shedding was observed for $Re_D \geq 3.3 \times 10^5$. The current results show significantly different behavior from typical smooth cylinder data. They are nearly constant, as observed for smooth cylinder data in either the subcritical or transcritical regimes, and vortex shedding was observed at higher Reynolds number than possible without the trip. Comparison between the Strouhal scaling with and without the fin installed in the cylinder wake shows that there was negligible variation between the two measurement sets. This is in contrast to the static base pressure coefficient data, which had a slight but measurable difference with and without the fin installed. This suggests that while the fin might impact the pressure recovery on the cylinder, the vortex shedding frequency is not impacted.

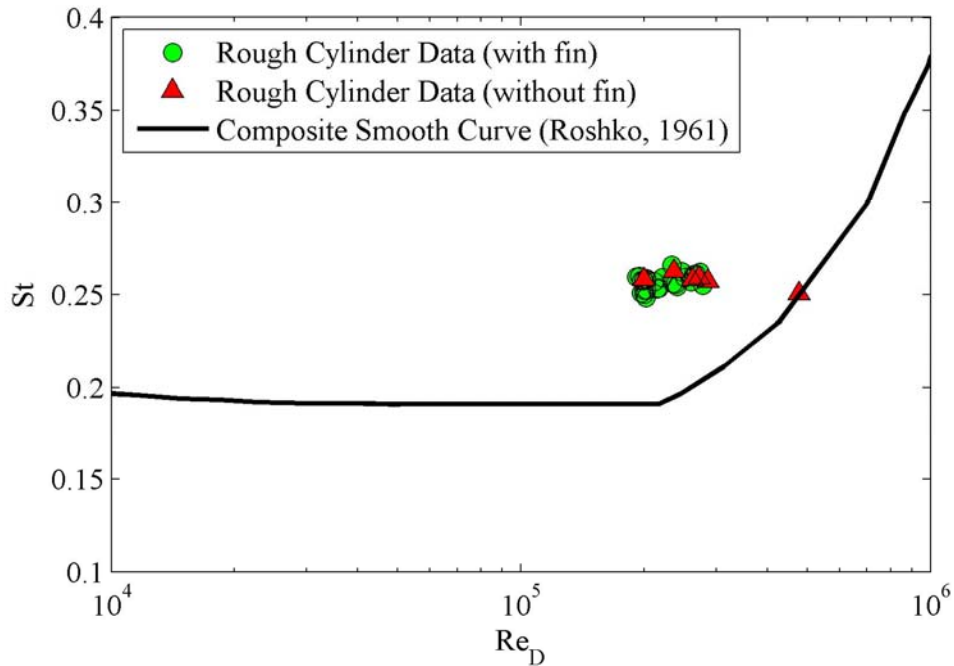


Figure 85. Strouhal scaling results for the rough cylinder with and without the fin installed in the cylinder wake. The composite curve from Roshko (1961) for smooth cylinders is included for comparison.

5.5 Fin Motion

The fin motion was measured using high speed video and by scanning with a laser vibrometer.

The results from both methods are presented in this section.

5.5.1 Fin tip motion (high-speed-video)

High speed video provides significant information about the motion of the tip of the fin. In particular, the mean tip motion including mean translation and twist is discussed. Additionally, an estimate of the fin deflection spectra is made.

5.5.1.1 Mean and RMS tip deflection and twist

The fin tip deflections (translational motion) were measured with high-speed video, which the results are shown in Figure 86. These results were acquired from high-speed video focused specifically on the fin tip and from the high-speed PIV images (see Figure 77). Included in the plot are the mean

and RMS deflection measurements plotted versus the tunnel test section reference velocity (V_{ref}). The majority of the measurements shown were determined from 3000 samples (3 seconds of data acquired at 1 kHz), but a subset of the conditions had a shorter sample size with some as low as 500 images (0.5 seconds at 1 kHz). If only the data from the 3 second long measurements were shown, the scatter in both the mean and fluctuating measurements is noticeably reduced. Thus while there appears to be slightly more scatter from the PIV images, the data follows the same trends and most of the scatter is likely the result of a relatively small sample size. While 3 seconds seems to be sufficiently long given that the shedding frequency is on the order of 10 Hz (i.e. 30 cycles), the coupling of the fin motion with the fluid flow results in the fin motion having much more broadband frequency content. As a result a longer period was desired to precisely quantify the mean and RMS deflection levels. The scatter in the final results has the mean and RMS values nominally within $\pm 7\%$ ($\leq \pm 0.15$ mm) and $\pm 9\%$ ($\leq \pm 0.2$ mm) of the measured values, respectively. The general trend in the data shows the average deflection becoming more negative with increasing velocity. The sign of the deflection is based on the Y-coordinate direction, and the negative angle of attack creates the non-zero mean deflection of the fin tip in the flow. Similarly, the magnitude of the RMS deflection measurements increases with increasing velocity. Furthermore it appears that the increase might be increasing in a non-linear fashion, though it is difficult to assess due to the scatter, especially at the higher velocities.

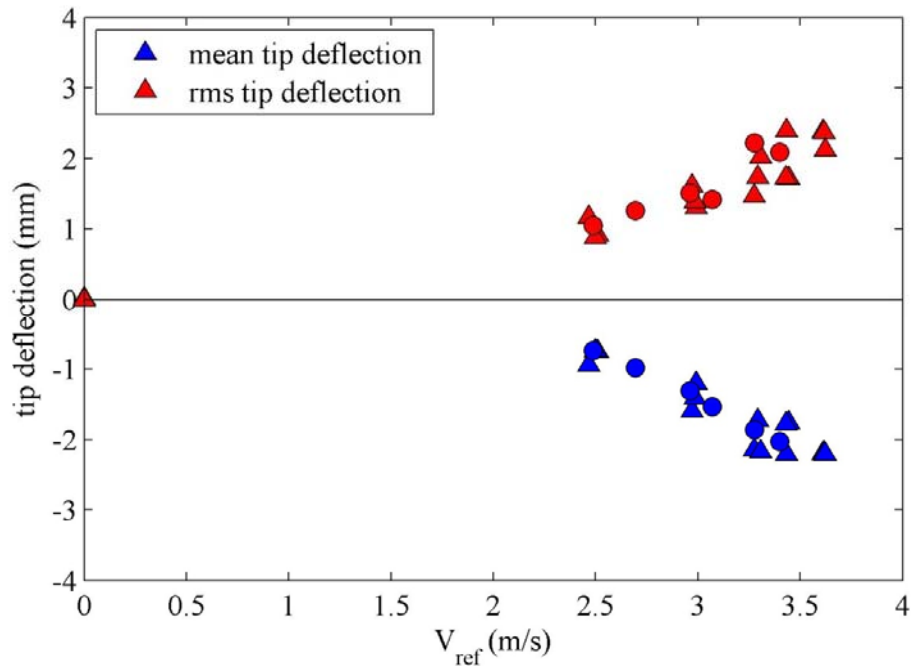


Figure 86. The mean and rms fin tip deflections plotted versus the tunnel reference velocity. Data was acquired from (o) high-speed video and (Δ) high-speed PIV image pairs. The symbol colors denote whether the measurement is (blue) the mean deflection or (red) the standard deviation of the deflection. The relatively large amount of scatter shown is likely the result of the fin tip motion having broadband frequency content and a relatively short sample period.

Since the goal of the experiment was to produce large amplitude fluctuations that produced maximum deflections of $\pm 3.5\%$ of the span (± 8.05 mm), it is useful to not only investigate the mean and standard deviation of the fin tip deflection measurements, but also the maximum and minimum values. There will be greater scatter in these results due to the relatively short duration of these measurements, which will be discussed subsequently, but it gives a sense of whether or not the experimental design goal was achieved. Figure 87 shows the measured maximum and minimum fin tip deflections in addition to the mean deflection from each test run plotted versus the reference velocity. The deflections are plotted as the percentage of the fin span, and red dashed lines mark the $\pm 3.5\%$ of the fin span experimental design goal. This shows that the goal was achieved in the negative direction with the largest deflection measured reaching -4.2% of the span, but on the positive side the maximum deflection achieved was only 2.6% of the span. Thus the maximum measured peak-to-peak fin tip

deflection observed during the experiment was 6.8% of the span, which is very close to the design goal of 7%. The only deviation was due to the mean deflection created by the angle-of-attack not considered in the design analysis.

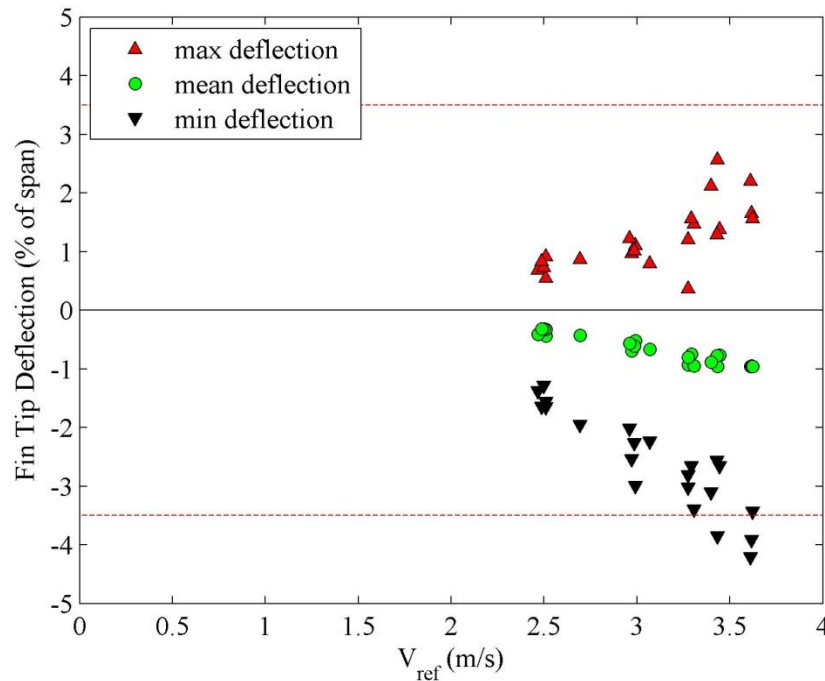


Figure 87. The maximum, average and minimum fin tip deflection shown as a percentage of the fin span plotted versus the test section reference velocity. The red dashed lines mark the $\pm 3.5\%$ span locations, which were the target for the experimental design.

The same images were used to measure the amount of twist (rotational motion) at the fin tip. However, the high-speed PIV images did not produce a sufficiently sharp edge to measure the relatively small amount of twist at the fin tip. Consequently, there are noticeable few measurements of twist available relative to the deflection results. Fortunately since the translational behavior was similar between the two measurement methods it is expected that the rotational movement was also similar throughout testing. The mean and RMS twist measurements are plotted versus the tunnel reference velocity in Figure 88. Here the mean and RMS twist results produce nearly equivalent results at a given velocity and the magnitude increases with increasing velocity. However, it shows that over the

range of velocities tested there was minimal twist at the fin tip, which the maximum observed mean and RMS twist levels being 0.31° and 0.33° , respectively.

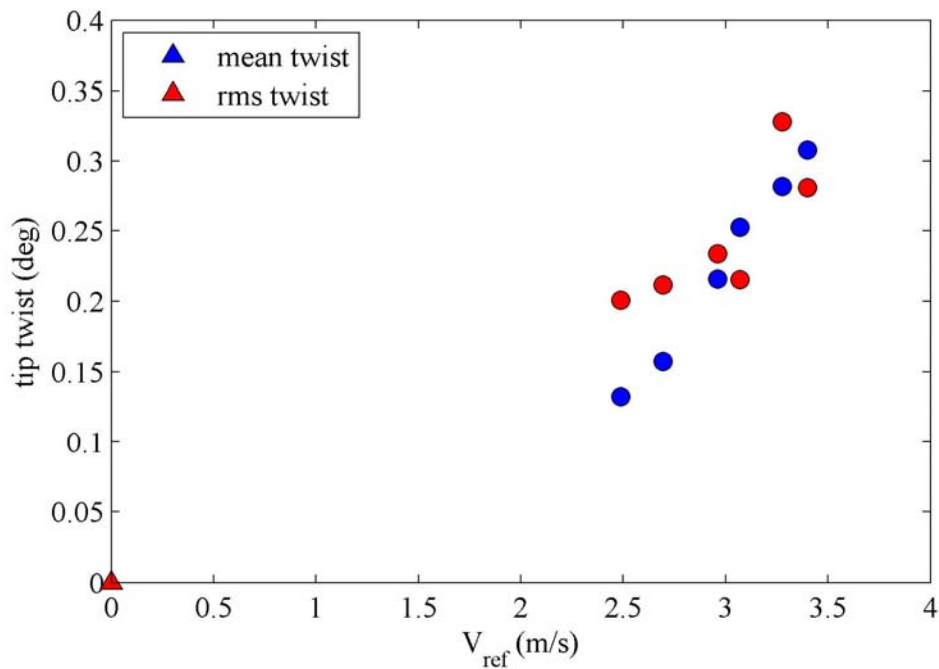


Figure 88. The mean and RMS fin tip twist measurements plotted versus the tunnel reference velocity. Data was only acquired from the (o) high-speed video. The symbol colors denote whether the measurement is the (blue) mean twist or (red) rms twist.

5.5.1.2 Fin deflection spectra

A representative time trace of the fin tip deflections is provided in Figure 89. Shown is the measurement with the high-speed-video focused on the fin tip at a test section reference velocity of 3.4 m/s. Due to the relatively large data sets produced from imaging data being acquired at 1 kHz, the duration of these measurements were relatively short (maximum sample length was 3 seconds). Noting that the dominate frequency should correspond to the shedding frequency, which is on the order of 10 Hz, this duration should have been on the order of 30 cycles. This is insufficient to adequately resolve the power spectral density of the signal, especially when there is some broadband content in the signal, which can be seen in Figure 89 as well as to an observer watching the experiment. Consequently, the spectra from these samples are not provided. However, inspection of the time signals as well as

determining the peak in the autocorrelation allows for some of the dominate frequency content to be investigated.

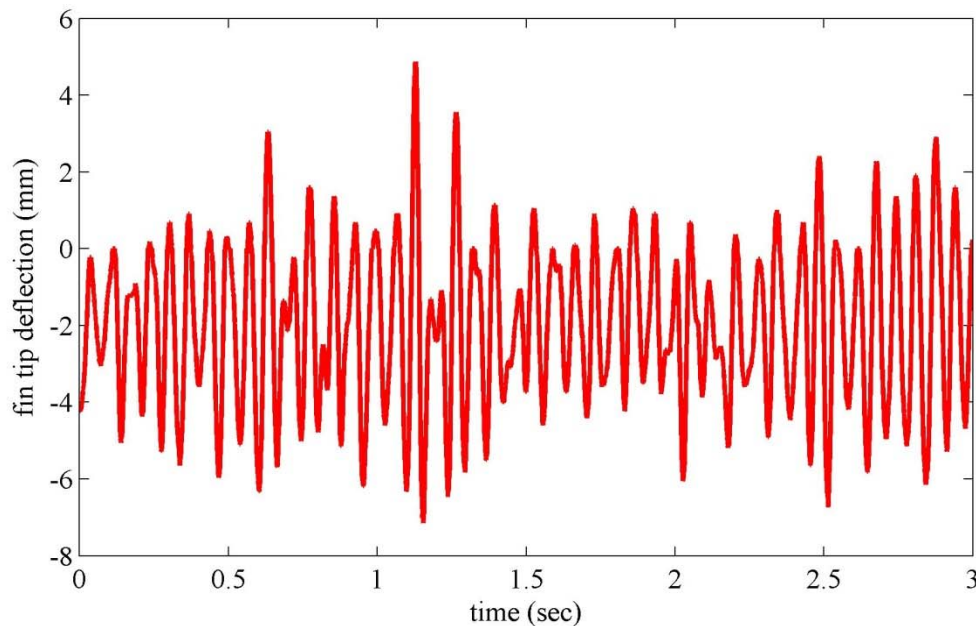


Figure 89. Example of the time trace produced from high-speed-video imaging of the fin tip. The condition shown was acquired at a flow velocity of 3.4 m/s (Test 20 – Run 7).

Figure 90 shows the dominate or fundamental frequency as determined from the autocorrelation and inspection of the time trace signals plotted versus the vortex shedding frequency measured with the dynamic pressure transducers. If the two frequencies were identical they would follow the solid line included in the figure. However, there appears to be significant scatter in the results compared to similar plots made from the fin load cell data. This is due to the fact that the fin tip motion has more broadband frequency content than merely that of the vortex shedding, which significantly impacts the results when a relatively short duration sample is investigated. Thus when this plot is made with the load cell data, which should have similar broadband content as the fin tip deflections, there is significantly less scatter in the results due to the fact that those measurements were for at least 60 seconds instead of 3 seconds. This issue is further exaggerated when the peak-to-peak displacements are investigated in Figure 91. Here the peak-to-peak displacement in millimeters is

plotted versus the vortex shedding frequency. The results show a very crude trend of the displacement increasing with increasing shedding frequency, but the trend is not very apparent. This is consistent with inspection of numerous time traces, which show there are periods where the fluctuations are relatively low (1.5 to 2.0 sec in Figure 89) and other periods with short bursts of large deflections (around ~1.25 sec in Figure 89). Hence if a given sample missed the large bursts the resulting peak-to-peak displacements would be biased low. Thus these results show that for the fin tip deflection measurements, a longer sample duration was required to determine well defined peak-to-peak displacement values for a given velocity.

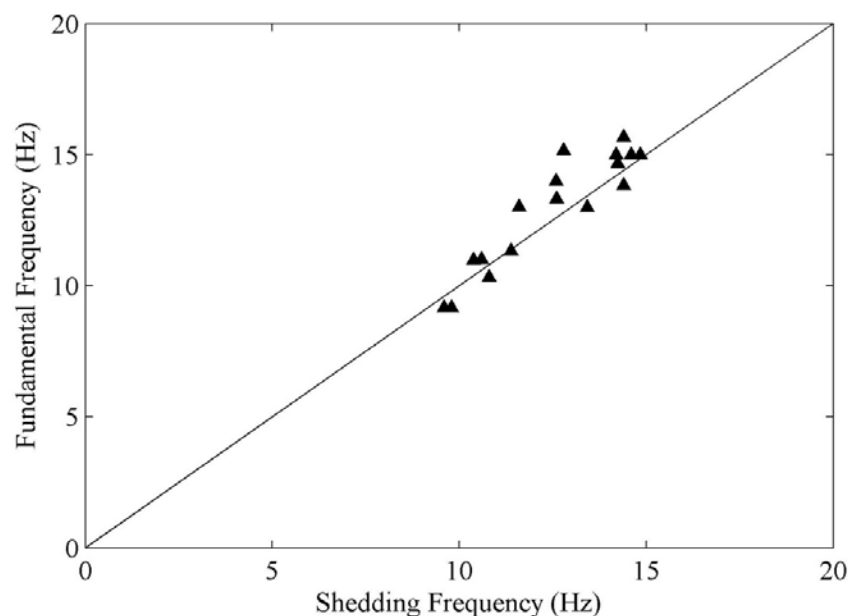


Figure 90. The fundamental frequency measured from the fin tip deflection time traces plotted versus the vortex shedding frequency measured from the cylinder dynamic pressure transducers. The solid line corresponds to the curve if the dominate frequency in the fin tip deflection was identical to the vortex shedding frequency.

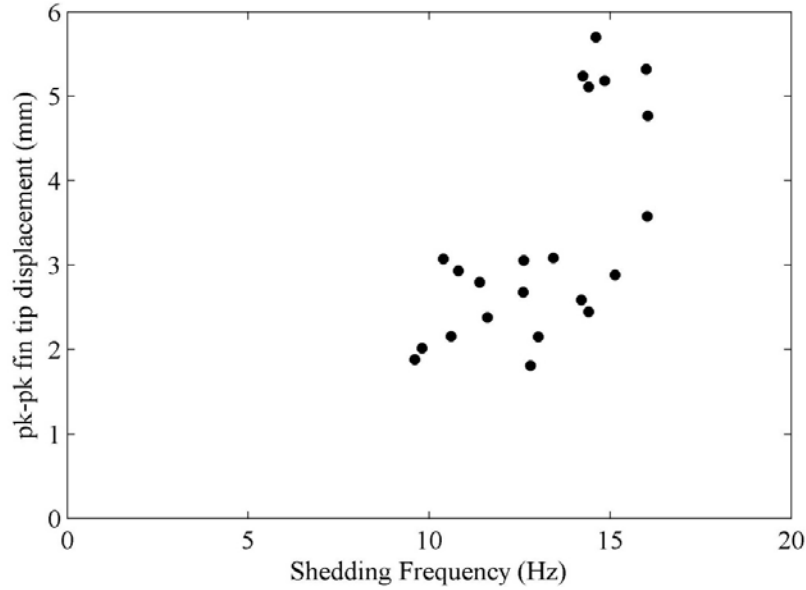


Figure 91. The measured peak-to-peak fin tip displacement measurements plotted versus vortex shedding frequency.

5.5.2 Fin surface motion (laser vibrometer)

Table 11 shows the rms surface velocity levels at the shedding frequency for the 21 fin measurement locations over the chord (50 mm) and span (230 mm). Surface velocity spectra were obtained for three tunnel velocities (2.95, 3.4 and 3.6 m/s). One 3.4 m/s condition was a repeat measurement. The rms surface velocity measured at the shedding frequency is determined by

$$u_s = \sqrt{G_{uu}(f_s) \cdot \Delta f},$$

where $G_{uu}(f_s)$ is the surface velocity power spectral density function at the shedding frequency f_s and Δf is the frequency resolution in Hz. Mean and standard deviations are given for the peak shedding frequency and Q values. Here, Q is defined as an effective “quality factor” that quantifies the bandwidth of the shedding frequency peak by

$$Q = \frac{f_o}{f_U - f_L},$$

where f_o is the peak shedding frequency, f_U is the frequency at the 3-dB down point on the upper side of the peak and f_L is the frequency at the 3-dB down point on the lower side of the peak.

Table 11. Fin vibrometer response characteristics at the shedding frequency peak for various runs and locations along the fin. For Run 077R03, the velocity response at point 19 was not recorded due to a vibrometer software error.

Location			3.4 m/s (Run 074R01)			3.6 m/s (Run 076R02)			3.4 m/s (Run 077R03)			2.95 m/s (Run 077R04)		
Span (%)	Chord (%)	Point	Peak Freq. (Hz)	Peak Vel (rms) (mm/s)	Q	Peak Freq. (Hz)	Peak Vel (rms) (mm/s)	Q	Peak Freq. (Hz)	Peak Vel (rms) (mm/s)	Q	Peak Freq. (Hz)	Peak Vel (rms) (mm/s)	Q
40	90	1	13.875	13.66	12.33	14.5	17.65	19.33	13.75	12.69	10.00	12	7.42	10.67
40	50	2	14	11.22	10.18	14.5	16.76	14.50	13.25	10.48	10.60	11.875	7.18	9.50
40	10	3	13.5	10.67	9.00	14	13.94	8.00	13.375	12.84	8.92	11.5	6.35	11.50
50	90	4	14.25	15.62	11.40	14.375	16.65	9.58	13.875	13.91	12.33	11.875	8.53	7.31
50	50	5	13.75	18.36	11.00	14.5	22.31	14.50	13.75	17.89	11.00	11.625	7.19	6.20
50	10	6	13.5	14.88	8.31	14.5	17.72	8.92	13.875	14.37	5.55	11.875	8.85	9.50
60	90	7	13.75	22.13	15.71	14.25	22.47	6.00	14	21.83	11.20	12.125	10.96	6.93
60	50	8	13.625	19.32	9.91	14.125	20.15	8.69	14	18.47	7.47	11.875	11.71	13.57
60	10	9	13.625	19.88	9.91	14.375	21.97	9.58	13.625	17.43	10.90	12	9.49	7.38
70	90	10	13.75	26.17	11.00	14.25	27.42	14.25	13.75	20.79	9.17	11.875	12.55	9.50
70	50	11	13.75	19.18	4.58	14	22.83	8.00	13.875	23.51	13.88	11.875	12.49	7.92
70	10	12	14	25.27	10.18	14.75	25.84	14.75	13.75	23.87	11.00	12.375	14.22	9.00
80	90	13	13.75	23.28	6.11	14.75	31.97	16.86	14	30.40	11.20	11.625	13.72	4.65
80	50	14	14.125	26.97	9.42	14.25	29.88	10.36	13.75	20.89	7.33	12.25	13.28	6.53
80	10	15	14	23.10	9.33	14.375	31.76	8.85	14	23.16	11.20	12.125	14.01	6.93
90	90	16	13.625	28.79	8.38	14.75	36.42	13.11	13.875	24.49	6.94	11.625	16.78	8.45
90	50	17	14	26.45	11.20	14.625	36.38	9.75	13.375	30.06	13.38	11.625	16.94	6.64
90	10	18	13.5	25.38	6.00	14.375	37.43	11.50	13.375	26.19	7.13	11.75	16.65	5.53
95	90	19	13.5	28.74	7.71	14.5	37.93	11.60	n/a	n/a	n/a	11.75	18.05	9.40
95	50	20	13.25	25.85	5.58	14.625	37.69	11.70	13.875	28.96	6.94	12	17.89	8.00
95	10	21	14	23.59	5.09	14.625	39.73	10.64	13.625	29.54	8.38	11.625	16.19	6.20
		Average	13.77		9.16	14.43		11.45	13.74		9.73	11.87		8.16
		Standard Deviation	0.25		2.70	0.23		3.30	0.23		2.32	0.23		2.13

Figure 92 shows displacement power spectral density functions at the point located at 95% span and 90% chord (measurement point 19). The surface velocity measured by the vibrometer was integrated to get displacement. The spectra show the mean-square displacement per Hz for the three tunnel velocities and include two peaks below 50 Hz. The first peak corresponds to the response of the fin due to the excitation of the cylinder flow. The second peak corresponds to the first-bending mode response of the fin due to its structural characteristics. The higher-frequency peaks correlate to higher order modes of the fin. The shedding frequency is shown to increase with higher flow velocity as does the displacement. The bandwidth of the peaks also changes with flow velocity. Figure 93 shows the fin rms displacement at 14.50 Hz for a tunnel velocity of 3.60 m/s. As expected, the predominant mode is first cross-stream bending and is made evident from the large deflection at the tip of the blade.

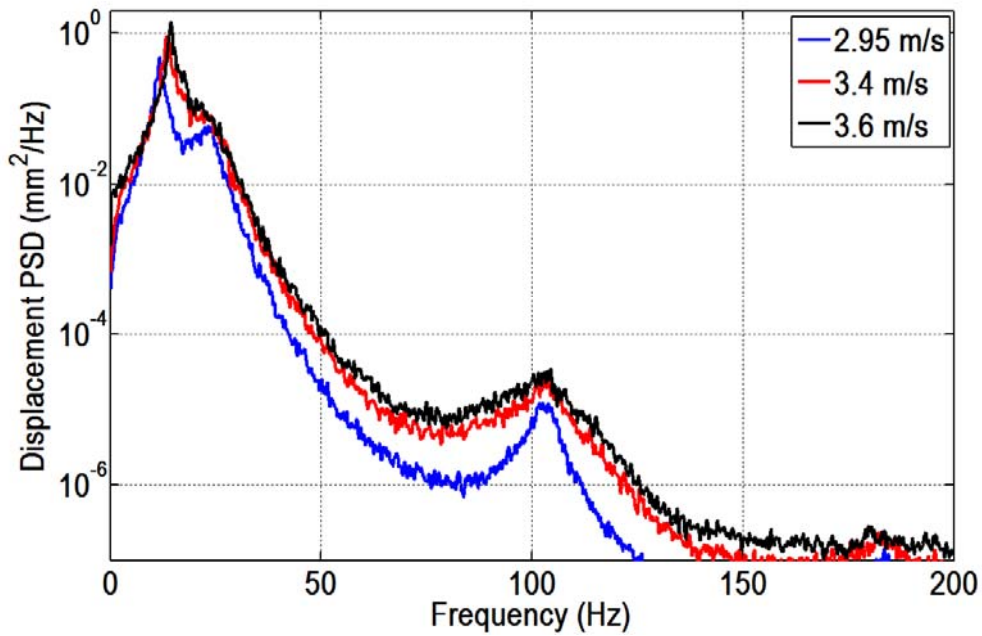


Figure 92. Displacement power spectral densities (PSDs) at the tip location (point 19) for three measured water tunnel velocities. The second and third peaks correspond to the fin first and second cross-stream bending modes (23 and 103 Hz, respectively) reported in Table 9.

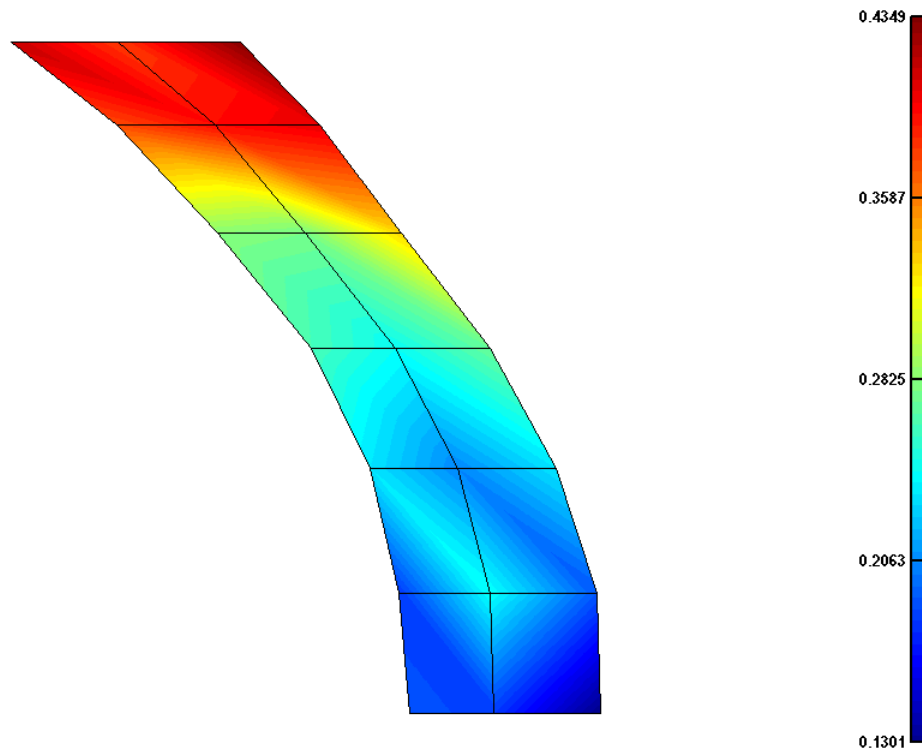


Figure 93. Fin rms displacement (mm) at 14.50 Hz for the tunnel velocity of 3.60 m/s.

It is known that the shedding from a cylinder results in a wake flow downstream that has some correlation in time or coherence in space from one point on the fin to another. One quantitative measure of this is the coherence as defined in Bendat & Piersol (1980) as

$$\gamma_{xy}^2 = \frac{|G_{xy}(f)|^2}{G_{xx}(f)G_{yy}(f)},$$

where G_{xy} is the cross spectra between locations x and y , G_{xx} is the autospectrum at location x and G_{yy} is the autospectrum at location y . The value of the coherence must always be between zero and unity. It is expected that the coherence, like the correlation, will decrease with increasing separation distance. Figure 94 shows the coherence as a function of separation distance between each of the vibrometer measurement points and the reference point at Location 13. For the shedding frequency near 14.50 Hz, we see very high coherence with separation distance. This may be somewhat surprising since the shedding flow from the cylinder has correlation lengths less than that of the fin length. However, in this frequency range, as exhibited by the operating deflection shape shown in Figure 93, the vibration is dominated by a single mode and hence the very high coherence.

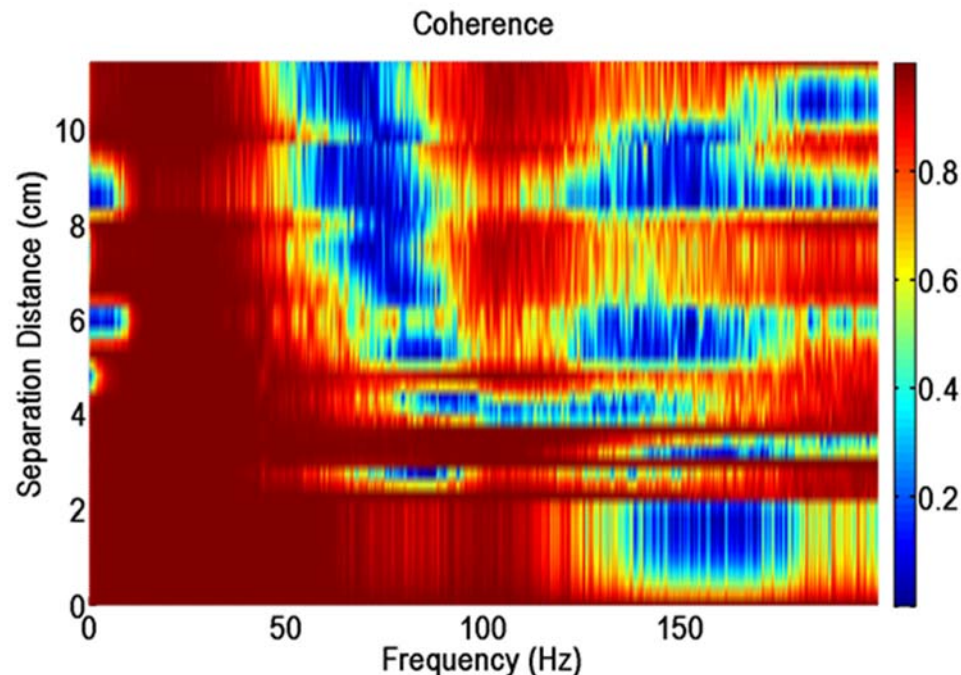


Figure 94. Blade vibration coherence plotted versus separation distance as a function of frequency relative to Location 13 (as described in Table 11).

The vortex shedding generated by the roughened cylinder applied an oscillating force to the fin causing fin loading and movement. Measurements of the fin motion were performed using high-speed PIV, high-speed video and laser vibrometry. Figure 95 shows a comparison of measured fin deflection at the tip from high-speed video and laser vibrometry acquisition for a tunnel test section velocity of 3.4 m/s and fin angle-of-attack of approximately -9.7° . The data were taken for two separate tests, Test 0020 (high-speed video) and Test 0074 (laser vibrometry); however, the agreement between acquisition systems at this condition is very comparable. The measurements show roughly the same magnitude of fin tip deflection, and the rms displacement values of the 3-second measurement are 2.086 mm (high-speed video) and 2.078 mm (laser vibrometer). For comparison, the rms displacement of the 3.4 m/s power spectral density shown in Figure 92 is 1.870 mm, computed over the full measurement scan time of 64 seconds.

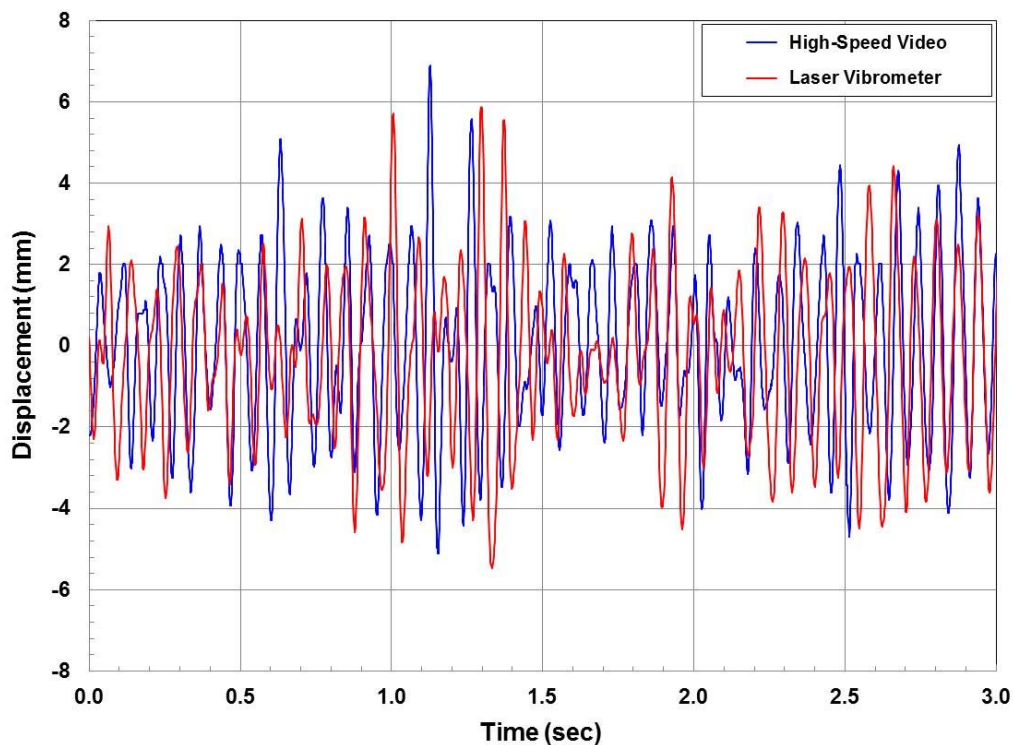


Figure 95. Fin tip deflection measured by high-speed video and laser vibrometer at 3.4 m/s and -9.7° angle-of-attack.

5.6 Fin Load Cell Measurements

5.6.1 Mean lift and drag forces

It was mentioned in the experimental methods section, that the load cell was designed such that it would measure the drag and lift components when the fin was at zero angle of attack. However, the final test condition was at an angle-of-attack of -9.64° (nominal target value was -10° , but the average measured angle-of-attack was -9.64°), which requires the following conversion,

$$\begin{aligned} L &= L_{LC} \cos(\alpha) - D_{LC} \sin(\alpha) \\ D &= D_{LC} \cos(\alpha) + L_{LC} \sin(\alpha) \end{aligned}$$

Here α is the fin angle-of-attack, L is the lift force, D is the drag force, L_{LC} is the lift force measured by the load cell (i.e. equal to L when $\alpha = 0^\circ$) and D_{LC} is the drag force measured by the load cell (i.e. equal to D when $\alpha = 0^\circ$). Figure 96 shows the resulting mean lift and drag forces on the fin when correcting the measurements for the given angle of attack. The results are plotted versus the chord-based Reynolds number ($Re_c = c V_{ref}/\nu$), where c is the fin chord length (50 mm), ν is the kinematic viscosity of water at the given temperature and V_{ref} is the test section reference velocity. The data were fitted with a power-law best-fit curve producing

$$\begin{aligned} L &= -1.0811 V_{ref}^{1.0512} \\ D &= 0.7059 V_{ref}^{1.90} \end{aligned}$$

Here the lift and drag forces are in N when V_{ref} is in m/s. The basic trends observed in the mean loading results are that the magnitudes of both the lift and drag increase with increasing tunnel velocity. With the fin at a negative angle-of-attack the stagnation pressure from the flow acting normal to the fin surface creates forces in the positive-X and the negative-Y directions. Hence, the drag becomes more positive with increasing tunnel velocity while the lift becomes more negative with increasing tunnel velocity. Note that the mean lift force will produce an average fin deflection at a given tunnel velocity, thus explaining why the average fin tip deflection at a given tunnel velocity was non-zero.

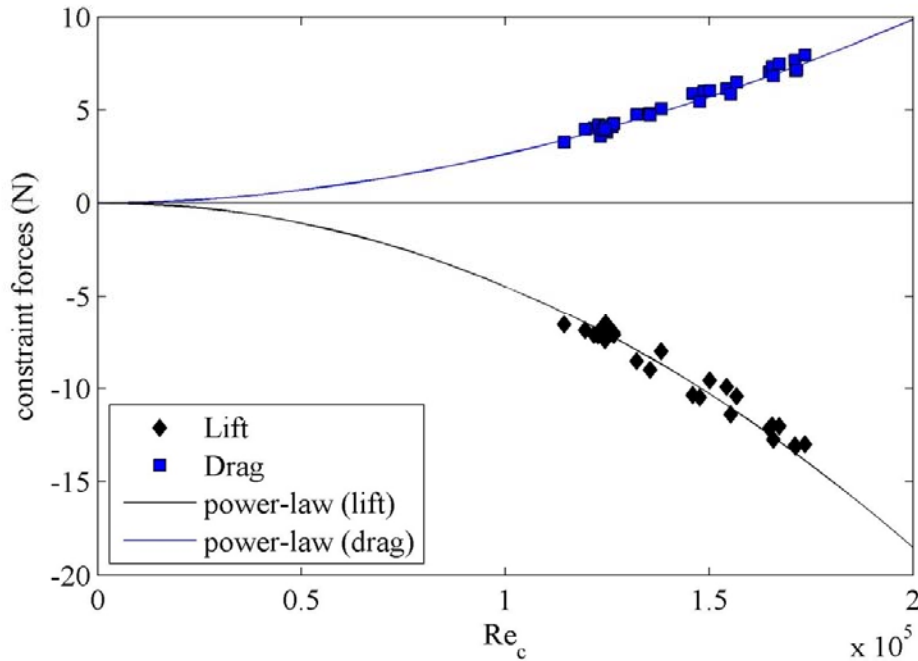


Figure 96. Average fin forces (lift and drag) plotted versus the fin-chord-length Reynolds number (Re_c). The forces were determined from the load cell measurements and corrected for the given fin angle-of-attack. Thus shown are the true lift and drag components of the fin loading.

While the torque moment does not need to be corrected for the fin angle-of-attack, the moments about the X- and Y-coordinates need to be corrected. Unfortunately, since the moment cell dominated by the lift contribution was not optimized before any data was acquired this correction cannot be made. Thus, Figure 97 only plots torque moment and moment about the axis perpendicular to the axis aligned with the fin chord, which is termed the “drag moment”. Once again these results are plotted versus the chord-based Reynolds number ($Re_c = c V_{ref}/\nu$), where c is the fin chord length (50 mm), ν is the kinematic viscosity of water at the given temperature and V_{ref} is the test section reference velocity. The data were fitted with a power-law best fit curve producing

$$T_q = 0.05431 V_{ref}^{1.9812}$$

$$DM = 0.04534 V_{ref}^{1.8406}$$

Here T_q is the torque moment in Nm, DM is the drag moment in Nm and V_{ref} is the reference velocity in m/s. The basic trend in the data has both the torque and drag moment positive and increasing with

increasing tunnel velocity. The primary value of measuring the moments was to determine the center-of-pressure for the lift and drag components, but this cannot be done since the moments cannot be resolved into the X- and Y-directions. However, the drag moment and the drag measured by the load cell can be used to determine a center-of-pressure for the force component aligned with the chord length. Note this is not the center of pressure for the drag or the lift force. Using the load cell measured drag curve fit ($D_{LC} = 0.51199V_{ref}^{1.8475}$), this results in a nominal center-of-pressure of 88 mm measured from the fin base. This suggests that the loading is dominated by the forces acting towards the base of the fin.

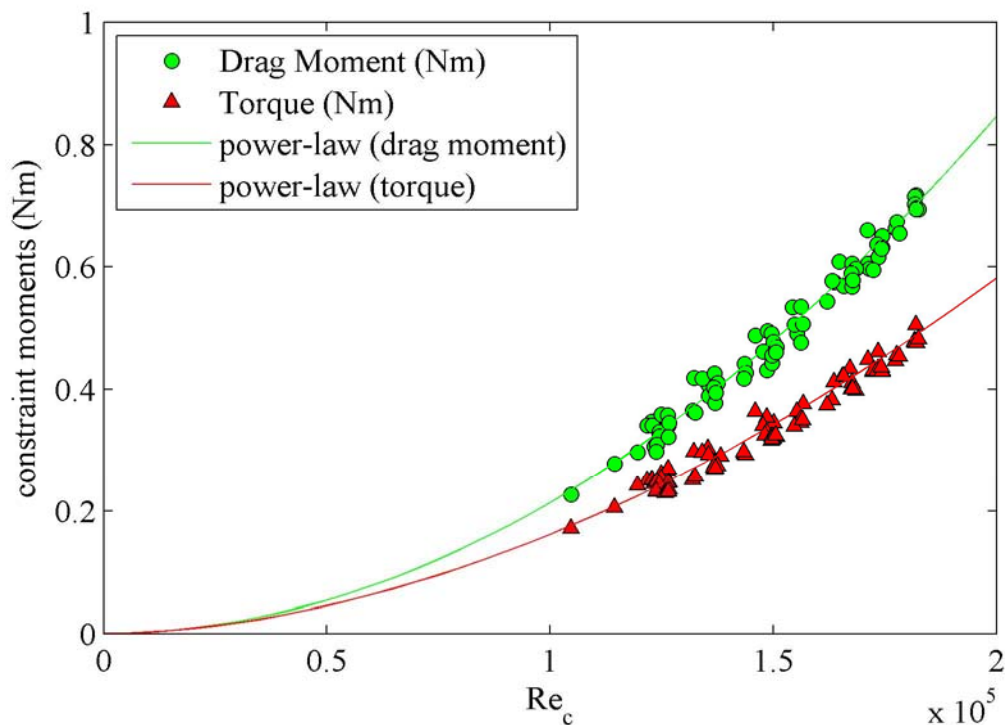


Figure 97. Average load cell moments (torque and drag-moment) plotted versus chord-based Reynolds number. Due to the inability to resolve the lift moment about the X- and Y-coordinates, the “drag moment” shown is the moment about the axis perpendicular to the axis aligned with the chord length.

5.6.2 Load cell spectra

In addition to steady load levels reported earlier for the fin, the dynamic measurements from the load cell reported in this section detail how the unsteadiness of the cylinder wake influences the forces and moments action on the fin.

5.6.2.1 Time sample of fin forces and moments

Spectral analysis was also performed on the fin forces and moments, similar to what was done with the cylinder dynamic pressure measurements to identify the vortex shedding frequency. The fluctuating forces (lift and drag) and moments (twist and drag moment) are illustrated in Figure 98 with a one second time signal sample from a single test run at 3.4 m/s. This short of a sample was selected to show the phase relationship between the fin force and moment measurements as well as how the shedding frequency dominates the signals. The fin lift is 180° out-of-phase with the drag, twist and drag moment signals.

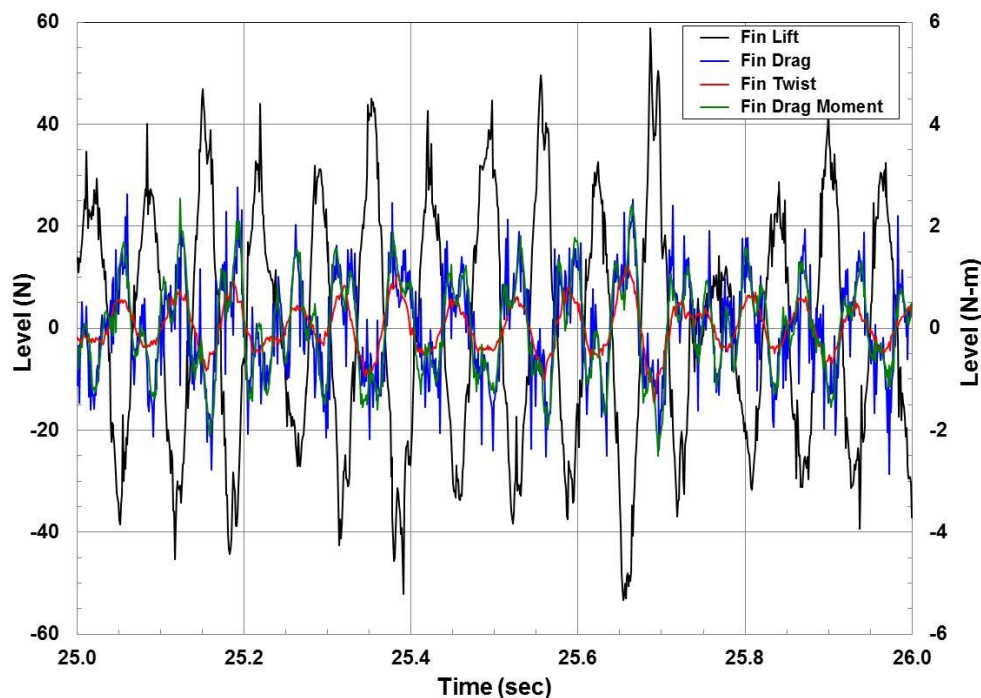


Figure 98. A one second sample of time signals for the fin forces (lift and drag) and moments (twist and drag moment) acquired at 3.4 m/s from a single test run (Test 20).

5.6.2.2 *Repeatability of tunnel conditions and fluid-loading*

During preparations for the forced fin testing (Part 4), there were concerns about the repeatability of the tunnel velocity as well as the fluid forcing generated by the roughened cylinder. Thus early in the forced fin testing (Part 4) a single velocity was selected (3.1 m/s) and it was repeated numerous times throughout testing during one day. This was done prior to the removal of the mechanical stop because (1) this question needed to be addressed as early as possible and (2) any disturbance from the mechanical stop would need to be repeatable. Also to protect the fin from potential fatigue failure, the testing was performed at a near-zero angle-of-attack and at a tunnel velocity below that expected to produce the desired fin tip deflections. The power spectral density of the fin lift force from these repeatability tests are shown in Figure 99. The condition was repeated seven times over the day of testing, with each test starting from the tunnel at no-flow condition and then ramping to the desired velocity of 3.1 m/s. The repeated runs produced a fluctuating fin RMS lift force variability of 16.66 ± 0.38 N, or approximately $\pm 2.3\%$ uncertainty. The shedding frequency varied by $\pm 1.5\%$ at 13.67 ± 0.02 Hz, and the tunnel test section velocity was measured as 3.10 ± 0.02 m/s. This condition was repeated throughout the duration of the experiment, and the resulting power spectral densities at various angles-of-attack with and without the mechanical stop are shown in Figure 100. Comparing these results shows that the fluctuating fin RMS lift force level is 16.69 ± 0.43 N, or approximately $\pm 2.6\%$ uncertainty. The fin angle-of-attack appears to have minimal impact on the fluctuating fin lift forces at the shedding frequency. This does not imply that angle of attack does not impact the mean lift force, only the fluctuating lift force. This also shows that the mechanical stop had minimal impact on the fin loading because the results from Test 20 were without the mechanical stop while the other tests had the stop installed. Overall these repeatability results provide confidence both in the repeatability of the facility and the fluid loading, in addition to the accuracy of the experimental measurements.

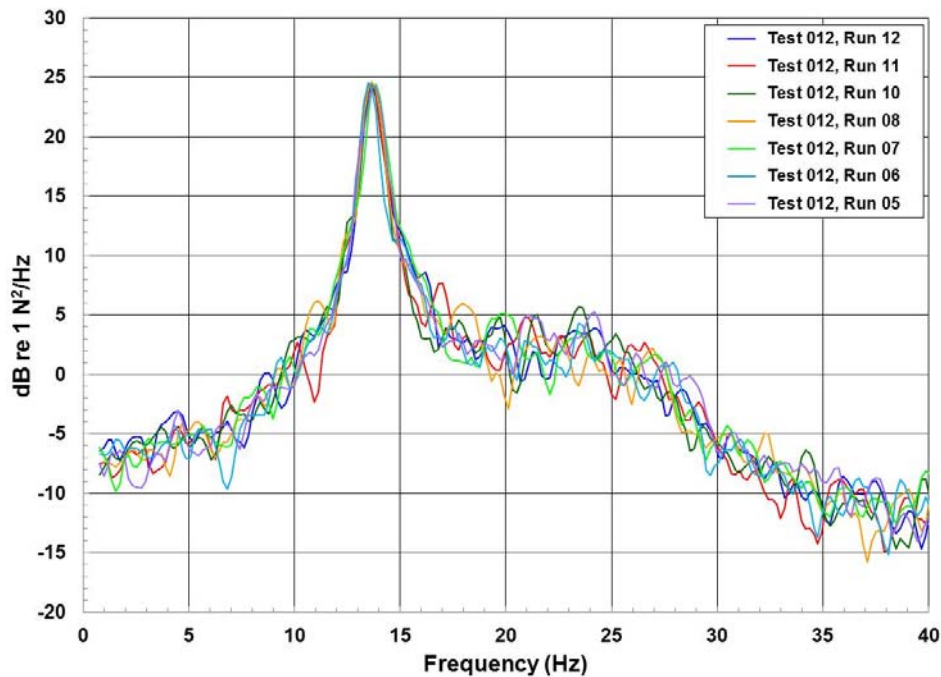


Figure 99. Power spectral density of the fin lift force at a test section velocity of 3.1 m/s and the angle-of-attack fixed at 0°. These measurements were acquired with the mechanical stop installed in the tunnel. Shown are seven repeated measurements acquired over an entire day with the tunnel stopped and restarted in between each run in order to assess the repeatability of the flow-field and resulting fin loading.

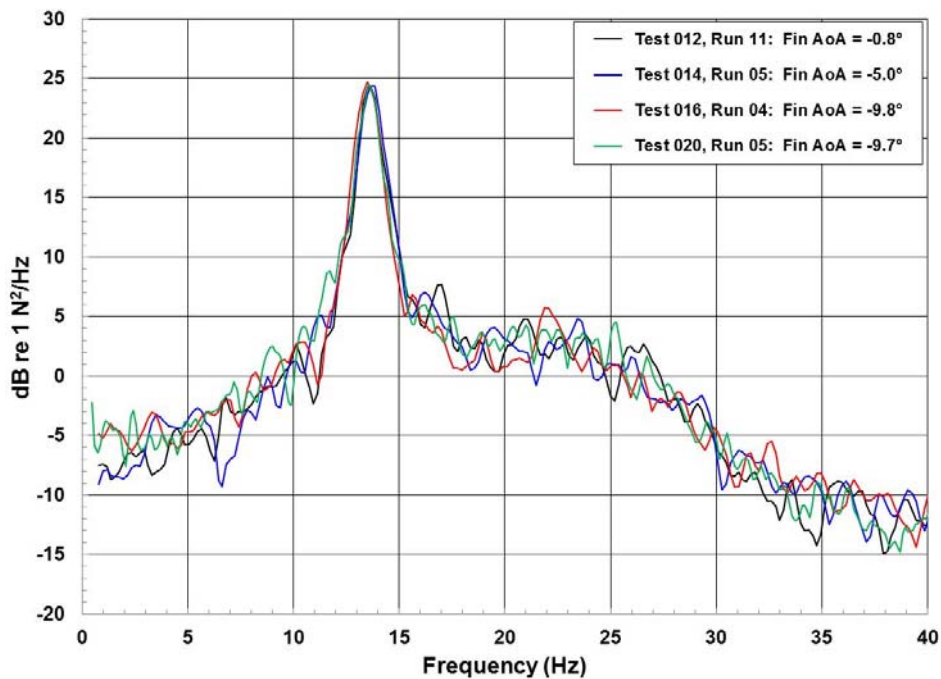


Figure 100. Fin lift power spectral density repeatability at a test section velocity of 3.1 m/s with data acquired over multiple tests, at various angles-of-attack and with and without the mechanical stop installed. Test 20 had the mechanical stop removed from the tunnel while the other measurements had it installed.

5.6.2.3 Loading spectral comparisons

Figure 101 shows the power spectral density of the fin forces (drag and lift) and moments (twist and drag moment) measurements at a reference velocity of 3.4 m/s. From the figure, the fin lift force at the shedding frequency of 14.9 Hz is ~10 dB greater than that of the drag. However, the drag shows an additional peak at roughly three times the shedding frequency. This same peak at approximately 44 Hz is also seen in the drag moment measurement and corresponds to the first streamwise bending mode given in Table 9. The fin twist level only measures ~0.275 N-m at the shedding frequency, suggesting that the twist moment on the fin is relatively weak at this operating condition. This is consistent with fin tip measurements, which showed that the fin tip experienced minimal twist over the range of velocities tested.

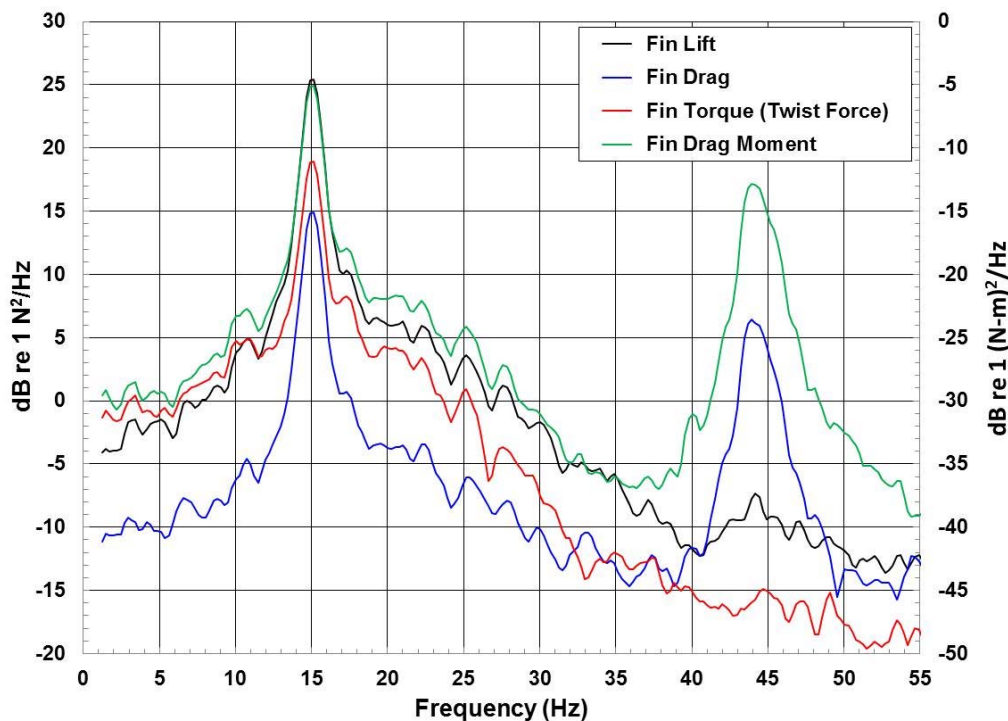


Figure 101. Fin force and moment power spectral densities at a tunnel test section velocity of 3.4 m/s from a single test (Test 20).

5.6.2.4 Spectral velocity dependence

Figure 102 shows the power spectral density of the fin lift force measured over a range of tunnel velocities. As with the cylinder lift spectra from the pressure measurements (see Figure 82), the fin lift increases as the shedding increases in frequency and level with increasing tunnel test section velocity. A potential mode is observed between 20 and 25 Hz at low tunnel velocities (2.5 to 2.95 m/s). This corresponds to the first cross-stream bending mode at 23 Hz given in Table 9. The fin lift spectra provide a means to quantify the effect that the inflow has on fin loading and movement. The resulting fin displacement measurements are provided subsequently.

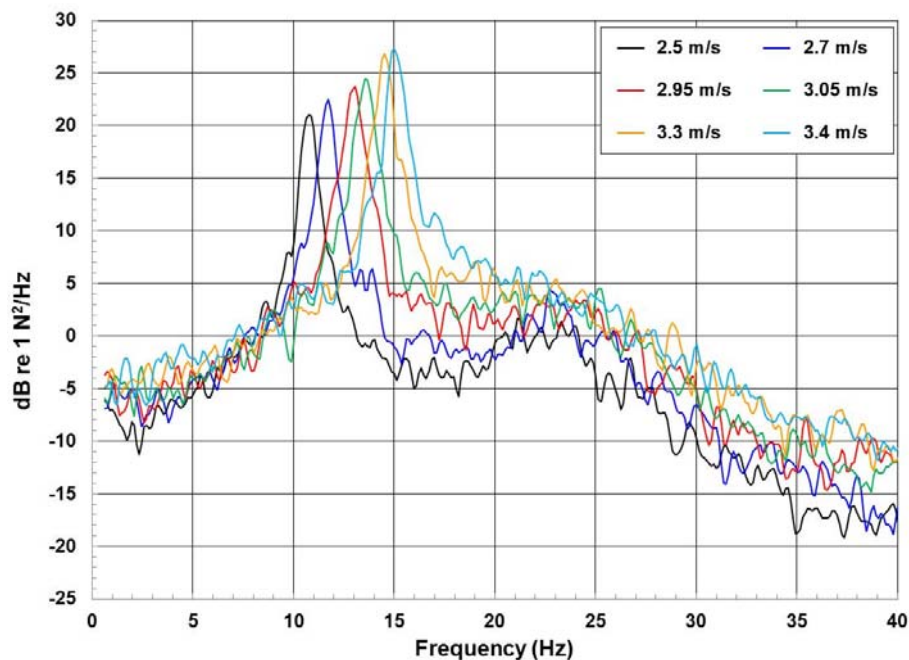


Figure 102. Fin lift force power spectral density measured over a range of tunnel velocities during a single test (Test 20) with the angle-of-attack fixed at nominally -10° and the mechanical stop removed. The legend provides the given reference test section velocity for each spectral density measurement.

The resulting fin RMS lift levels at the shedding frequency were computed in the same manner as the cylinder lift results by integrating over the bandwidth of the shedding frequency tone using the trapezoidal rule. Figure 103 shows the RMS lift force on the fin generated by the roughened cylinder shedding at the nominal -10° angle-of-attack *versus* shedding frequency. The fin RMS lift force is shown relative to the cylinder RMS lift computations for the smooth cylinder-only, roughened

cylinder-only and roughened cylinder with fin installed configurations. However, these are not considered direct comparisons given that cylinder and fin are subjected to different aspects of the vortex shedding flow field, have different areas that the lift force acts on and due to the flexibility of the fin structure the force is not a direct measure of the fluid loading. The proper comparisons of the fin loading will be done with fluid-structure interaction (FSI) models for validation purposes and determining the resulting fin motion generated by the fluid forcing.

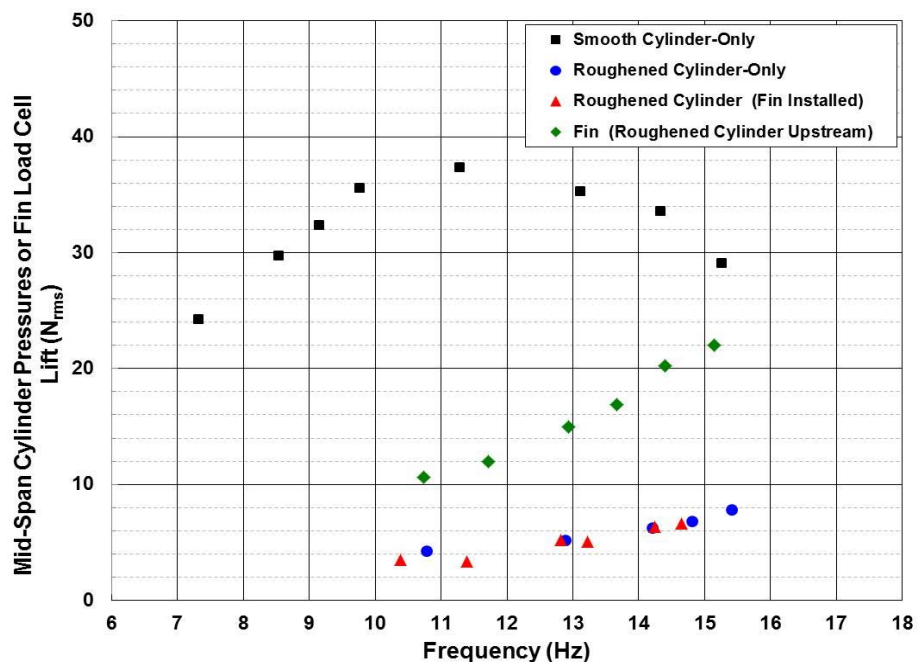


Figure 103. Fin RMS lift force as the shedding frequency versus the shedding frequency for the fin at the nominal -10° angle-of-attack during Test 20. These results are compared to the cylinder lift calculations for both the smooth and roughened cylinders.

The RMS forces (lift and drag) and moments (torque and drag moment) from all the measurements acquired throughout testing with the fin at the nominal -10° angle-of-attack without the mechanical stop installed are shown in Figure 104. The scatter in the results is nominally $\pm 10\%$ of the measured values, which is slightly larger than the load cell measurement uncertainties that were previously stated to be between 4% and 5%. While it is not necessarily expected that the instrumentation uncertainty will be the same as the uncertainty in the RMS measurements, the primary reason for the scatter is due to the fact that the loading is expected to be more of a broadband

measurement than the shedding frequency. This is due to the fact that there is a fluid-structure interaction such that the fin deflections and resulting fin loading having frequency content that are more complex than the cylinder vortex shedding. Consequently, the final results are expected to have more scatter due to the physical processes that are active in this FSI experiment. While the functional relationship of the results is unknown, the results appear non-linear and thus as an approximation each force and moment measurement was fitted with a power-law function. The results from these power-law fits are

$$\begin{aligned} L_{rms} &= 0.0668 f_{shed}^{2.1071}, \\ D_{rms} &= 0.0165 f_{shed}^{2.1943}, \\ Tq_{rms} &= 0.0331 f_{shed}^{1.8023} \text{ and} \\ DM_{rms} &= 0.0201 f_{shed}^{2.2086}. \end{aligned}$$

Here L_{rms} is the RMS lift force in N, D_{rms} is the RMS drag force in N, Tq_{rms} is the RMS torque moment in Nm, DM_{rms} is the RMS drag moment in Nm and f_{shed} is the shedding frequency for the given measurement. Note that shedding frequency is well approximated as $f_{shed} = 4.773 V_{ref} - 1.246$.

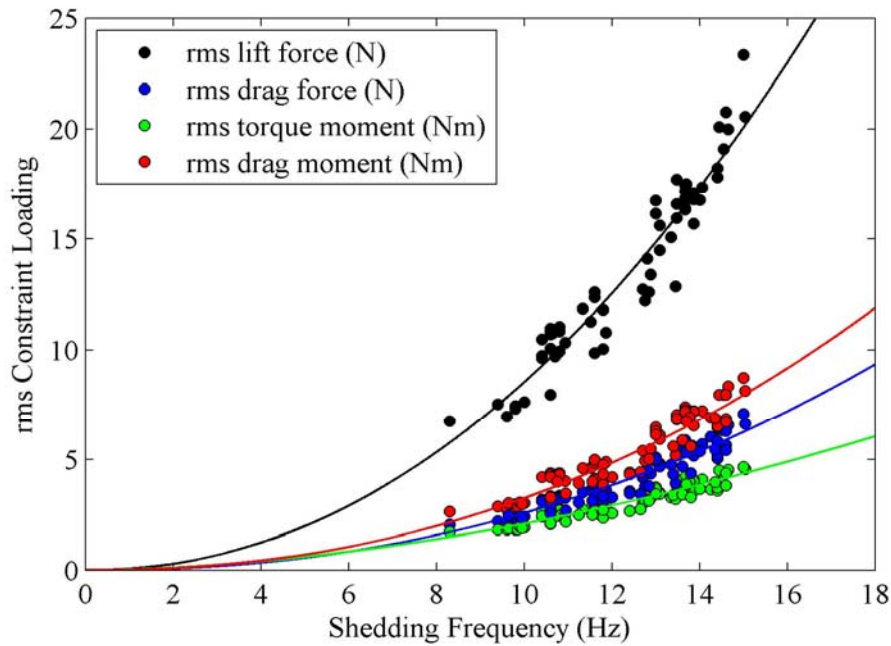


Figure 104. The RMS forces (lift and drag) and moments (torque and drag moment) plotted versus the measured shedding frequency for all the conditions tested during Part 4 at the nominal -10° angle-of-attack without the mechanical stop. Included are the power-law best fit curves for each rms force and moment measurement.

5.7 Flow-Field (cylinder wake)

PIV measurements were made of the cylinder wake using the same field of view as the cylinder-only case discussed in Section 3. However, the oscillating fin motion was also observed in the FOV. This section describes the results.

5.7.1 Field of view

Figure 105 shows sample vector-fields from a single test (Test 75 – Run 14) at a tunnel impeller frequency of 84 rpm, which corresponds to $V_{ref} = 3.6$ m/s. There are four instantaneous vector fields equally spaced in time and the background subtracted raw images are superimposed behind each computed vector field. This allows for the fin to be seen in the center along the right edge of each image and its corresponding tip location. Due to the laser light entering the tunnel from the positive Y direction (top edge of each image), the fin cast a shadow from the fin towards the negative Y side of the tunnel preventing vectors to be computed there due to no light for the tracer particles to scatter. The vector color corresponds to the velocity magnitude with the scale shown on the right. The scale was arbitrarily assigned and vectors at or above 4.0 m/s are not saturated. It is apparent that each image has small patches within the flow-field where the velocity is greater or equal to 4.0 m/s. This is over 10% above the measured tunnel reference velocity, but upon inspection of the location of these patches it can be seen that they correspond to locations in the flow where the fluid is being accelerated due to the given flow pattern. Consequently, these measurements are assumed to be physical and consistent with the reference velocity measurement given that the majority of the flow-field unaffected by the wake is nearly constant at ~ 3.6 m/s.

In the individual realizations it can be seen whether the cross-stream velocity is predominately positive or negative relative to the fin tip deflection. In the upper right image the near-wake is primarily downward (i.e. V is negative) and the fin tip is undergoing significant deflection in the negative Y direction (downward in the image). It is apparent that the deflection is significant because a

large region appears white in the raw image. This is produced by the fin being bent over enough that a large portion of the fin surface can be viewed by the camera positioned directly above the fin. The laser light reflects off this deflected surface sending a significant amount of light to the camera. The upper right image is still deflected in the negative Y direction but the wake is switching from negative to positive V . The lower left image then shows an image where the wake is still switching from negative to positive V , but the fin tip is now near the zero deflection point. At this position the fin tip is outlined and a bright line slightly above the fin tip outline towards the right edge is viewable. That bright line marks the height on the fin where the PIV measurements are being acquired ($Z = 188$ mm). Finally in the lower right image the near wake now has a positive V velocity and the fin tip is significantly deflected in the positive Y direction. The deflection is noticeable because the line marking the laser height location is no longer visible, indicating that the fin is bent over sufficiently such that the tip masks all the laser light reflecting off the fin surface. While it is not apparent in this image due to the vector-field, the outline of the fin tip is still apparent when deflected in the positive Y direction.

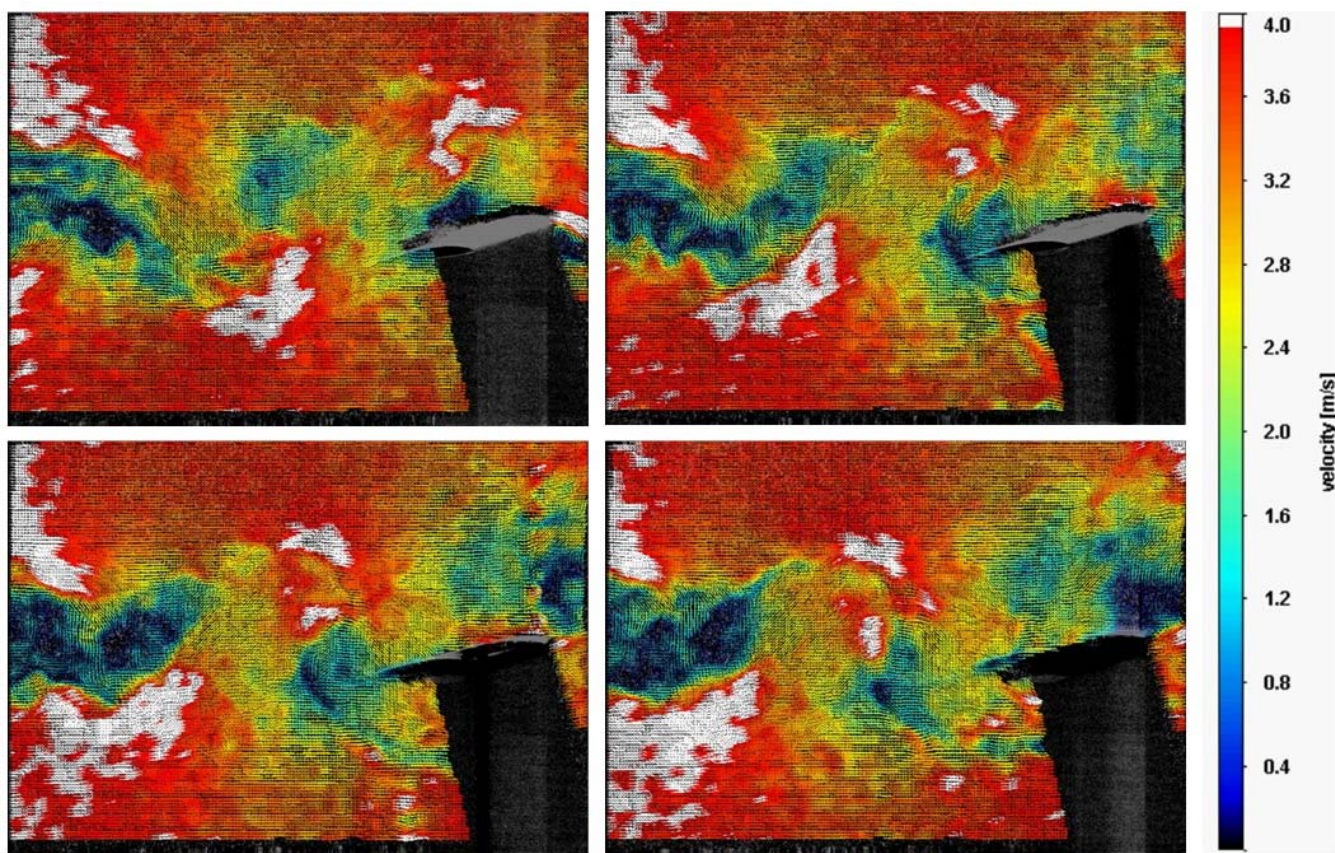


Figure 105. Instantaneous high-speed PIV vector fields produced during a single test (Test 75 – Run 14) at $V_{ref} = 3.6$ m/s. The sequence of the images is from left to right and top to bottom with each equal spaced. The color of the vectors is based on the velocity magnitude with the scale shown on the right of the image. Superimposed behind each vector-field is the background subtracted raw image, which the fin can be seen in the middle right edge of each image.

Figure 106 shows a top view schematic of the water tunnel test section layout including the cylinder, fin and tunnel walls. Also shown is the nominal field-of-view (FOV) for the high-speed PIV measurements. Within this FOV there are 12 red dots, which illustrate the nominal locations where the time histories were extracted. Each probe location was averaged from the three closest vectors to the location of interest. The averaging was done to minimize potential random noise from an individual vector, but inspection with and without averaging showed minimal variation. These points were used to produce a profile in the streamwise direction ($X = 160, 200, 240$ and 280 mm) along the test section centerline ($Y = 0$ mm) and cross-stream profiles ($Y = 0, \pm 30$ and ± 80 mm) in the near wake region ($X = 160$ mm) and the far wake near the fin tip leading edge location ($X = 280$ mm). The streamwise

positions correspond to 1.3, 2.0, 2.7 and 3.3 diameters downstream of the cylinder trailing edge. The cross-stream locations correspond to 0, ± 0.5 and ± 1.3 cylinder diameters from the tunnel centerline.

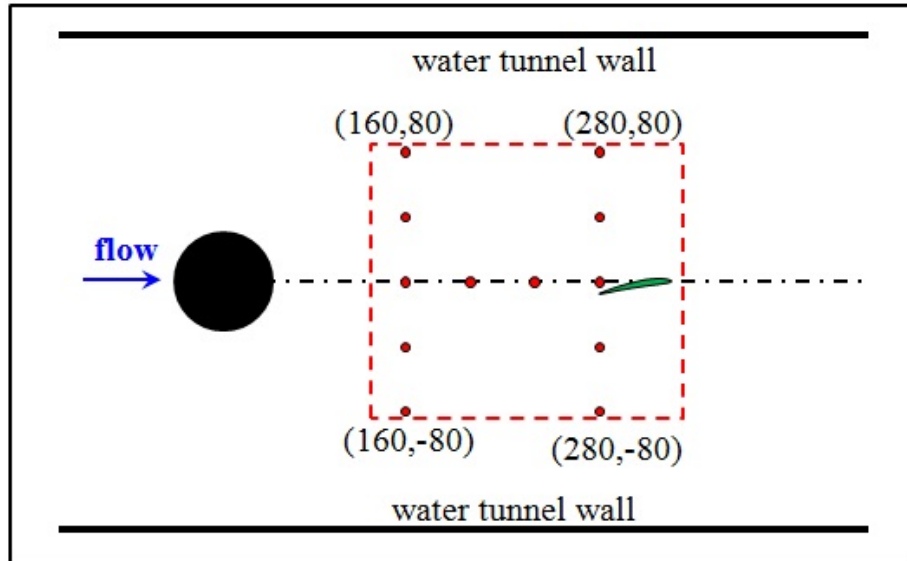


Figure 106. Top view schematic showing the layout of the water tunnel testing during the forced fin testing (Part 4) including the (large black circle) cylinder, (thick black lines) tunnel walls and (green object) fin location at the tip height ($Z = 230$ mm). Also shown is the (red dashed line box) nominal location of the high-speed PIV FOV and (red dots) the locations within the FOV where the velocity time traces were extracted from the 1kHz PIV results. The coordinates shown are in millimeters and measured from the test section inlet (X) and the tunnel centerline (Y). All high-speed PIV measurements were acquired at $Z = 188$ mm.

5.7.2 Mean contour plots

Now that the general trends and expected ranges have been established by inspecting the time traces for given locations within the flow, it is useful to inspect a representative contour plot of the mean and fluctuating velocities for each component. Figure 107 shows the mean and fluctuating contour plots for the streamwise velocity component (U) scaled with the reference velocity from a single test run (Test 75 – Run 14) at $V_{ref} = 3.6$ m/s. Similarly, Figure 108 shows the mean and fluctuating contour plots for the cross-stream velocity component (V) scaled with the reference velocity from the same test run. Contour plots for all conditions tested with the fin installed in the

roughened cylinder wake (Part 4) are provided in Appendix B.2. In each contour plot the fin chord-wise profile and the resulting shadow for $Y > 0$ have been masked out showing the results as zero in that region. Unlike the rough cylinder only results (Part 2b), the current results are symmetric about $Y = 0$ except for in the region near the fin location. Thus the misalignment problem with the laser sheet observed in Part 2b must have happened while the fin was being removed from the tunnel prior to Part 2b.

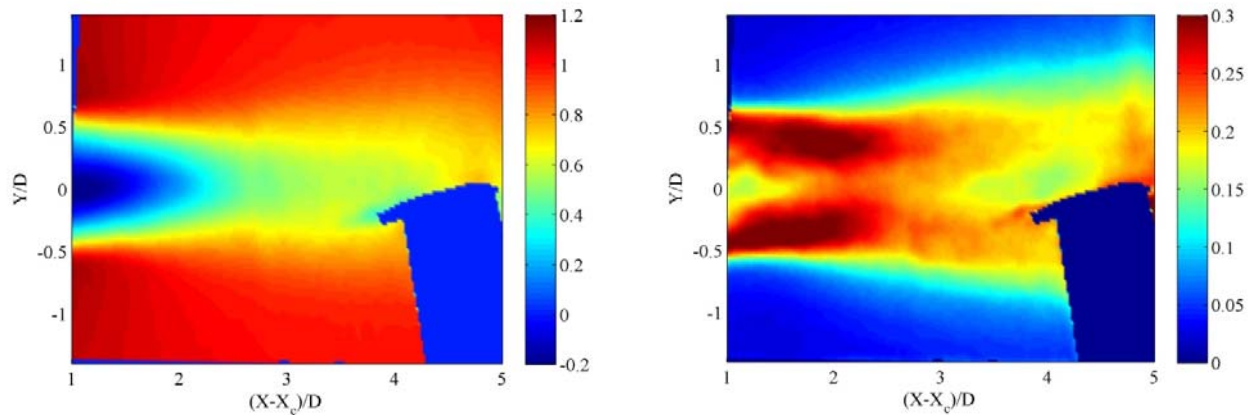


Figure 107. Contour plots of the streamwise velocity (left – mean; right – fluctuating) scaled with the reference velocity (U/V_{ref}) from a single test condition (Test 75 – Run 14) at $V_{ref} = 3.6$ m/s.

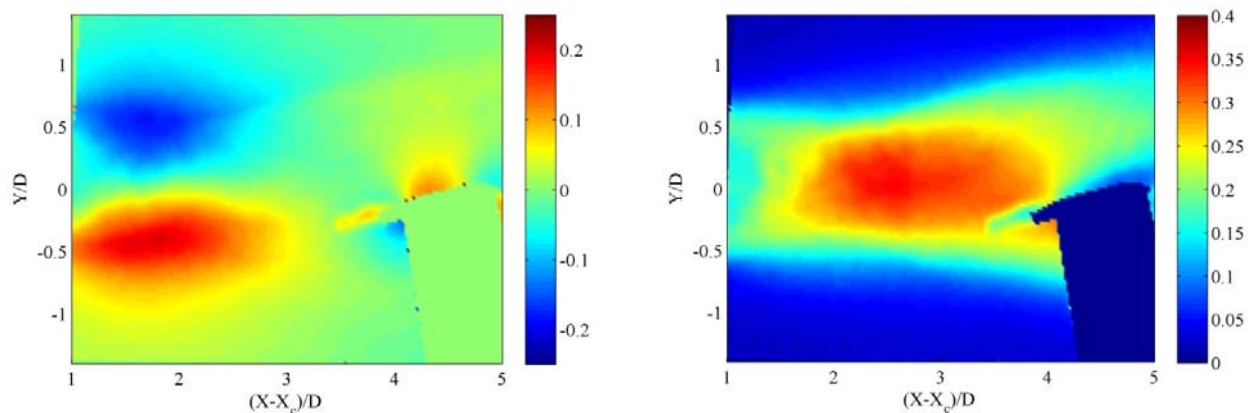


Figure 108. Contour plots of the cross-stream velocity component (left – mean; right – fluctuating) scaled with the reference velocity (V/V_{ref}) from a single test condition (Test 75 – Run 14) at $V_{ref} = 3.6$ m/s.

5.7.3 Flow-field angle-of-attack profiles

Now that a global picture of the mean flow-field has been established, it is useful to take some representative profiles through the FOV to better quantify the trends in the data. Prior to looking at the mean and fluctuating velocity profiles, it is informative to view the mean flow-field angle-of-attack measured relative to the streamwise direction, $\alpha_{\text{flow}} = \tan^{-1}(V/U)$. Figure 109 shows the mean flow-field angle-of-attack versus the downstream distance (X) from the cylinder trailing edge (X_c) scaled with the cylinder diameter (D). The profiles were acquired at either $Y/D = 0$ or ± 0.5 with the fin installed in the cylinder wake (Part 4). In each figure there are results from five separate test section velocities ($V_{\text{ref}} = 2.5, 3.0, 3.3, 3.4$ and 3.6 m/s), which shows excellent collapse of the data. There is increased scatter in the centerline ($Y/D = 0$) results near $(X-X_c)/D = 1.7$. Inspection of the mean streamwise velocity shows that at this point in the flow the mean streamwise velocity is nearly zero, which results in a rapid increase in the angle of attack towards 90° . Thus this represents the end of the recirculation zone and is noted in the figure with the solid black line. Note that without the fin installed, the recirculation zone was $\sim 1.5D$ downstream of the cylinder trailing edge (see Figure 50). Thus the recirculation zone was slightly shorter without the fin installed. The angle-of-attack in the far-wake appears to be nearly zero except at the fin leading edge at the height of the PIV plane ($Z = 188$ mm). Here the flow-field mean angle-of-attack increases to nearly 20° . While it is expected that on average the mean cross-stream velocity should be positive, these measurements are too close to the fin surface to confidently state if the increase is purely physical or a measurement error. The results from $Y/D = \pm 0.5$ show that the flow on average has a positive flow-field angle-of-attack for $Y < 0$ and a negative flow-field angle-of-attack when $Y > 0$. As will be seen subsequently, this is due to the mean V velocity having an opposite sign of the Y -location in the near-wake region.

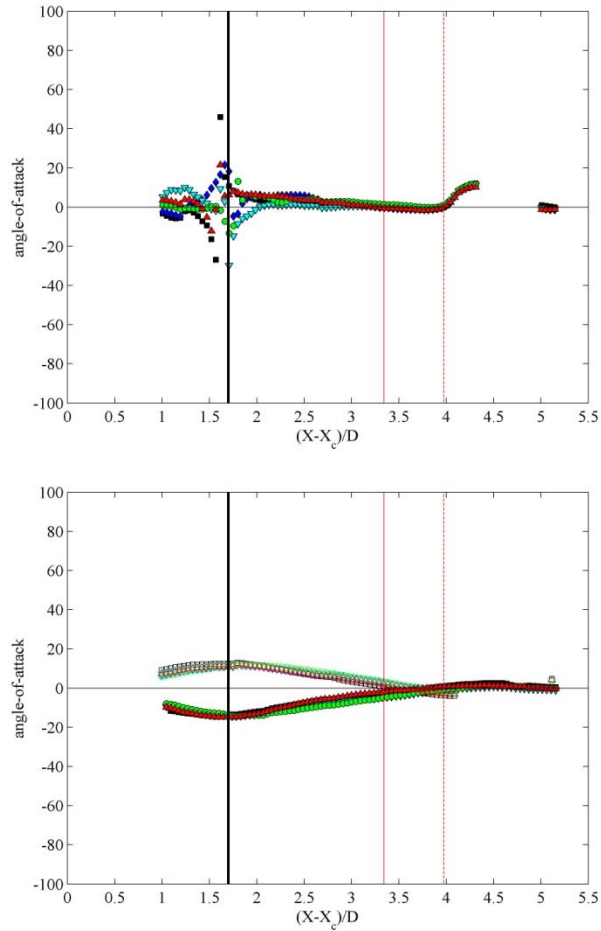


Figure 109. Mean flow-field angle-of-attack measured relative to the streamwise direction, $\alpha_{\text{flow}} = \tan^{-1}(V/U)$, plotted versus the scaled downstream distance from the cylinder trailing edge, $(X-X_c)/D$, with the fin installed (Part 4). The symbol colors correspond to $V_{\text{ref}} =$ (black) 2.5, (blue) 3.0, (cyan) 3.3, (green) 3.4 and (red) 3.6 m/s. The data shown are the average results from a given velocity at (left) $Y/D = 0$ and (right) $Y/D = \pm 0.5$. In the right image, the open and closed symbols were acquired at $Y/D = -0.5$ and $+0.5$, respectively. The solid black line represents the nominal location of the end of the recirculation region. The two thin red lines downstream show the nominal locations of the fin tip leading edge and the leading edge at the PIV plane ($Z = 188$ mm).

Cross-stream profiles of the mean flow-field angle-of-attack are provided in Figure 110, which the cross-stream direction (Y) is scaled with the cylinder diameter (D). These profiles were acquired in the near or far wake regions, which correspond to $(X-X_c)/D = 1.3$ or 3.3 , respectively. The far wake position was selected because it corresponds to the nominal downstream position of the fin tip leading edge. Each profile was produced by averaging the repeated conditions from a given velocity, and the symbol colors denote the given test section velocity ($V_{\text{ref}} = 2.5, 3.0, 3.3, 3.4$ and 3.6 m/s). Once again the data has excellent collapse independent of the test section velocity. The only significant scatter is

for data between $Y/D = \pm 0.2$. The near-wake position ($X = 160$ mm) is less than the end of the recirculation zone ($X \sim 180$ mm), and consequently the near-wake profile crosses through two points where the streamwise velocity approaches zero. At each of these positions the angle-of-attack rapidly approaches $\pm 90^\circ$. Thus at $X = 160$ mm the cross-stream distance between these two asymptotes could define the width of the recirculation zone at the given downstream position. In the far wake the mean flow-field angle-of-attack approaches zero across the entire profile. This does not indicate that there are not large fluctuations, which were observed in the time-trace signals, but that the fluctuations across the entire wake fluctuate about zero degrees.

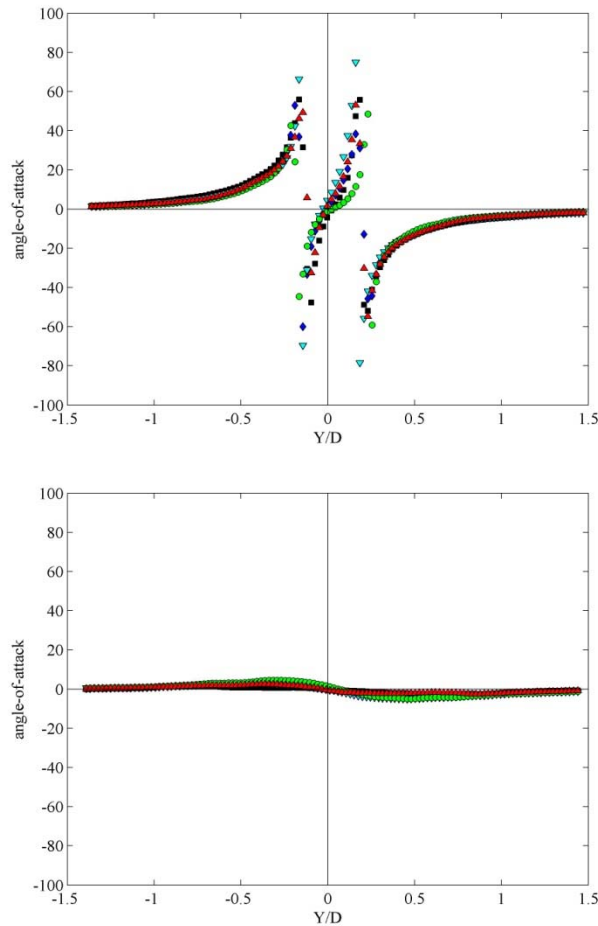


Figure 110. Mean flow-field angle-of-attack measured relative to the streamwise direction, $\alpha_{\text{flow}} = \tan^{-1}(V/U)$, plotted versus the scaled cross-stream direction (Y/D). The data shown are the average results from a given velocity in the (left) near-wake region at $X = 160$ mm and (right) far wake near the fin tip leading edge ($X = 280$ mm). The symbol colors correspond to $V_{\text{ref}} =$ (black) 2.5, (blue) 3.0, (cyan) 3.3, (green) 3.4 and (red) 3.6 m/s.

The above plots demonstrate that the acquired data collapses reasonably well independent of the given test section velocity, thus in Figure 111 the results for the streamwise and cross-stream profiles are shown with the mean flow-field angle-of-attack determined from the average of all the conditions tested independent of the test section velocity. These two plots help show the spatial trends in the cylinder wake results. The streamwise profiles show the nominal location of the end of the recirculation zone (i.e. centerline location where the streamwise velocity goes to zero and consequently the angle-of-attack rapidly approaches $\pm 90^\circ$). Then the symmetry between the $\pm Y$ locations can be observed as well as the dissipation of the fluctuations when moving away from the centerline. The cross-stream profile shows that for locations prior to the end of the recirculation zone, the edges of the recirculation zone are noted by the angle of attack approaching $\pm 90^\circ$. Then beyond the recirculation zone there is a smooth continuous curve with a peak in magnitude nominally at $Y/D = \pm 0.25$. This peak dissipates with increasing downstream distance.

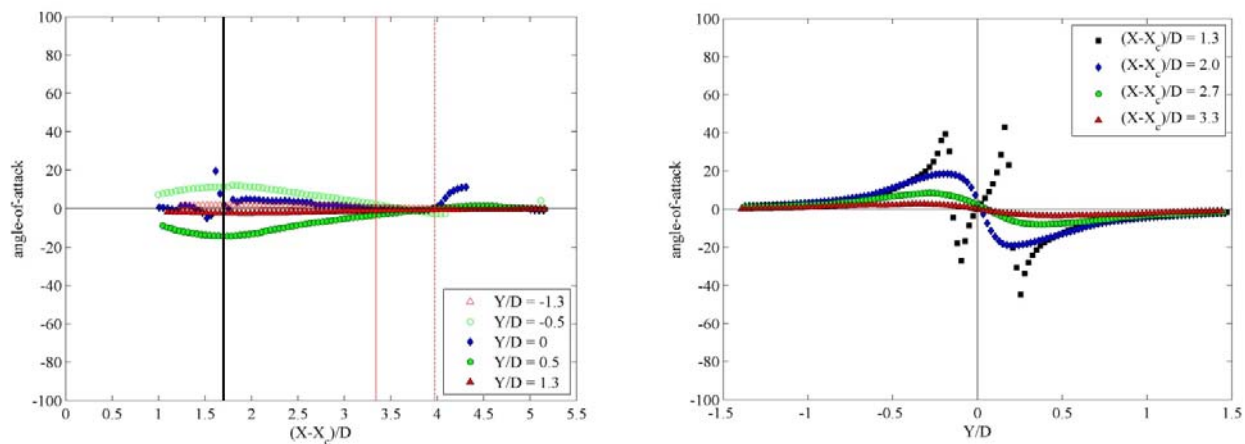


Figure 111. Mean flow-field angle-of-attack measured relative to the streamwise direction, $\alpha_{\text{flow}} = \tan^{-1}(V/U)$, plotted versus (left) scaled distance downstream of the cylinder trailing edge or (right) the scaled cross-stream direction with the fin installed in the cylinder wake (Part 4). The data shown are the average results from all conditions independent of the test section velocity. In the left image the solid black line denotes the end of the recirculation zone, the solid red line notes the position of the fin tip leading edge and the dashed red line denotes the fin leading edge in the PIV plane ($Z = 188$ mm).

Figure 112 shows three plots of the flow-field mean angle-of-attack versus the scaled downstream distance from the cylinder trailing edge, $(X-X_c)/D$. Each of the plots shows results from a separate cross-stream position ($Y/D = 0, \pm 0.5$ or ± 1.3) with and without the fin installed in the cylinder wake. Then in Figure 113 the flow-field mean angle-of-attack is plotted versus the scaled cross-stream distance (Y/D) with and without the fin installed in the cylinder wake. There are two plots in that figure, one from the near-wake region and one in the far-wake region near the fin tip leading edge location. All the profiles show negligible difference with and without the fin installed with the exception of the centerline angle-of-attack beyond the downstream location of the fin leading edge in the PIV plane. This suggests that the presence of the fin has minimal impact on flow-field upstream of the fin, though individual velocity components are investigated subsequently.

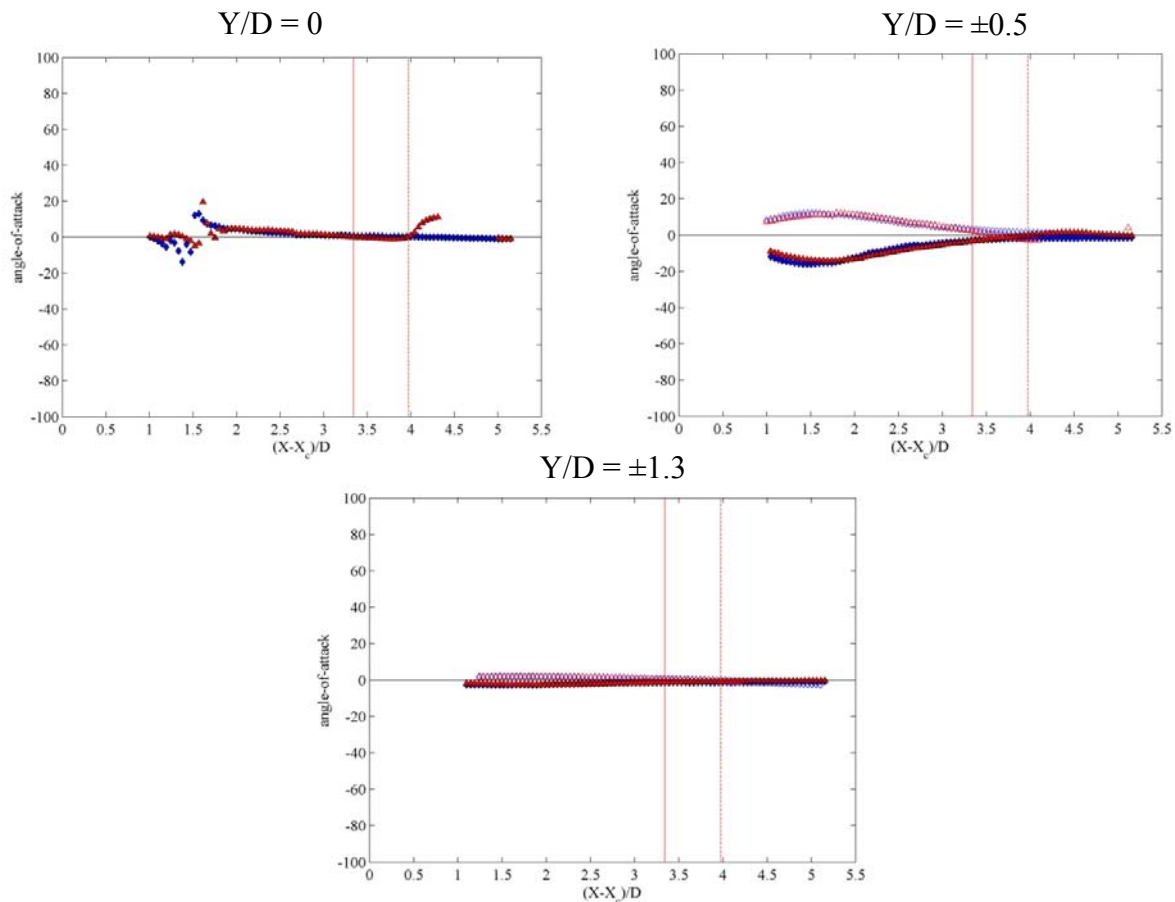


Figure 112. Mean flow-field angle-of-attack measured relative to the streamwise direction, $\alpha_{\text{flow}} = \tan^{-1}(V/U)$, plotted versus the downstream distance (X) from the cylinder trailing edge (X_c) scaled with the cylinder diameter. The data

shown are the average results from all conditions from (upper left) $Y/D = 0$, (upper right) $Y/D = \pm 0.5$ and (lower) $Y/D = \pm 1.3$. Blue symbols are results from the rough cylinder without the fin (Part 2b) and the red symbols are with the fin installed in the rough cylinder wake (Part 4). Open symbols correspond to negative- Y locations and solid symbols are positive- Y locations. The two thin red lines downstream show the nominal locations of the fin tip leading edge and the leading edge at the PIV plane ($Z = 188$ mm).

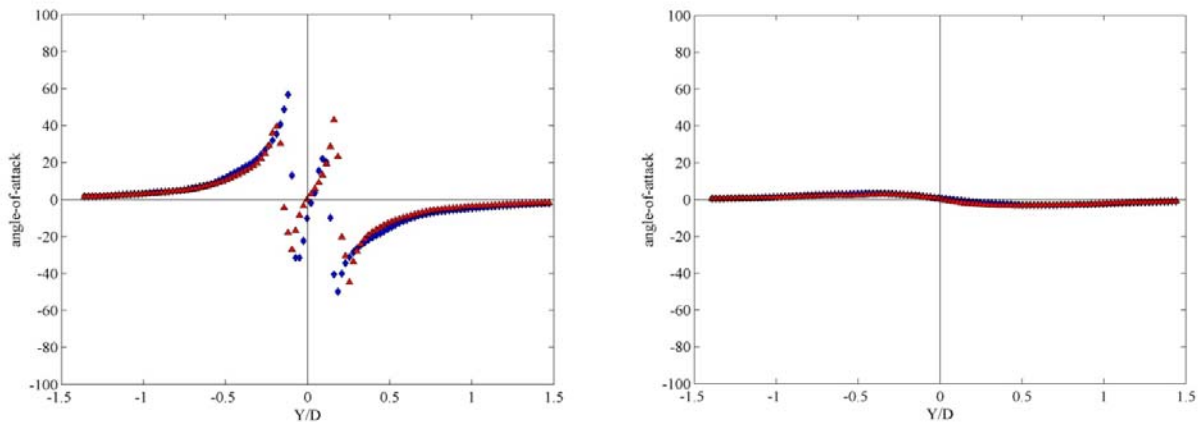


Figure 113. Mean flow-field angle-of-attack measured relative to the streamwise direction, $\alpha_{\text{flow}} = \tan^{-1}(V/U)$, plotted versus the cross-stream location (Y) scaled with the cylinder diameter. The data shown are the average results from all conditions from (left) the near wake at $(X-X_c)/D = 1.3$ and (right) the far wake near the fin tip leading edge at $(X-X_c)/D = 3.3$. The blue symbols are testing without the fin (Part 2b) and the red symbols are with the fin (Part 4).

5.7.4 Streamwise velocity

As discussed before, the PIV provides both streamwise and transverse components of velocity. In this section the mean and fluctuating velocity components of the streamwise velocity component are discussed.

5.7.4.1 Mean velocity

While there was some variation in the results when comparing scaled results between velocities, it is apparent from the time trace data and the mean angle-of-attack data that the results scale reasonably well with the reference velocity. Thus the discussion of the streamwise and cross-stream velocity results will only show results averaged from all velocities tested. However, all the results averaged at a given velocity are provided in Appendix B.3, which shows that there is scatter but the scatter appears independent of velocity. Figure 114 shows the mean streamwise velocity scaled with the test section reference velocity (U/V_{ref}) plotted versus the downstream distance from the cylinder

trailing edge scaled with the cylinder diameter $((X-X_c)/D)$. The results are from a given Y-location and average from all the velocities tested. Five separate profiles spanning $Y/D = \pm 1.3$ are shown. The profile acquired along the centerline ($Y/D = 0$) shows a gradual increase in U with increasing downstream distance until $\sim 2.5D$ downstream of the cylinder trailing edge where the velocity flattens out and becomes nearly constant. Data for $Y/D \leq 0$ is not valid beyond $4D$ downstream of the cylinder trailing edge due to the influence of the oscillating fin and the shadow/reflections. The profiles from $Y/D = \pm 1.3$ are nearly identical and show that the free-stream velocity is nominally equal to the test section reference velocity except in the near-wake region where the blockage effect causes the average velocity to be greater than the reference velocity. Comparing data from $Y/D = \pm 0.5$ shows that the two profiles are not identical. This indicates that the fin has some impact on the average flow-field, even in the near-wake region.

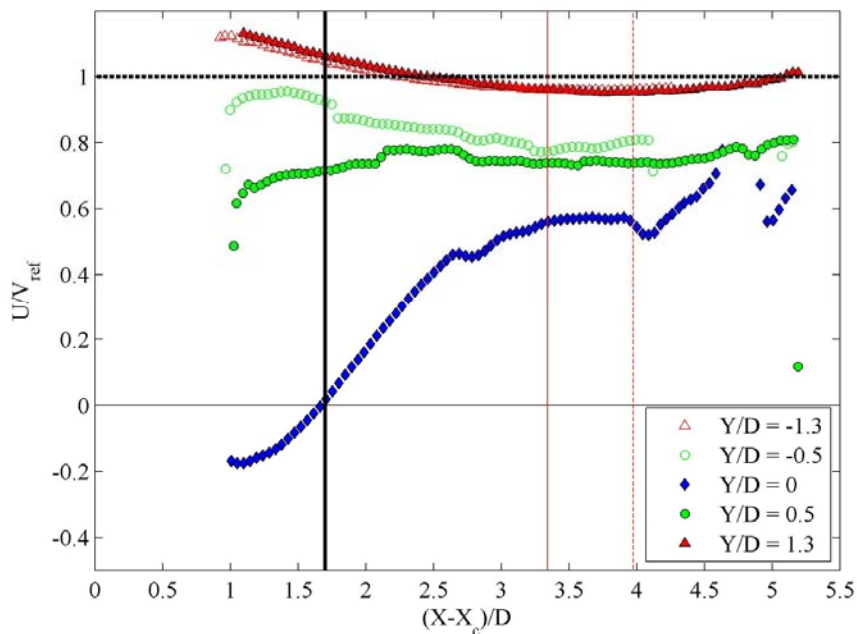


Figure 114. Mean streamwise velocity (U) scaled with the test section reference velocity (V_{ref}) plotted versus the downstream distance (X) from the cylinder trailing edge (X_c) scaled with the cylinder diameter (D). The data shown are the average results from all conditions with the fin installed in the rough cylinder wake (Part 4). The solid black line represents the nominal location where the recirculation zone ends, $(X-X_c)/D = 1.7$. The two thin red lines downstream show the nominal locations of the fin tip leading edge and the leading edge at the PIV plane ($Z = 188$ mm).

Figure 115 shows several cross-stream profiles of the scaled streamwise velocity (U/V_{ref}) with the fin installed in the downstream wake (Part 4). Unlike the profiles from Part 2b (see Figure 54), these are symmetric about $Y/D = 0$, which is the reason the laser misalignment issue is assumed to only impact the results from Part 2b. The profile from the near-wake region, $(X-X_c)/D = 1.3$, shows that it crosses through the recirculation zone since there are two locations where the mean streamwise velocity equals zero. Also, at this location the blockage effect can still be measured as the profile plateaus on both sides of the wake to a value greater than V_{ref} . The rest of the profiles are beyond the recirculation zone (i.e. the minimum velocity is greater than zero), and the minimum velocity is along the tunnel centerline ($Y/D = 0$). The wake deficit decreases and the wake widens with increasing downstream distance. Furthermore, the profiles beyond the recirculation zone asymptote to V_{ref} on each side of the wake.

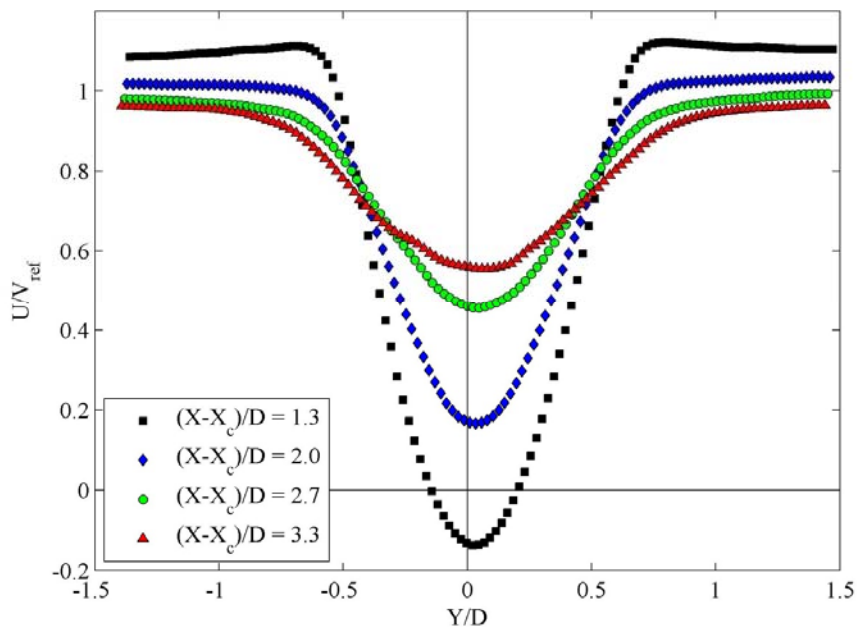


Figure 115. Scaled mean streamwise velocity (U/V_{ref}) plotted versus the scaled cross-stream location (Y/D). The data shown are the average results from all conditions acquired with the fin installed in the rough cylinder wake (Part 4).

The mean streamwise velocity with and without the fin installed in the wake are compared in Figure 116 and Figure 117. Figure 116 shows the scaled streamwise velocity plotted versus the scaled downstream distance from the cylinder trailing edge, $(X-X_c)/D$, at $Y/D = 0, \pm 0.5$ and ± 1.3 . Along the centerline there is a slight difference in the near-wake, but in the far-wake (i.e. beyond $2.5D$ downstream of the cylinder trailing edge) the two profiles are quite similar. The profiles at $Y/D = \pm 0.5$ have relatively poor agreement. Finally the profiles at $Y/D = \pm 1.3$ follow similar trends when excluding the cylinder only data at $Y/D = -1.3$, which is known to have errors due to laser misalignment. There is less agreement in the cross-stream profiles in Figure 117, primarily due to the misalignment issue. However, the same trends are observed with the wake widening and decaying.

$Y/D = 0$

$Y/D = \pm 0.5$

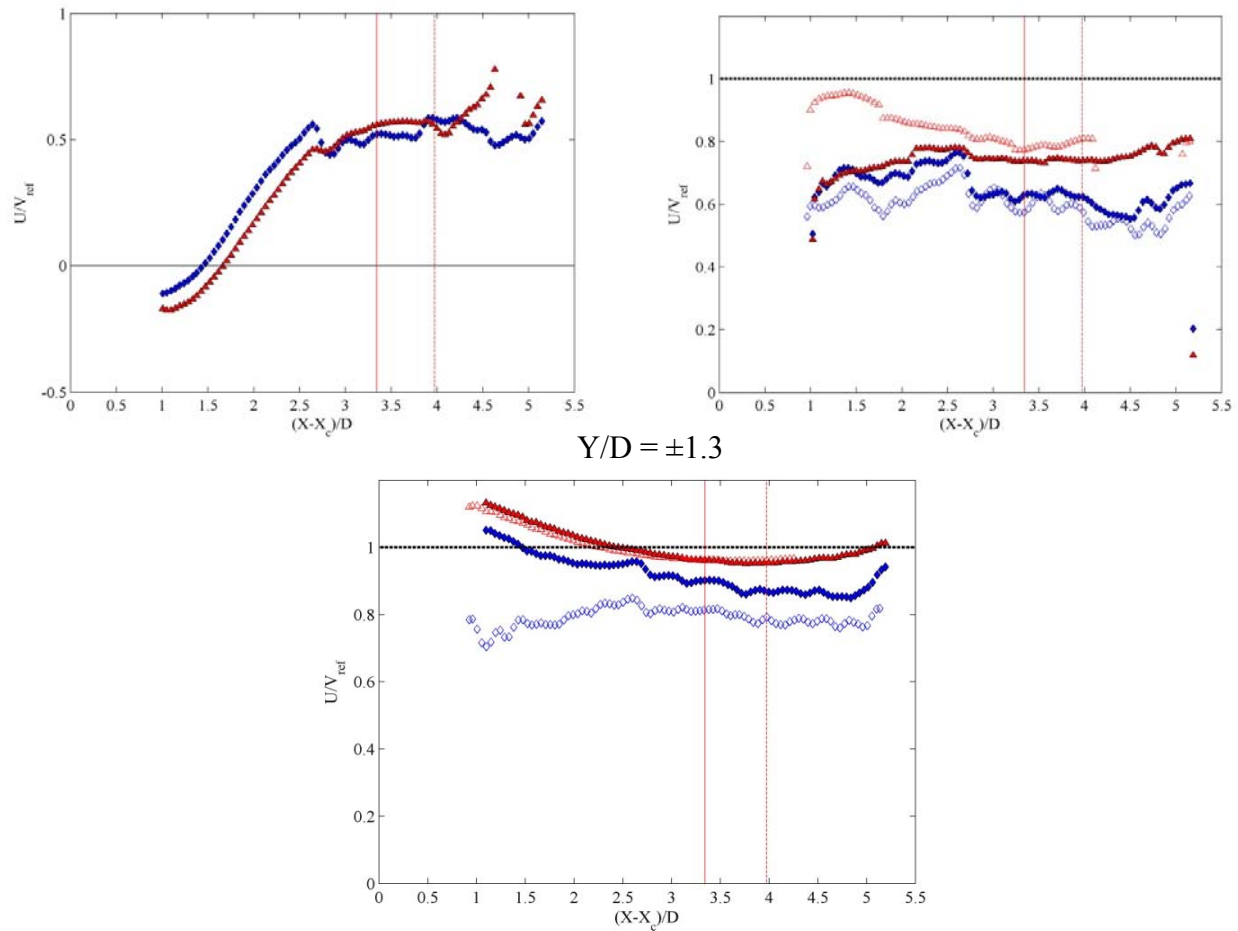


Figure 116. Comparison of the scaled mean streamwise velocity (U/V_{ref}) with and without the fin installed in the rough cylinder wake. The data shown are the average results from all conditions from (upper left) $Y/D = 0$, (upper right) $Y/D = \pm 0.5$ and (lower) $Y/D = \pm 1.3$ plotted versus the scaled distance downstream from the cylinder trailing edge, $(X-X_c)/D$. Blue symbols are results from the rough cylinder without the fin (Part 2b) and the red symbols are with the fin installed in the rough cylinder wake (Part 4). Open symbols correspond to negative- Y locations and solid symbols are positive- Y locations. The two thin red lines downstream show the nominal locations of the fin tip leading edge and the leading edge at the PIV plane ($Z = 188$ mm).

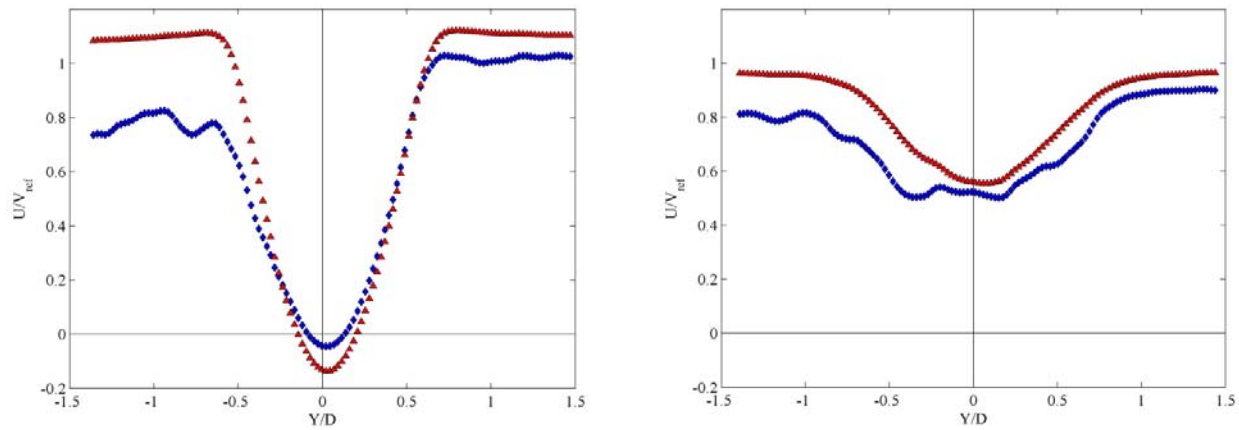


Figure 117. Comparison of the scaled mean streamwise velocity (U/V_{ref}) with and without the fin installed in the rough cylinder wake. The data shown are the average results from all conditions from (left) the near wake region at $(X-X_c)/D = 1.3$ and (right) the far wake near the fin tip leading edge at $(X-X_c)/D = 3.3$ plotted versus the scaled cross-stream distance (Y/D). Blue symbols are results from the rough cylinder without the fin (Part 2b) and the red symbols are with the fin installed in the rough cylinder wake (Part 4).

5.7.4.2 Fluctuating velocity

Figure 118 shows the fluctuating streamwise velocity scaled with the test section reference velocity (u'/V_{ref}) plotted versus the distance downstream from the cylinder trailing edge scaled with the cylinder diameter ($(X-X_c)/D$) with the fin installed in the rough cylinder wake (Part 4). These results are from the same Y -locations as was shown for the mean velocity profiles. The profiles at $Y/D = \pm 1.3$ are in excellent agreement and show that the fluctuations are increasing with increasing downstream distance. This is consistent with the blockage effect suppressing fluctuations at the inlet and the wake growth having a greater impact on the free-stream with increasing downstream distance. The profiles at $Y/D = \pm 0.5$ once again are not in agreement in the near-wake but show similar trends. These results would indicate that the presence of the fin suppresses streamwise velocity fluctuations on the side where the fin is installed. Finally the centerline profile shows the fluctuations gradually increasing until about $2-2.5D$ downstream of the cylinder trailing edge, and then gradually decreasing with increasing downstream distance. Once again the results beyond $(X-X_c)/D = 4$ are not reliable due to the fin oscillations and the resulting shadows and reflections.

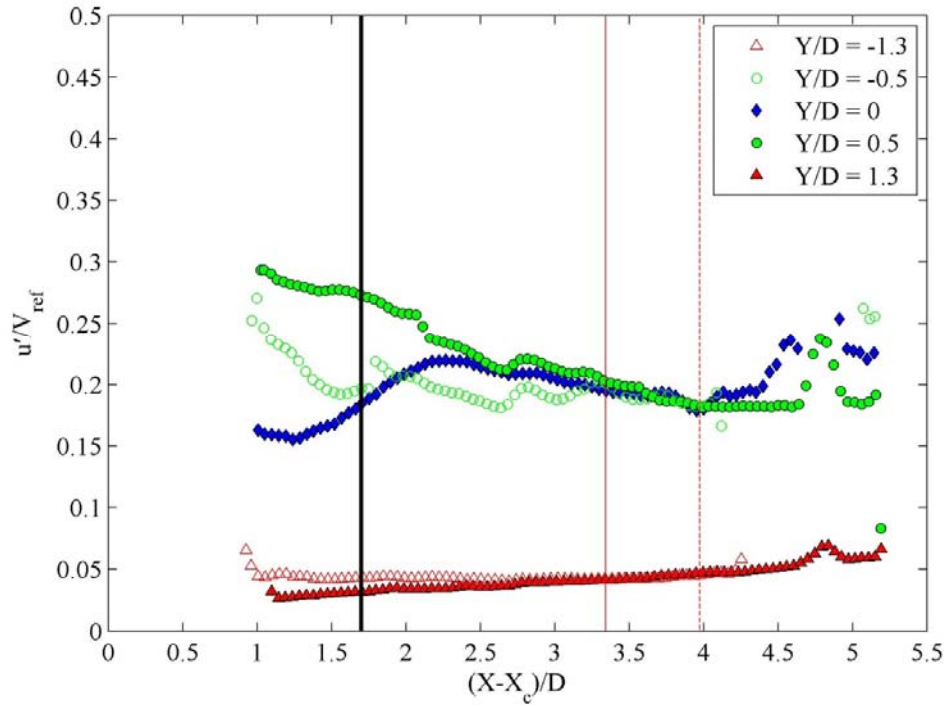


Figure 118. Fluctuating streamwise velocity (u') scaled with the test section reference velocity (V_{ref}) plotted versus the downstream distance (X) from the cylinder trailing edge (X_c) scaled with the cylinder diameter (D). The data shown are the average results from all conditions acquired with the fin installed in the rough cylinder wake (Part 4). The solid black line represents the nominal location where the recirculation zone ends, $(X-X_c)/D = 1.7$, the thin solid red line denotes the fin tip leading edge and the thin dashed red line denotes the leading edge of the fin at the PIV plane height ($Z = 188$ mm).

Figure 119 shows cross-stream profiles of the scaled streamwise fluctuating velocity (u'/V_{ref}) from the same streamwise locations as shown for the mean streamwise velocity profiles. Unlike the roughened cylinder only results (see Figure 56), these profiles are symmetric about the tunnel centerline ($Y/D = 0$) with peaks at $Y/D = \pm 0.5$. The peaks decrease with increasing downstream distance, and the core of the wake flattens out with increasing downstream distance. Conversely the fluctuations increase with increasing downstream distance outside of the wake core, which indicates that the wake is decaying and widening with increasing downstream distance.

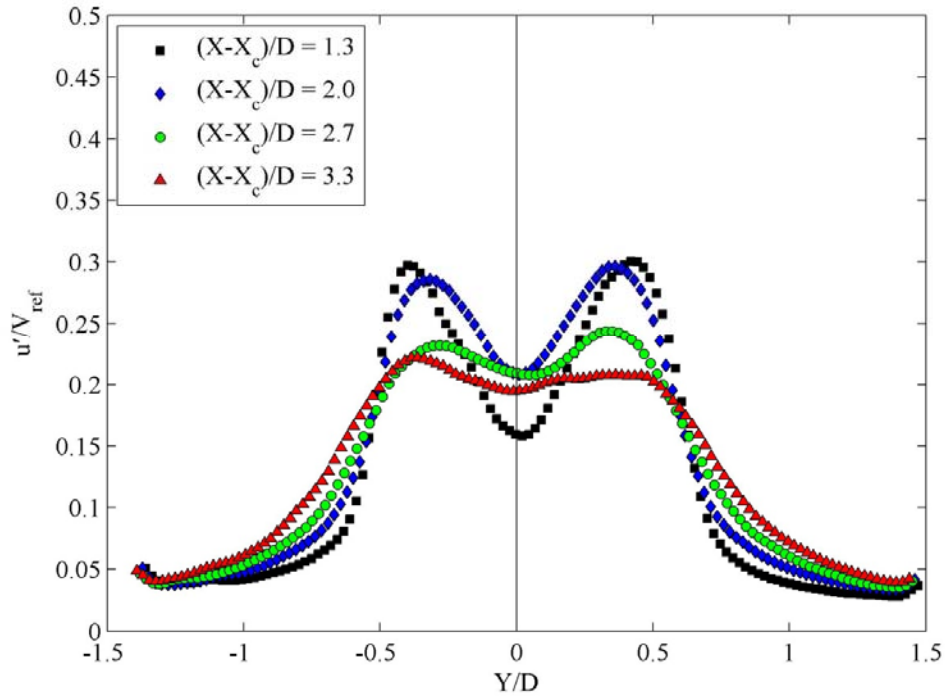


Figure 119. Scaled fluctuating streamwise velocity (u'/V_{ref}) plotted versus the scaled cross-stream location (Y/D). The data shown are the average results from all conditions with the fin installed in the rough cylinder wake (Part 4).

The fluctuating streamwise velocity with and without the fin installed in the wake are compared in Figure 120 and Figure 121. Figure 120 shows the scaled streamwise velocity fluctuations plotted versus the scaled downstream distance from the cylinder trailing edge, $(X-X_c)/D$, at $Y/D = 0, \pm 0.5$ and ± 1.3 . With the exception of the cylinder only data at $Y/D = -1.3$, the remainder of the results are in excellent agreement with each other. There are minor variations, but the variation is less than that observed in the mean streamwise velocity results. Figure 121 shows cross-stream profiles in the near and far wake regions. Excluding the data influenced by the laser misalignment issue ($Y/D < -0.5$), there is minimal variation between results with and without the fin installed in the cylinder wake. The overall conclusion from these comparisons is that the installation of the fin has minimal impact on the streamwise velocity fluctuations upstream of the fin.

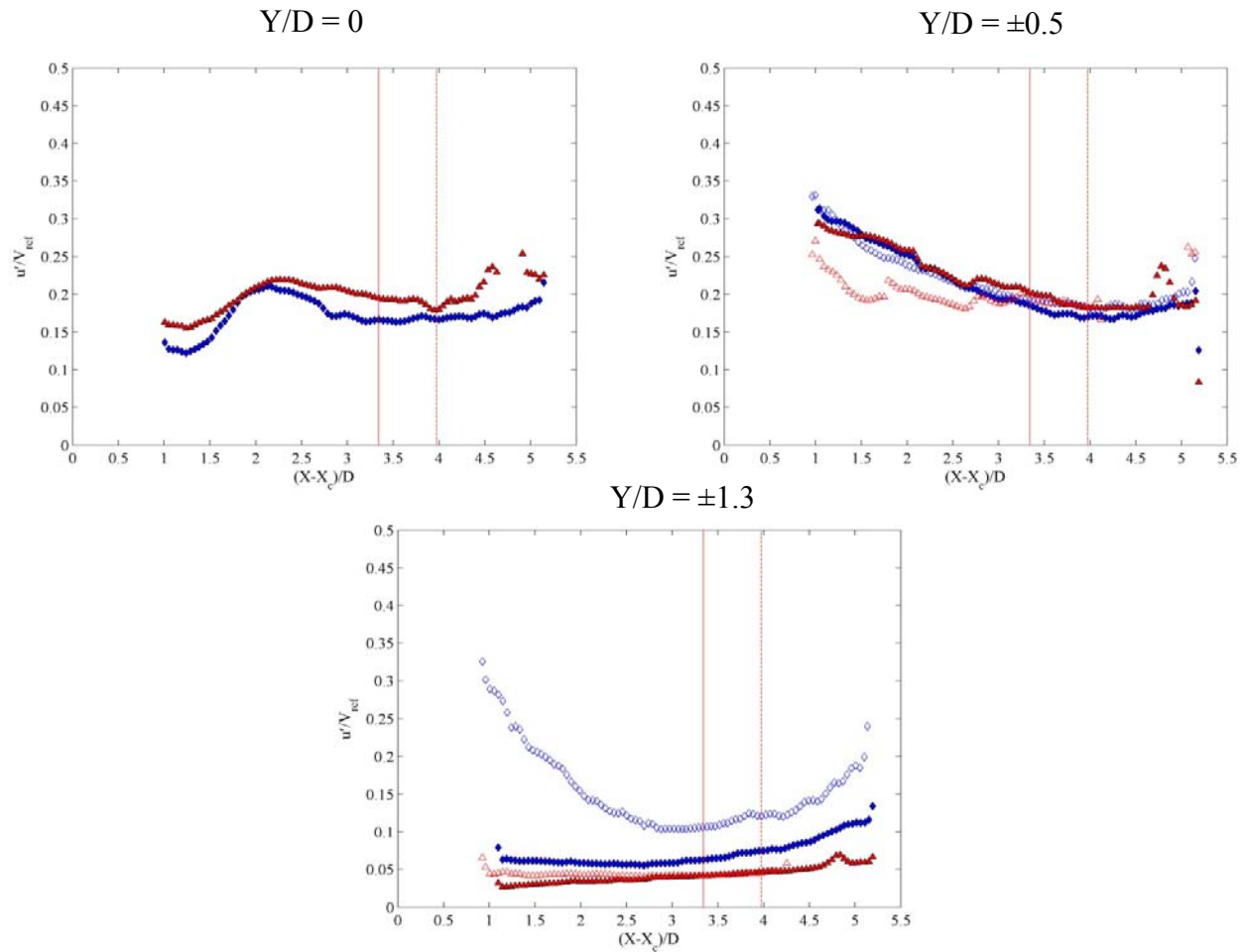


Figure 120. Scaled fluctuating streamwise velocity (u'/V_{ref}) plotted versus the scaled distance downstream from the cylinder trailing edge, $(X-X_c)/D$. Shown are the average results from all conditions at (upper left) $Y/D = 0$, (upper right) $Y/D = \pm 0.5$ and (lower) $Y/D = \pm 1.3$. Blue symbols are from the rough cylinder only (Part 2b) and red symbols are with fin (Part 4). Open symbols correspond to negative- Y locations and solid symbols are positive- Y locations. The two thin red lines mark the nominal leading edge locations at the fin tip and at the PIV plane ($Z = 188$ mm).

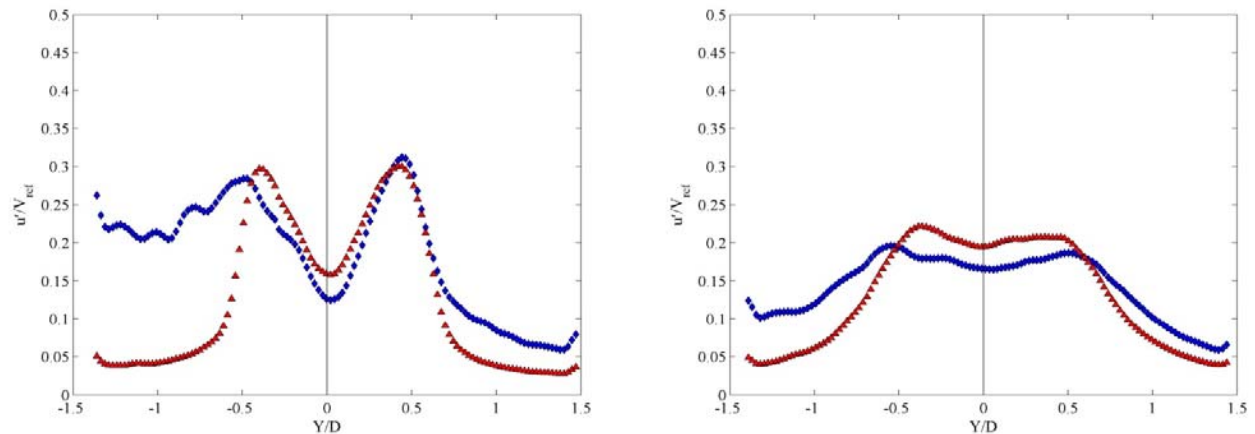


Figure 121. Scaled fluctuating streamwise velocity (u'/V_{ref}) plotted versus the scaled cross-stream distance (Y/D). The data shown are the average results from all conditions from (left) the near wake region at $(X-X_c)/D = 1.3$ and (right) the far wake near the fin tip leading edge at $(X-X_c)/D = 3.3$. Blue symbols are results from the rough cylinder without the fin (Part 2b) and the red symbols are with the fin installed in the rough cylinder wake (Part 4).

5.7.5 Cross-stream velocity

As discussed before, the PIV provides both streamwise and transverse components of velocity. In this section the mean and fluctuating velocity components of the transverse velocity component are discussed.

5.7.5.1 Mean velocity

Once again the cross-stream velocity profiles are shown as average profiles from all velocities tested, but the average from a given velocity can be viewed in Appendix B.3. Figure 122 shows the mean cross-stream velocity scaled with the test section reference velocity (V/V_{ref}) plotted versus the downstream distance from the cylinder trailing edge scaled with the cylinder diameter ($(X-X_c)/D$). The centerline velocity profile ($Y/D = 0$) shows that the mean cross-stream velocity is nearly zero, though downstream it appears biased towards a positive velocity. Since this was also observed in the fin only results (see Figure 57), this is likely the product of the accuracy of the centerline location rather than the influence of the fin on the mean velocity. Near the fin the velocity rapidly increases with increasing downstream distance, which could be physical as the fin should on average accelerate the flow in the positive-Y direction, but measurements near the oscillating fin can easily be contaminated with noise due to shadows and reflections. The profiles acquired away from the centerline appear to be symmetric with a peak at the end of the recirculation zone.

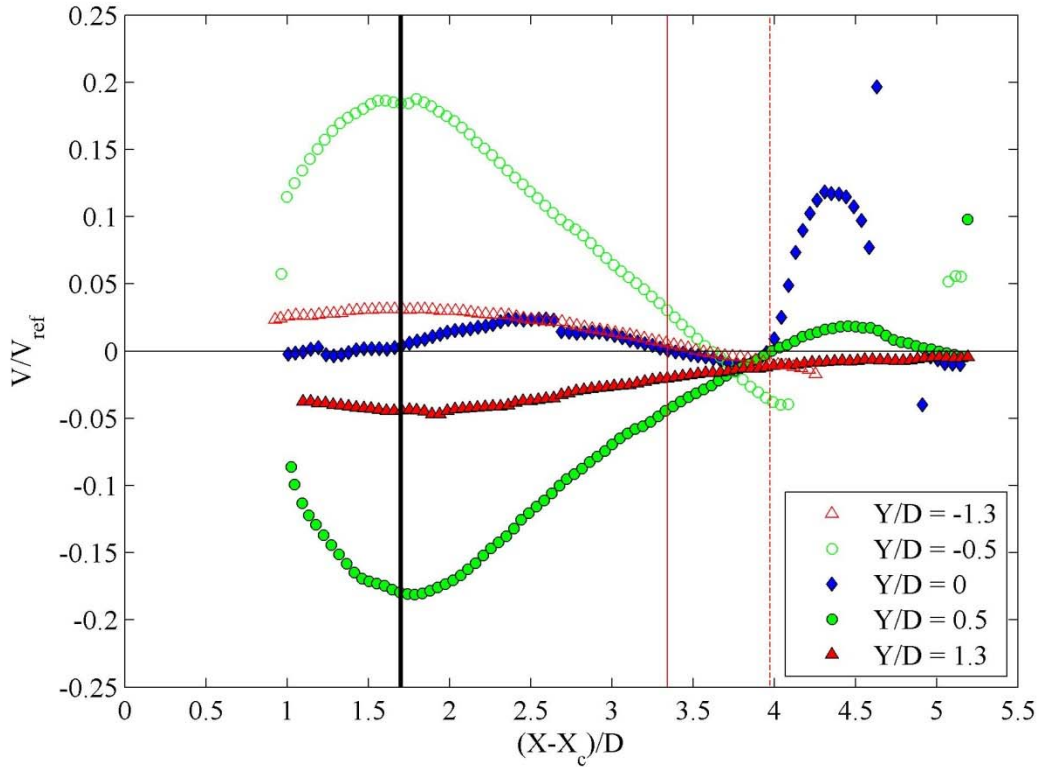


Figure 122. Mean cross-stream velocity (V) scaled with the test section reference velocity (V_{ref}) plotted versus the downstream distance (X) from the cylinder trailing edge (X_c) scaled with the cylinder diameter (D). The data shown are the average results from all conditions acquired with the fin installed in the cylinder wake (Part 4). Open symbols are from $Y/D < 0$ and closed symbols are from $Y/D \geq 0$. The solid black line represents the nominal location where the recirculation zone ends, $(X-X_c)/D = 1.7$, the solid thin red line denotes the location of the fin tip leading edge and the thin dashed red line denotes the fin leading edge at the height of the PIV plane ($Z = 188$ mm).

Figure 123 shows cross-stream profiles of the scaled cross-stream velocity component (V/V_{ref}) at several downstream locations. These results show excellent symmetry in magnitude about $Y/D = 0$. These results show that for a given downstream position the peak magnitude of V is nominally located at $Y/D = \pm 0.5$. The peak and the entire profile decreases with increasing downstream distance. The same trends were observed in Part 2b, Figure 58.

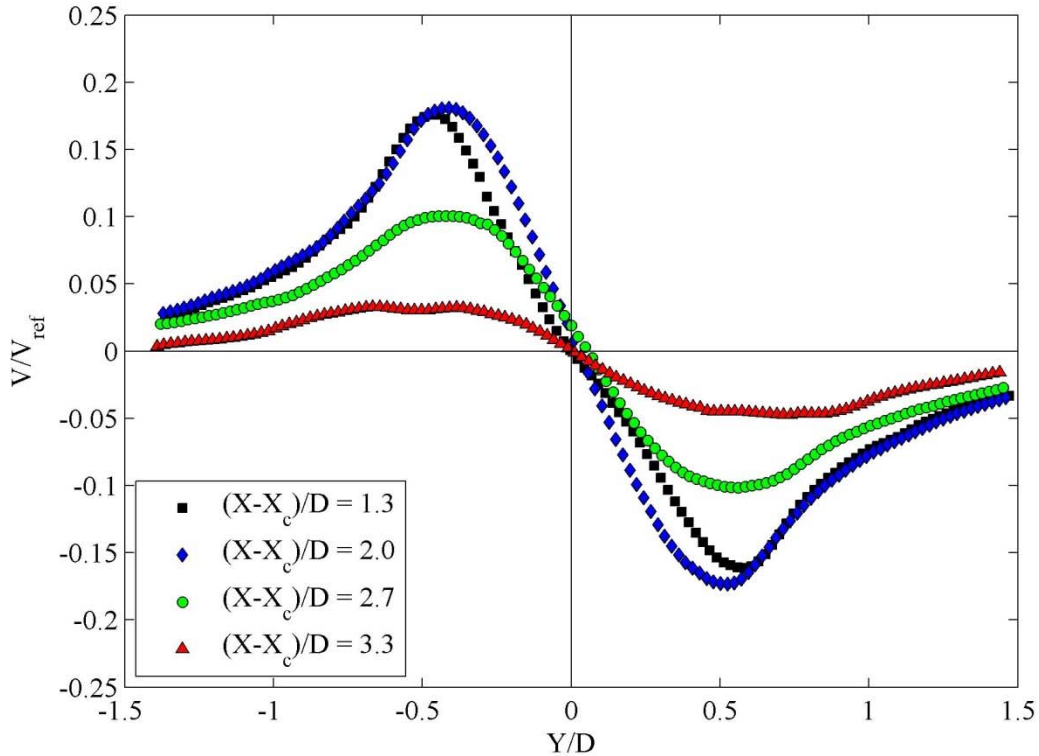


Figure 123. Scaled mean cross-stream velocity (V/V_{ref}) plotted versus the scaled cross-stream location (Y/D). The data shown are the average results from all conditions acquired with the fin installed within the rough cylinder wake (Part 4).

The mean cross-stream velocity with and without the fin installed in the wake are compared in Figure 124 and Figure 125. Figure 124 shows the scaled mean cross-stream velocity plotted versus the scaled downstream distance from the cylinder trailing edge, $(X-X_c)/D$, at $Y/D = 0, \pm 0.5$ and ± 1.3 . These results are in excellent agreement with each other except for data acquired along the tunnel centerline beyond the fin leading edge in the PIV plane. This shows that the only influence the fin has on the flow field is the cross-stream velocity near the fin location. Figure 125 shows cross-stream profiles in the near and far wake regions. Similar to the streamwise profiles, the cross-stream profiles are in excellent agreement with each other. Note that there is agreement between the two data sets even when comparing cylinder only data with $Y/D < -0.5$. This supports the earlier claim that the laser misalignment did not impact the cross-stream velocity component, but only the streamwise component.

The overall conclusion from the mean cross-stream velocity comparisons is that the fin has negligible impact on the mean cross-stream velocity component, except at the fin location where the fin causes an increase in the mean cross-stream velocity.

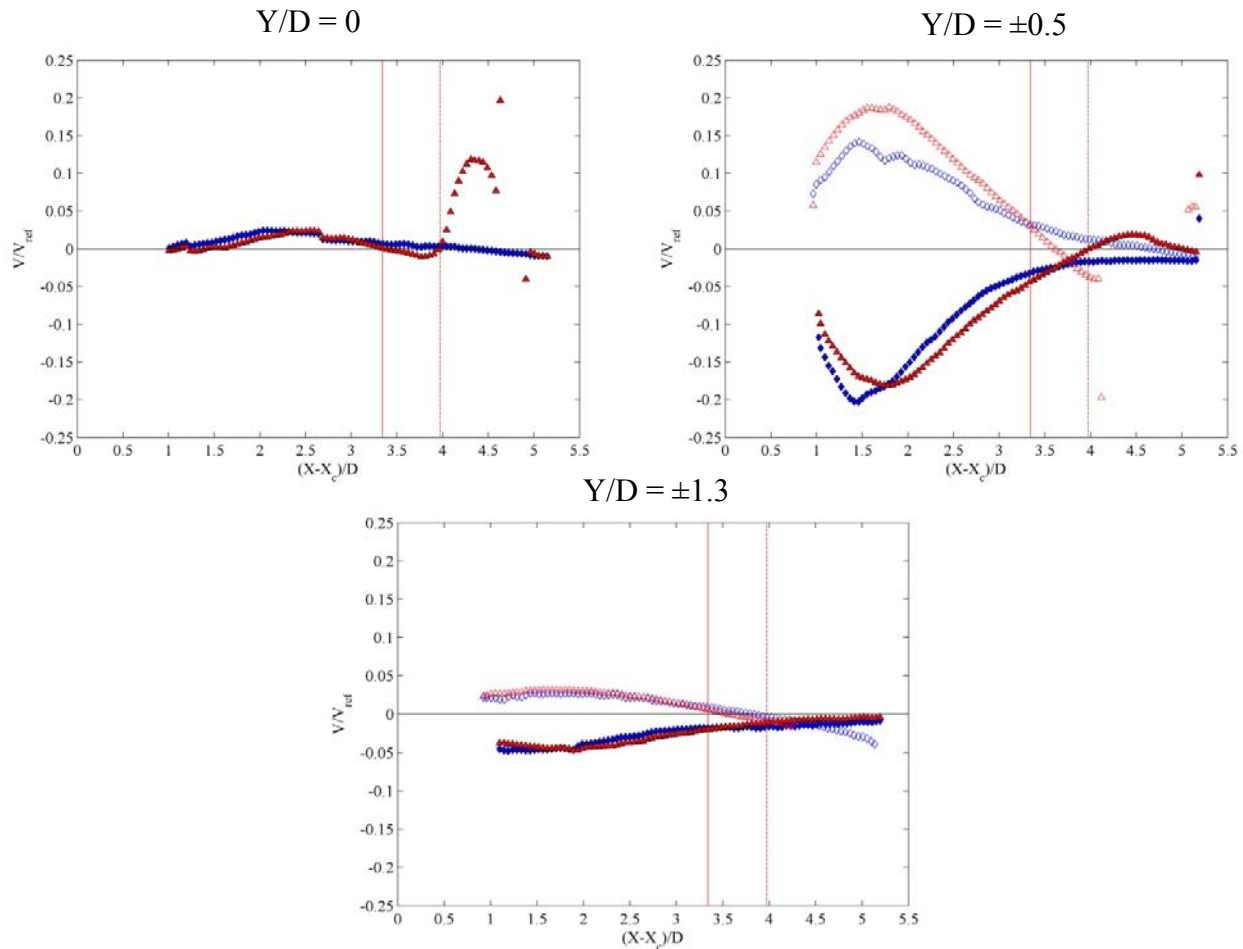


Figure 124. Comparison of the scaled mean cross-stream velocity (V/V_{ref}) with and without the fin installed in the rough cylinder wake. The data shown are the average results from all conditions from (upper left) $Y/D = 0$, (upper right) $Y/D = \pm 0.5$ and (lower) $Y/D = \pm 1.3$ plotted versus the scaled distance downstream from the cylinder trailing edge, $(X-X_c)/D$. Blue symbols are results from the rough cylinder without the fin (Part 2b) and the red symbols are with the fin installed in the rough cylinder wake (Part 4). Open symbols correspond to negative- Y locations and solid symbols are positive- Y locations. The two thin red lines downstream show the nominal locations of the fin tip leading edge and the leading edge at the PIV plane ($Z = 188$ mm).

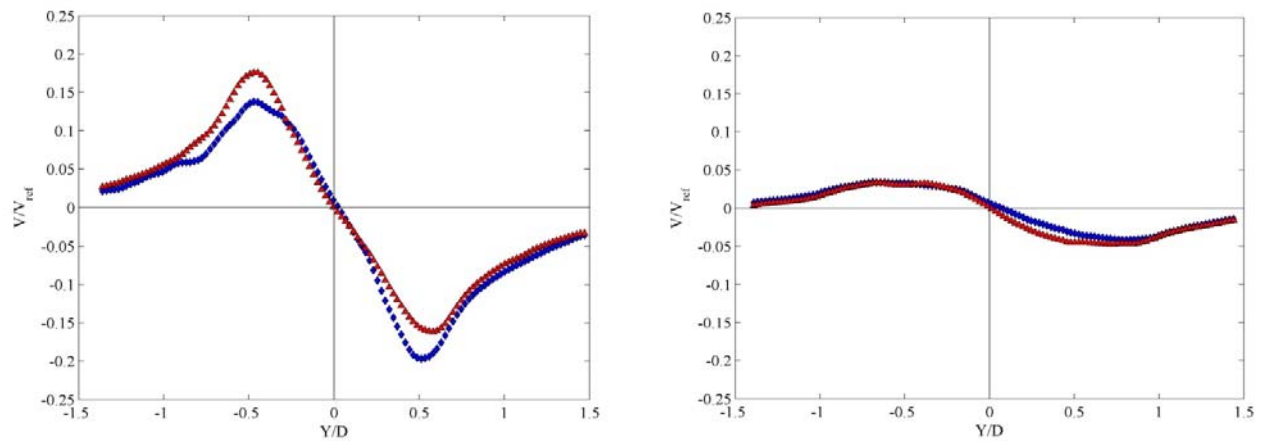


Figure 125. Comparison of the scaled mean cross-stream velocity (V/V_{ref}) with and without the fin installed in the rough cylinder wake. The data shown are the average results from all conditions from (left) the near wake region at $(X-X_c)/D = 1.3$ and (right) the far wake near the fin tip leading edge at $(X-X_c)/D = 3.3$ plotted versus the scaled cross-stream distance (Y/D). Blue symbols are results from the rough cylinder without the fin (Part 2b) and the red symbols are with the fin installed in the rough cylinder wake (Part 4).

5.7.5.2 Fluctuating velocity

Figure 126 shows the fluctuating cross-stream velocity scaled with the test section reference velocity (v'/V_{ref}) plotted versus the distance downstream from the cylinder trailing edge scaled with the cylinder diameter ($(X-X_c)/D$) with the fin installed in the rough cylinder wake (Part 4). These results are from the same Y -locations as was shown for the mean velocity profiles. The centerline profiles ($Y/D = 0$) show that the cross-stream velocity fluctuations increase with increasing downstream distance until $\sim 2.5D$ downstream of the cylinder trailing edge, which is nominally the location where the streamwise velocity ceases to increase with increasing downstream distance (at least as rapidly as observed in the near-wake region). Beyond that location, the centerline fluctuating velocity gradually decreases with increasing downstream distance. The fluctuations rapidly decrease once beyond the downstream position corresponding to the leading edge of the fin in the PIV plane. While data from this region is unreliable, this is expected given that the flow would be locally accelerating resulting in a suppression of turbulent fluctuations. There is a slight difference in magnitudes between the data at

$Y/D = \pm 0.5$, but the general trends are similar. Here the fluctuations gradually increase with increasing downstream distance until the fin leading edge is encountered. Finally the profiles from $Y/D = \pm 1.3$ show excellent agreement in the fluctuation levels independent of the downstream location. The levels show a slight increase with increasing downstream distance, but with the entire test section the fluctuations are less than 5% of V_{ref} .

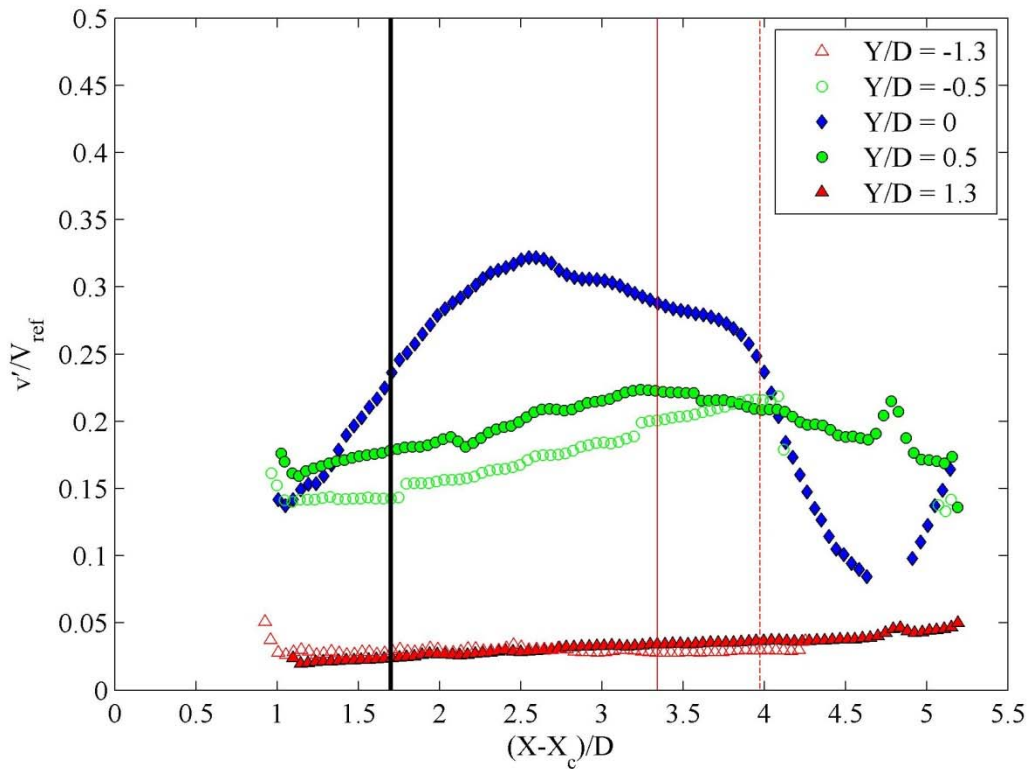


Figure 126. Fluctuating cross-stream velocity (v') scaled with the test section reference velocity (V_{ref}) plotted versus the downstream distance (X) from the cylinder trailing edge (X_c) scaled with the cylinder diameter (D). The data shown are the average results from all conditions with the fin installed in the rough cylinder wake (Part 4). The solid black line represents the nominal location where the recirculation zone ends, $(X-X_c)/D = 1.7$, the thin red lines denotes the position of the fin tip leading edge and the thin dashed red line denotes the location of the fin leading edge at the height of the PIV plane ($Z = 188$ mm).

Figure 127 provides the cross-stream profiles of the scaled fluctuating velocity (v'/V_{ref}) from the same streamwise locations as shown for the mean cross-stream velocity results. Except for the furthest upstream position, the peak in magnitude of the cross-stream velocity fluctuations is observed

on the tunnel centerline ($Y/D = 0$). The profile at $(X-X_c)/D = 1.3$ crosses the recirculation zone and has two peaks symmetric about the centerline ($Y/D = 0$). The peak initially increases with increasing downstream distance until $\sim 2.7D$ downstream of the cylinder trailing edge, which then it appears to decrease. As the peak decreases the wake widens, which is consistent with the wake dissipating with increasing downstream distance.

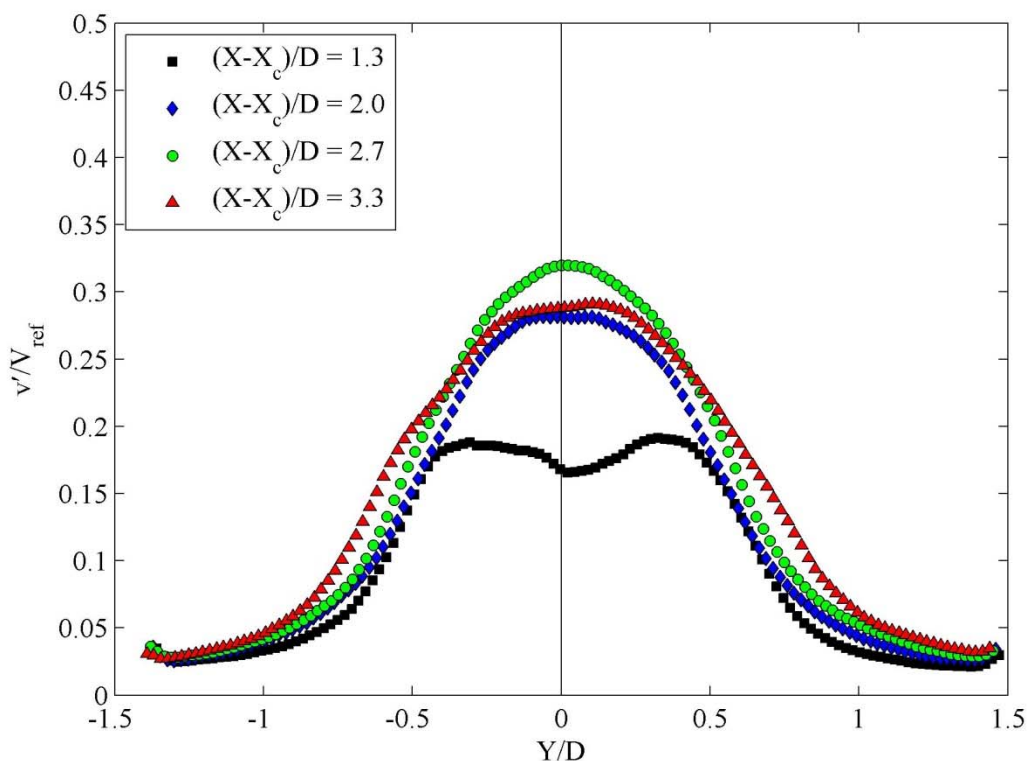


Figure 127. Scaled fluctuating cross-stream velocity (v'/V_{ref}) plotted versus the scaled cross-stream location (Y/D). The data shown are the average results from all conditions acquired with the fin installed in the rough cylinder wake (Part 4).

The fluctuating cross-stream velocity with and without the fin installed in the wake are compared in Figure 128 and Figure 129. Figure 128 shows the scaled fluctuating cross-stream velocity plotted versus the scaled downstream distance from the cylinder trailing edge, $(X-X_c)/D$, at $Y/D = 0$, ± 0.5 and ± 1.3 . These results are in excellent agreement with each other except for data acquired along the tunnel centerline beyond the fin leading edge in the PIV plane. This shows that the only influence

the fin has on the flow field is the cross-stream velocity near the fin location. Figure 129 shows cross-stream profiles in the near and far wake regions. Similar to the streamwise profiles, the cross-stream profiles are in excellent agreement with each other. Note that there is agreement between the two data sets even when comparing cylinder only data with $Y/D < -0.5$. This supports the earlier claim that the laser misalignment did not impact the cross-stream velocity component, but only the streamwise component. The overall conclusion from the fluctuating cross-stream velocity comparisons is that the fin has negligible impact on the fluctuating cross-stream velocity component, except at the fin location.

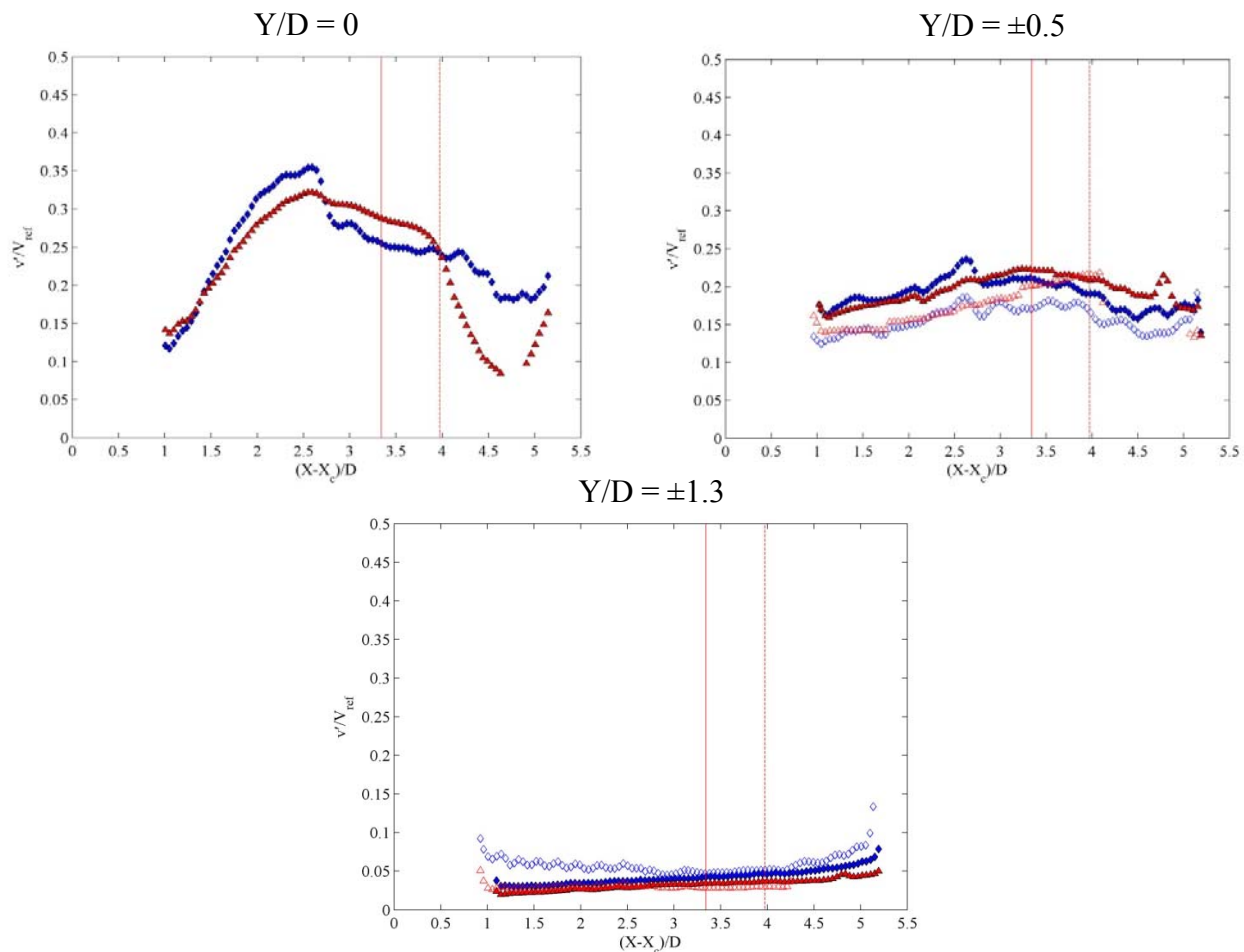


Figure 128. Comparison of the scaled fluctuating cross-stream velocity (v'/V_{ref}) with and without the fin installed in the rough cylinder wake. The data shown are the average results from all conditions from (upper left) $Y/D = 0$, (upper right) $Y/D = \pm 0.5$ and (lower) $Y/D = \pm 1.3$ plotted versus the scaled distance downstream from the cylinder trailing edge, $(X-X_c)/D$. Blue symbols are results from the rough cylinder without the fin (Part 2b) and the red symbols are with the fin installed in the rough cylinder wake (Part 4). Open symbols correspond to negative- Y locations and solid symbols are positive- Y locations. The two thin red lines downstream show the nominal locations of the fin tip leading edge and the leading edge at the PIV plane ($Z = 188$ mm).

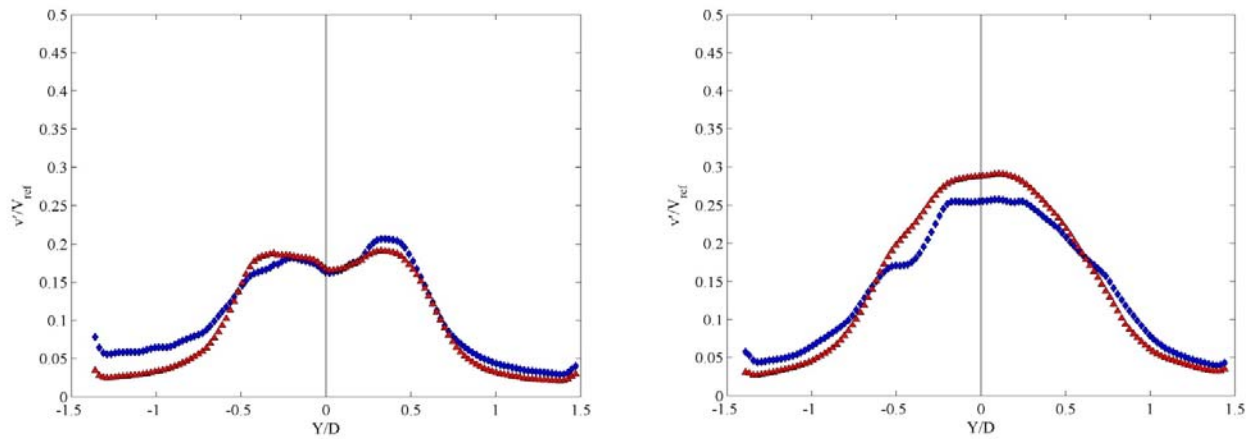


Figure 129. Comparison of the scaled fluctuating cross-stream velocity (v'/V_{ref}) with and without the fin installed in the rough cylinder wake. The data shown are the average results from all conditions from (left) the near wake region at $(X-X_c)/D = 1.3$ and (right) the far wake near the fin tip leading edge at $(X-X_c)/D = 3.3$ plotted versus the scaled cross-stream distance (Y/D). Blue symbols are results from the rough cylinder without the fin (Part 2b) and the red symbols are with the fin installed in the rough cylinder wake (Part 4).

5.7.6 Spectral results

As with the no-fin case, measurements at exactly the same location were made with the fin installed. Spatial autocorrelations of the x - and y - component of velocity were obtained without the fin installed for three tunnel velocities (2.50, 2.99 and 3.61) m/s and are displayed as two contour plots in Figure 130, Figure 131 and Figure 132. The general shape is similar between the velocities although the levels increase with velocity squared as expected.

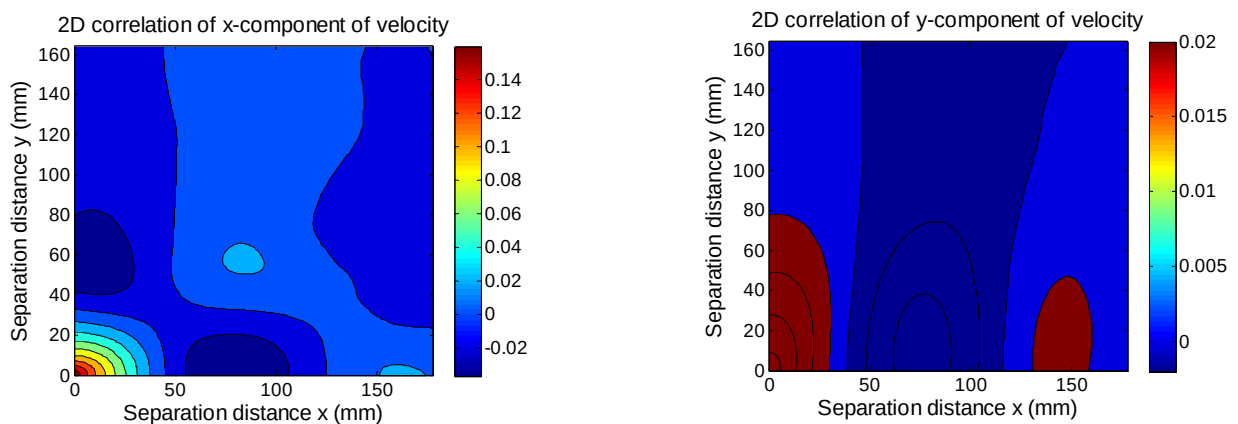


Figure 130. Spatial auto correlation for x - and y - components of velocity with fin, $V_{ref}=2.50$ m/s. (Run 42-5) The units of the contours are $(m/s)^2$.

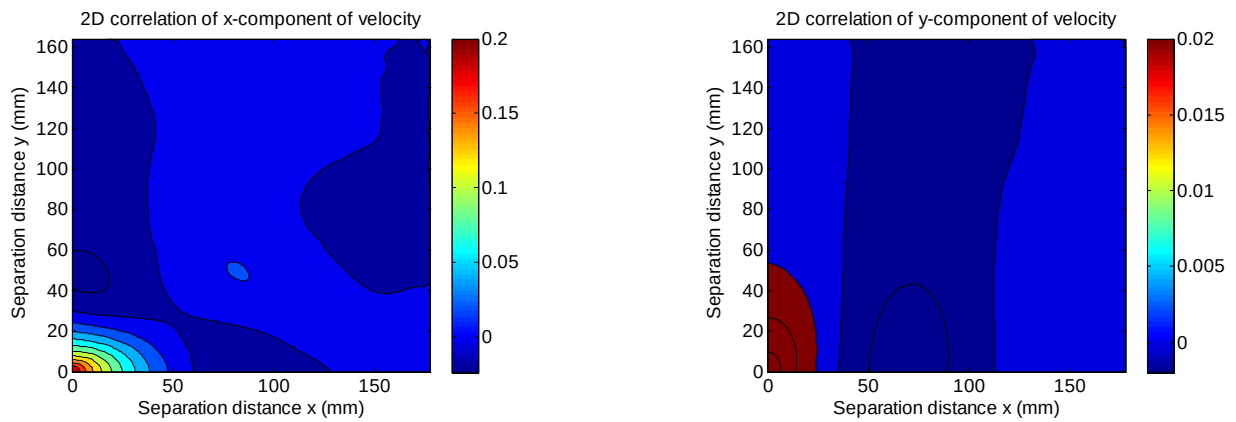


Figure 131. Spatial auto correlation for x- and y- components of velocity with fin, $V_{ref}=2.99$ m/s. (Run 75-48) The units of the contours are $(\text{m/s})^2$.

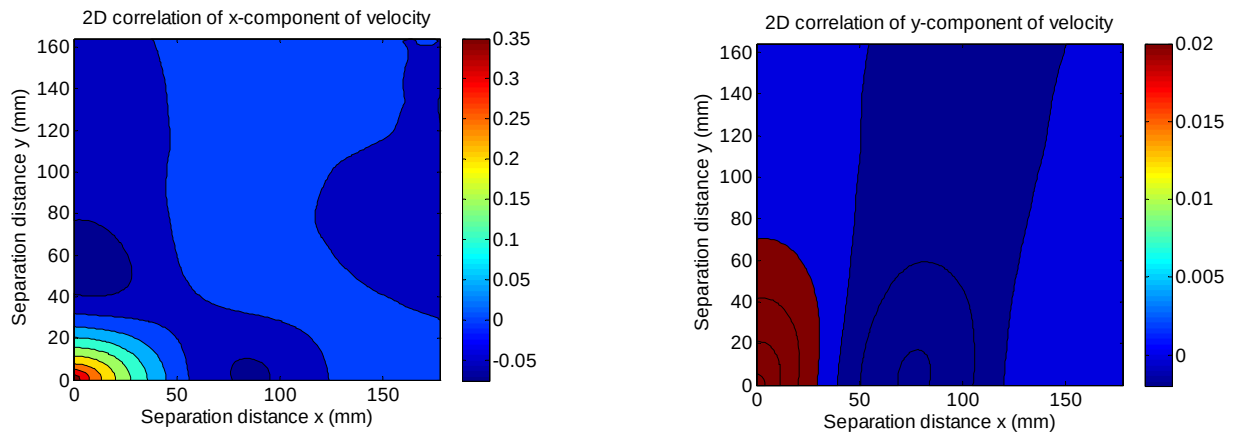


Figure 132. Spatial auto correlation for x- and y- components of velocity with fin, $V_{ref}=3.61$ m/s. (Run 75-14) The units of the contours are $(\text{m/s})^2$.

Figure 133 shows normalized autocorrelation cuts along the x- and y- axes. The plots on the left-hand side are the x- and y- components of velocity as a function of x-direction separation distance. The plots on the right-hand side are the x- and y- components of velocity as a function of y-direction separation distance. For three of the curves within Figure 133 the correlations have an oscillating character typical of the shedding of the cylinder, however the variation of the y-component of velocity in the y-direction shows a monotonically decreasing trend with no oscillation. Because the ordinate is normalized by the variance of the velocity and the predominant flow structure is based on a 60 mm diameter cylinder, it is not surprising that all four plots on Figure 133 collapse.

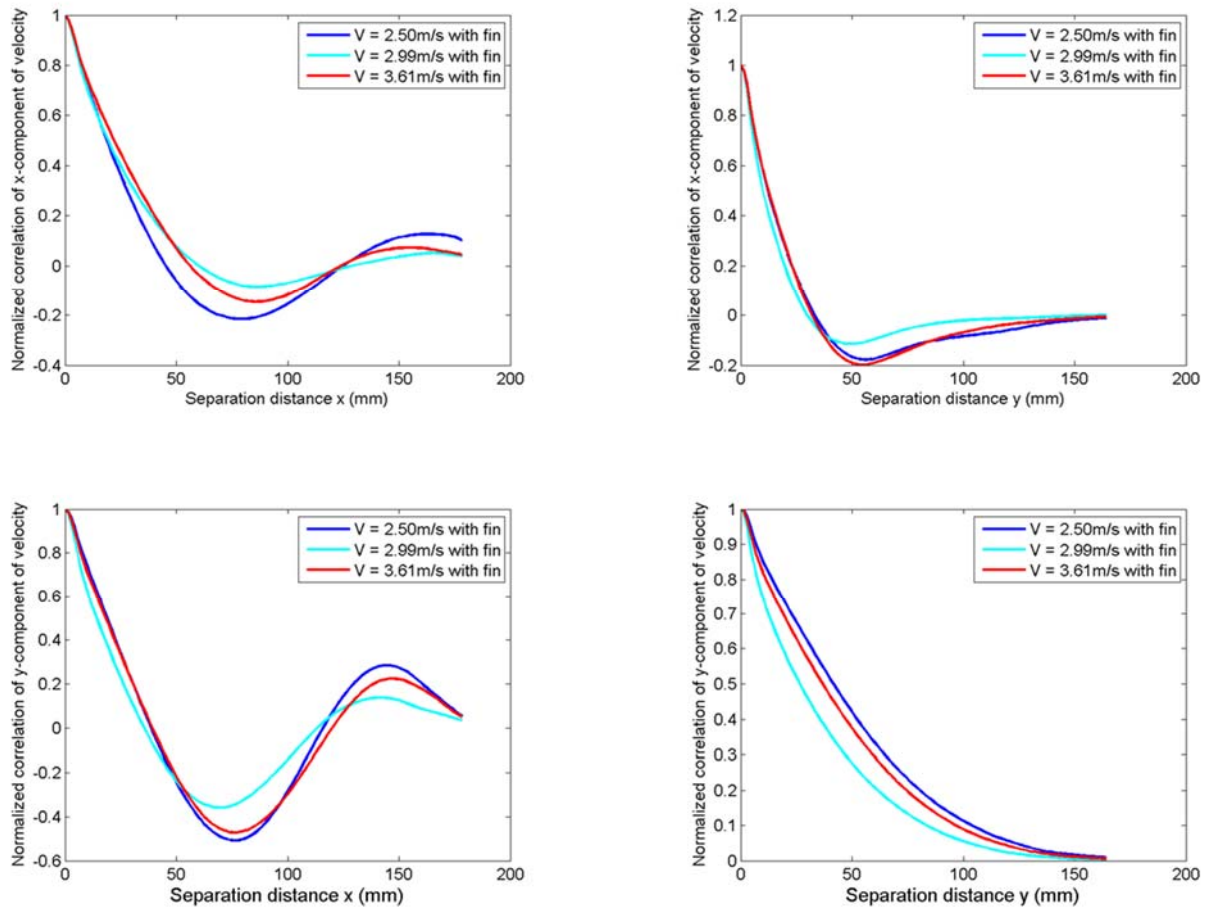


Figure 133. Comparison of velocity correlations with fin along x - and y - axis for x - and y - components of velocity.

Figure 134, Figure 135 and Figure 136 show the corresponding wavenumber spectra for the x - and y - component of velocity for the three reference velocities. As was discussed for the cylinder only section, the cylinder wake contains a mean deficit due to the cylinder drag and fluctuations due to the shedding from both sides of the cylinder. For the shedding, the flow becomes non-uniform and nearly periodic both spatially and temporally. In past sections the temporal aspect was analyzed by showing typical flow velocity, cylinder vibration and pressures levels as a function of time. The plots in this section show the spatial variation of the flow. For the streamwise and transverse velocities components we can show how these quantities in an average sense vary in the streamwise direction (separation distance x) and the corresponding variation in the transvers direction (separation distance y). Analogous the frequency spectrum, the wavenumber is computed both in the streamwise direction (k_x)

and the transverse direction (k_y). We can see from the wave number plots, that the streamwise velocity component has wavenumber peak k_{xpeak} and k_{ypeak} associated with the wavelength of the cylinder shedding. We can see this by examining the red blob is centered 45 degrees from the k_x axis. In hindsight it would have been good to resolve the actual k_{xpeak} and k_{ypeak} better. To do this, the PIV window would need to be much larger so several wavelength could be captured. In contrast, the wavenumber spectrum of the transverse velocity component is has only k_{xpeak} and no k_{ypeak} . An inkling of fact is evidence from contrasting the sinusoidal nature of the velocity correlations shown in left versus right figures in Figure 133.

The corresponding wavenumber level for the y-component of velocity is on the k_x axis. This explains the monotonically decreasing trend for the bottom right curve in Figure 133. To add additional quantitative detail, the line curves are provided below the contour plots to show the spectral levels along the k_x axis for various constant k_y values.

Comparing the results of the forced fin case (Part 4) to the roughened cylinder only case (Part 2b), we see negligible differences. This is not surprising since the flow being measured here is upstream of the fin, and there appears to be no feedback mechanism at play.

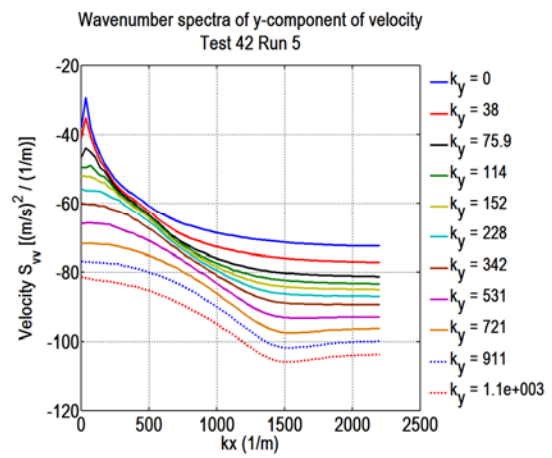
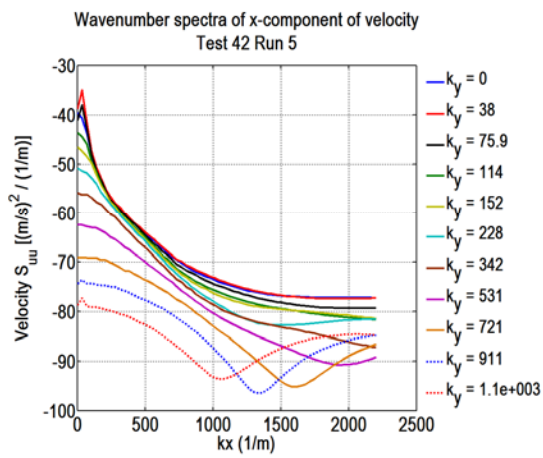
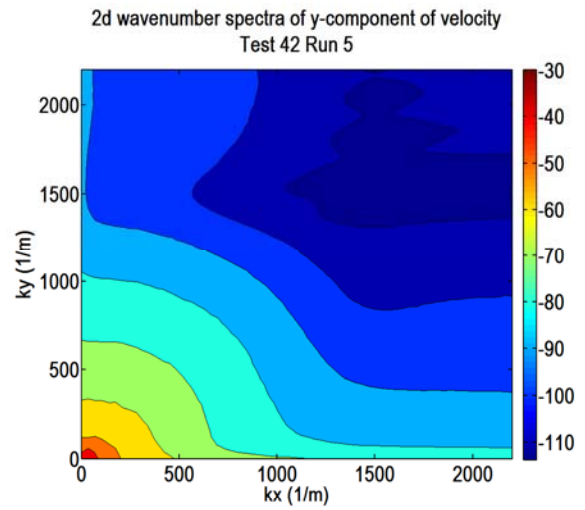
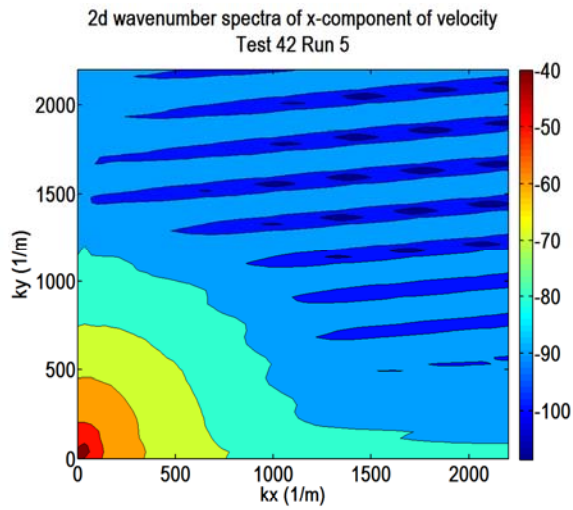


Figure 134. Wavenumber spectra for no fin for $V_{ref}=2.50$ m/s (Run 42-5). The bandwidth along k_x is 35.1 m^{-1}

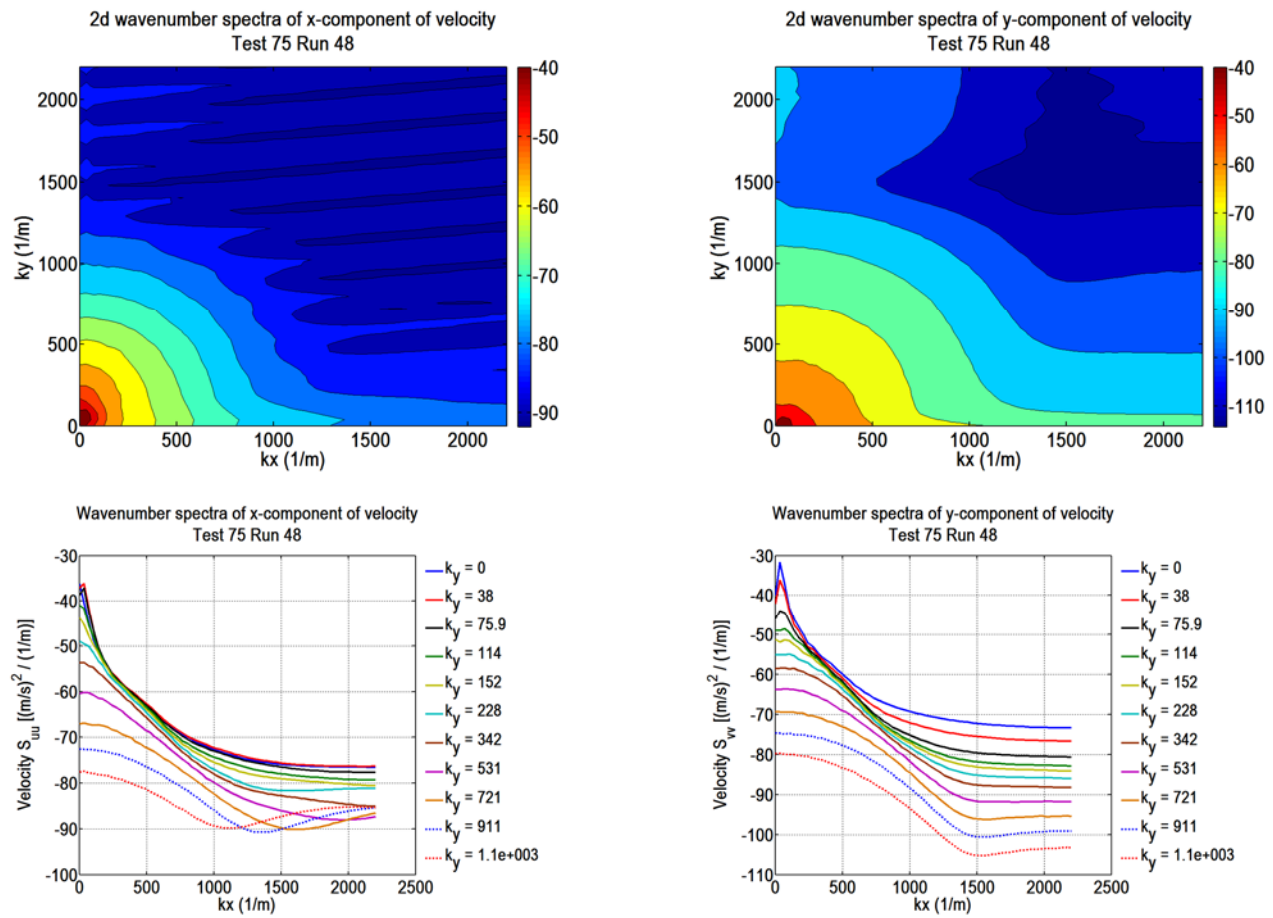


Figure 135. Wavenumber spectra for no fin for $V_{ref}=2.99$ m/s (Run 75-48). The bandwidth along k_x is 35.1 m^{-1}

Comparing the results of the fin case to the no-fin case we see negligible differences. This is not surprising since the flow being measured here is upstream of the fin and there appears to be no feedback mechanism at play.

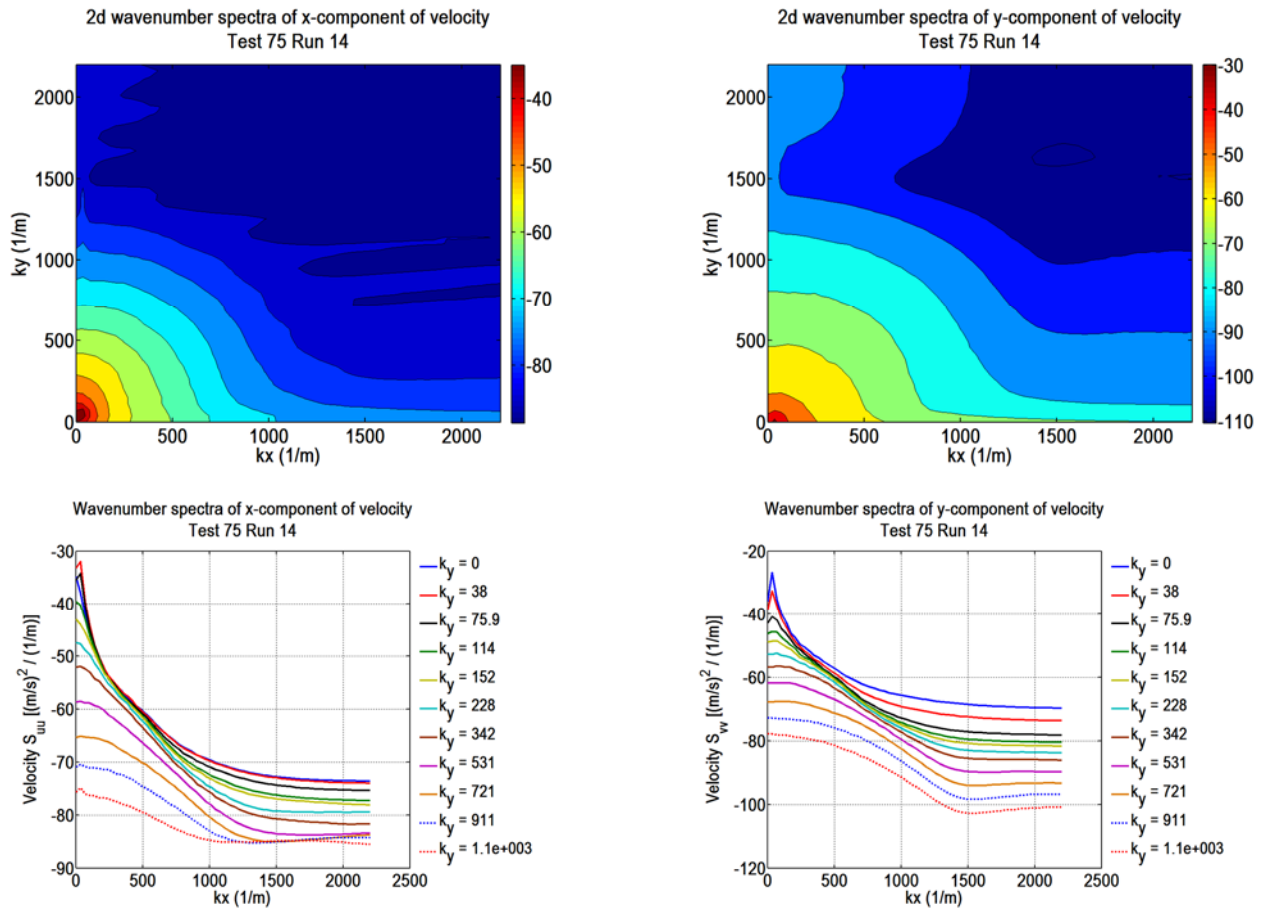


Figure 136. Wavenumber spectra for no fin for $V_{ref}=3.61$ m/s (Run 75-14). The bandwidth along k_x is 35.1 m^{-1}

5.8 Synchronous Measurements

5.8.1 Time trace

During testing, three independent data acquisition systems were used to make the primary measurements. These measurements included (i) load cell force and moments, (ii) flow-field/fin tip imaging and (iii) dynamic signals (i.e. dynamic pressure, accelerometers and laser vibrometry signals). The dynamic signals were not synchronized with the other two systems, though other signals of interest were simultaneously recorded with the dynamic signals. The load cell data acquisition system also recorded the tunnel operating conditions (total and static pressure, water temperature, impeller frequency), cylinder static pressure and fin monitoring (angle-of-attack and optical switch). The

imaging data acquisition system acquired the high-speed-video focused on the fin tip and the high-speed PIV measurements. The load cell and imaging systems were synchronized by having the load cell data acquisition system also record the triggering signal for the high-speed camera. This allows the time trace signals from any of these measurements to be directly compared. A representative synchronized time trace from 3.4 m/s of the lift force and fin tip deflection are shown in Figure 137. In this figure the lift and tip deflections have been normalized by their maximum magnitudes, which were 63.3 N and 7.14 mm, respectively. During this test run (Test 20 – Run 7) the lift force fluctuated between -63.3 N and 52.1 N, and the fin tip deflection fluctuated between -7.14 mm (3.1% of the span) and 4.86 mm (2.1% of the span). This time trace shows that the two signals are in-phase with each other, which is expected since the fluid-loading causes the fin motion that results in the strains measure by the load cell. In addition, the normalization shows that their relative amplitudes are also in excellent agreement with both showing a bias towards negative values.

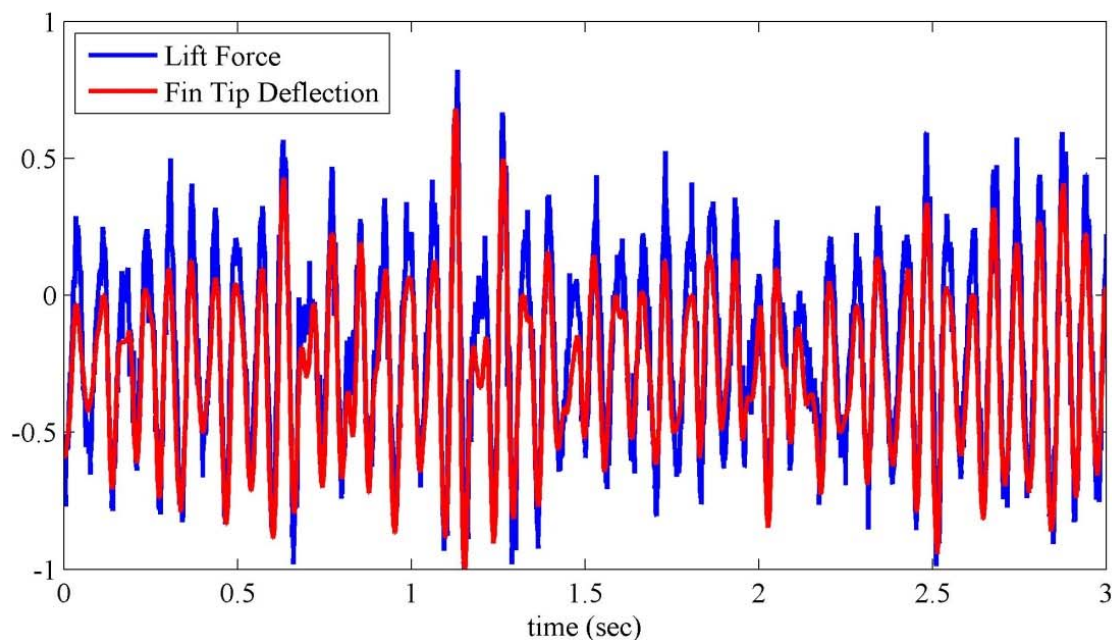


Figure 137. Representative time trace of the normalized lift force and fin tip motion. This was acquired from a single test run (Test 20 – Run 7) at a test section reference velocity of 3.4 m/s. The measurements were acquired with two independent acquisition systems, which were synchronized by recording the triggering signal from the fin tip imaging system with the load cell data acquisition system.

5.8.2 General Trends

Synchronized time traces of the load cell data (lift, drag, torque and drag moment), fin tip motion (deflections and twist) and the flow-field upstream of the fin are available for several test conditions. Ideally the relationship between these individual signals would be investigated by looking at the phase and coherence between the two signals. The phase can be determined by taking the inverse tangent of the ratio of the imaginary part to the real part of the cross-spectrum between two of the synchronized signals, and the coherence is the normalized cross-spectrum. However, the relatively short duration of the imaging data (fin tip motion and flow-field) limits the accuracy of this approach. Consequently, a crude method is used here to show the basic trends in the data. Here all the data is plotted as a function of the lift force. Due to the uncertainty in both the measurement of interest and the lift force measurement, these plots tend to be quite noisy and difficult to identify the trend. Thus to minimize the influence of random error on the trends, the results shown are averaged based on the corresponding lift force measurement. The lift force range (-80 N to 60 N) was divided into 100 bins, each 1.4 N wide. Then all the measurements of interest (e.g. drag, torque, fin deflection, etc.) were placed in the corresponding bin based on synchronized lift measurements. The average from each bin was then plotted with a minimum of 10 samples required to be included in the plot. However, the majority of points shown had between 100 and 1000 samples included in the average. Note this averaging was done independent of the given tunnel velocity.

Figure 138 shows the averaged drag, drag moment and torque plotted versus the lift force. In the plot, the moment measurements (drag moment and torque) have been multiplied by a factor of 10 in order to make the trend more apparent when plotted along with the drag measurement. Here we see that the drag, torque and drag moment all are inversely related to the lift force (i.e. positive lift force results in a negative loading and a negative lift force results in a positive loading). The drag is known to be out-of-phase with the lift force, which explains why the drag force and the drag moment are

inversely related. Due to the coordinate system used a positive torque would rotate the fin counterclockwise when looking from above, and a counterclockwise rotation occurs when a negative lift force is applied at the fin tip. Hence, it is also expected that the torque and lift force would be inversely related. All four loads intersect at a single point, but it is not exactly at zero lift and zero loading as expected. This is an indication that there was a small bias error in the loading measurements.

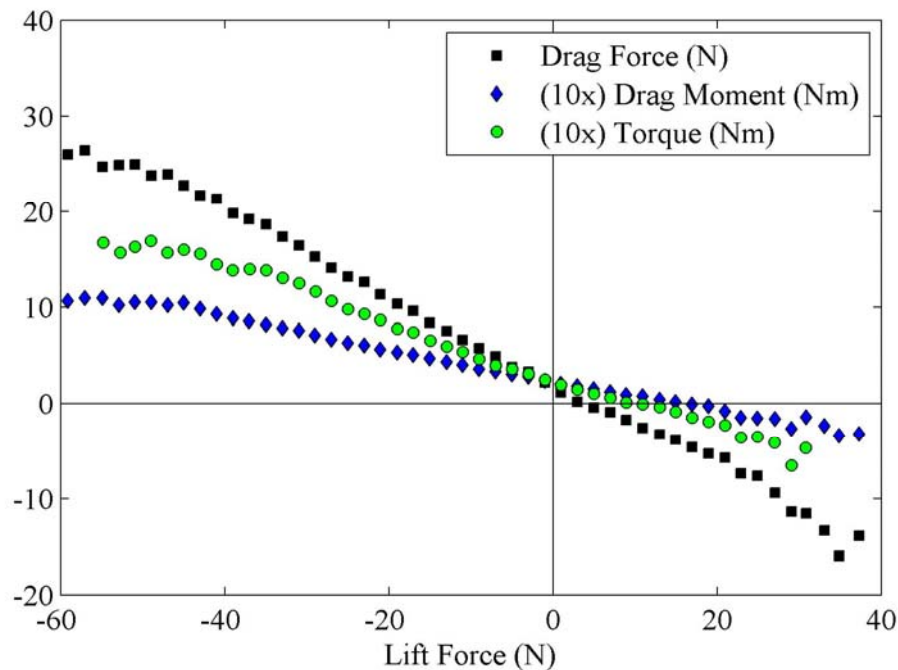


Figure 138. The average constraint loading (drag, drag moment and torque) plotted versus the average lift force. Averaging was done based on the given lift force measurement. The moments have been multiplied by a factor of 10 to help show the relative trends.

The average fin tip deflections and fin tip twist are plotted versus the lift force in Figure 139. The twist measurements in degrees have been multiplied by a factor of 10 to make the trend more apparent when plotted with the fin tip deflection in millimeters. Here the fin tip deflection is directly proportional to the lift force while the fin tip twist is inversely related to the lift force. It is expected that the lift force and fin tip deflection would be in-phase since the sign of the deflection and lift are defined in the same manner and the fin tip deflection causes strains in the load cell, which is how the lift force is measured. It might seem unexpected that the zero fin tip deflection does not occur at zero

lift force, but due to the negative angle-of-attack the fin has a negative mean deflection. Thus the zero lift force has a negative fin tip deflection on average. Note that this averaging was done independent of the given tunnel flow velocity, but the average zero-lift fin tip deflection is velocity dependent. Hence, these plots are qualitative in nature and not quantitative. The inverse relationship for the twist is for the same reason that the torque is inversely related (i.e. positive twist results in a counterclockwise fin tip rotation, which occurs when a negative lift force is applied to the fin tip). Overall, this shows that for the majority of tests the fin tip experienced minimal twist, and even in the most extreme lift loading the twist was $\sim 0.4^\circ$.

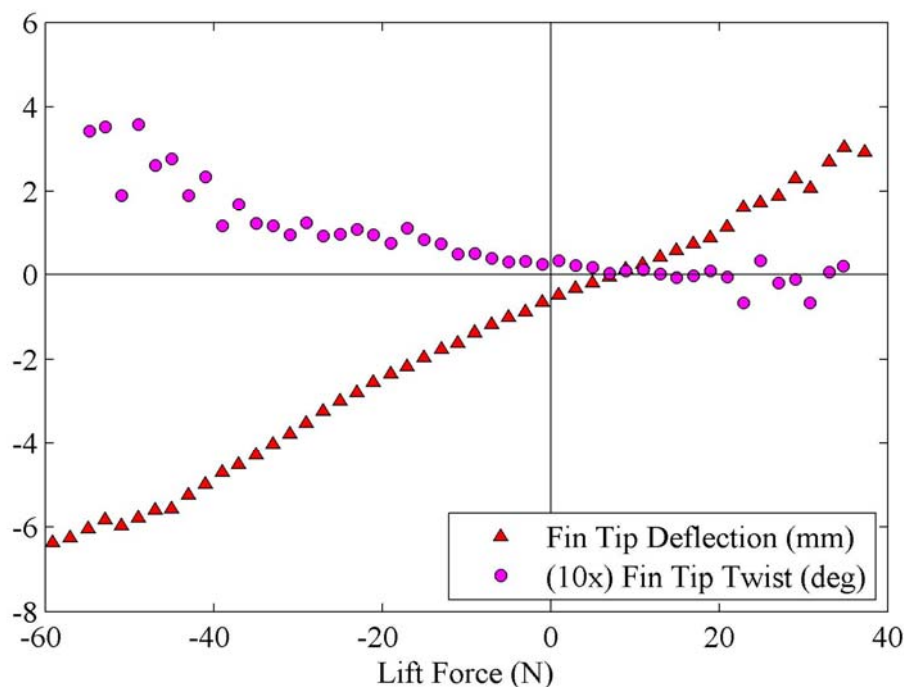


Figure 139. The average fin tip deflection and fin tip twist plotted versus the average lift force. Averaging was done based on the given lift force measurement. The twist measurement in degrees was multiplied by a factor of 10 to help show the relative trends (i.e. maximum average twist was $\sim 0.4^\circ$).

To make a qualitative assessment of the high-speed PIV results, time traces were extracted from all the test conditions at a single point. Ideally the point would be near the fin surface, but the closer the measurements are to the fin surface the larger the measurement uncertainty due to the fin motion and the resulting shadows and reflections it generates. Consequently, a point further upstream

from the fin was selected ($X = 260$ mm, $Y = 0$ mm), and these results are plotted versus the lift force in Figure 140. The streamwise velocity is nearly constant over the lift force range tested, but there appears to be some evidence that the curve if extended would make a U-shape. This would be expected since at higher streamwise velocities the cross-stream velocity fluctuations should also increase, which would result in lift load oscillating over a wider range (i.e. the extreme negative and positive load values are most likely to occur at higher tunnel velocities). The cross-stream velocity shows an inverse relationship with the fin lift force, and passes through the origin (i.e. no lift force when the cross-stream velocity is zero). While it is expected that the trend would pass through the origin, it is counterintuitive that it would have an inverse relationship because the cross-stream velocity component is the fluid-loading source aligned with the lift force measurement. The reason for this unexpected result is that the point selected is upstream of the fin. The given point is approximately 20 mm upstream of the fin tip leading edge, and approximately 58 mm upstream of the leading edge in the PIV plane ($Z = 188$ mm). Thus a fluid particle at the PIV measurement would have to convect 83 mm downstream to be at the 50% chord position in the PIV plane. To check the validity of this estimate, the PIV results were compared to the lift force measurement in Figure 141, but this time the PIV time trace was shifted ahead to estimate when the measured fluid particle would impact the fin. Here the number of images shifted forward in the PIV time trace was equal to the data acquisition rate (1,000 Hz) multiplied by the distance traveled (83 mm) and divided by the convection velocity, which was approximated by taking the average streamwise velocity for the given run. While the streamwise velocity shows minimal variation from Figure 140, the cross-stream velocity shown in Figure 141 is now directly proportional to the lift force as expected.

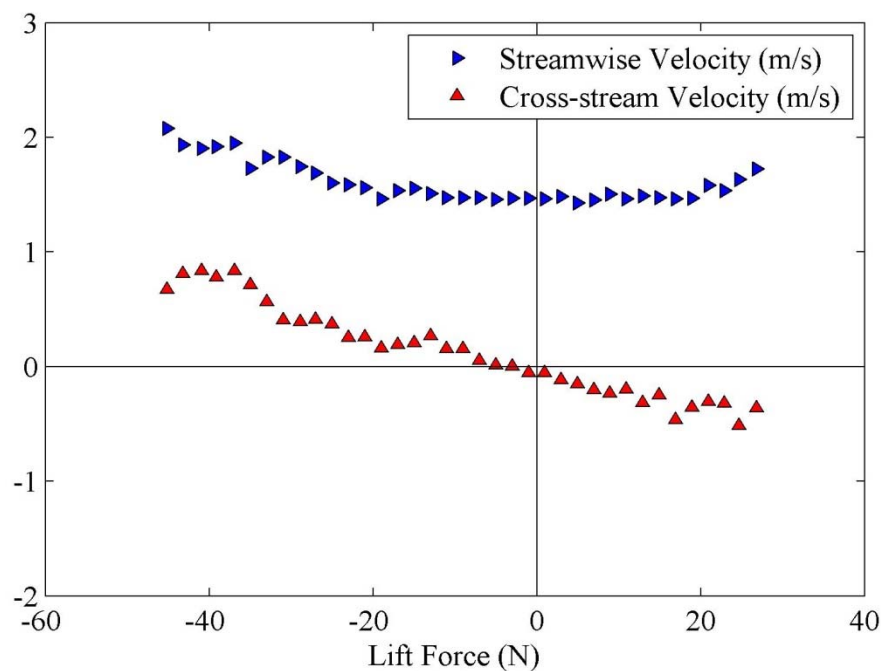


Figure 140. The average streamwise (U) and cross-stream (V) velocity measured with the high-speed PIV plotted versus the average lift force. Averaging was done based on the given lift force measurement. The velocity time traces were extracted from a single point in the plot ($X = 260$ mm, $Y = 0$ mm).

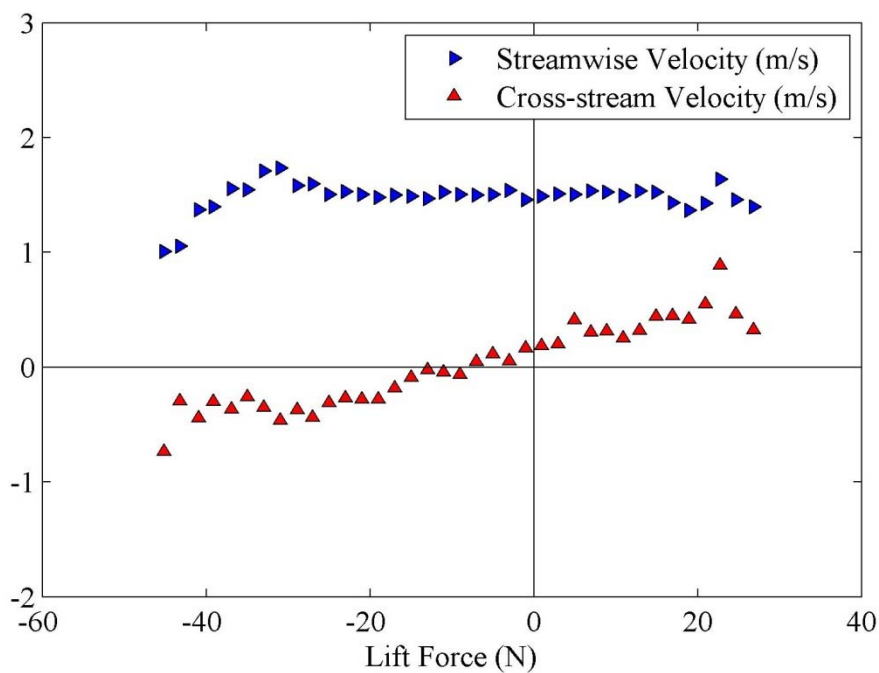


Figure 141. The same data as shown in Figure 140, but the time trace signal has been shifted such that the measurement point ($X = 260$ mm, $Y = 0$ mm) would have convected to the fin location within the PIV plane ($Z = 188$ mm).

6 Summary

The second phase of the Defense Advanced Research Projects Agency's (DARPA)'s Hybrid Multi-Material Rotor (HMMR) program focused on conducting a validation-quality fluid-structure-interaction (FSI) experiment in the Pennsylvania State University Applied Research Laboratory (ARL) 12-inch diameter recirculating water tunnel. The goal of the experiment was to produce and accurately measure the low-frequency, high-amplitude structural motion of a fin exposed to an unsteady flow induced forcing function. The resulting dataset would provide an open-source reference that could be used for development and validation of FSI codes. The test model consisted of a generically designed fin mounted downstream of a 60 mm diameter circular cylinder spanning the entrance of the tunnel test section. The fin model consisted of a 230 mm span by 50 mm chord NACA 4408 foil incorporating an aft sweep starting at the 50 % span location and terminating with a 75 mm displacement of the fin at 100% span. The fin was oriented in a reverse flow configuration to simulate a propeller crashback type event. Forced fin testing was conducted with a fin angle of attack of -10 degrees.

The experimental plan was divided the testing into three parts; (Part 1) empty test section, (Part 2) cylinder only, and (Part 4) fin and cylinder or forced fin testing. This protocol provides the stepwise test characterization needed in a validation type program. The fin only tests were removed from the test plan due to time constraints. The empty test section configuration was performed to provide inlet conditions for computational models. The cylinder only testing was required to confirm the required CFD models to produce the oscillatory flow-field experienced by the fin. This part of testing was done twice, first with a smooth cylinder (Part 2a) and then with the cylinder leading edge roughened (Part 2b). The forced fin testing (Part 4) produced a rich dataset that includes synchronized measurements of the fin loading (lift, drag, torque and drag moment), time-resolved velocity field spanning from one diameter downstream of the cylinder to beyond the fin and the fin tip motion (deflections and twist).

The objective of this document was to summarize the experimental test program in detail including discussion of the measurements that were acquired and presentation of key observations produced from the dataset. This test report is one component of the validation data set providing the details necessary 1) properly set up a computational model of the test to be used in a model-the-test protocol and 2) allow proper comparisons between the experiment and any FSI code results obtained. Along these lines, the experimental data set also includes tunnel operating conditions such as reference velocity, fluid properties, a detailed description of where measurement were made and how they were made, and the normalizing protocols used in the data analysis and presentation. This report is a necessary compliment to the released data set.

The bare tunnel tests (Part 1) confirmed a near zero pressure gradient flow in the region of interest within the test section. The axial velocity variation along the test section was found to be nearly zero with measured free stream velocity variation of less than 1% with axial displacement along the test section. Cross plane LDV profiles quantified a symmetric flow field in the tunnel with tunnel wall boundary layers that qualitatively follow expected trends for development in a zero pressure gradient flow. Typical tunnel wall boundary layers ranged from ~ 6 mm to ~ 15 mm over the test conditions set in this program. Measured tunnel wall boundary layers all showed excellent collapse when scaled on outer variables exhibiting the expected $1/7^{\text{th}}$ power law profile for a zero pressure gradient, moderate Re turbulent boundary layer. The LDV measurements also showed that the empty test section turbulence level was $\leq 0.3\%$.

The cylinder only tests were comprised of two test series, a smooth wall cylinder (Part 2a) and a rough-walled cylinder (Part 2b). The initial focus of the test program was to use a smooth walled cylinder to generate the unsteady forcing flow driving the downstream fin performance. However, the velocity conditions necessary to produce the desired unsteady fin forcing, fin displacement and driving frequency of the cyclic forcing function put the cylinder Reynolds number in the transitional regime. This created an unsteady flow separation on the cylinder that was unable to generate the fin load levels

required to produce the designed maximum tip deflections ($\pm 3.5\%$ span). The leading edge of the cylinder was roughened to provide a control transition and stabilize the shedding frequency over the range of flow conditions of the test. The measured Strouhal shedding frequencies scaled with a nearly flat Strouhal number of ~ 0.26 . Detailed mean and unsteady flow mapping characterizing the cylinder wake, including spanwise and streamwise, development are available. Analysis of the spectral content of the unsteady flow shows good agreement with the shedding frequency of the upstream cylinder as expected. This detailed quantification of the flow behavior downstream of the cylinder provides the necessary un-steady inflow characterization driving the unsteady fin performance.

The final test configuration (Part 4) involved quantifying the unsteady fin behavior and proximal flow field generated by the unsteady inflow forcing function by the upstream cylinder. Early forced fin tests included a mechanical stop with the fin at multiple angles of attack to determine the extent of fin tip deflections and protect the fin from any immediate fatigue failure. The repeatability of the fin lift force measurements was investigated during these early tests, and the variability in the fluctuating fin RMS lift force was determined to be 16.69 ± 0.43 N ($\pm 2.6\%$) for a shedding frequency of 13.67 ± 0.02 Hz ($\pm 1.5\%$) measured at a reference velocity of 3.10 ± 0.02 m/s ($\pm 0.6\%$). These results showed the mechanical stop and fin angle-of-attack had minimal effect on the fluctuating fin lift forces at the shedding frequency, providing confidence in the repeatability of the fluid loading and accuracy of the measurements. With the mechanical stop removed and the fin angle-of-attack set to approximately -9.6 degrees, fin tip deflections ranging from -4.2% to 2.6% of the fin span (6.8% peak-to-peak) were measured with high-speed video from 3.4 to 3.6 m/s, which is in good agreement with the design deflection of $\pm 3.5\%$ span. A comparison of the fin tip deflections measured independently by the high-speed video and laser vibrometer systems over a 3-second time window at 3.4 m/s produced RMS values of 2.086 and 2.078 mm (within 1%), respectively. In addition to tip deflection, tip twist was also measured and only varied from ~ 0.1 degree to ~ 0.3 degrees over the test range of conditions. Comparisons of the roughened cylinder dynamic pressures and computed RMS lift force

levels at the shedding frequency with and without the fin installed were very comparable, indicating the presence of the fin had no significant impact on the cylinder induced fluctuations in the near-wake region. Detailed flow-field quantification was performed using PIV in a similar manner to the cylinder only tests and showed the presence of the fin had minimal impact on the mean and fluctuating streamwise and cross-stream velocity components, indicating that the fin motion had negligible feedback on the cylinder flow.

This report details a comprehensive experimental study of the forced vibration of a fin for FSI modeling. In addition to this document, DVD's are available that include measured and processed data, as described in this detailed test report, and CAD files of the tunnel test section and fin assembly required for proper computational modeling of the experiment.

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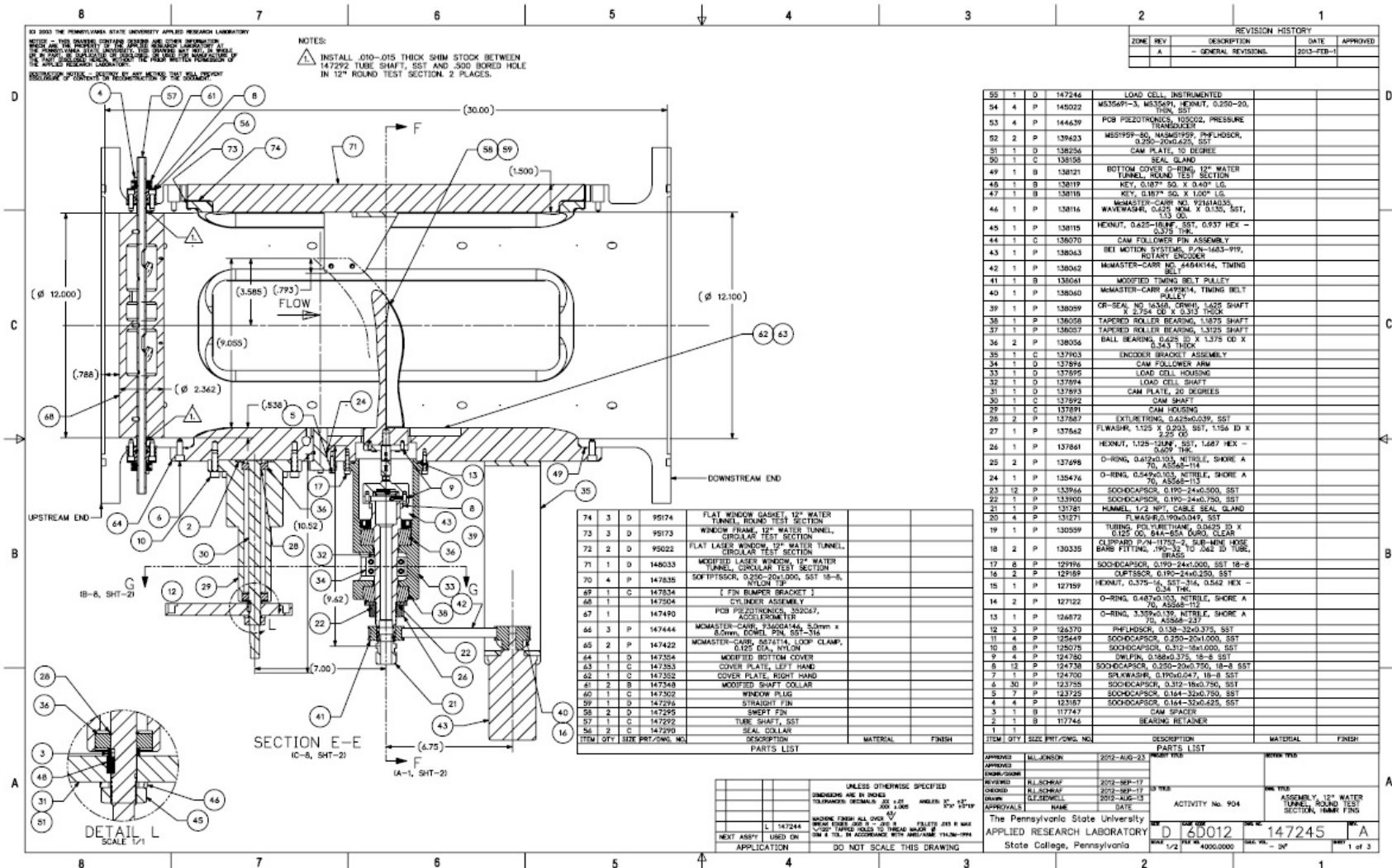
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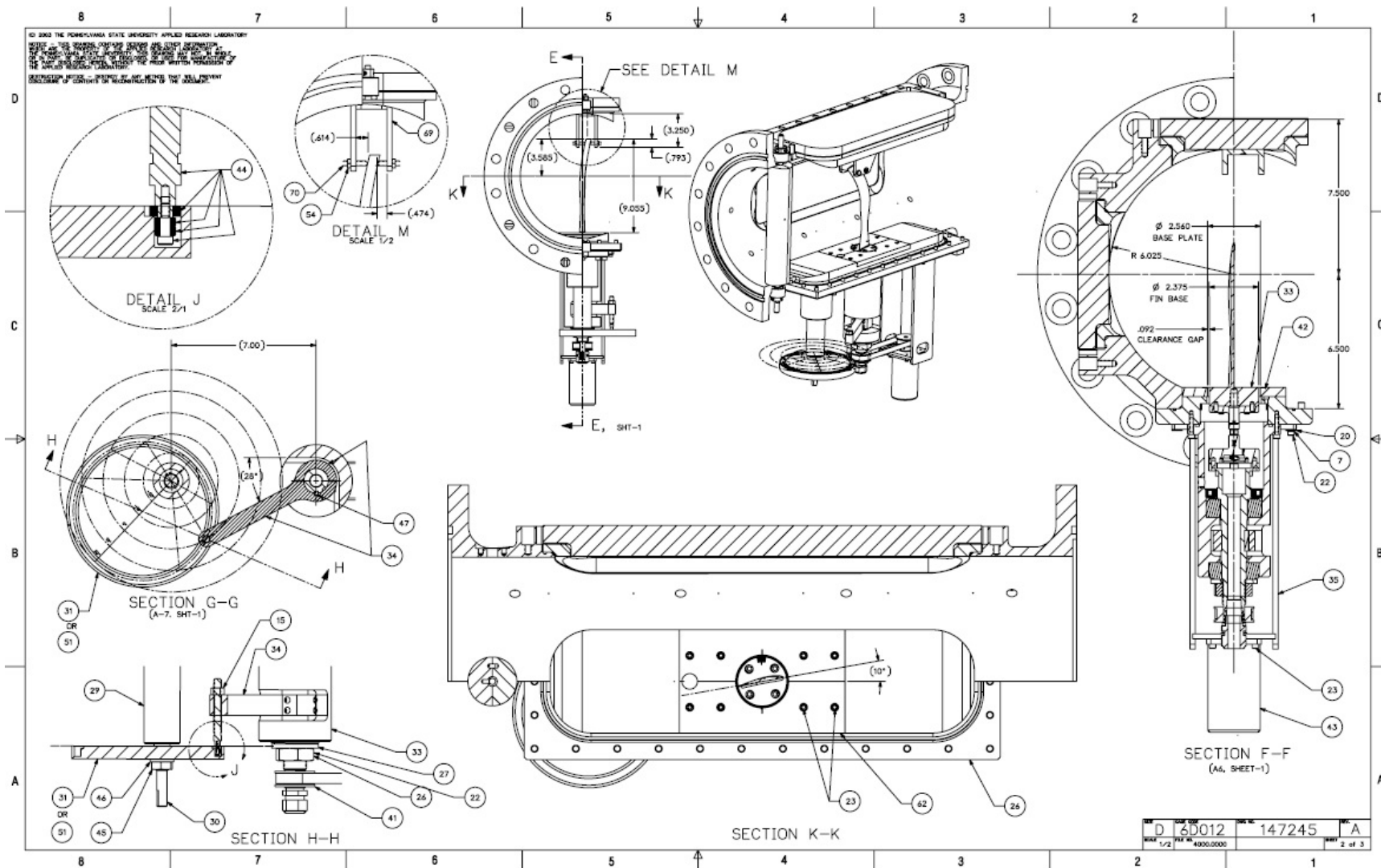
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Appendix A: Mechanical Drawings

A.1 Assembly Drawings

This section contains assembly drawings for the cylinder, the load cell and the fin.

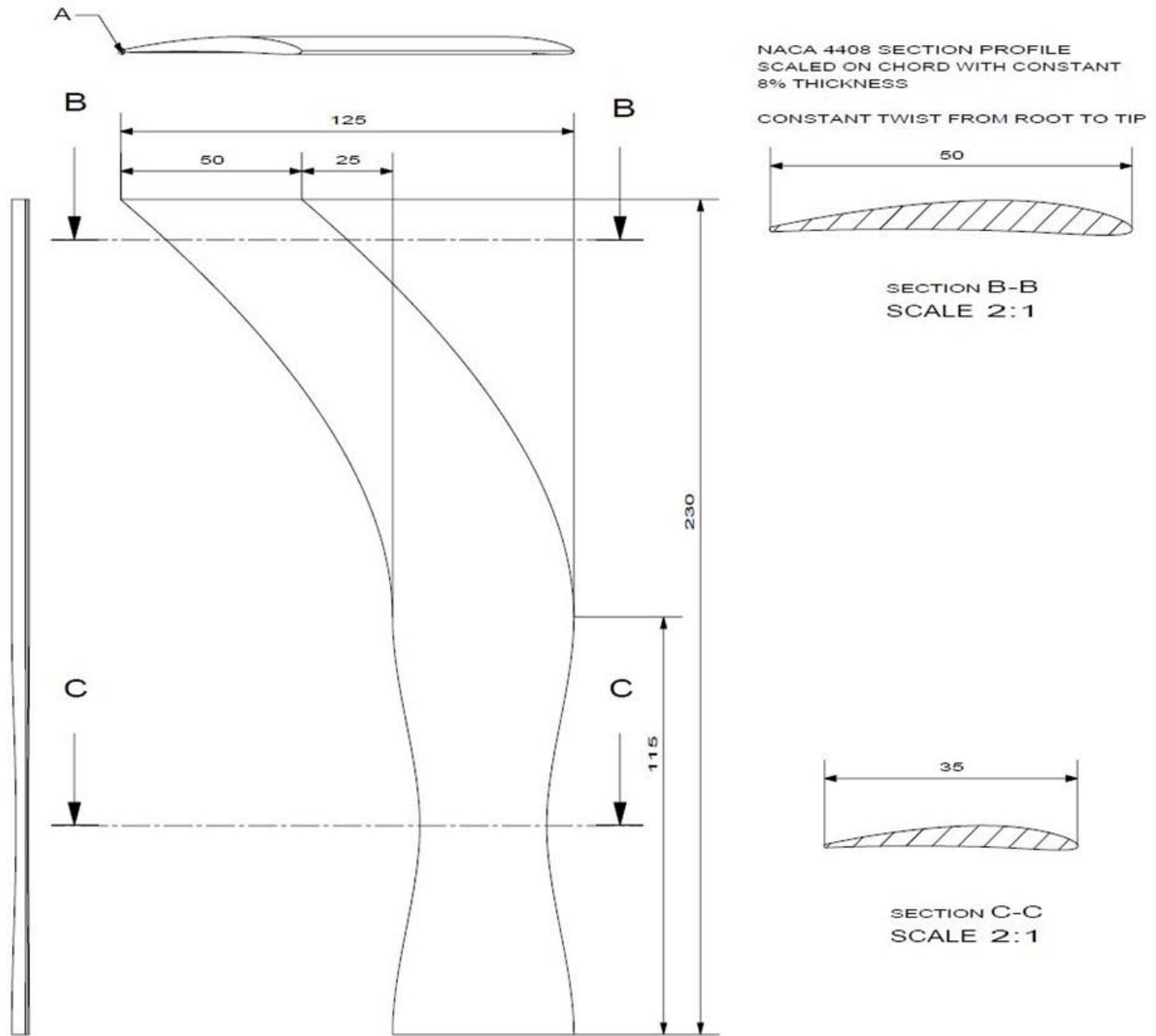
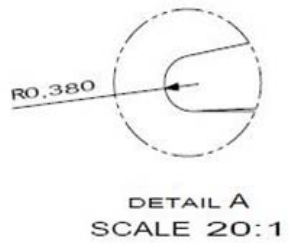




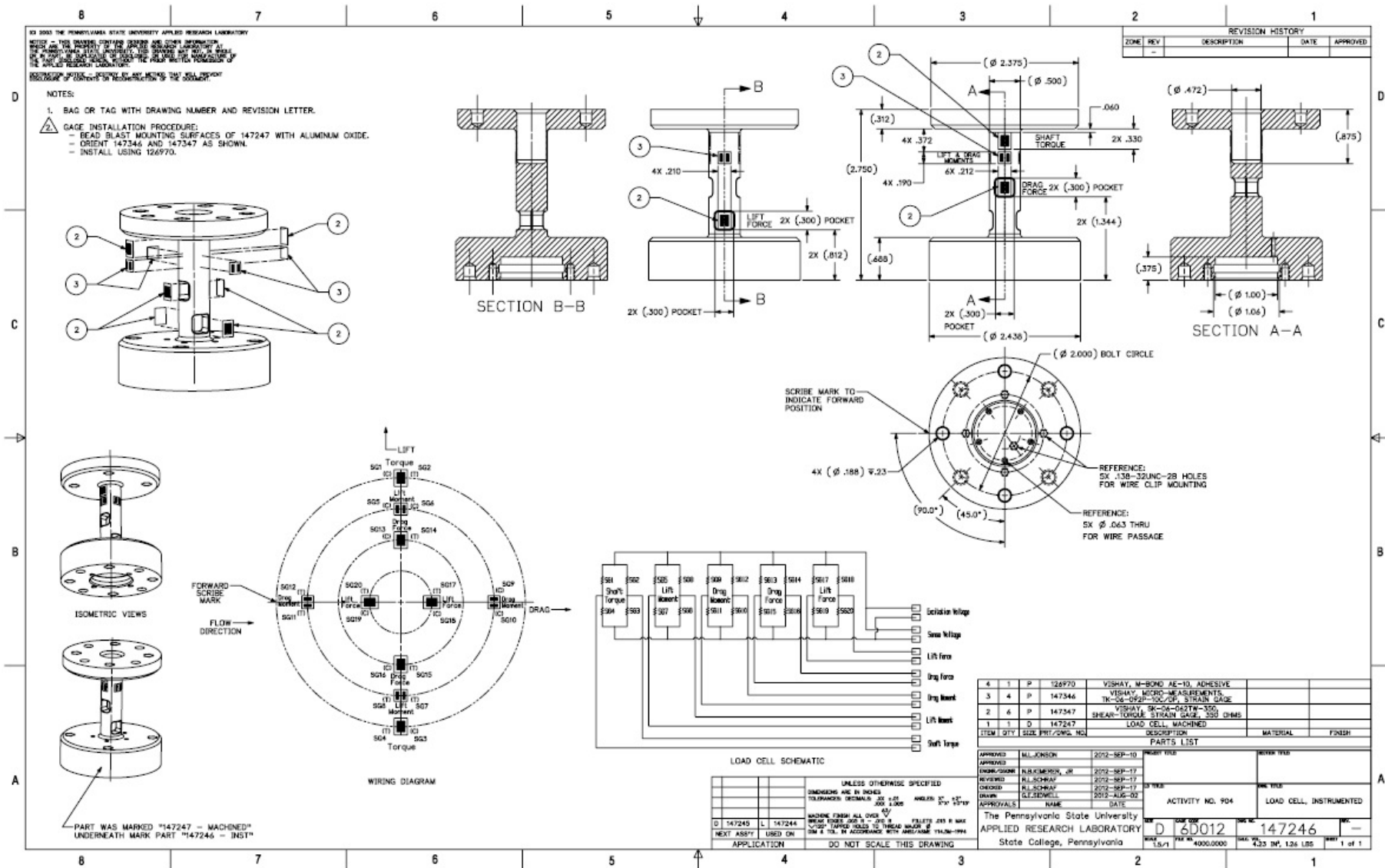


Swept Fin r.4
09 February 2012

ALL DIMENSIONS IN MM





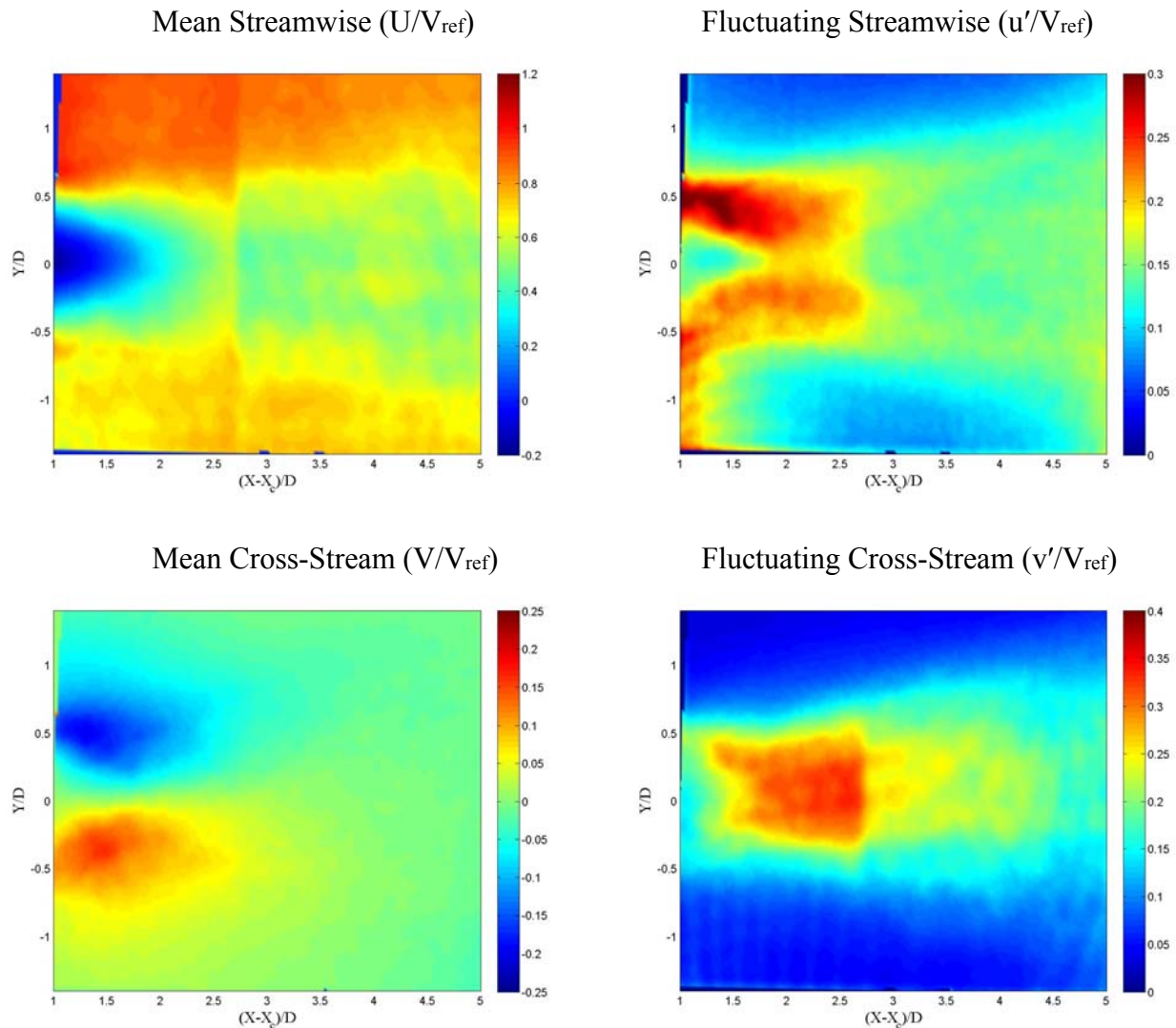


Appendix B: High-Speed PIV Results

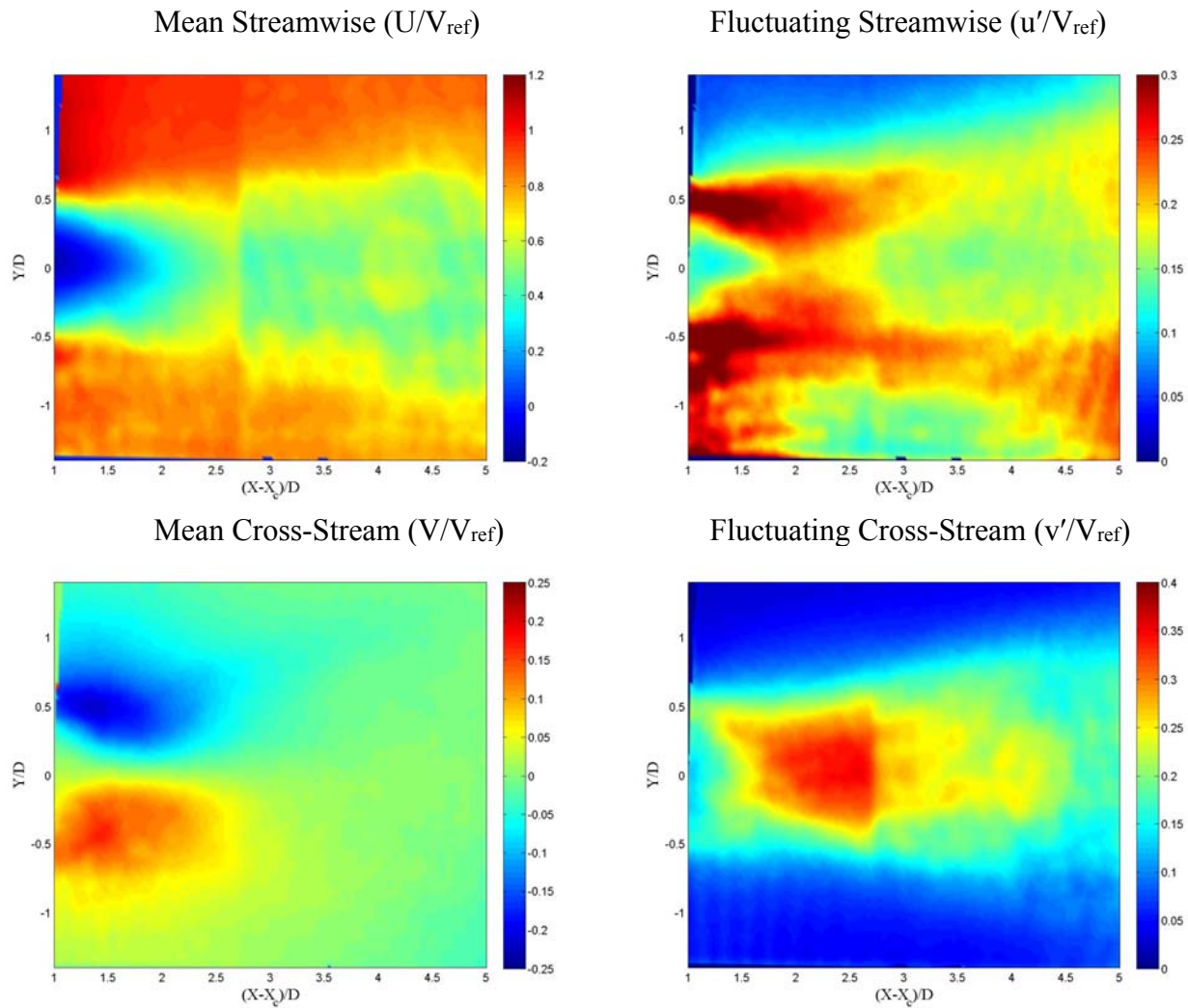
B.1 Mean and Fluctuating Contour Plots (Part 2b)

This section shows the mean and fluctuating components of velocity for the rough cylinder case.

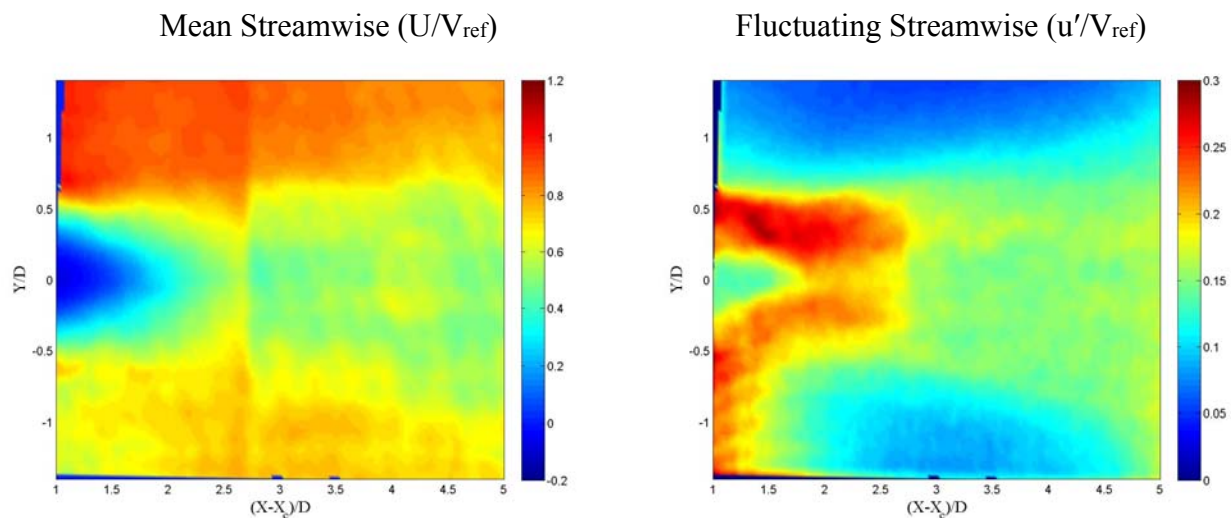
Test 79 – Run 26 (58 rpm)



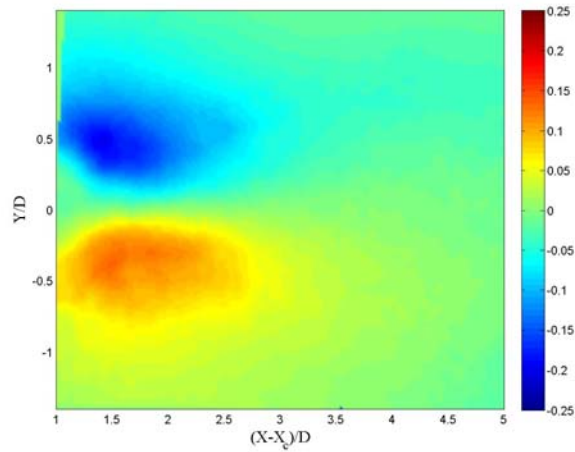
Test 79 – Run 38 (58 rpm)



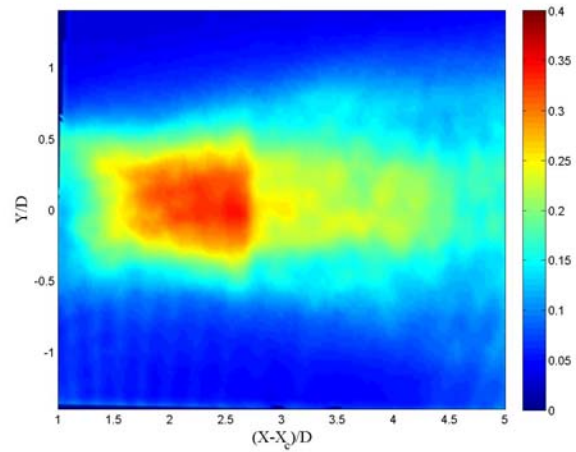
Test 79 – Run 11 (69 rpm)



Mean Cross-Stream (V/V_{ref})

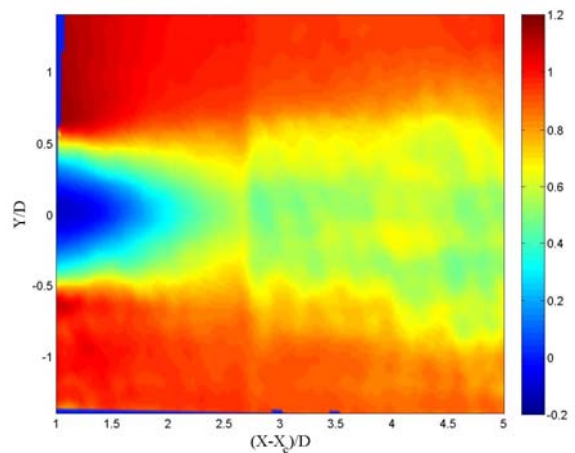


Fluctuating Cross-Stream (v'/V_{ref})

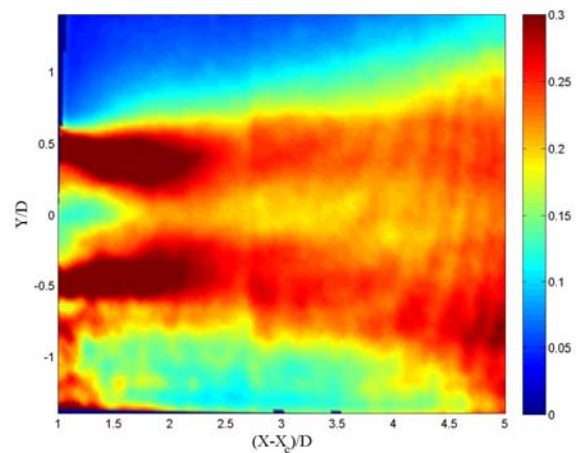


Test 79 – Run 44 (77 rpm)

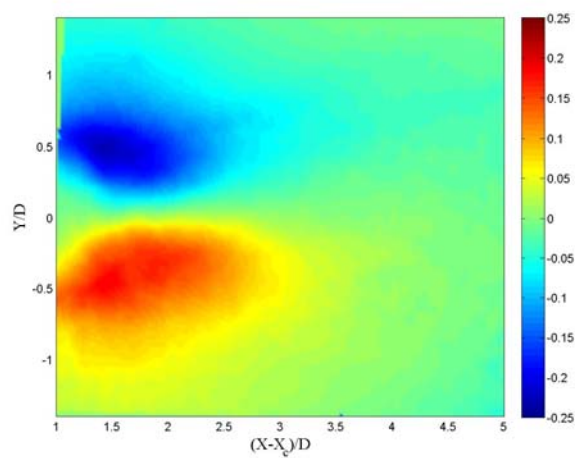
Mean Streamwise (U/V_{ref})



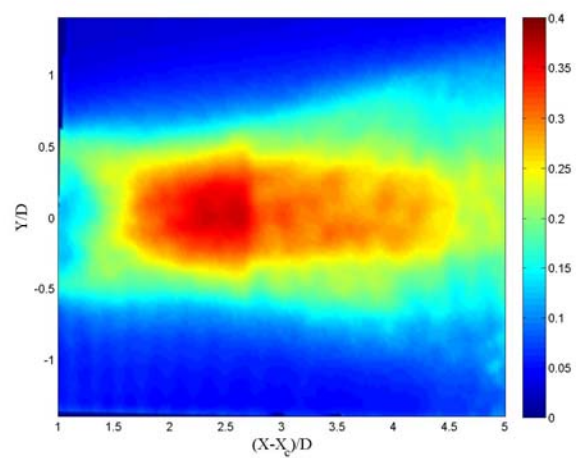
Fluctuating Streamwise (u'/V_{ref})



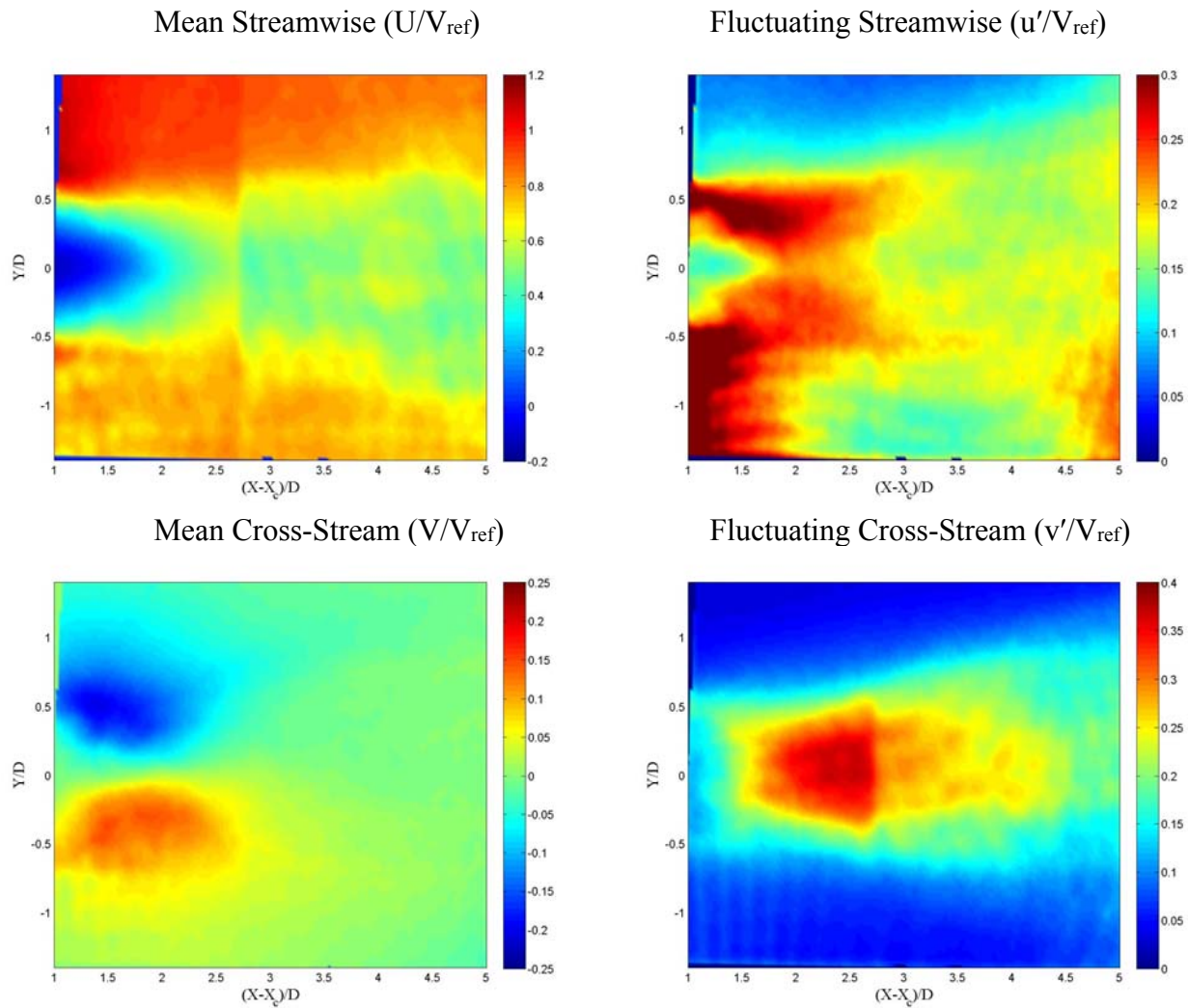
Mean Cross-Stream (V/V_{ref})



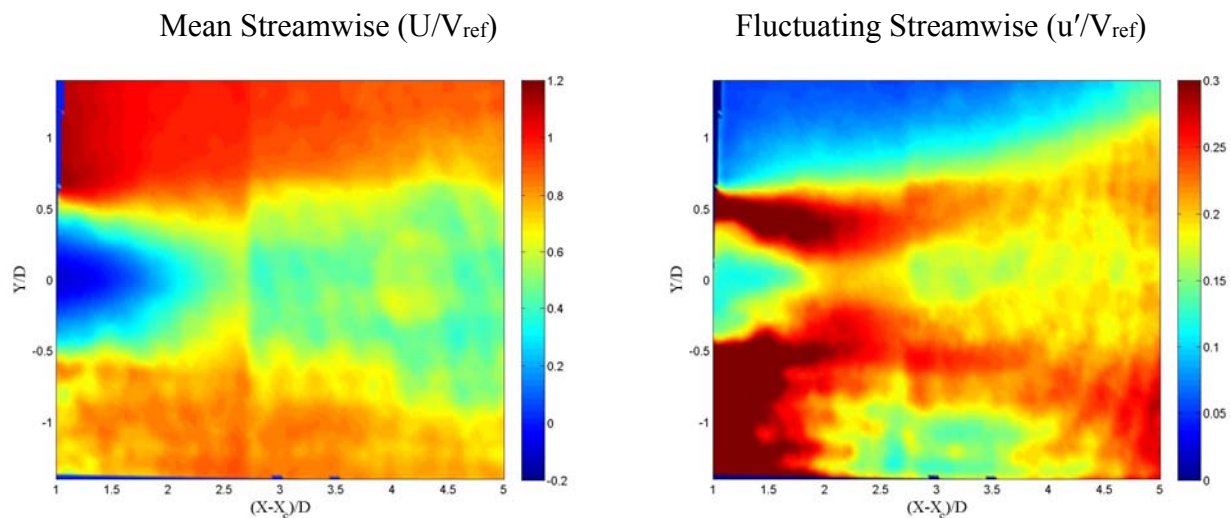
Fluctuating Cross-Stream (v'/V_{ref})



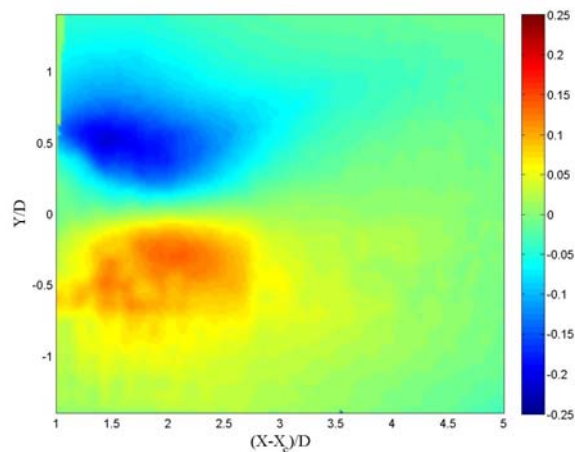
Test 79 – Run 17 (80 rpm)



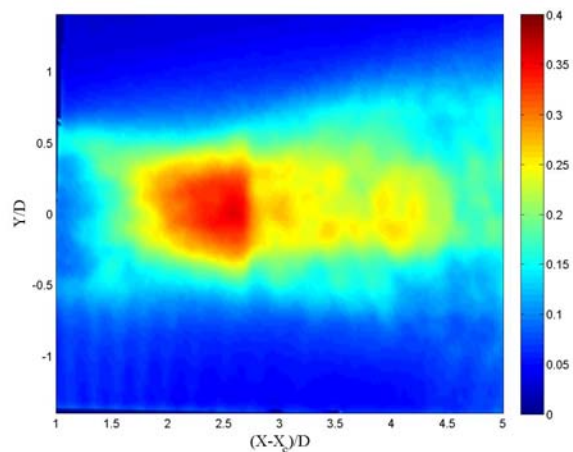
Test 79 – Run 54 (80 rpm)



Mean Cross-Stream (V/V_{ref})

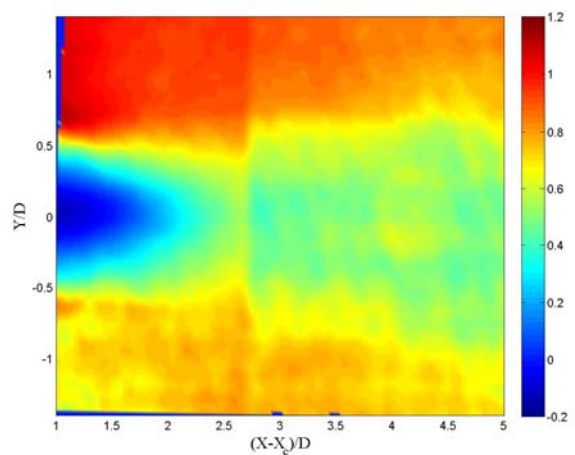


Fluctuating Cross-Stream (v'/V_{ref})

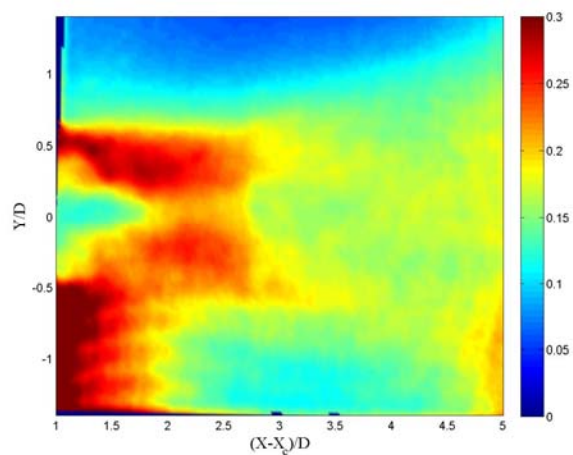


Test 79 – Run 2 (84 rpm)

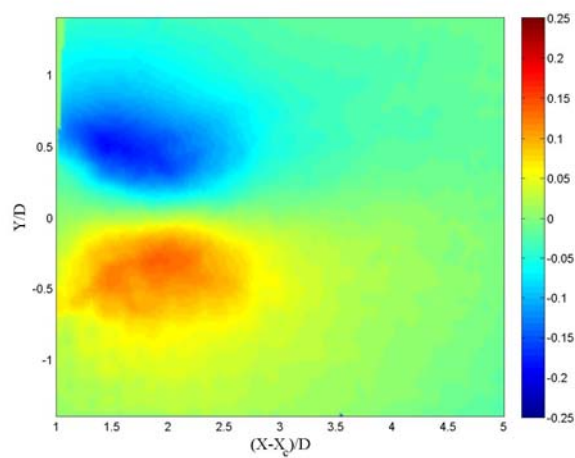
Mean Streamwise (U/V_{ref})



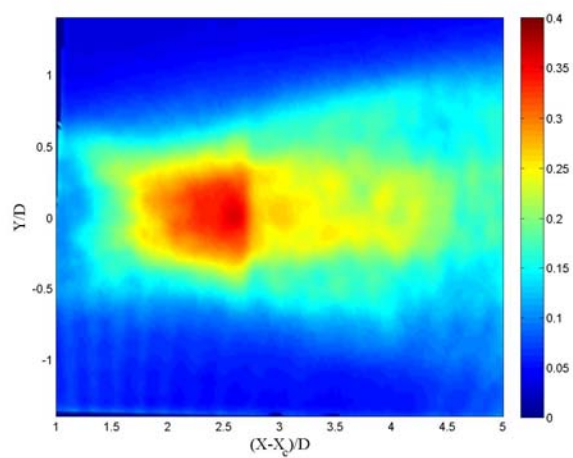
Fluctuating Streamwise (u'/V_{ref})



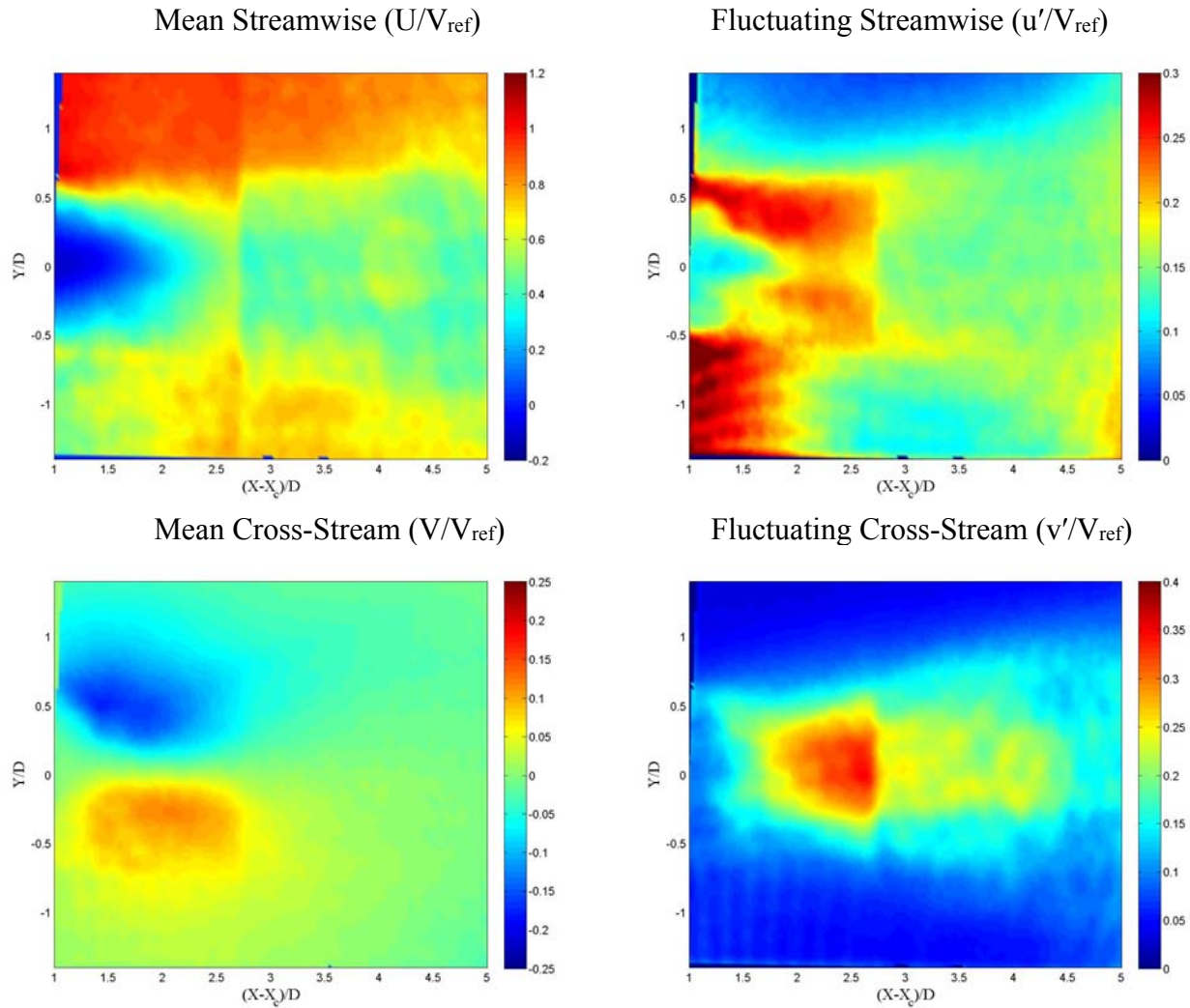
Mean Cross-Stream (V/V_{ref})



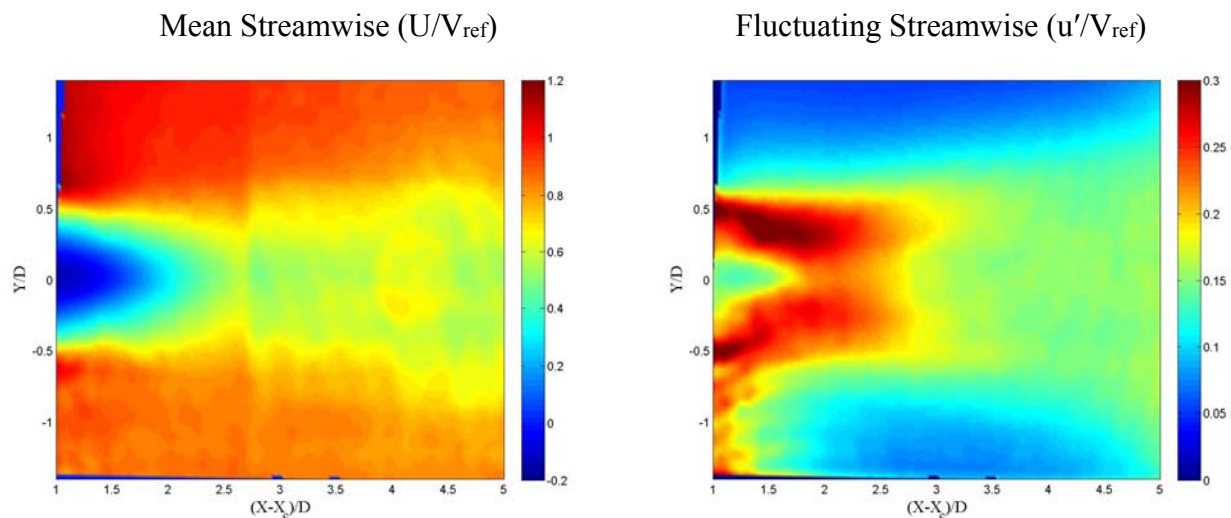
Fluctuating Cross-Stream (v'/V_{ref})



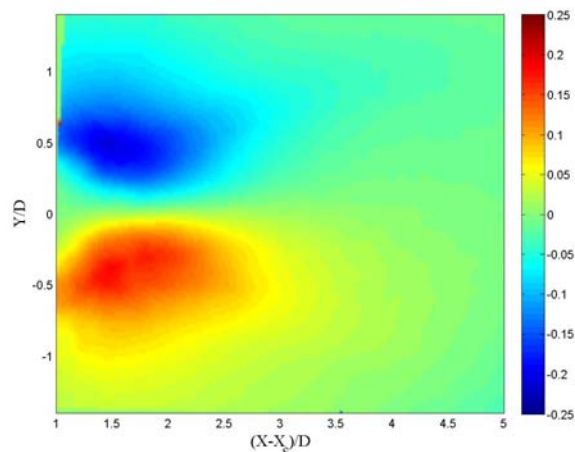
Test 79 – Run 34 (84 rpm)



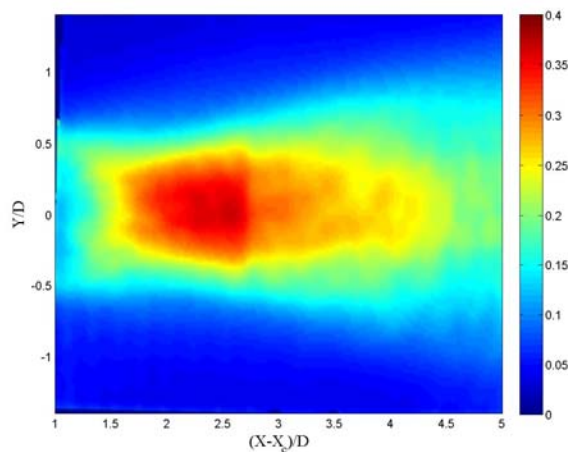
Test 79 – Run 77 (84 rpm)



Mean Cross-Stream (V/V_{ref})

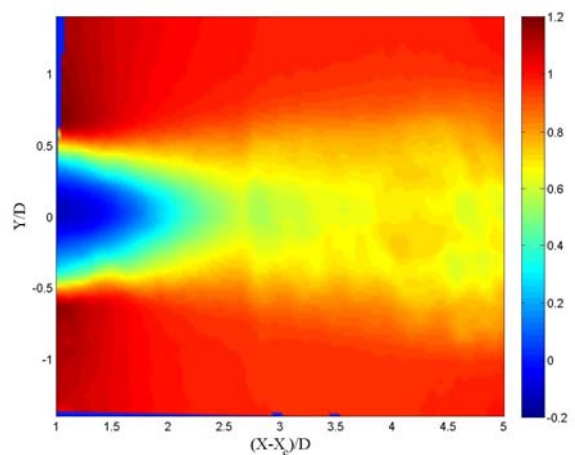


Fluctuating Cross-Stream (v'/V_{ref})

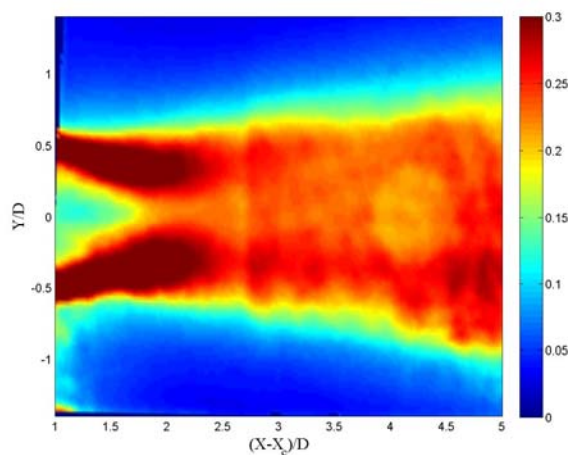


Test 79 – Run 66 (140 rpm)

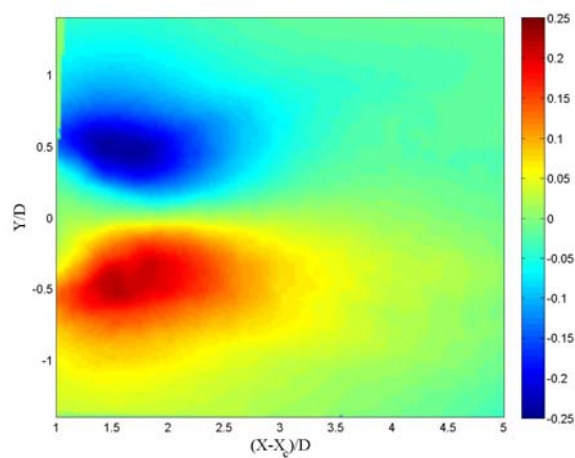
Mean Streamwise (U/V_{ref})



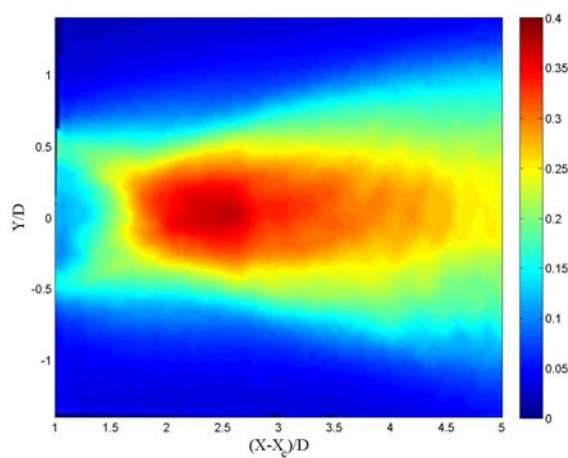
Fluctuating Streamwise (u'/V_{ref})



Mean Cross-Stream (V/V_{ref})



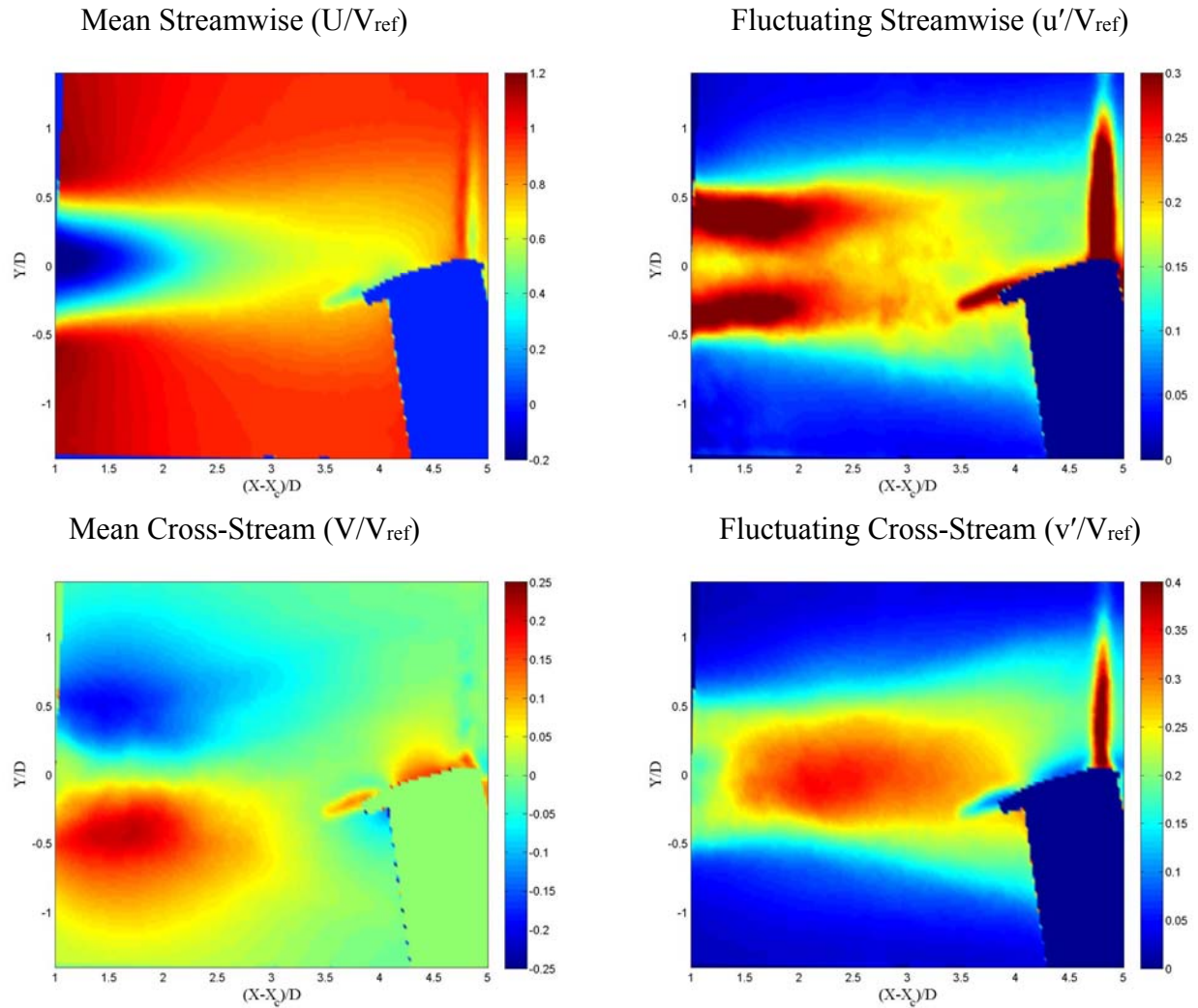
Fluctuating Cross-Stream (v'/V_{ref})



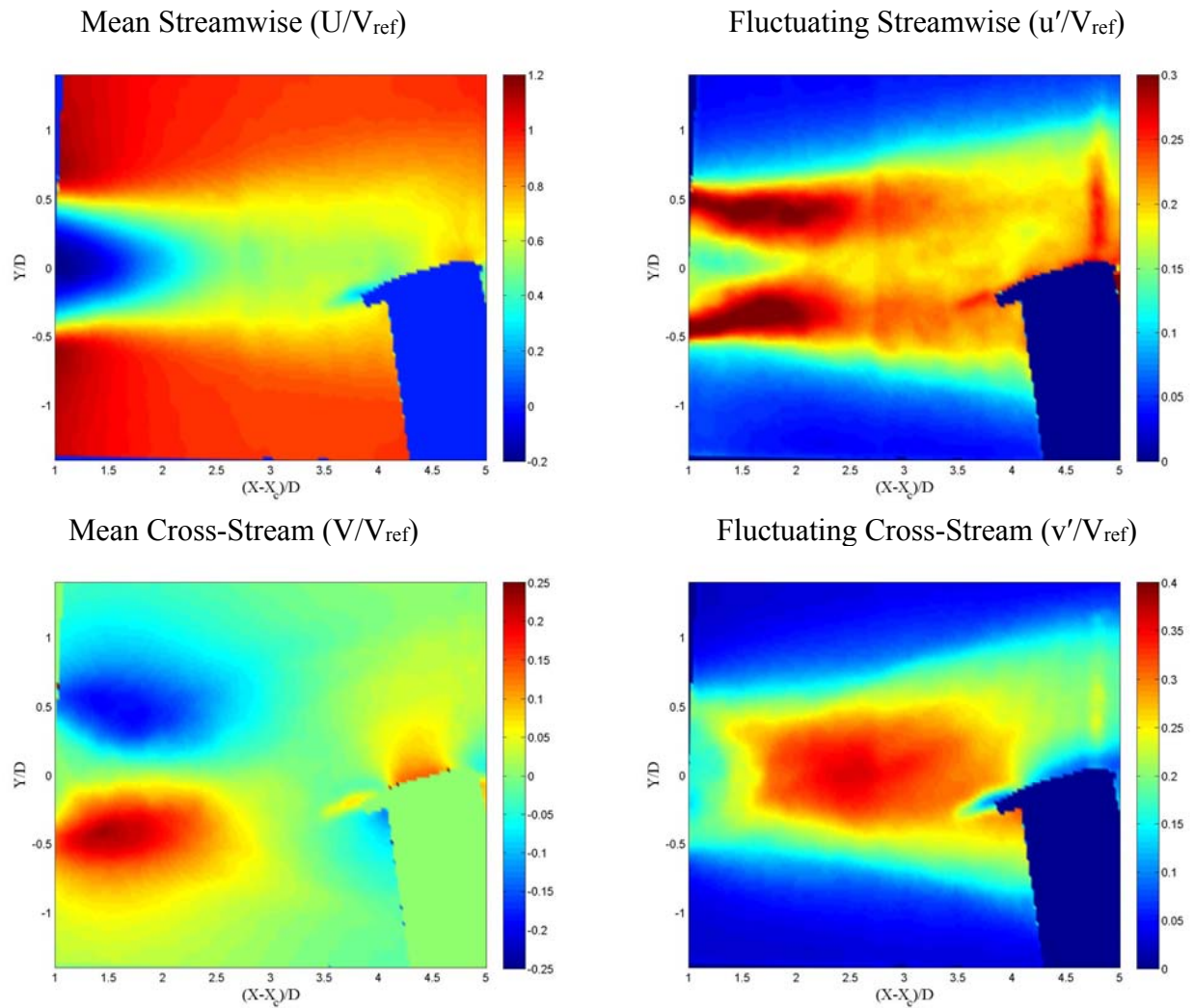
B.2 Mean and Fluctuating Contour Plots (Part 4)

This section shows the mean and fluctuating components of velocity for the forced fin case.

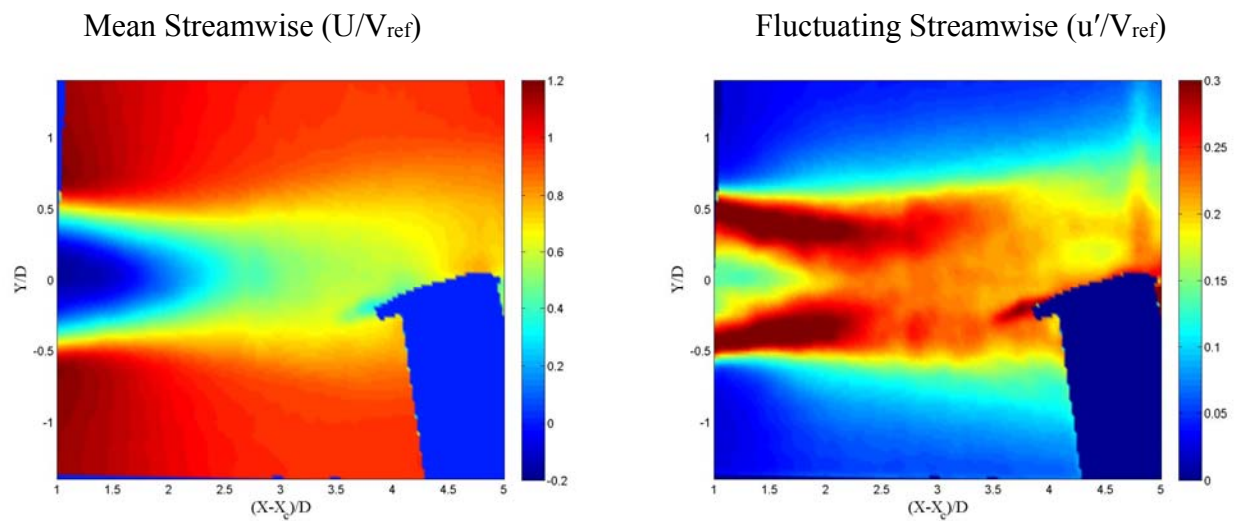
Test 42 – Run 2 (58 rpm)



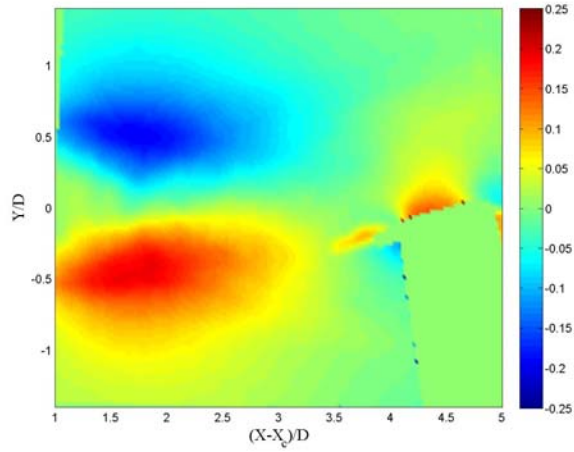
Test 42 – Run 4 (58 rpm)



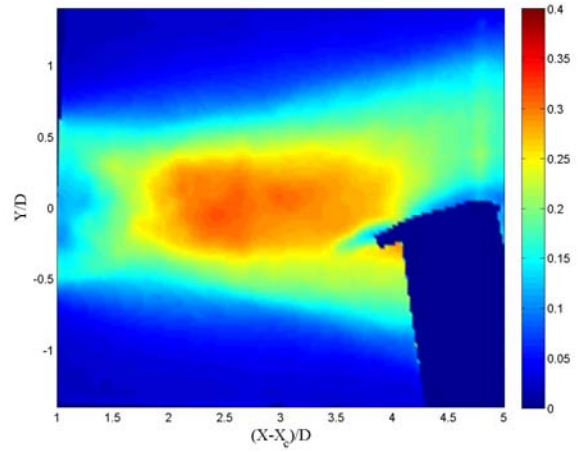
Test 42 – Run 7 (69 rpm)



Mean Cross-Stream (V/V_{ref})

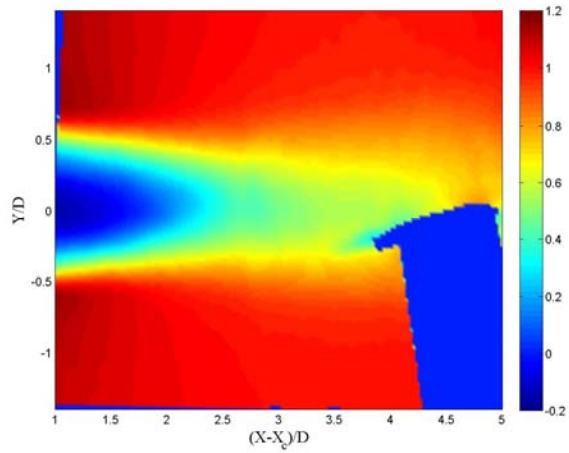


Fluctuating Cross-Stream (v'/V_{ref})

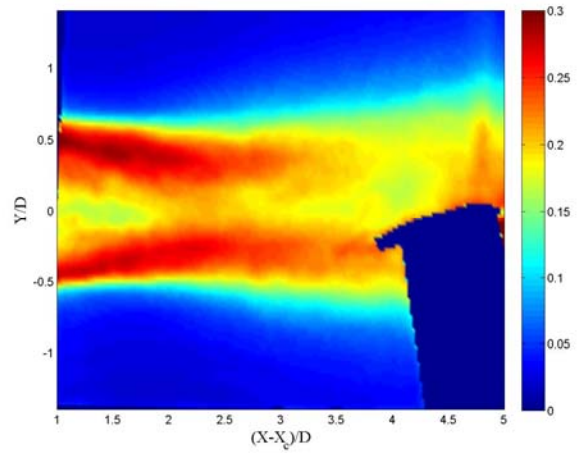


Test 75 – Run 48 (69 rpm)

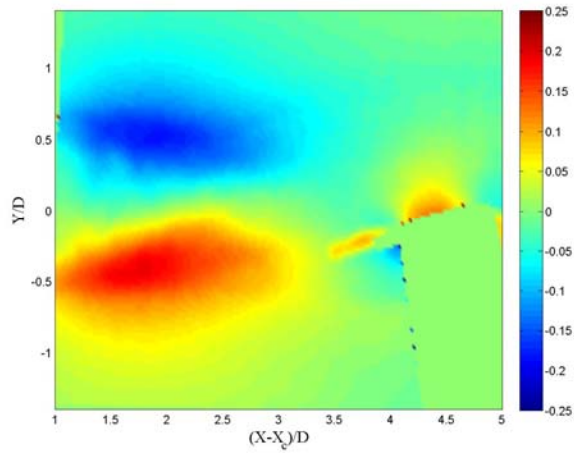
Mean Streamwise (U/V_{ref})



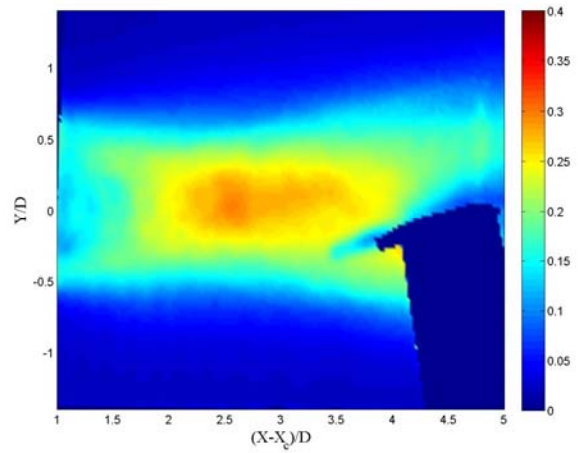
Fluctuating Streamwise (u'/V_{ref})



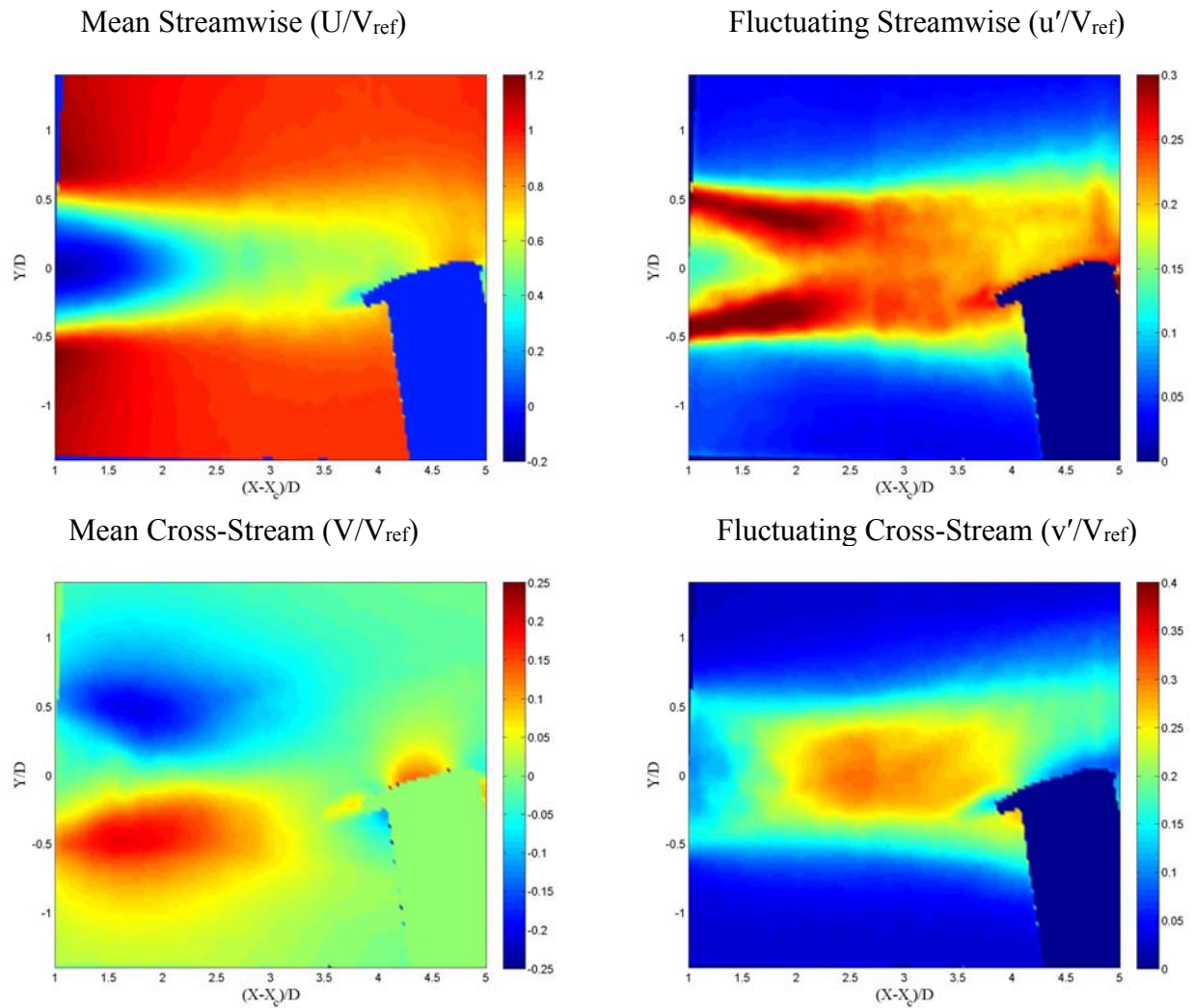
Mean Cross-Stream (V/V_{ref})



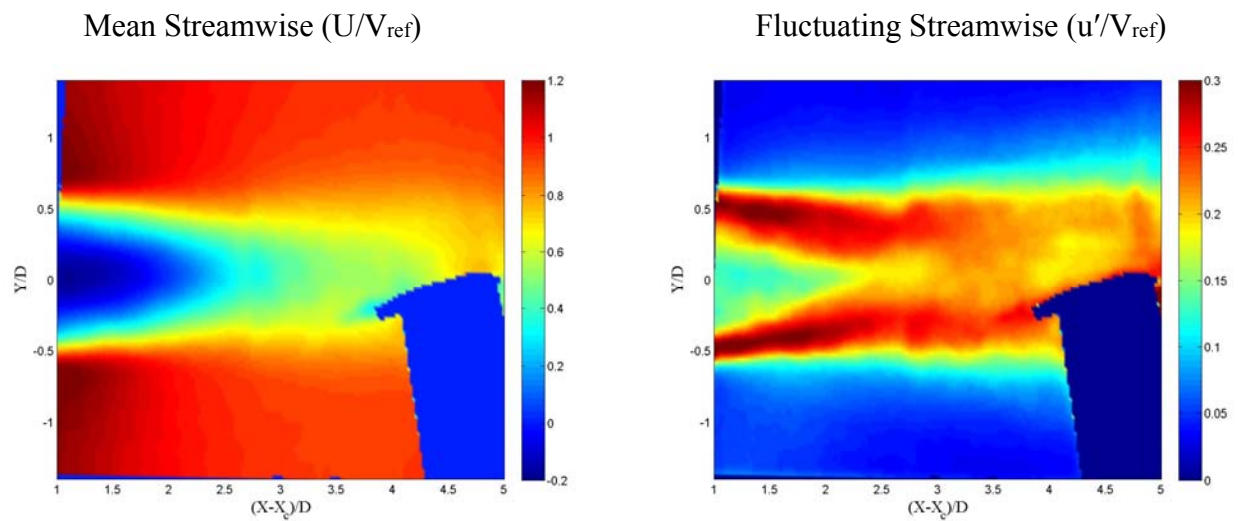
Fluctuating Cross-Stream (v'/V_{ref})



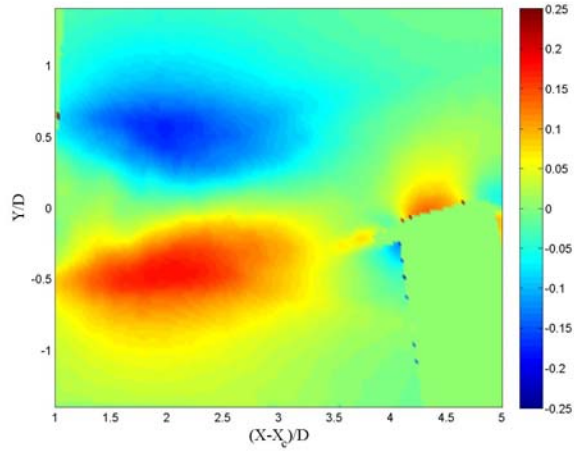
Test 42 – Run 10 (77 rpm)



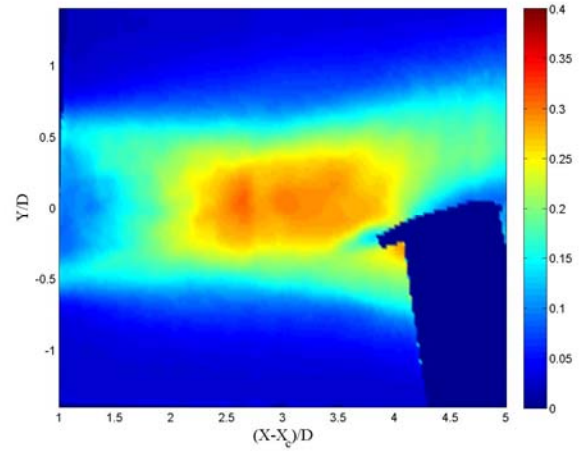
Test 42 – Run 13 (80 rpm)



Mean Cross-Stream (V/V_{ref})

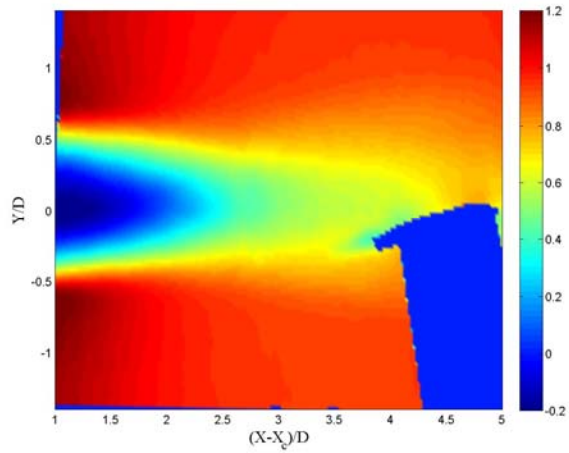


Fluctuating Cross-Stream (v'/V_{ref})

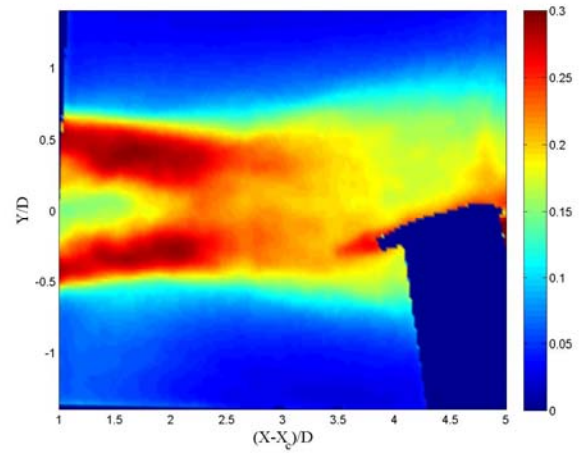


Test 75 – Run 4 (80 rpm)

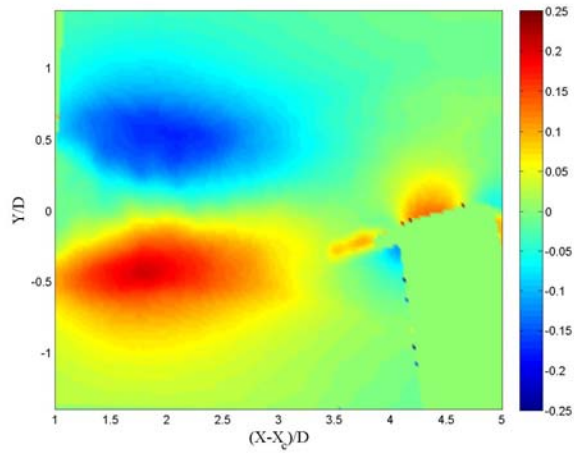
Mean Streamwise (U/V_{ref})



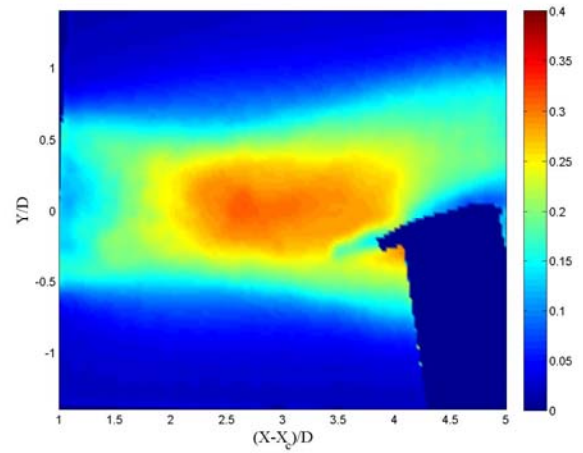
Fluctuating Streamwise (u'/V_{ref})



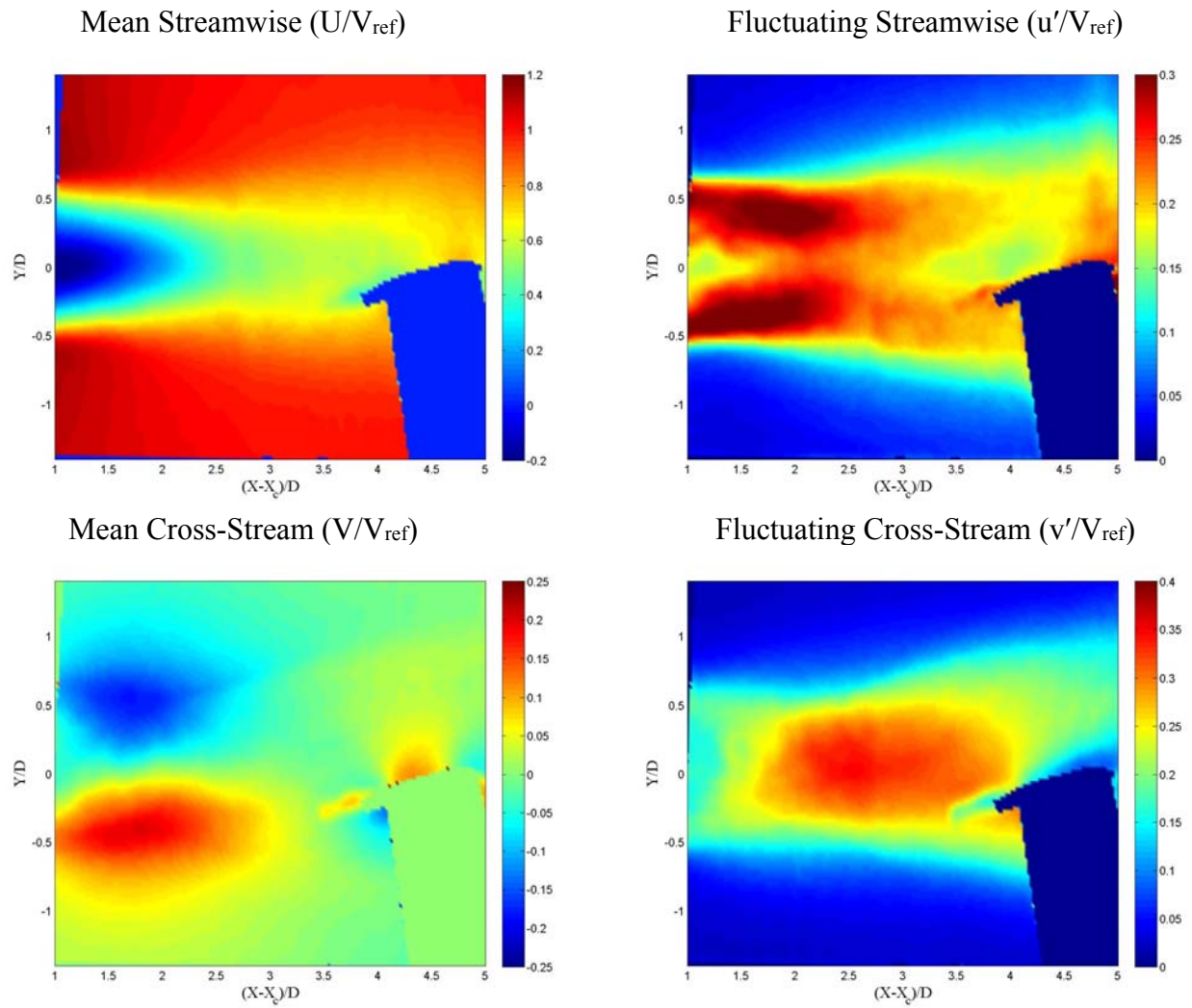
Mean Cross-Stream (V/V_{ref})



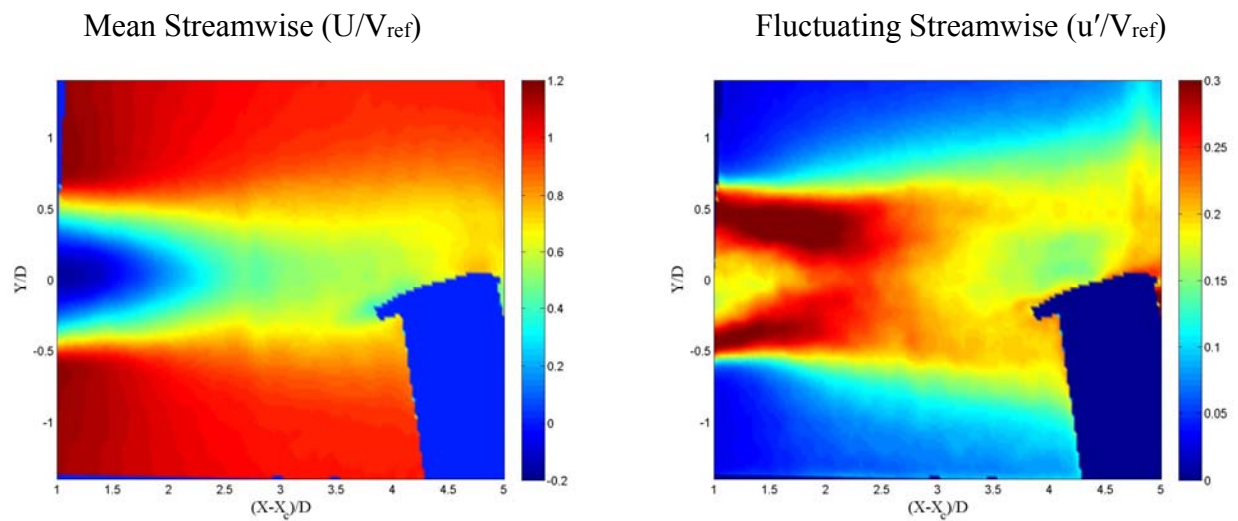
Fluctuating Cross-Stream (v'/V_{ref})



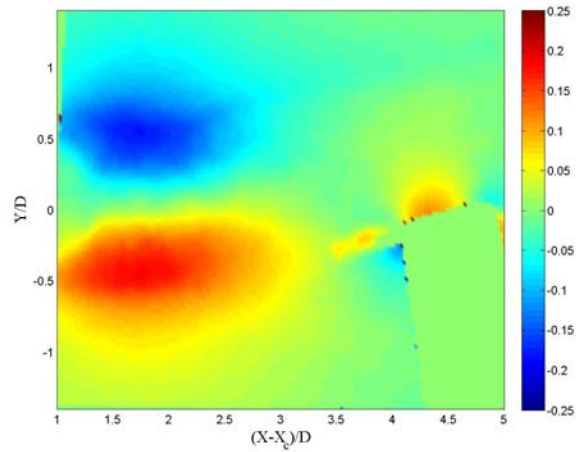
Test 75 – Run 14 (84 rpm)



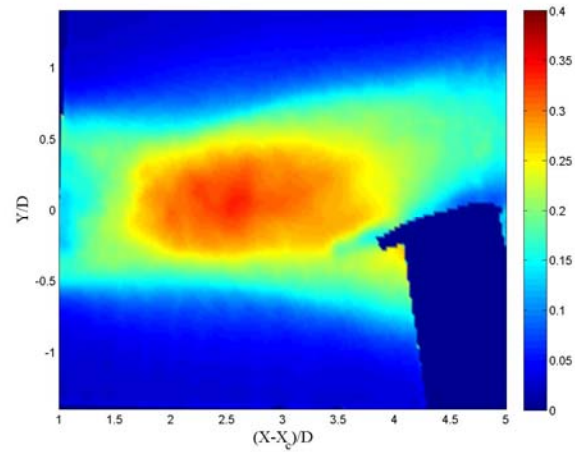
Test 75 – Run 27 (84 rpm)



Mean Cross-Stream (V/V_{ref})

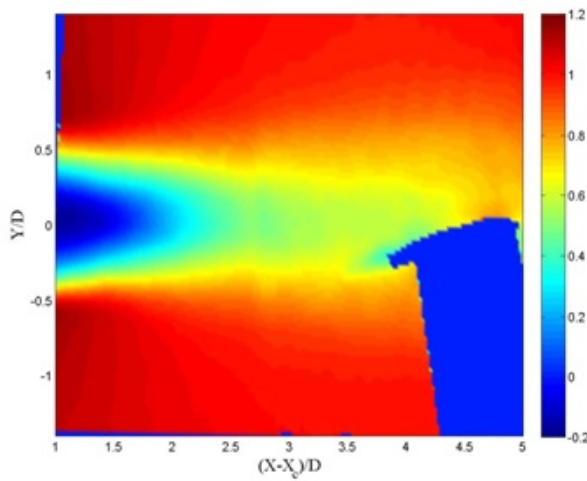


Fluctuating Cross-Stream (v'/V_{ref})

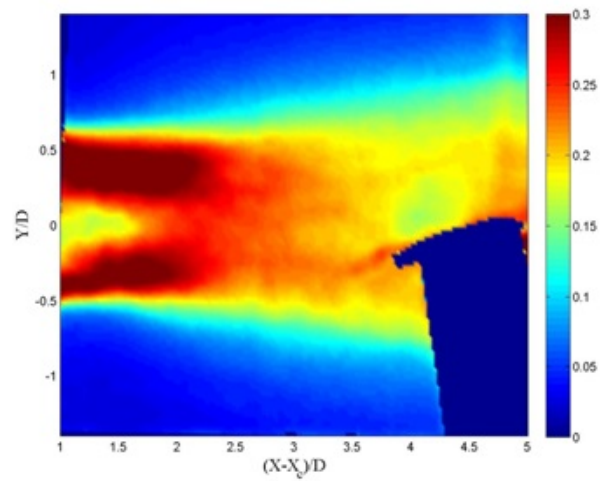


Test 75 – Run 36 (84 rpm)

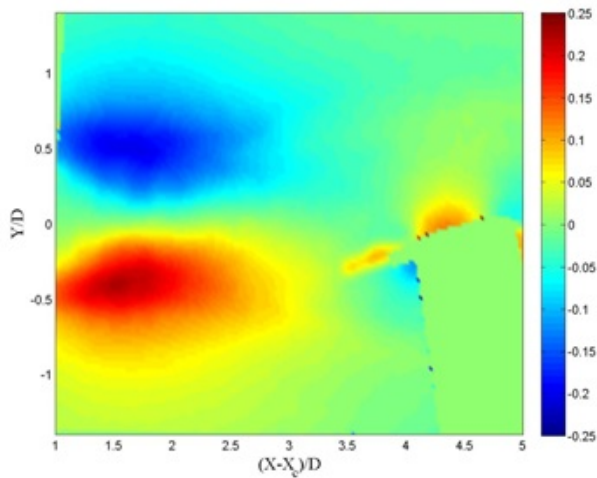
Mean Streamwise (U/V_{ref})



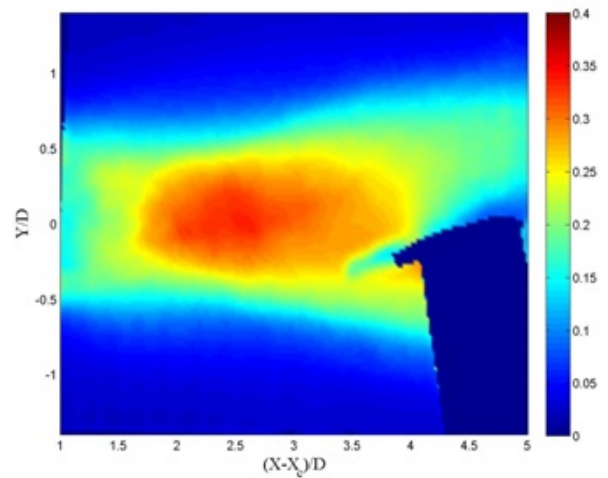
Fluctuating Streamwise (u'/V_{ref})



Mean Cross-Stream (V/V_{ref})



Fluctuating Cross-Stream (v'/V_{ref})



B.3 Mean Profiles (Part 2b and Part 4)

This section shows the mean streamwise and cross-stream velocity profiles for the roughened cylinder with and without the fin present.

Mean Streamwise Velocity Profiles

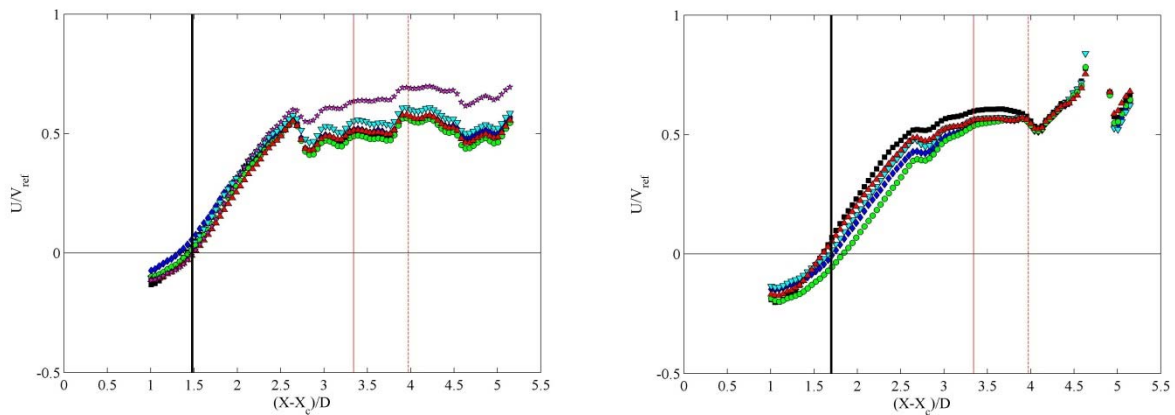


Figure 142. Mean streamwise velocity (U) scaled with the test section reference velocity (V_{ref}) plotted versus the downstream distance (X) from the cylinder trailing edge (X_c) scaled with the cylinder diameter. The data shown are the average results from a given speed from $Y = 0$ mm for (left) the rough cylinder only and (right) rough cylinder with the fin mounted in the wake (Part 4). The symbol colors correspond to (black) $V_{ref} = 2.5$ m/s, (blue) $V_{ref} = 3.0$ m/s, (cyan) $V_{ref} = 3.3$ m/s, (green) $V_{ref} = 3.4$ m/s, (red) $V_{ref} = 3.6$ m/s and (magenta) $V_{ref} = 6.0$ m/s. The solid black line represents the nominal location where the recirculating region ends, which corresponds to $(X-X_c)/D = 1.48$ and 1.7 for the without and with the fin installed, respectively. The two gray lines downstream show the nominal locations of the fin tip leading edge and the leading edge at the PIV plane ($Z = 188$ mm).

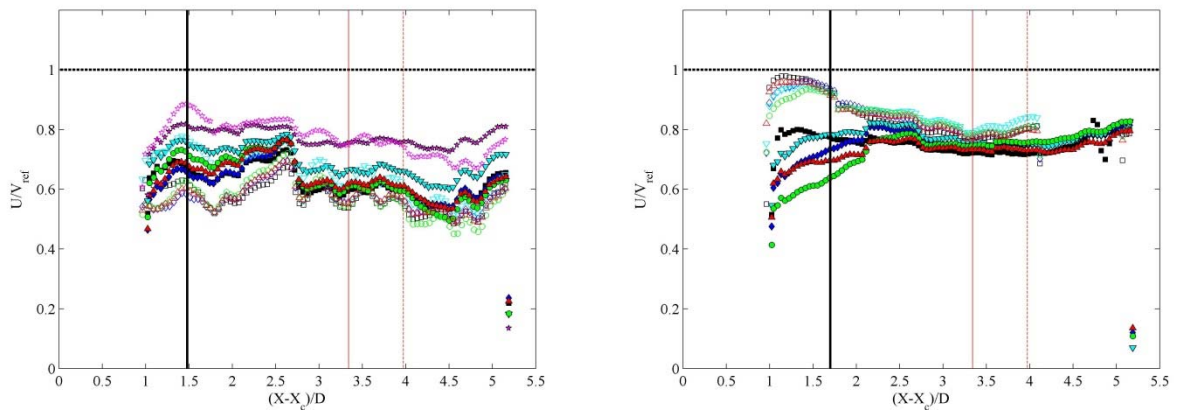


Figure 143. Same caption as Figure 142 except the profiles were acquired at $Y/D = \pm 0.5$. The closed symbols are for data acquired at $Y/D = +0.5$ and the open symbols are from $Y/D = -0.5$. (left image is from Part 2b and right is from Part 4).

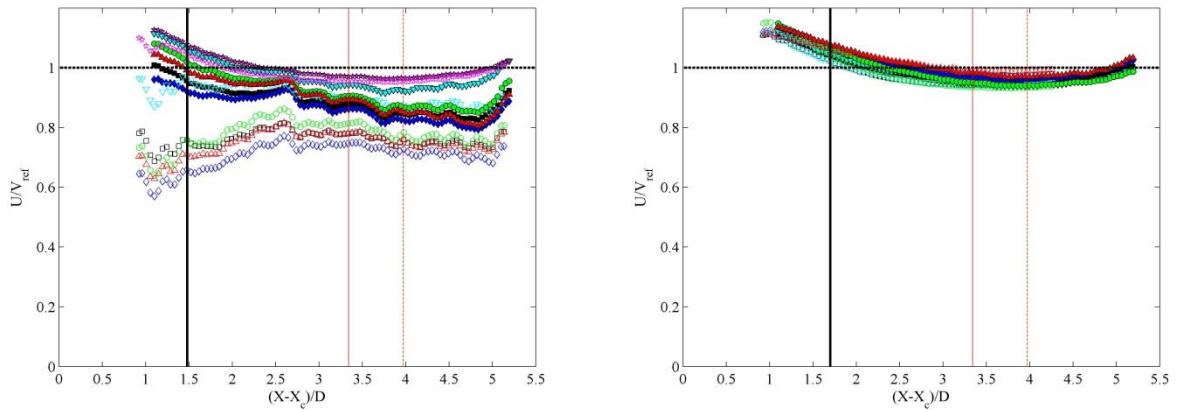


Figure 144. Same caption as Figure 142 except the profiles were acquired at $Y/D = \pm 1.3$. The closed symbols are for data acquired at $Y/D = +1.3$ and the open symbols are from $Y/D = -1.3$. (left image is from Part 2b and right is from Part 4).

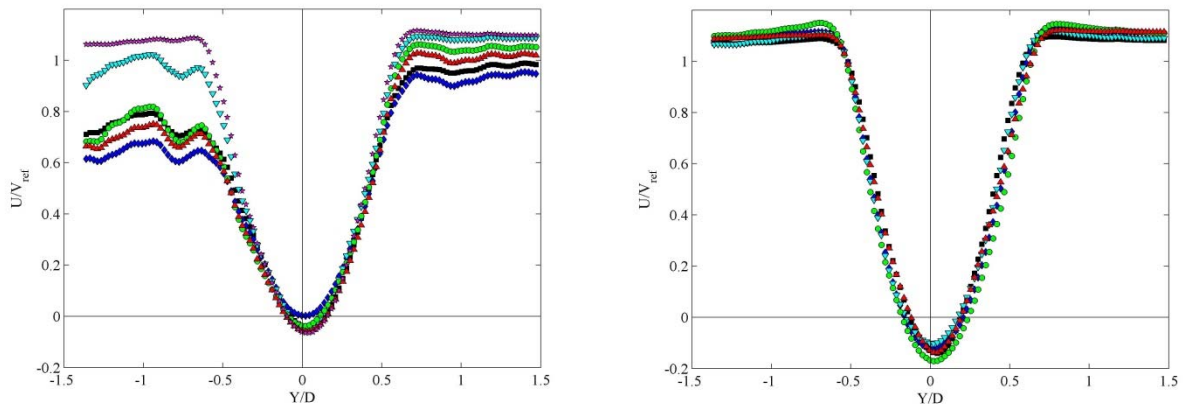


Figure 145. Mean streamwise velocity (U) scaled with the test section reference velocity (V_{ref}) plotted versus the cross-stream direction (Y) scaled with the cylinder diameter. The data shown are the average results from a given speed in the near-wake region ($X = 160$ mm) for (left) the rough cylinder only (Part 2b) and (right) rough cylinder with the fin mounted in the wake (Part 4). The symbol colors correspond to (black) $V_{ref} = 2.5$ m/s, (blue) $V_{ref} = 3.0$ m/s, (cyan) $V_{ref} = 3.3$ m/s, (green) $V_{ref} = 3.4$ m/s, (red) $V_{ref} = 3.6$ m/s and (magenta) $V_{ref} = 6.0$ m/s.

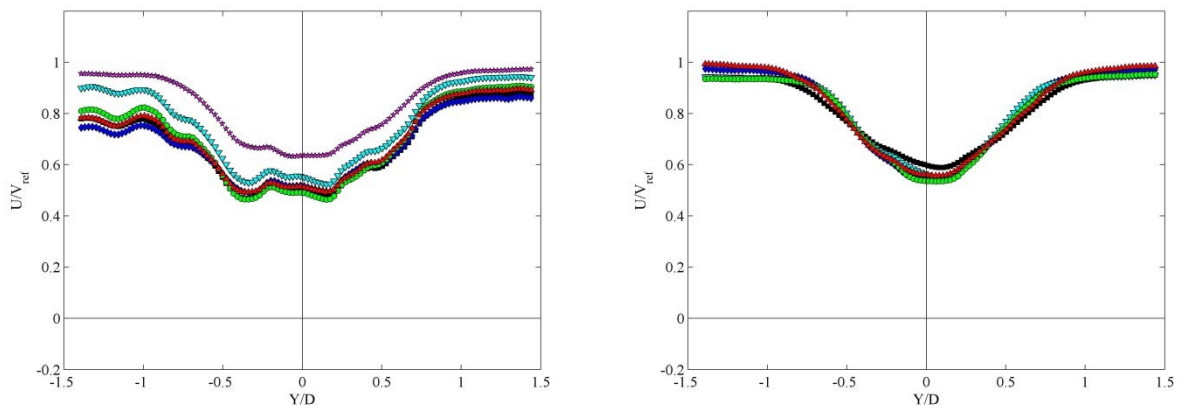


Figure 146. Same caption as Figure 145 except the profiles were acquired in the far wake region near the fin tip leading edge location ($X = 280$ mm). (left image is from Part 2b and right is from Part 4).

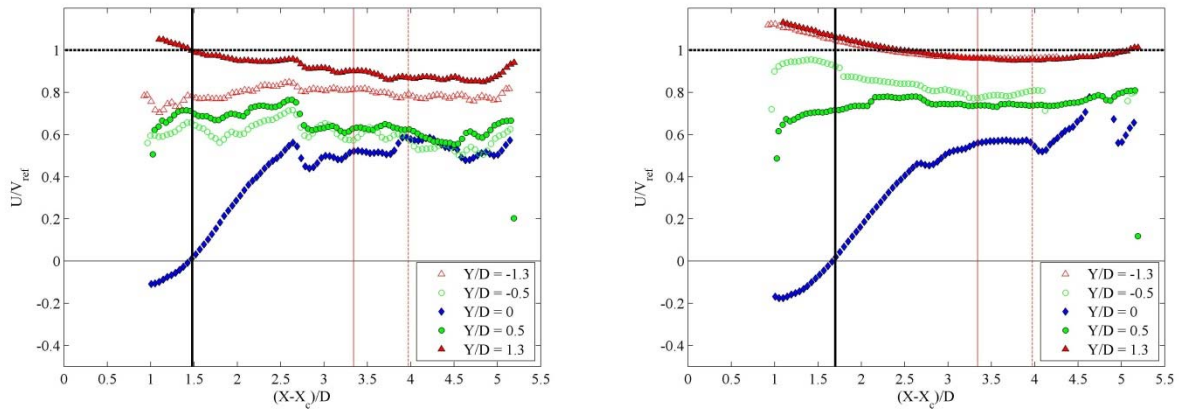


Figure 147. Mean streamwise velocity (U) scaled with the test section reference velocity (V_{ref}) plotted versus the downstream distance (X) from the cylinder trailing edge (X_c) scaled with the cylinder diameter. The data shown are the average results from all conditions from (left) the rough cylinder only testing (Part 2b) and (right) rough cylinder with the fin (Part 4). The solid black line represents the nominal location where the recirculating region ends, which corresponds to $(X-X_c)/D = 1.48$ and 1.7 without and with the fin installed, respectively. The two thin red lines downstream show the nominal locations of the fin tip leading edge and the leading edge at the PIV plane ($Z = 188$ mm).

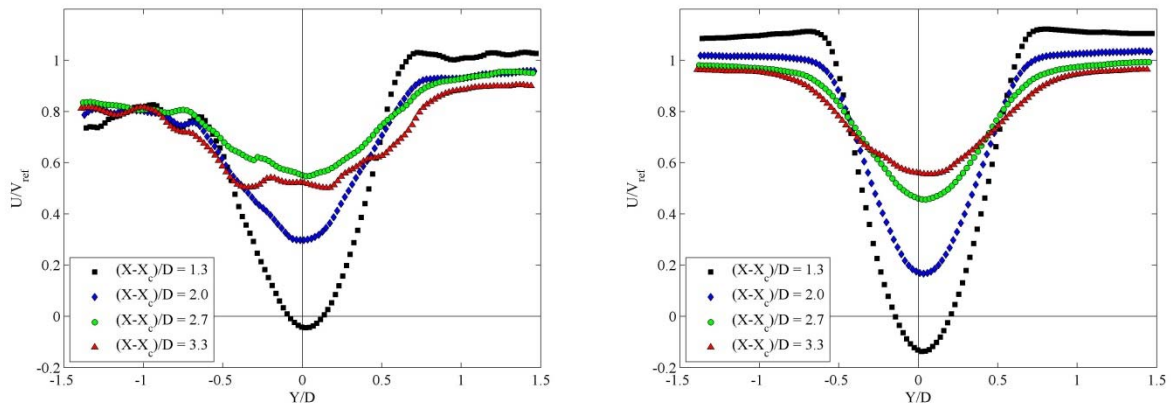


Figure 148. Mean streamwise velocity (U) scaled with the test section reference velocity (V_{ref}) plotted versus the cross-stream location (Y) scaled with the cylinder diameter. The data shown are the average results from all conditions from (left) the rough cylinder only testing (Part 2b) and (right) rough cylinder with the fin (Part 4).

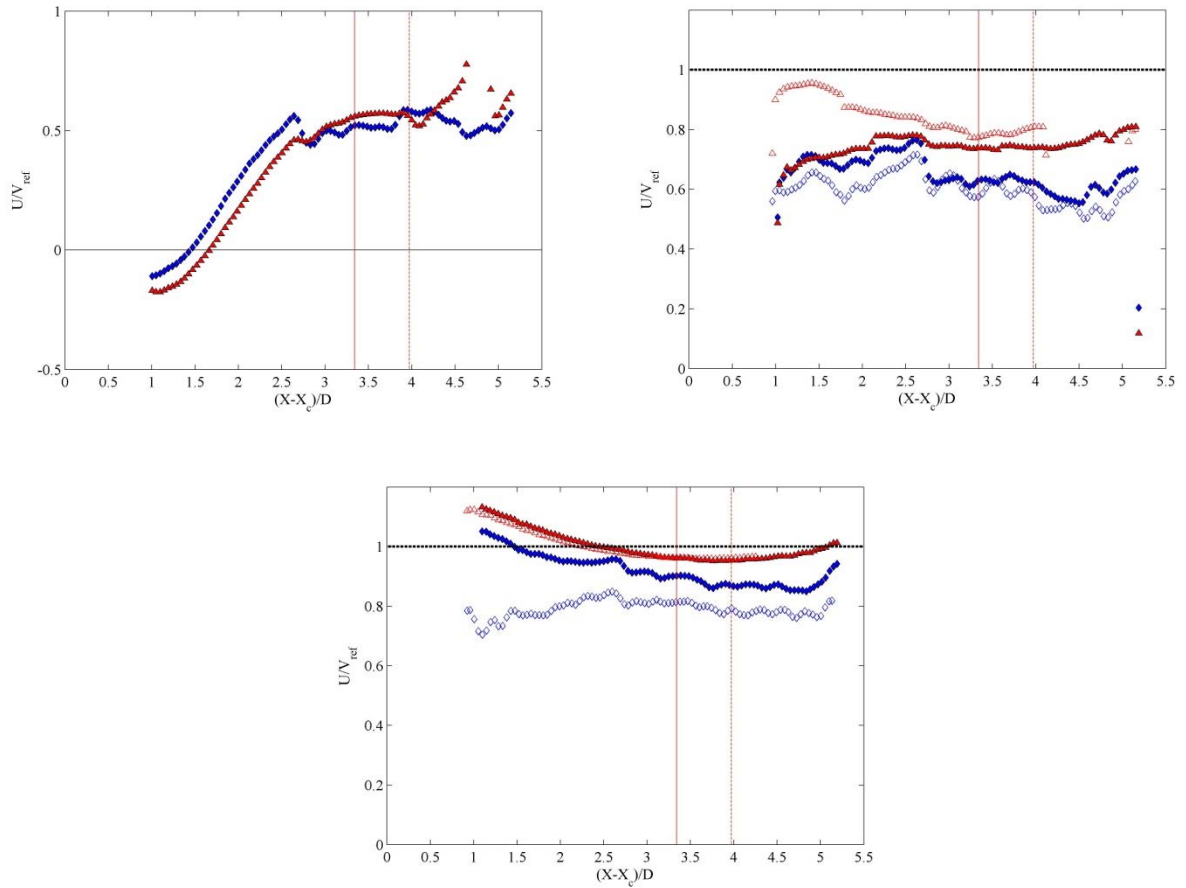


Figure 149. Mean streamwise velocity (U) scaled with the test section reference velocity (V_{ref}) plotted versus the downstream distance (X) from the cylinder trailing edge (X_c) scaled with the cylinder diameter. The data shown are the average results from all conditions from (upper left) $Y/D = 0$, (upper right) $Y/D = \pm 0.5$ and (lower) $Y/D = \pm 1.3$. The blue symbols are testing without the fin (Part 2b) and the red symbols are with the fin (Part 4). Open symbols correspond to negative- Y locations and solid symbols are positive- Y locations. The two thin red lines downstream show the nominal locations of the fin tip leading edge and the leading edge at the PIV plane ($Z = 188$ mm).

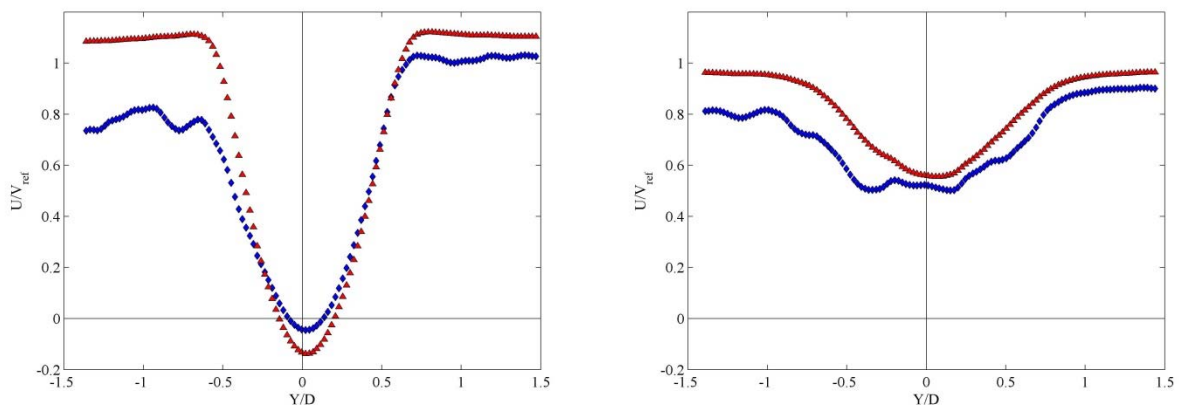


Figure 150. Mean streamwise velocity (U) scaled with the test section reference velocity (V_{ref}) plotted versus the cross-stream location (Y) scaled with the cylinder diameter. The data shown are the average results from all conditions from (left) the near wake at $(X-X_c)/D = 1.3$ and (right) the far wake near the fin tip leading edge at $(X-X_c)/D = 3.3$. The blue symbols are testing without the fin (Part 2b) and the red symbols are with the fin (Part 4).

Mean Cross-Stream Velocity Profiles

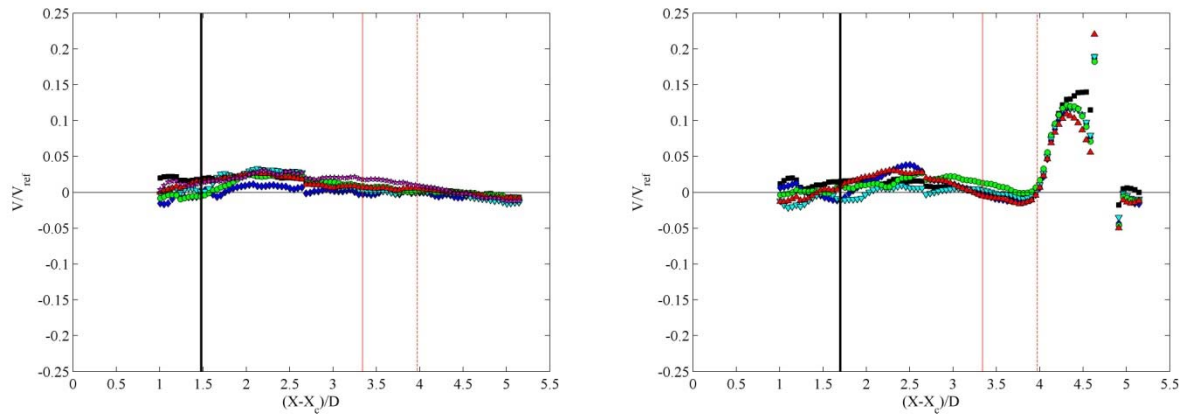


Figure 151. Mean cross-stream velocity (V) scaled with the test section reference velocity (V_{ref}) plotted versus the downstream distance (X) from the cylinder trailing edge (X_c) scaled with the cylinder diameter. The data shown are the average results from a given speed from $Y = 0$ mm for (left) the rough cylinder only and (right) rough cylinder with the fin mounted in the wake (Part 4). The symbol colors correspond to (black) $V_{ref} = 2.5$ m/s, (blue) $V_{ref} = 3.0$ m/s, (cyan) $V_{ref} = 3.3$ m/s, (green) $V_{ref} = 3.4$ m/s, (red) $V_{ref} = 3.6$ m/s and (magenta) $V_{ref} = 6.0$ m/s. The solid black line represents the nominal location where the recirculating region ends, which corresponds to $(X-X_c)/D = 1.48$ and 1.7 for the without and with the fin installed, respectively. The two thin red lines downstream show the nominal locations of the fin tip leading edge and the leading edge at the PIV plane ($Z = 188$ mm).

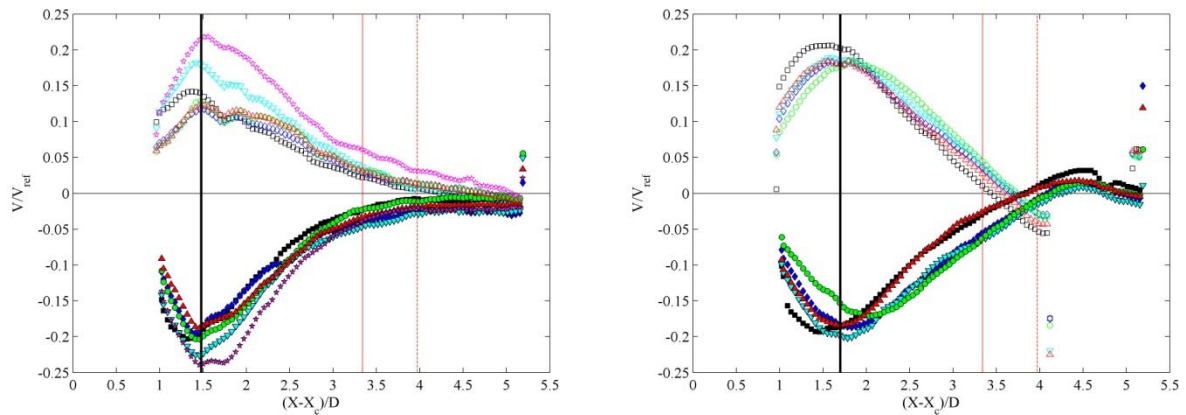


Figure 152. Same caption as Figure 151 except the profiles were acquired at $Y/D = \pm 0.5$. The closed symbols are for data acquired at $Y/D = +0.5$ and the open symbols are from $Y/D = -0.5$. (left image is from Part 2b and right is from Part 4).

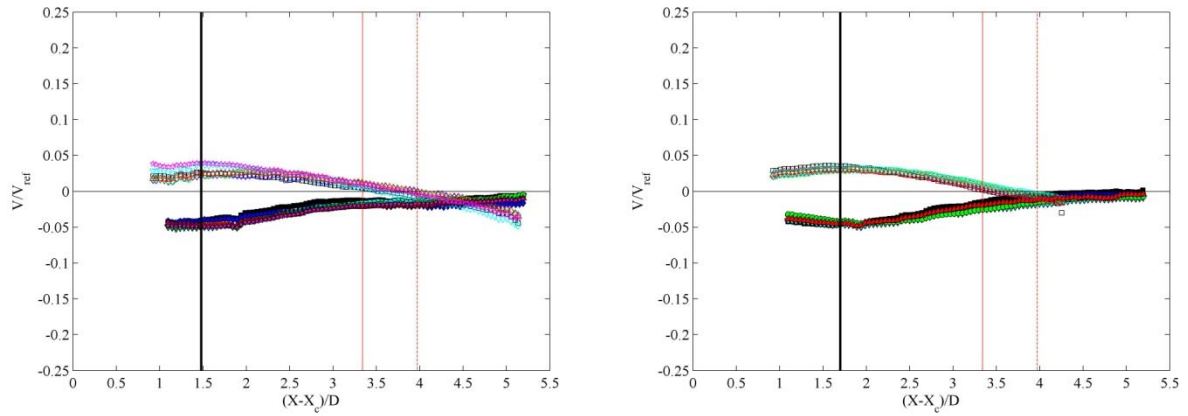


Figure 153. Same caption as Figure 151 except the profiles were acquired at $Y/D = \pm 1.3$. The closed symbols are for data acquired at $Y/D = +1.3$ and the open symbols are from $Y/D = -1.3$. (left image is from Part 2b and right is from Part 4).

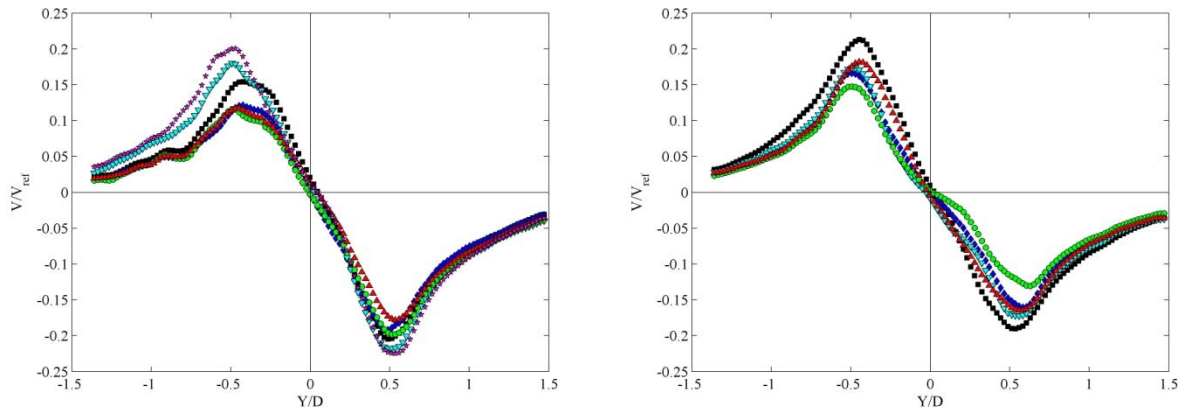


Figure 154. Mean cross-stream velocity (V) scaled with the test section reference velocity (V_{ref}) plotted versus the cross-stream direction (Y) scaled with the cylinder diameter. The data shown are the average results from a given speed in the near-wake region ($X = 160$ mm) for (left) the rough cylinder only (Part 2b) and (right) rough cylinder with the fin mounted in the wake (Part 4). The symbol colors correspond to (black) $V_{ref} = 2.5$ m/s, (blue) $V_{ref} = 3.0$ m/s, (cyan) $V_{ref} = 3.3$ m/s, (green) $V_{ref} = 3.4$ m/s, (red) $V_{ref} = 3.6$ m/s and (magenta) $V_{ref} = 6.0$ m/s.

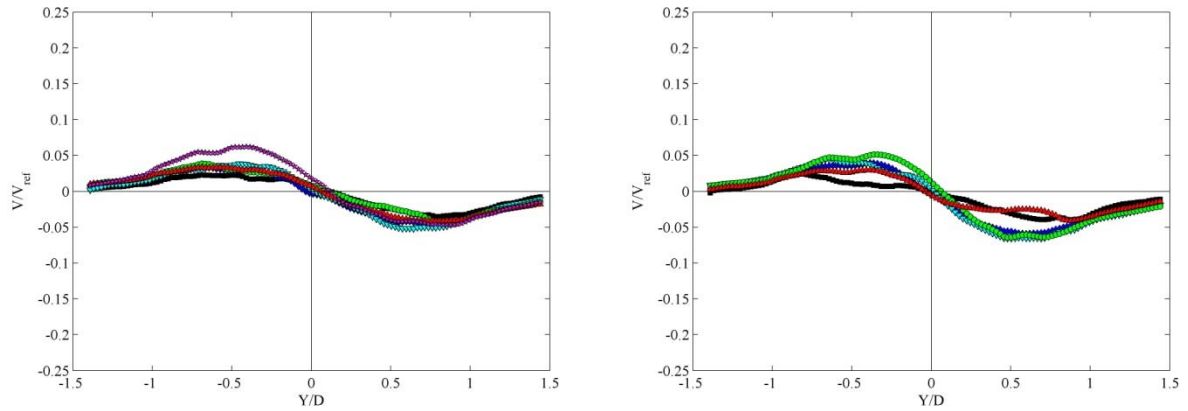


Figure 155. Same caption as Figure 154 except the profiles were acquired in the far wake region near the fin tip leading edge location ($X = 280$ mm). (left image is from Part 2b and right is from Part 4).

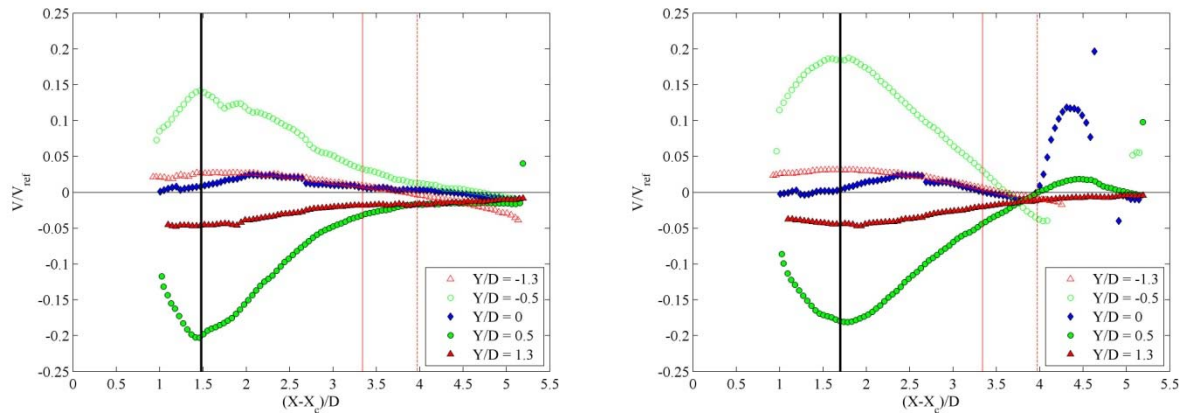


Figure 156. Mean cross-stream velocity (V) scaled with the test section reference velocity (V_{ref}) plotted versus the downstream distance (X) from the cylinder trailing edge (X_c) scaled with the cylinder diameter. The data shown are the average results from all conditions from (left) the rough cylinder only testing (Part 2b) and (right) rough cylinder with the fin (Part 4). The solid black line represents the nominal location where the recirculating region ends, which corresponds to $(X-X_c)/D = 1.48$ and 1.7 without and with the fin installed, respectively. The two thin red lines downstream show the nominal locations of the fin tip leading edge and the leading edge at the PIV plane ($Z = 188$ mm).

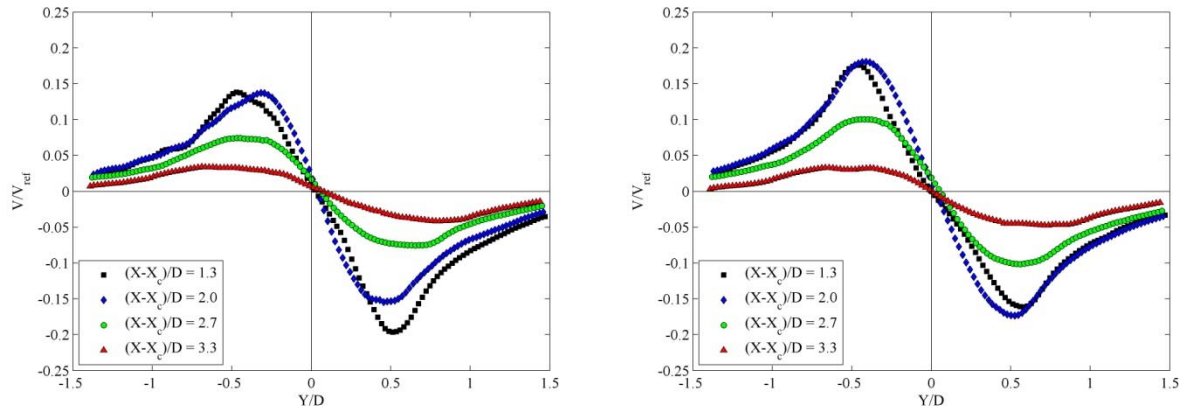


Figure 157. Mean cross-stream velocity (V) scaled with the test section reference velocity (V_{ref}) plotted versus the cross-stream location (Y) scaled with the cylinder diameter. The data shown are the average results from all conditions from (left) the rough cylinder only testing (Part 2b) and (right) rough cylinder with the fin (Part 4).

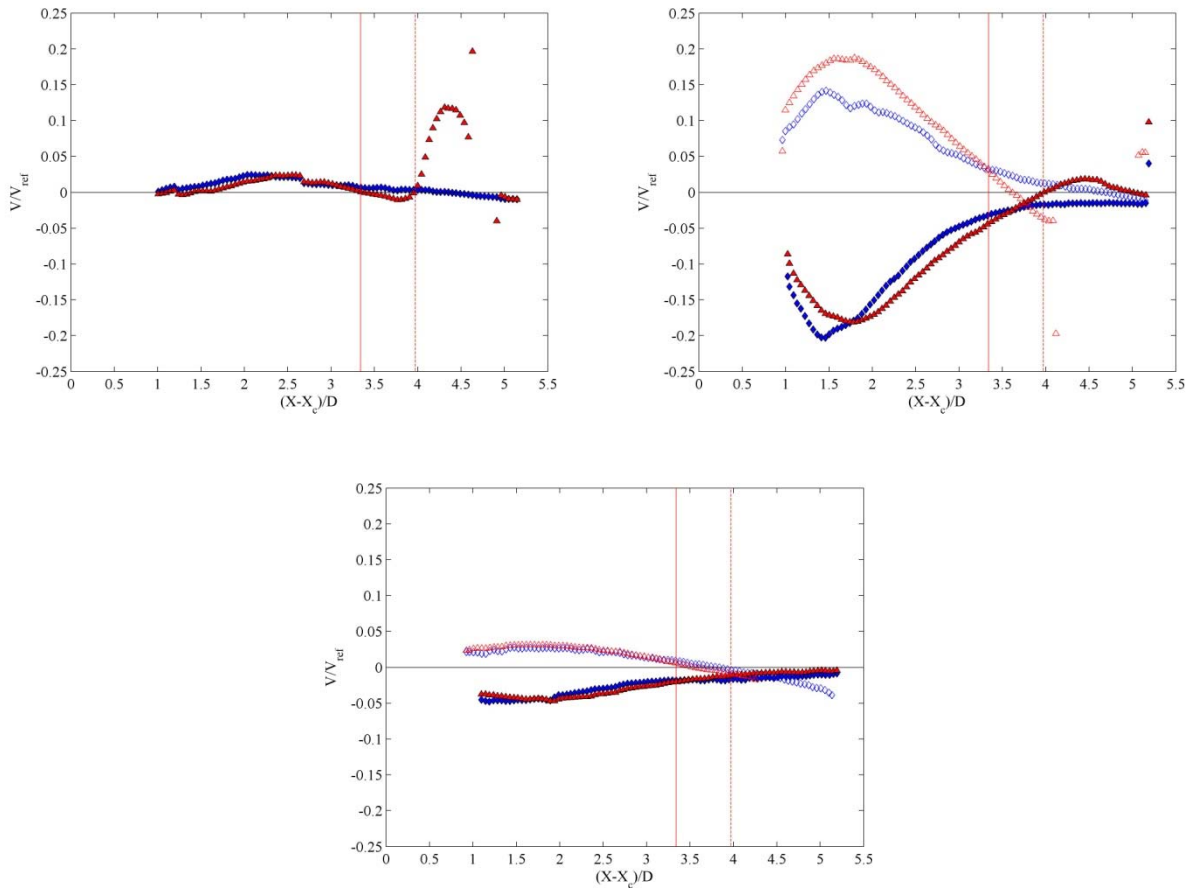


Figure 158. Mean cross-stream velocity (V) scaled with the test section reference velocity (V_{ref}) plotted versus the downstream distance (X) from the cylinder trailing edge (X_c) scaled with the cylinder diameter. The data shown are the average results from all conditions from (upper left) $Y/D = 0$, (upper right) $Y/D = \pm 0.5$ and (lower) $Y/D = \pm 1.3$. The blue symbols are testing without the fin (Part 2b) and the red symbols are with the fin (Part 4). Open symbols correspond to negative- Y locations and solid symbols are positive- Y locations. The two thin red lines downstream show the nominal locations of the fin tip leading edge and the leading edge at the PIV plane ($Z = 188$ mm).

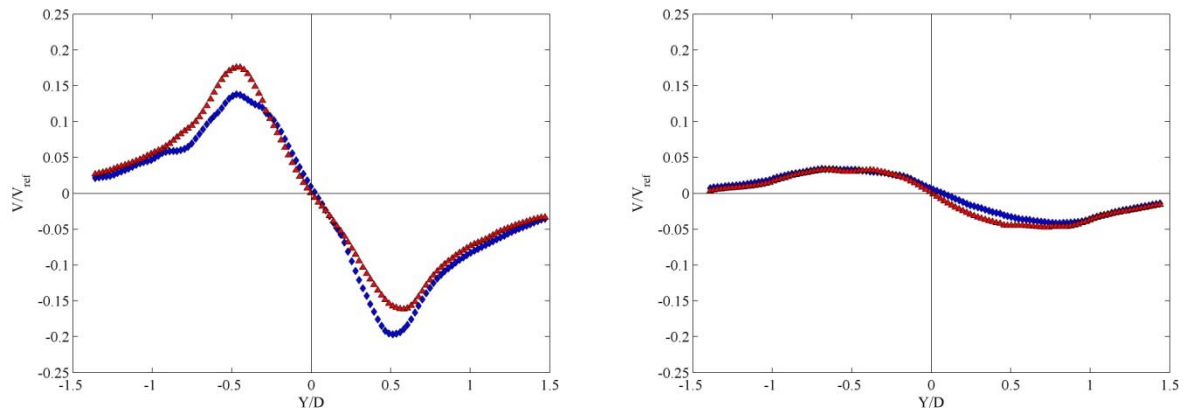


Figure 159. Mean cross-stream velocity (V) scaled with the test section reference velocity (V_{ref}) plotted versus the cross-stream location (Y) scaled with the cylinder diameter. The data shown are the average results from all conditions from (left) the near wake at $(X-X_c)/D = 1.3$ and (right) the far wake near the fin tip leading edge at $(X-X_c)/D = 3.3$. The blue symbols are testing without the fin (Part 2b) and the red symbols are with the fin (Part 4).

B.4 Fluctuating Profiles (Part 2b and Part 4)

This section shows the fluctuating streamwise and cross-stream velocity profiles for the roughened cylinder with and without the fin present.

Fluctuating Streamwise Velocity Profiles

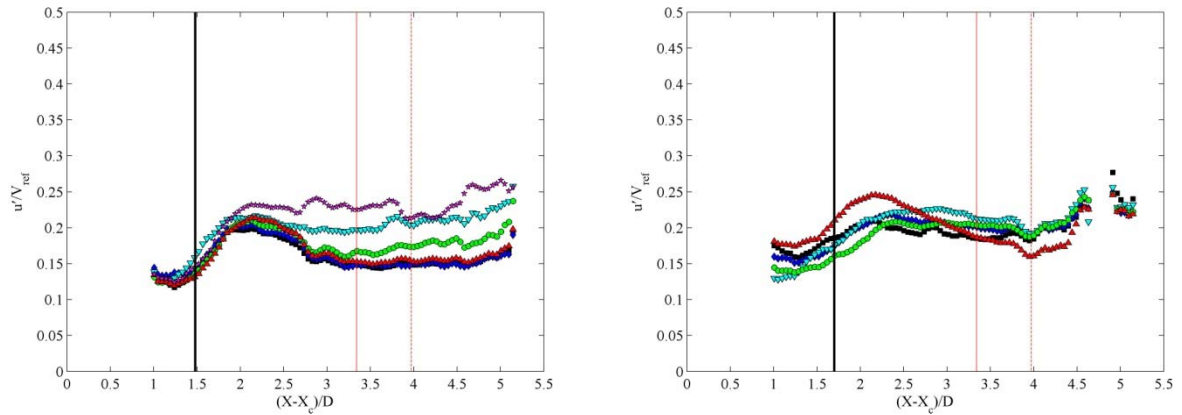


Figure 160. Fluctuating streamwise velocity (u') scaled with the test section reference velocity (V_{ref}) plotted versus the downstream distance (X) from the cylinder trailing edge (X_c) scaled with the cylinder diameter. The data shown are the average results from a given speed from $Y = 0$ mm for (left) the rough cylinder only and (right) rough cylinder with the fin mounted in the wake (Part 4). The symbol colors correspond to (black) $V_{ref} = 2.5$ m/s, (blue) $V_{ref} = 3.0$ m/s, (cyan) $V_{ref} = 3.3$ m/s, (green) $V_{ref} = 3.4$ m/s, (red) $V_{ref} = 3.6$ m/s and (magenta) $V_{ref} = 6.0$ m/s. The solid black line represents the nominal location where the recirculating region ends, which corresponds to $(X-X_c)/D = 1.48$ and 1.7 for the without and with the fin installed, respectively. The two gray lines downstream show the nominal locations of the fin tip leading edge and the leading edge at the PIV plane ($Z = 188$ mm).

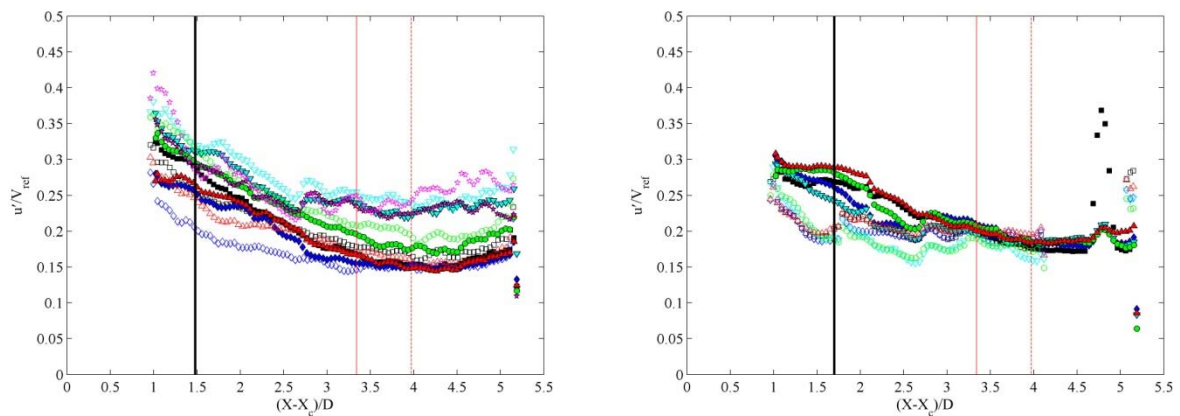


Figure 161. Same caption as Figure 160 except the profiles were acquired at $Y/D = \pm 0.5$. The closed symbols are for data acquired at $Y/D = +0.5$ and the open symbols are from $Y/D = -0.5$. (left image is from Part 2b and right is from Part 4).

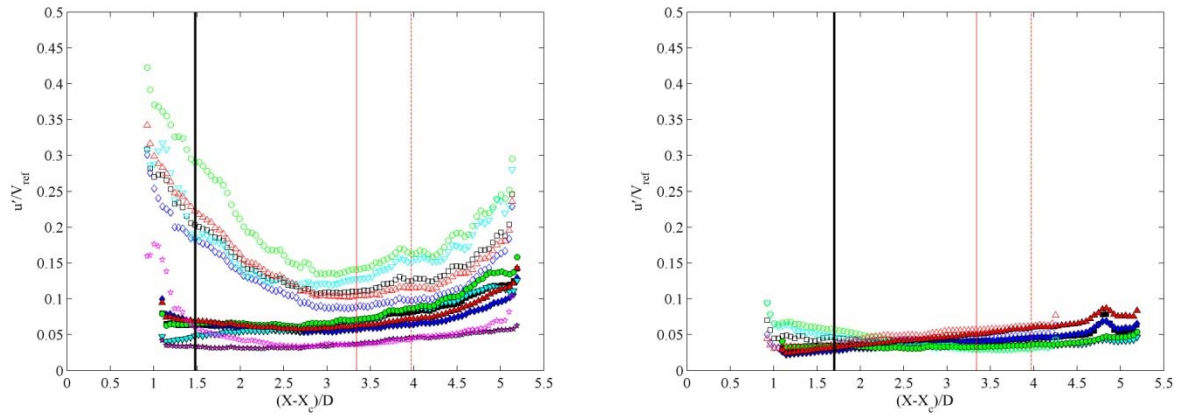


Figure 162. Same caption as Figure 160 except the profiles were acquired at $Y/D = \pm 1.3$. The closed symbols are for data acquired at $Y/D = +1.3$ and the open symbols are from $Y/D = -1.3$. (left image is from Part 2b and right is from Part 4).

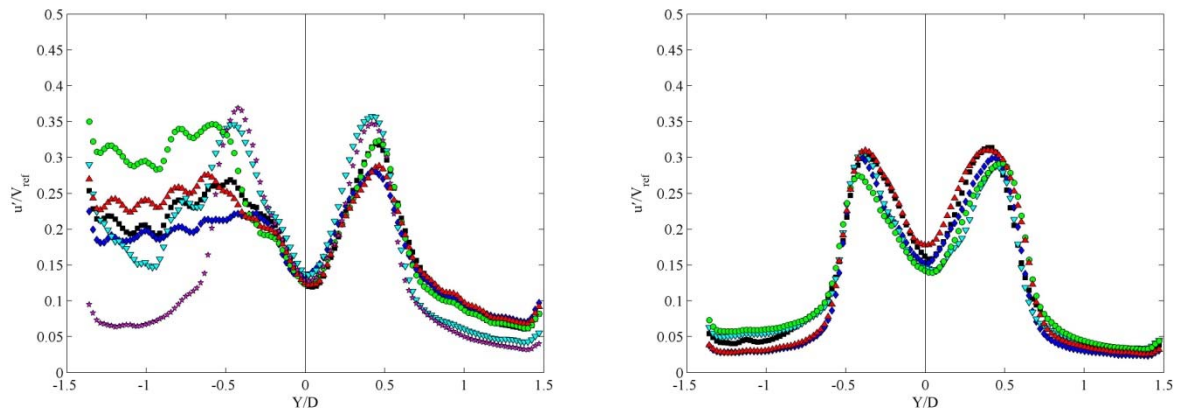


Figure 163. Fluctuating streamwise velocity (u') scaled with the test section reference velocity (V_{ref}) plotted versus the cross-stream direction (Y) scaled with the cylinder diameter. The data shown are the average results from a given speed in the near-wake region ($X = 160$ mm) for (left) the rough cylinder only (Part 2b) and (right) rough cylinder with the fin mounted in the wake (Part 4). The symbol colors correspond to (black) $V_{ref} = 2.5$ m/s, (blue) $V_{ref} = 3.0$ m/s, (cyan) $V_{ref} = 3.3$ m/s, (green) $V_{ref} = 3.4$ m/s, (red) $V_{ref} = 3.6$ m/s and (magenta) $V_{ref} = 6.0$ m/s.

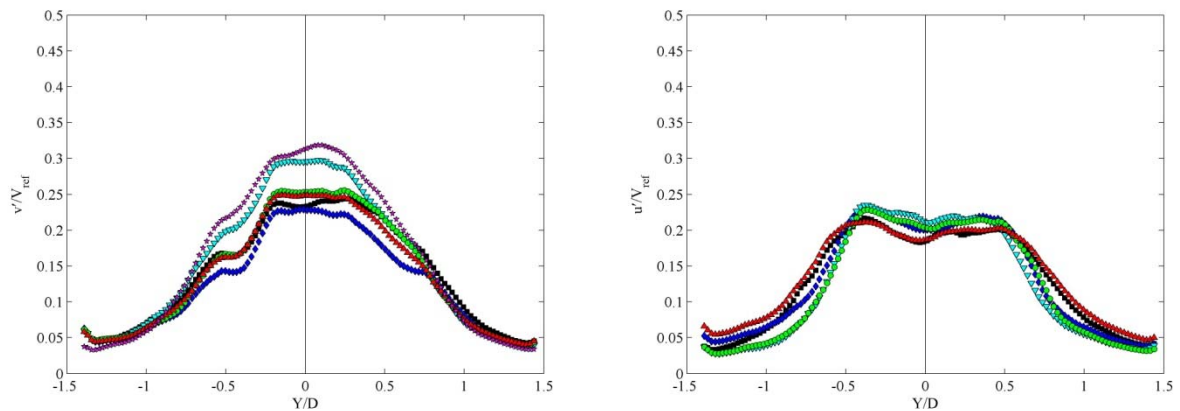


Figure 164. Same caption as Figure 163 except the profiles were acquired in the far wake region near the fin tip leading edge location ($X = 280$ mm). (left image is from Part 2b and right is from Part 4).

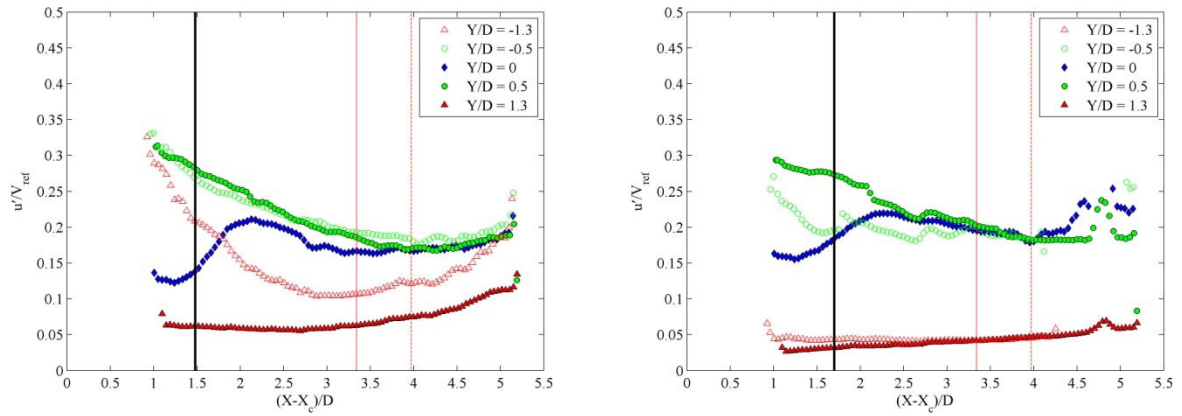


Figure 165. Fluctuating streamwise velocity (u') scaled with the test section reference velocity (V_{ref}) plotted versus the downstream distance (X) from the cylinder trailing edge (X_c) scaled with the cylinder diameter. The data shown are the average results from all conditions from (left) the rough cylinder only testing (Part 2b) and (right) rough cylinder with the fin (Part 4). The solid black line represents the nominal location where the recirculating region ends, which corresponds to $(X-X_c)/D = 1.48$ and 1.7 without and with the fin installed, respectively. The two thin red lines downstream show the nominal locations of the fin tip leading edge and the leading edge at the PIV plane ($Z = 188$ mm).

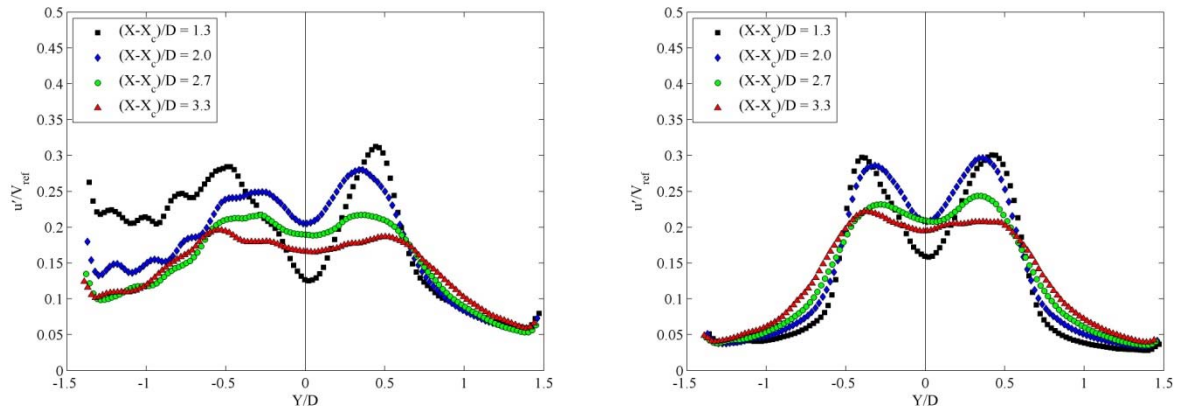


Figure 166. Fluctuating streamwise velocity (u') scaled with the test section reference velocity (V_{ref}) plotted versus the cross-stream location (Y) scaled with the cylinder diameter. The data shown are the average results from all conditions from (left) the rough cylinder only testing (Part 2b) and (right) rough cylinder with the fin (Part 4).

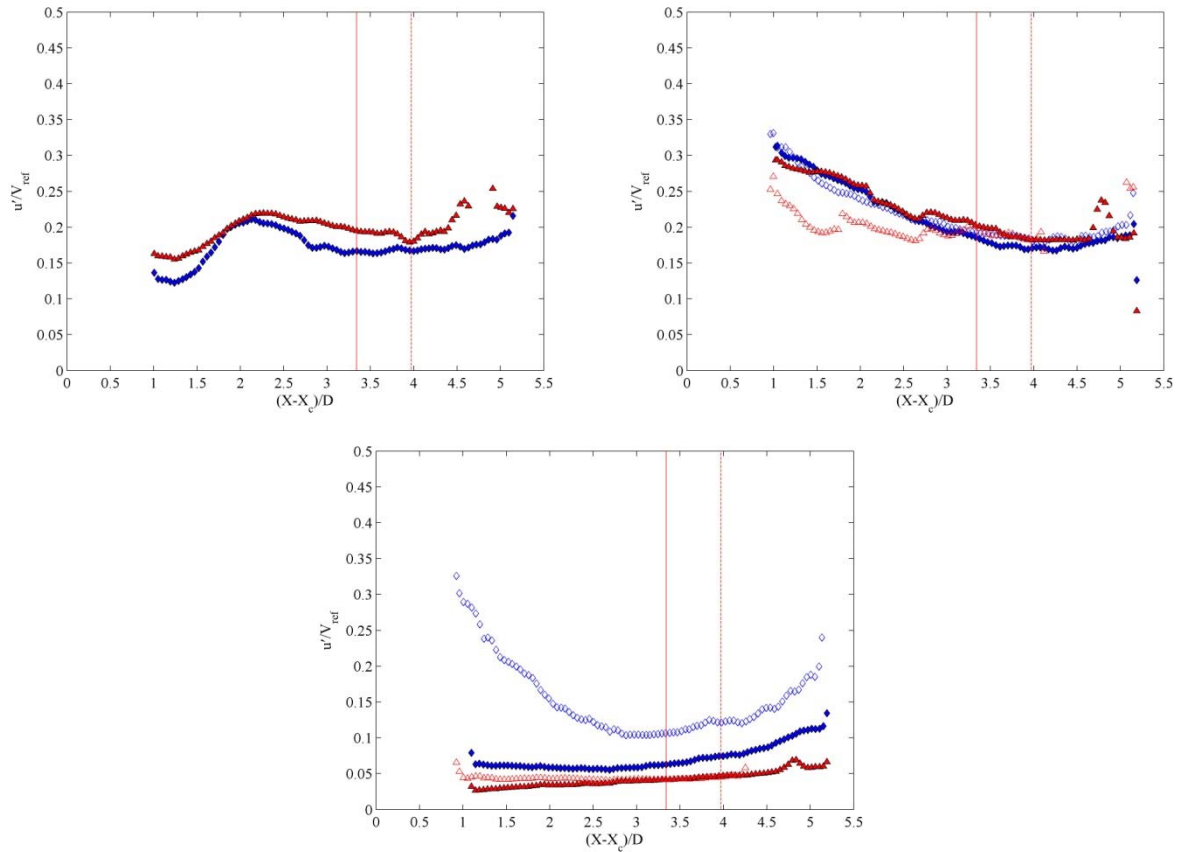


Figure 167. Fluctuating streamwise velocity (u') scaled with the test section reference velocity (V_{ref}) plotted versus the downstream distance (X) from the cylinder trailing edge (X_c) scaled with the cylinder diameter. The data shown are the average results from all conditions from (upper left) $Y/D = 0$, (upper right) $Y/D = \pm 0.5$ and (lower) $Y/D = \pm 1.3$. The blue symbols are testing without the fin (Part 2b) and the red symbols are with the fin (Part 4). Open symbols correspond to negative- Y locations and solid symbols are positive- Y locations. The two thin red lines downstream show the nominal locations of the fin tip leading edge and the leading edge at the PIV plane ($Z = 188$ mm).

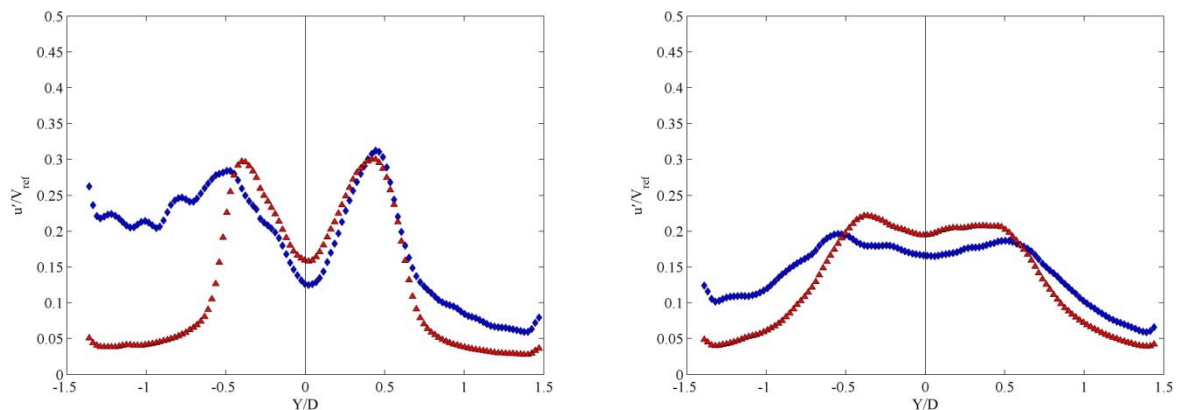


Figure 168. Fluctuating streamwise velocity (u') scaled with the test section reference velocity (V_{ref}) plotted versus the cross-stream location (Y) scaled with the cylinder diameter. The data shown are the average results from all conditions from (left) the near wake at $(X-X_c)/D = 1.3$ and (right) the far wake near the fin tip leading edge at $(X-X_c)/D = 3.3$. The blue symbols are testing without the fin (Part 2b) and the red symbols are with the fin (Part 4).

Fluctuating Cross-Stream Velocity Profiles

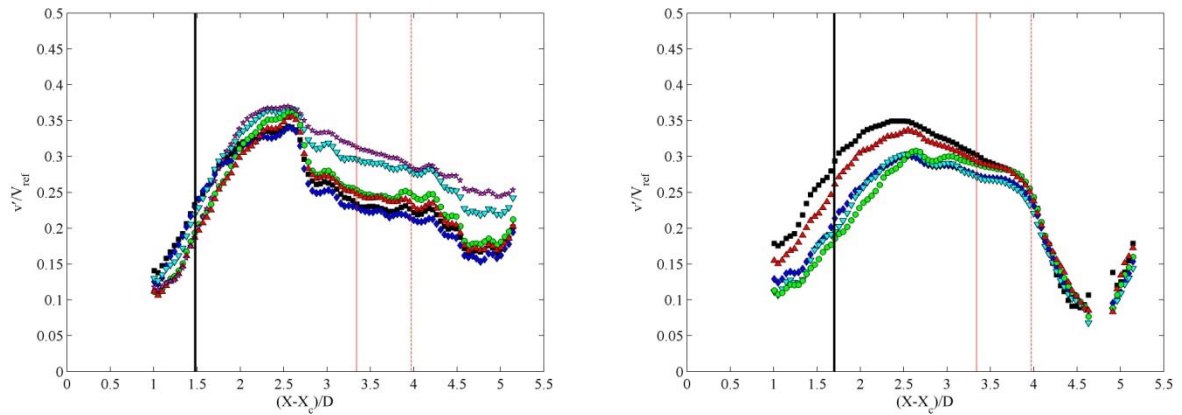


Figure 169. Fluctuating cross-stream velocity (v') scaled with the test section reference velocity (V_{ref}) plotted versus the downstream distance (X) from the cylinder trailing edge (X_c) scaled with the cylinder diameter. The data shown are the average results from a given speed from $Y = 0$ mm for (left) the rough cylinder only and (right) rough cylinder with the fin mounted in the wake (Part 4). The symbol colors correspond to (black) $V_{ref} = 2.5$ m/s, (blue) $V_{ref} = 3.0$ m/s, (cyan) $V_{ref} = 3.3$ m/s, (green) $V_{ref} = 3.4$ m/s, (red) $V_{ref} = 3.6$ m/s and (magenta) $V_{ref} = 6.0$ m/s. The solid black line represents the nominal location where the recirculating region ends, which corresponds to $(X-X_c)/D = 1.48$ and 1.7 for the without and with the fin installed, respectively. The two thin red lines downstream show the nominal locations of the fin tip leading edge and the leading edge at the PIV plane ($Z = 188$ mm).

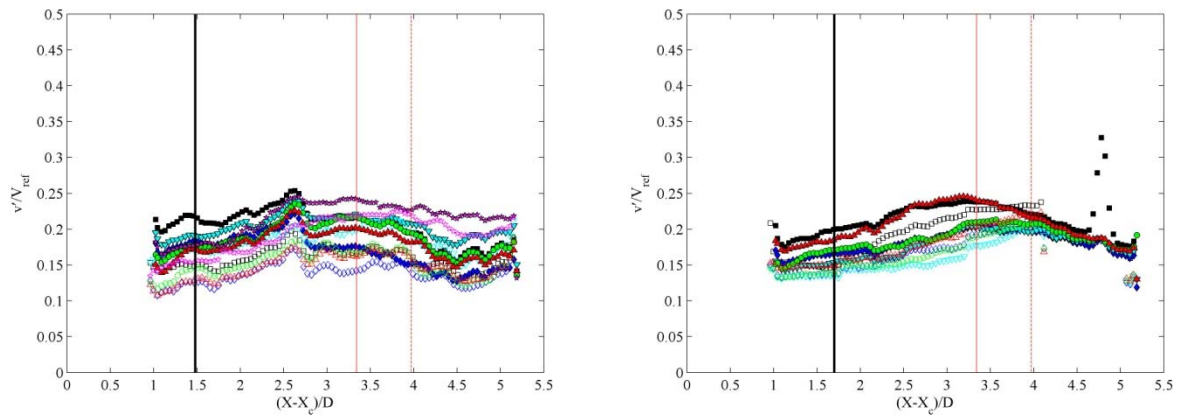


Figure 170. Same caption as Figure 169 except the profiles were acquired at $Y/D = \pm 0.5$. The closed symbols are for data acquired at $Y/D = +0.5$ and the open symbols are from $Y/D = -0.5$. (left image is from Part 2b and right is from Part 4).

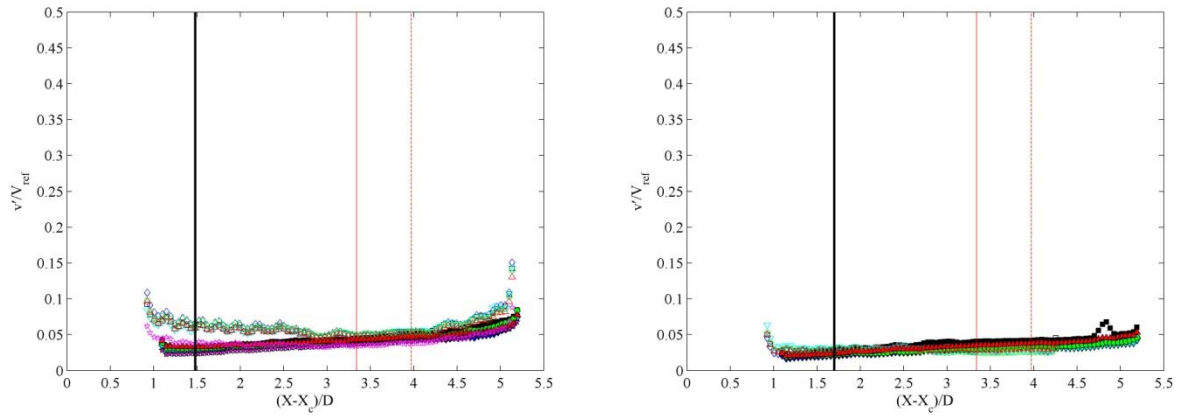


Figure 171. Same caption as Figure 169 except the profiles were acquired at $Y/D = \pm 1.3$. The closed symbols are for data acquired at $Y/D = +1.3$ and the open symbols are from $Y/D = -1.3$. (left image is from Part 2b and right is from Part 4).

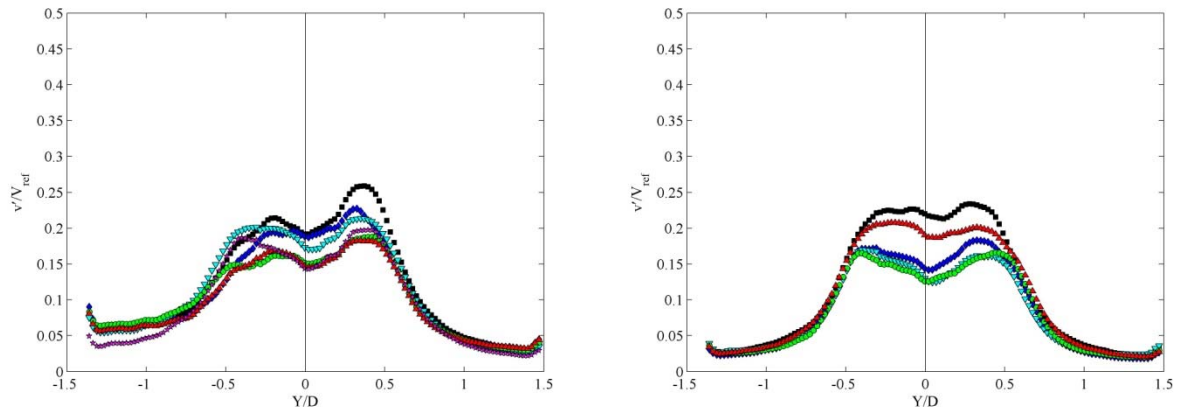


Figure 172. Fluctuating cross-stream velocity (v') scaled with the test section reference velocity (V_{ref}) plotted versus the cross-stream direction (Y) scaled with the cylinder diameter. The data shown are the average results from a given speed in the near-wake region ($X = 160$ mm) for (left) the rough cylinder only (Part 2b) and (right) rough cylinder with the fin mounted in the wake (Part 4). The symbol colors correspond to (black) $V_{ref} = 2.5$ m/s, (blue) $V_{ref} = 3.0$ m/s, (cyan) $V_{ref} = 3.3$ m/s, (green) $V_{ref} = 3.4$ m/s, (red) $V_{ref} = 3.6$ m/s and (magenta) $V_{ref} = 6.0$ m/s.

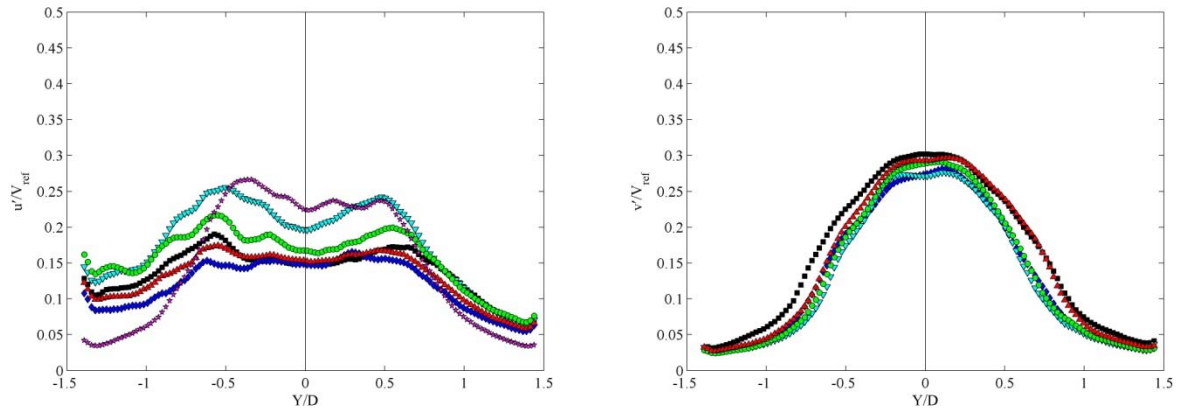


Figure 173. Same caption as Figure 172 except the profiles were acquired in the far wake region near the fin tip leading edge location ($X = 280$ mm). (left image is from Part 2b and right is from Part 4).

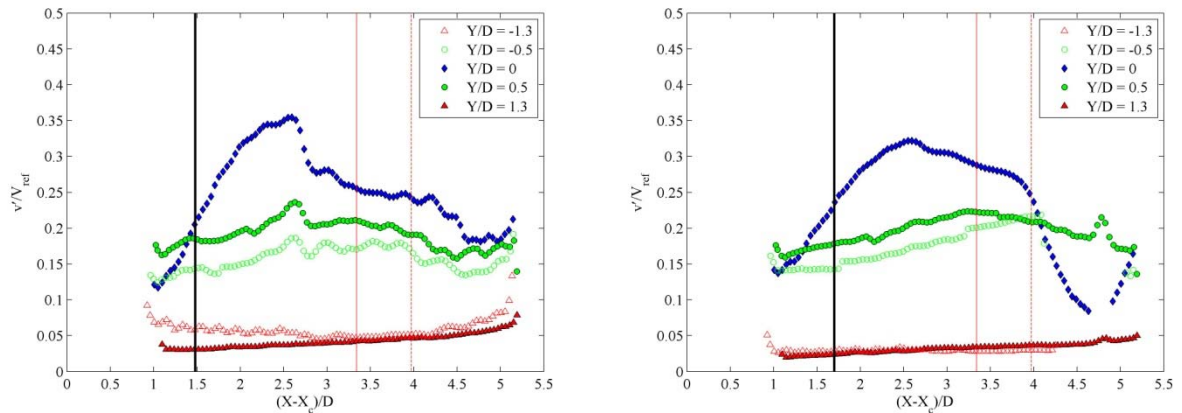


Figure 174. Scaled fluctuating cross-stream velocity (v'/V_{ref}) plotted versus the scaled downstream distance from the cylinder trailing edge, $(X-X_c)/D$. The data shown are the average results from all conditions from (left) the rough cylinder only (Part 2b) and (right) rough cylinder with the fin (Part 4). The solid black line represents the nominal location where the recirculating zone ends, which corresponds to $(X-X_c)/D = 1.48$ and 1.7 without and with the fin installed, respectively. The two thin red lines downstream show the nominal locations of the fin tip leading edge and the leading edge at the PIV plane ($Z = 188$ mm).

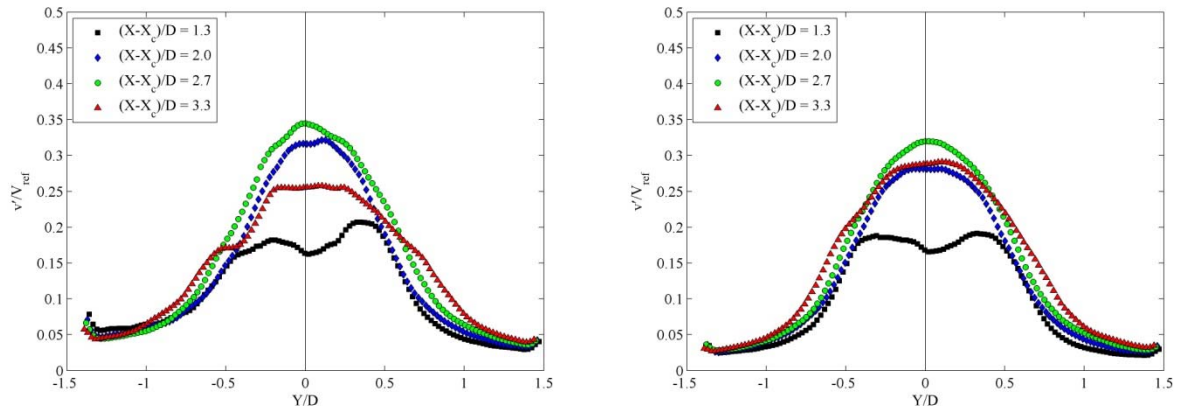


Figure 175. Fluctuating cross-stream velocity (v') scaled with the test section reference velocity (V_{ref}) plotted versus the cross-stream location (Y) scaled with the cylinder diameter. The data shown are the average results from all conditions from (left) the rough cylinder only testing (Part 2b) and (right) rough cylinder with the fin (Part 4).

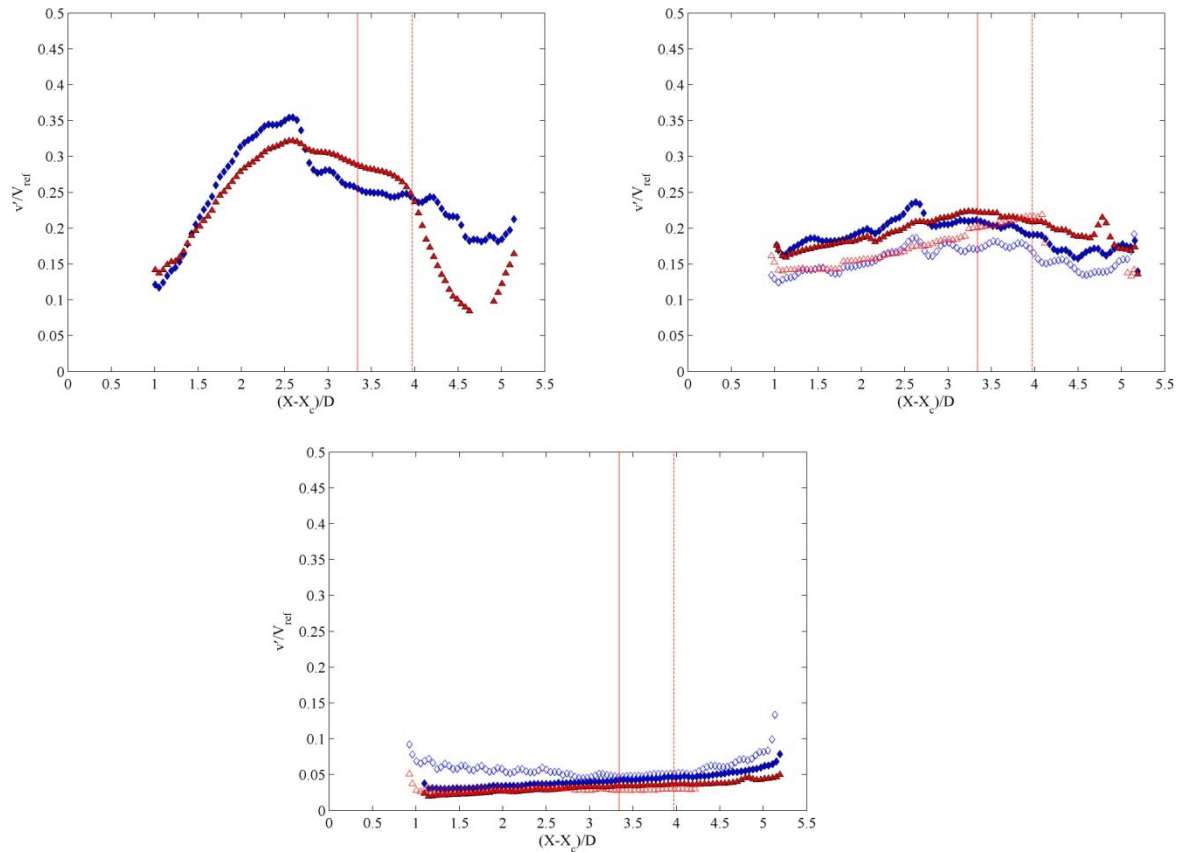


Figure 176. Fluctuating cross-stream velocity (v') scaled with the test section reference velocity (V_{ref}) plotted versus the downstream distance (X) from the cylinder trailing edge (X_c) scaled with the cylinder diameter. The data shown are the average results from all conditions from (upper left) $Y/D = 0$, (upper right) $Y/D = \pm 0.5$ and (lower) $Y/D = \pm 1.3$. The blue symbols are testing without the fin (Part 2b) and the red symbols are with the fin (Part 4). Open symbols correspond to negative- Y locations and solid symbols are positive- Y locations. The two thin red lines downstream show the nominal locations of the fin tip leading edge and the leading edge at the PIV plane ($Z = 188$ mm).

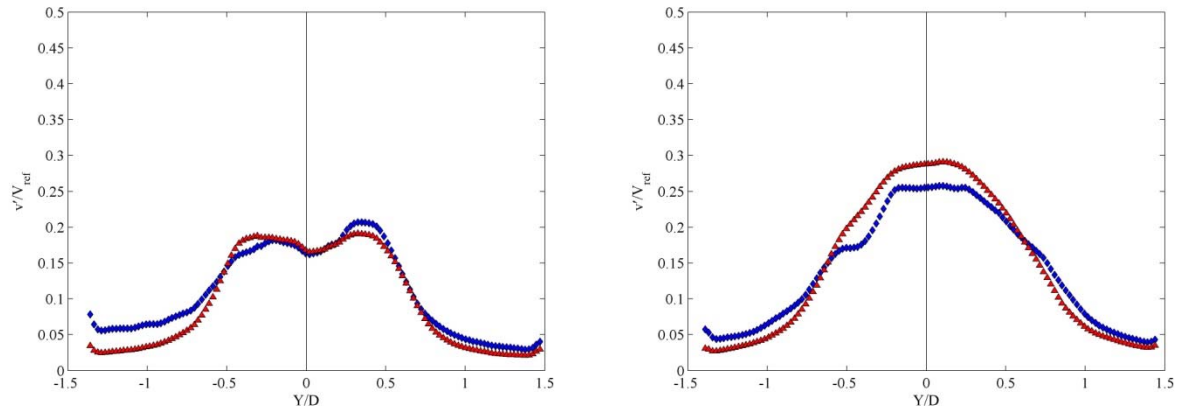


Figure 177. Fluctuating cross-stream velocity (v') scaled with the test section reference velocity (V_{ref}) plotted versus the cross-stream location (Y) scaled with the cylinder diameter. The data shown are the average results from all conditions from (left) the near wake at $(X-X_c)/D = 1.3$ and (right) the far wake near the fin tip leading edge at $(X-X_c)/D = 3.3$. The blue symbols are testing without the fin (Part 2b) and the red symbols are with the fin (Part 4).

B.5 Angle-of-Attack Profiles (Part 2b and Part 4)

This section shows the mean flow-field angle-of-attack of the fin relative to the streamwise direction.

Profiles of the Relative Angle-of-Attack

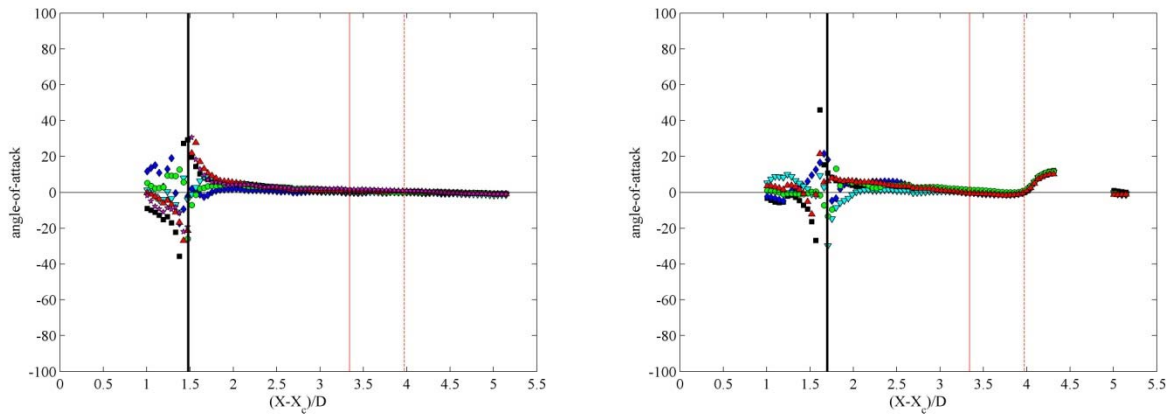


Figure 178. Mean flow-field angle-of-attack measured relative to the streamwise direction, $\alpha_{\text{flow}} = \tan^{-1}(V/U)$, plotted versus the downstream distance (X) from the cylinder trailing edge (X_c) scaled with the cylinder diameter. The data shown are the average results from a given speed from $Y = 0$ mm for (left) the rough cylinder only and (right) rough cylinder with the fin mounted in the wake (Part 4). The symbol colors correspond to (black) $V_{\text{ref}} = 2.5$ m/s, (blue) $V_{\text{ref}} = 3.0$ m/s, (cyan) $V_{\text{ref}} = 3.3$ m/s, (green) $V_{\text{ref}} = 3.4$ m/s, (red) $V_{\text{ref}} = 3.6$ m/s and (magenta) $V_{\text{ref}} = 6.0$ m/s. The solid black line represents the nominal location where the recirculating region ends, which corresponds to $(X-X_c)/D = 1.48$ and 1.7 for the without and with the fin installed, respectively. The two thin red lines downstream show the nominal locations of the fin tip leading edge and the leading edge at the PIV plane ($Z = 188$ mm).

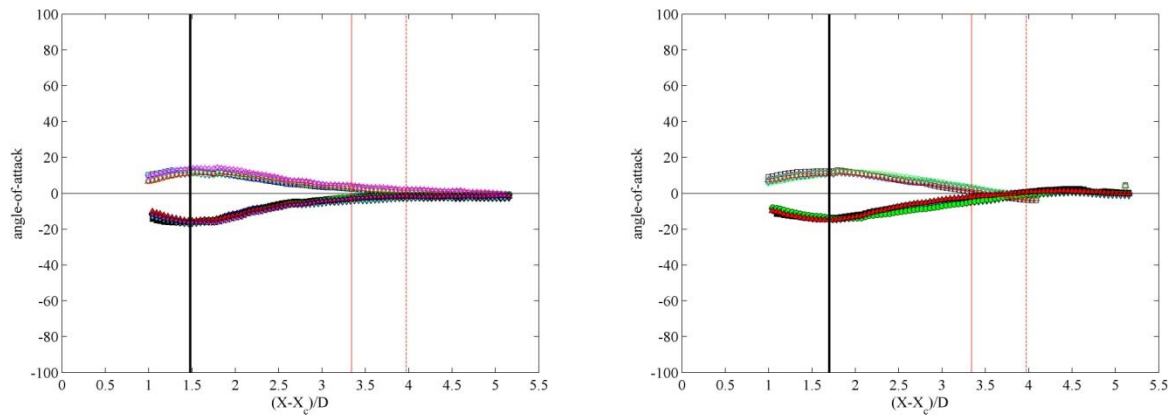


Figure 179. Same caption as Figure 178 except the profiles were acquired at $Y/D = \pm 0.5$. The closed symbols are for data acquired at $Y/D = +0.5$ and the open symbols are from $Y/D = -0.5$. (left image is from Part 2b and right is from Part 4).

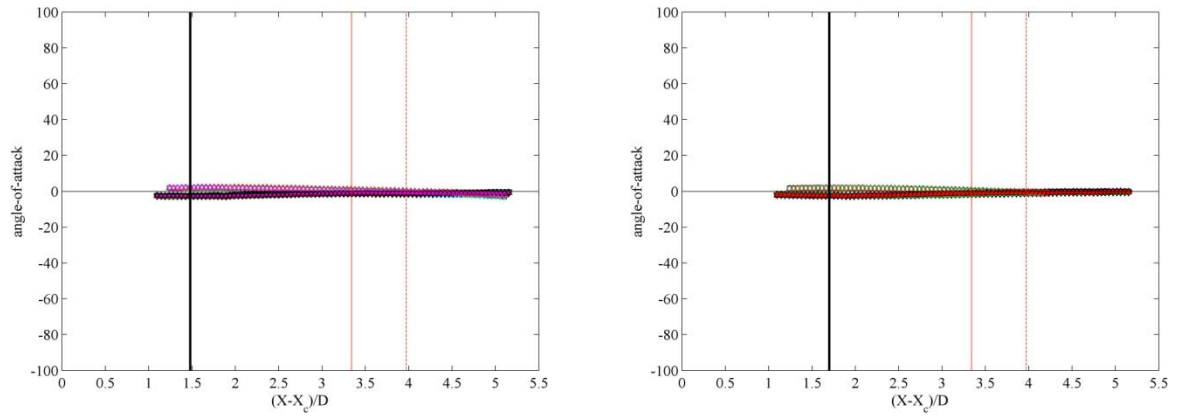


Figure 180. Same caption as Figure 178 except the profiles were acquired at $Y/D = \pm 1.3$. The closed symbols are for data acquired at $Y/D = +1.3$ and the open symbols are from $Y/D = -1.3$. (left image is from Part 2b and right is from Part 4).

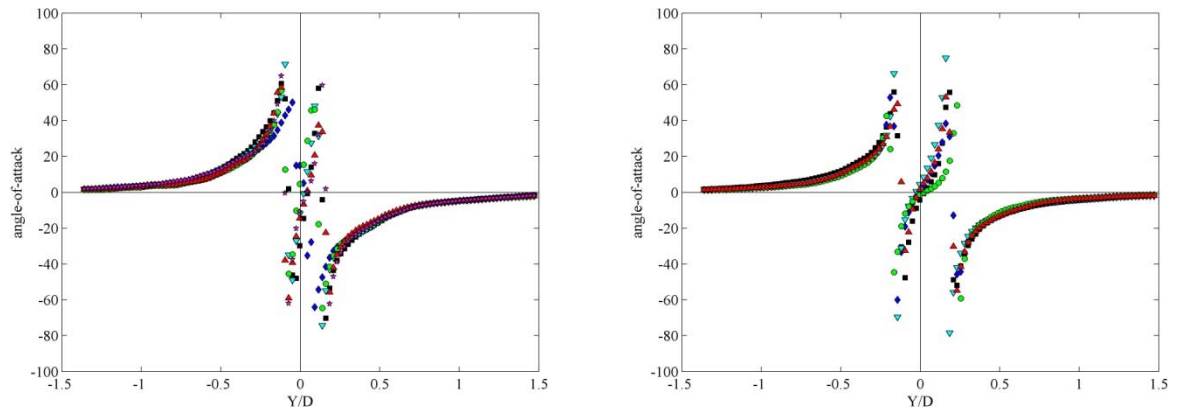


Figure 181. Mean flow-field angle-of-attack measured relative to the streamwise direction, $\alpha_{\text{flow}} = \tan^{-1}(V/U)$, plotted versus the cross-stream direction (Y) scaled with the cylinder diameter. The data shown are the average results from a given speed in the near-wake region ($X = 160$ mm) for (left) the rough cylinder only (Part 2b) and (right) rough cylinder with the fin mounted in the wake (Part 4). The symbol colors correspond to (black) $V_{\text{ref}} = 2.5$ m/s, (blue) $V_{\text{ref}} = 3.0$ m/s, (cyan) $V_{\text{ref}} = 3.3$ m/s, (green) $V_{\text{ref}} = 3.4$ m/s, (red) $V_{\text{ref}} = 3.6$ m/s and (magenta) $V_{\text{ref}} = 6.0$ m/s.

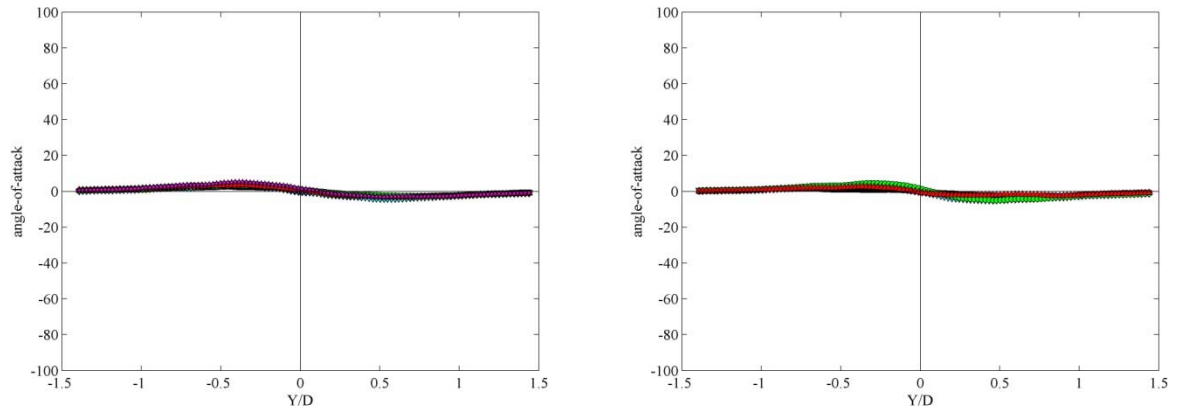


Figure 182. Same caption as Figure 181 except the profiles were acquired in the far wake region near the fin tip leading edge location ($X = 280$ mm). (left image is from Part 2b and right is from Part 4).

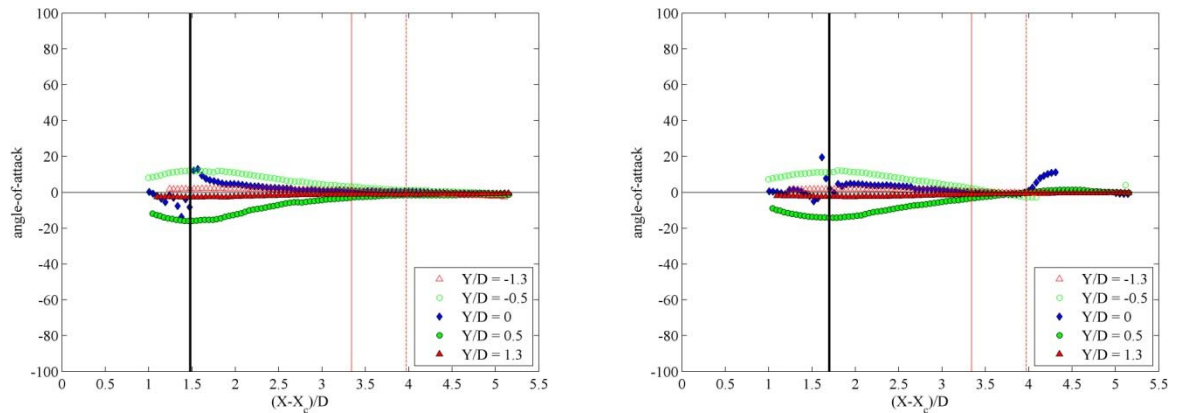


Figure 183. Mean flow-field angle-of-attack measured relative to the streamwise direction, $\alpha_{\text{flow}} = \tan^{-1}(V/U)$, plotted versus the downstream distance (X) from the cylinder trailing edge (X_c) scaled with the cylinder diameter. The data shown are the average results from all conditions from (left) the rough cylinder only testing (Part 2b) and (right) rough cylinder with the fin (Part 4). The solid black line represents the nominal location where the recirculating region ends, which corresponds to $(X - X_c)/D = 1.48$ and 1.7 without and with the fin installed, respectively. The two thin red lines downstream show the nominal locations of the fin tip leading edge and the leading edge at the PIV plane ($Z = 188$ mm).

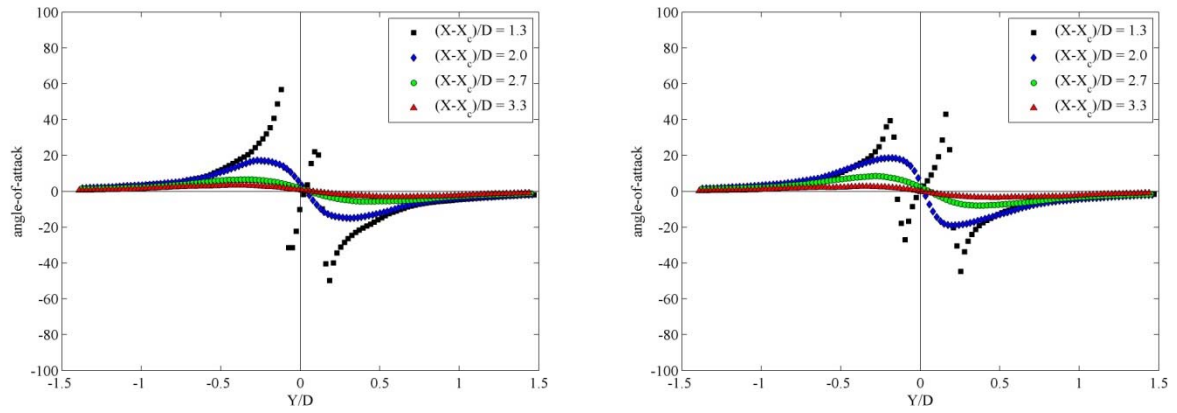


Figure 184. Mean flow-field angle-of-attack measured relative to the streamwise direction, $\alpha_{\text{flow}} = \tan^{-1}(V/U)$, plotted versus the cross-stream location (Y) scaled with the cylinder diameter. The data shown are the average results from all conditions from (left) the rough cylinder only testing (Part 2b) and (right) rough cylinder with the fin (Part 4).

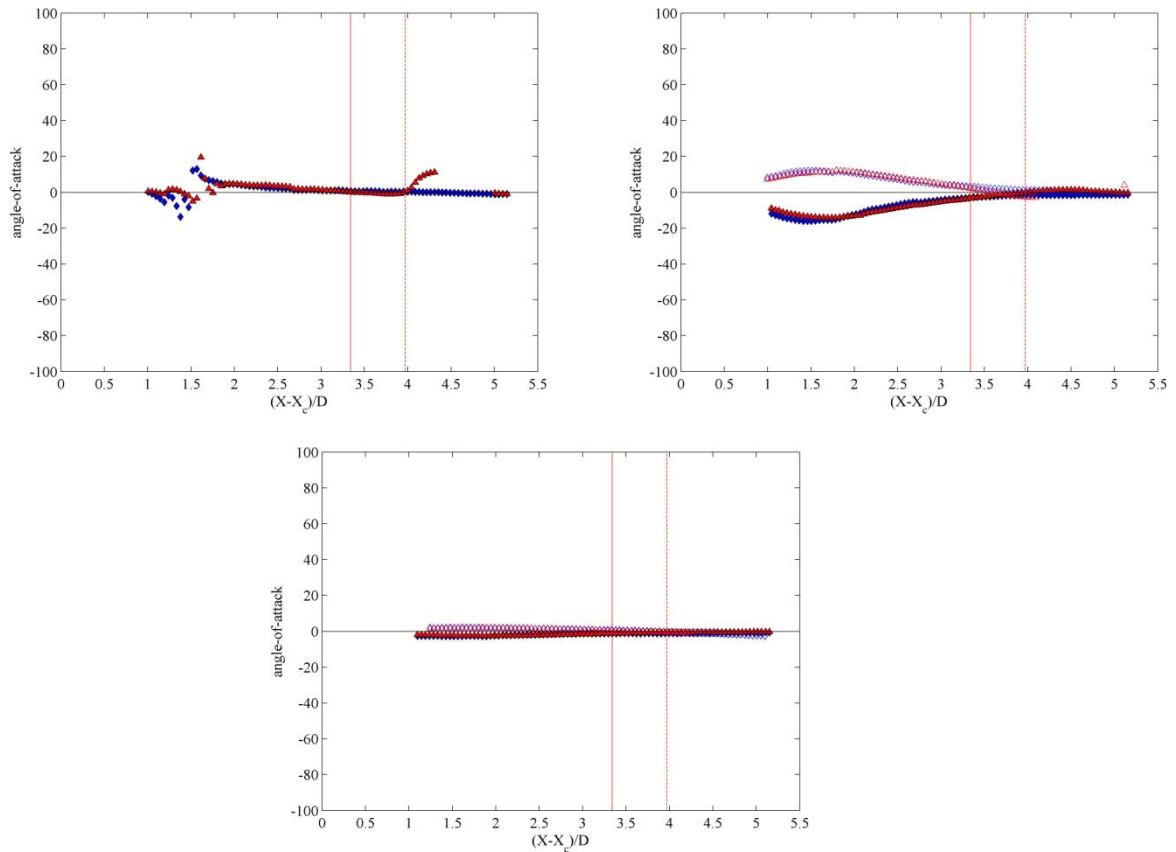


Figure 185. Mean flow-field angle-of-attack measured relative to the streamwise direction, $\alpha_{\text{flow}} = \tan^{-1}(V/U)$, plotted versus the downstream distance (X) from the cylinder trailing edge (X_c) scaled with the cylinder diameter. The data shown are the average results from all conditions from (upper left) $Y/D = 0$, (upper right) $Y/D = \pm 0.5$ and (lower) $Y/D = \pm 1.3$. The blue symbols are testing without the fin (Part 2b) and the red symbols are with the fin (Part 4). Open symbols correspond to negative- Y locations and solid symbols are positive- Y locations. The two thin red lines downstream show the nominal locations of the fin tip leading edge and the leading edge at the PIV plane ($Z = 188$ mm).

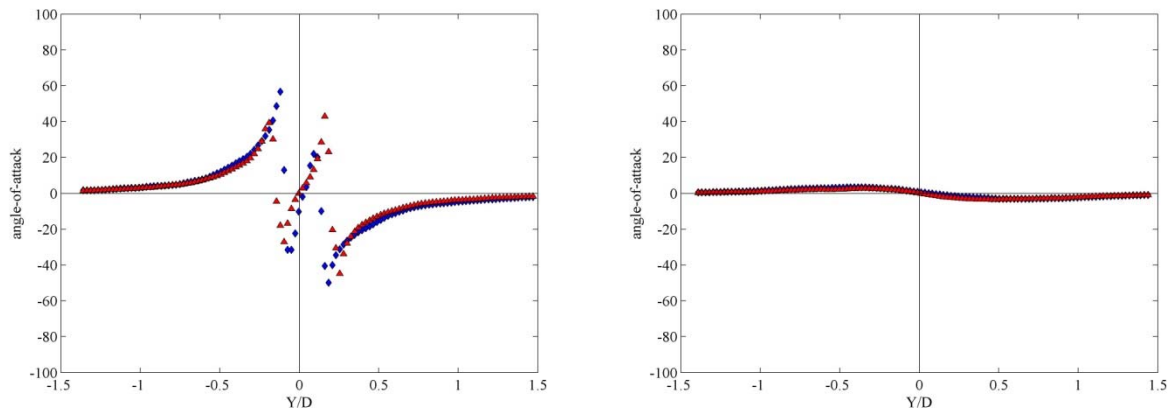


Figure 186. Mean flow-field angle-of-attack measured relative to the streamwise direction, $\alpha_{\text{flow}} = \tan^{-1}(V/U)$, plotted versus the cross-stream location (Y) scaled with the cylinder diameter. The data shown are the average results from all conditions from (left) the near wake at $(X-X_c)/D = 1.3$ and (right) the far wake near the fin tip leading edge at $(X-X_c)/D = 3.3$. The blue symbols are testing without the fin (Part 2b) and the red symbols are with the fin (Part 4).

Appendix C: Database Summary

C.1 Steady Data

Filename: **HMMR_Phase2_MasterLog.xlsx**

Part 1 *Excel spreadsheet tab (empty test section testing)*

Run Information

Column 1 – test number

Column 2 – run number

Column 3 – target f_{imp} (rpm), nominal tunnel impeller frequency

Steady

Column 4 – f_{imp} (rpm), measured average tunnel impeller frequency

Column 5 – V_{ref} (m/s), measured test section reference velocity

Column 6 – P_{total} (kPa), measured total tunnel pressure

Column 7 – T (°C), measured water temperature

Column 8 – ν (m²/s), water kinematic viscosity determined from water temperature

Column 9 – ρ (kg/m³), water density determined from water temperature

Part 2a *Excel spreadsheet tab (smooth cylinder only testing)*

Run Information

Column 1 – test number

Column 2 – run number

Column 3 – target f_{imp} (rpm), nominal tunnel impeller frequency

Steady

Column 4 – f_{imp} (rpm), measured average tunnel impeller frequency

Column 5 – V_{ref} (m/s), measured test section reference velocity

Column 6 – P_{total} (kPa), measured total tunnel pressure

Column 7 – T (°C), measured water temperature

Column 8 – ν (m²/s), water kinematic viscosity determined from water temperature

Column 9 – ρ (kg/m³), water density determined from water temperature

Column 10 – Re_D , blockage corrected cylinder diameter based Reynolds number

Column 11 – C_{pb} , cylinder average static base pressure coefficient

Part 2b *Excel spreadsheet tab (rough cylinder only testing)*

Run Information

Column 1 – test number

Column 2 – run number

Column 3 – target f_{imp} (rpm), nominal tunnel impeller frequency

Steady

Column 4 – f_{imp} (rpm), measured average tunnel impeller frequency

Column 5 – V_{ref} (m/s), measured test section reference velocity

Column 6 – P_{total} (kPa), measured total tunnel pressure

Column 7 – T (°C), measured water temperature

Column 8 – ν (m²/s), water kinematic viscosity determined from water temperature

Column 9 – ρ (kg/m³), water density determined from water temperature

Column 10 – Re_D , blockage corrected cylinder diameter based Reynolds number

Column 11 – C_{pb} , cylinder average static base pressure coefficient

Unsteady

Column 12 – Unsteady PIV images, number of PIV images acquired for given run

PSD – Dynamic Press

Column 13 –freq (Hz), shedding frequency determined from the dynamic pressure

Column 14 – dynamic press (rms Pa), fluctuating pressure at the shedding frequency

Part 4 (with mechanical stop) *Excel spreadsheet tab (forced fin testing)*

Run Information

Column 1 – test number

Column 2 – run number

Column 3 – target f_{imp} (rpm), nominal tunnel impeller frequency

Steady

Column 4 – f_{imp} (rpm), measured average tunnel impeller frequency

Column 5 – V_{ref} (m/s), measured test section reference velocity

Column 6 – P_{total} (kPa), measured total tunnel pressure

Column 7 – T (°C), measured water temperature

Column 8 – ν (m²/s), water kinematic viscosity determined from water temperature

Column 9 – ρ (kg/m³), water density determined from water temperature

Column 10 – AoA (deg), measured angle of attack at the fin base

Column 11 – Re_D , blockage corrected cylinder diameter based Reynolds number

Column 12 – C_{pb} , cylinder average static base pressure coefficient

Column 13 – Mean fin tip deflection (mm), average deflection of the fin tip

Column 14 – Mean fin tip twist (deg), average twist of the fin tip

Power Spectral Density Analysis Results

Column 15 – loading freq (Hz), shedding frequency determined from the average of the four load measurements

Column 16 – loading Lift (rms N), fluctuating lift force at the shedding frequency

Column 17 – loading Drag (rms N), fluctuating drag force at the shedding frequency

Column 18 – loading Torq (rms Nm), fluctuating torque moment at the shedding frequency

Column 19 – loading DM (rms Nm), fluctuating drag moment at the shedding frequency

Column 20 – dynamic pressure freq (Hz), shedding frequency determined from the average of the dynamic pressure measurements

Column 21 – dynamic pressure (rms Pa), fluctuating pressure at the shedding frequency

Part 4 (without mechanical stop) *Excel spreadsheet tab (forced fin test)*

Run Information

Column 1 – test number

Column 2 – run number

Column 3 – target f_{imp} (rpm), nominal tunnel impeller frequency

Steady

Column 4 – f_{imp} (rpm), measured average tunnel impeller frequency

Column 5 – V_{ref} (m/s), measured test section reference velocity

Column 6 – P_{total} (kPa), measured total tunnel pressure

Column 7 – T (°C), measured water temperature

Column 8 – ν (m²/s), water kinematic viscosity determined from water temperature

Column 9 – ρ (kg/m³), water density determined from water temperature

Column 10 – AoA (deg), measured angle of attack at the fin base

Column 11 – Re_D , blockage corrected cylinder diameter based Reynolds number

Column 12 – C_{pb} , cylinder average static base pressure coefficient
 Column 13 – Mean fin tip deflection (mm), average deflection of the fin tip
 Column 14 – Mean fin tip twist (deg), average twist of the fin tip

Synchronized

Column 15 – whether synchronized PIV data is available for this run (0 – no, 1 – yes)
 Column 16 – whether synchronized Fin Tip data is available for this run (0 – no, 1 – yes)
 Column 17 – whether synchronized Loading data is available for this run (0 – no, 1 – yes)
 Column 18 – Samples, number of points/images available at 1 kHz

Power Spectral Density Analysis Results

Column 19 – loading freq (Hz), shedding frequency determined from the average of the four load measurements
 Column 20 – loading Lift (rms N), fluctuating lift force at the shedding frequency
 Column 21 – loading Drag (rms N), fluctuating drag force at the shedding frequency
 Column 22 – loading Torq (rms Nm), fluctuating torque moment at the shedding frequency
 Column 23 – loading DM (rms Nm), fluctuating drag moment at the shedding frequency
 Column 24 – fin tip deflection freq (Hz), the dominate frequency determined from the fin tip motion measurements
 Column 25 – fin tip deflection (mm pk-pk), peak-to-peak fin tip motion
 Column 26 – fin surface LV freq (Hz), the dominate frequency determined from the laser vibrometer surface measurements
 Column 27 – fin surface LV (mm pk-pk), peak-to-peak fin surface motion
 Column 28 – PIV (single point) freq (Hz), shedding frequency determined from the average of cross-stream velocity (V) measurements at (X,Y) = (200 mm, ± 15 mm) and (279 mm, ± 15 mm)
 Column 29 – PIV (single point) US (m/s pk), peak-to-peak cross-stream fluctuating velocity the upstream points (X,Y) = (200 mm, ± 15 mm)
 Column 30 – PIV (single point) DS (m/s pk), peak-to-peak cross-stream fluctuating velocity the downstream points (X,Y) = (279 mm, ± 15 mm)
 Column 31 – dynamic pressure freq (Hz), shedding frequency determined from the average of the dynamic pressure measurements
 Column 32 – dynamic pressure (rms Pa), fluctuating pressure at the shedding frequency

C.2 Time Trace Data

Filename: **HMMR_Phase2_Part4_TimeTraces.mat**

data.list *list of conditions*

Column 1 – test number
 Column 2 – run number
 Column 3 – total number of images
 Column 4 – pixels/mm for the acquired image
 Column 5 – time in seconds from beginning of NI system time trace to start of image acquisition
 Column 6 – if PIV data is available (0 – not available, 1 – available)

data.(TEST).(RUN).data *time trace data for each run with high-speed video or PIV*

Column 1 – time (seconds)

Column 2 – lift force (lbs)
 Column 3 – drag force (lbs)
 Column 4 – torque moment (in-lb)
 Column 5 – drag moment (in-lb)
 Column 6 – fin tip deflection (mm)
 Column 7 – fin tip twist (degrees)
 Column 8 – streamwise inlet flow velocity (U) at (X, Y) = (260 mm, 0 mm)
 Column 9 – cross-stream inlet flow velocity (V) at (X, Y) = (260 mm, 0 mm)

```

test = list(i,1)
run = list(i,2)
TEST = strcat('test',num2str(test));
RUN = strcat('run',num2str(run));
  
```

Filename(s): **HMMR_(TEST)_(RUN).mat**

filename *name of the file that the data was saved/opened with*

list *log of all the conditions and the tunnel operating condition*

Column 1 – test number
 Column 2 – run number
 Column 3 – vector spacing in the X-direction (mm)
 Column 4 – X-reference point used for data processing
 Column 5 – vector spacing in the Y-direction (mm)
 Column 6 – Y-reference point used for data processing
 Column 7 – tunnel impeller frequency (f_{imp}) in RPM
 Column 8 – test section reference velocity (V_{ref}) in meters/second
 Column 9 – water density (ρ) in kg/m^3
 Column 10 – water kinematic viscosity (ν) in m^2/s

Data *instantaneous vector fields for the given run (3D matrix)*

Column 1 – streamwise position (X) in millimeters	$\text{Data}(:,1,k)$
Column 2 – cross-stream position (Y) in millimeters	$\text{Data}(:,2,k)$
Column 3 – streamwise velocity (U) in meters/second	$\text{Data}(:,3,k)$
Column 4 – cross-stream velocity (V) in meters/second	$\text{Data}(:,4,k)$

k – each k values corresponds to a given time sample with the sample rate = 1,000 Hz
 $\text{time} = (0:d-1)/fs$ where d = total # of images, fs = sample rate

X range	$140 \text{ mm} \leq X \leq 320 \text{ mm}$
Y range	$-75 \text{ mm} \leq Y \leq 90 \text{ mm}$ (for tests 42 and 75)
	$-30 \text{ mm} \leq Y \leq 90 \text{ mm}$ (for test 79)

Bad vectors are fixed at zero and should be omitted when analyzing data.