SPIV Measurements of Axisymmetric Turbulent Boundary Layers

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Abstract- This paper presents a description of turbulent boundary layer velocity measurements made on an experimental towed array during testing at the David Taylor Model Basin, Naval Surface Warfare Center Carderock Division in June 2007. The experimental array had an aspect ratio \( L/a = 7 \times 10^3 \) and was towed at Reynolds numbers \( Re \) varying from \( 4.6 \times 10^5 \) to \( 8.9 \times 10^5 \). This range falls well outside that which has been investigated to date in laboratories or with computational fluid dynamics. Previous lake tests of this array were performed and documented in Cipolla and Keith [1]. However, details of the high Reynolds turbulent boundary layer were not obtained during these tests. The goal of the follow-on tow tank testing was to obtain measurements of the mean and turbulent flow field which are not feasible in lake or sea trial testing.

A stationary stereo-particle image velocimetry (SPIV) system was used to obtain three-dimensional velocity measurements and evaluate the boundary layer flow development along full-scale fleet towed array modules. Measurements were collected at discrete transverse planes along the length at tow speeds between 6.2 and 15.4 m/s. Algorithms for image pre-processing and filtering were applied to enhance the instantaneous images and mask the array and its shadow. The data will be analyzed to extract mean velocity profiles and compared with wind tunnel measurements on cylinders [2]. Further, relevant boundary layer parameters will be used to refine the scaling of the wall pressure measurements obtained simultaneously as reported by [3]. Independent load cell measurements of the total drag on the towed model provided the momentum thickness at the end of the model and the spatially-averaged friction velocity \( u_\tau \). These data supplement the SPIV data near the array wall, completing the velocity profile over the entire boundary layer. The load cell also provided a highly accurate value of the mean wall shear stress which is traditionally very difficult to obtain.

The velocity profiles can be compared with existing models for the mean velocity which include the velocity defect law and Clauser’s log law. In particular, the velocity defect law is expected to provide the best collapse of the data in the outer region of the boundary layer, while the log law relation is expected to provide a good collapse very close to the surface of the towed array (near wall region). Trends in the data with Reynolds number will be evaluated. In addition, the boundary layer thickness and mean wall shear stress at particular streamwise locations along the array will be quantified. The growth of the turbulent boundary layer over the length of the array is an important metric with regard to estimating the maximum turbulent boundary layer thickness which exists over a fleet towed array. The underlying structure of the axisymmetric boundary layer, which leads to significant increases in wall shear stress with respect to flat plate cases, is of primary importance. These new insights will facilitate efforts toward towed array reliability and an accurate prediction of drag and flow noise for any towed array application.

INTRODUCTION

Towed arrays are important acoustic sensors for the submarine force and undersea surveillance community. The hydrodynamic problem can be described as the flow past a long, thin cylinder at zero and small angles of attack relative to the tow direction. The physics are dominated by the growth of a thick, high Reynolds number turbulent boundary layer, however, no velocity field information exists in the published literature for near-field full-scale towed array geometries. Current flow noise models for towed arrays are often based on data obtained for the flat plate boundary layer case and are approximate for cases of extremely long, small diameter arrays. The development of improved flow noise models therefore requires measurements at high Reynolds numbers and large values of \( \delta/a \) to more accurately measure the relevant wall and boundary layer parameters.

Historically, the problem of turbulent boundary layers that develop on long, thin cylinders at small angles of attack has received much less attention than has the analogous flat plate problem. This problem relates directly to towed sonar arrays in turns, maneuvers and transient motions, and in cases where arrays experience positive or negative buoyancy in steady-state tows. Early investigations [2, 4, 5, 6] into axisymmetric turbulent boundary layers in wind and water tunnels showed that the effects of transverse curvature typically resulted in mean wall shear stress increases of 5% when compared to flat plate flows at comparable Reynolds numbers. However, subsequent measurements in tow tanks on very small diameter lines [7, 8, 9] showed that the mean wall shear stress was two to three times higher and the boundary layer streamwise spatial growth was lower than for flat plate flows.
Specifically, measurements [7, 8] for which $\delta/a > 100$ and $L/a > 10,000$ and Reynolds numbers ranged from $10^4 < Re_0 < 10^6$ and $10^7 < Re_L < 10^9$, established that the wall shear stress is significantly higher and the spatial growth of the boundary layers is lower than that for a comparable flat-plate case. Also, the mean wall shear stress exhibited spatial variations not seen in zero-pressure gradient flat-plate turbulent boundary layers. The length scales of these variations are three orders of magnitude larger than the maximum momentum thickness at the end of the line. The effect was found for towing speeds of 3.1, 9.3, and 14.4 m/s, with the minimum shear stress occurring at approximately the same streamwise distance (90 m) for each tow speed. These results suggest that a length scale on the order of 100$\delta$ exists to observe this effect. Furthermore, stereo particle image velocimetry measurements [9] for towed lines of the same diameter reveal a decrease in the boundary layer thickness to a minimum value at the same location (90 m) as the minimum in the shear stress. The apparent quasi-periodic behavior in both $\delta$ and $\tau_w$ had never been experimentally observed before. In each of these investigations, the tow angle was less than 1°.

The aforementioned results, in part, motivated an experimental investigation using three full-scale towed array modules with an aspect ratio of $L/a = 7 \times 10^3$ (36.8 mm in diameter and 43 m long each) representative of fleet towed arrays. The data analysis focused on evaluating the instantaneous vector fields and the variation of the streamwise velocity profiles over the length of the array model. For each tow speed, profiles were generated and scaled with inner and outer variables for comparison to flat plate scaling. These profiles were also used to estimate the boundary layer thickness and momentum thickness. The instantaneous velocity profiles scaled with outer variables were compared to results from [2], and found to agree closely using velocity defect scaling. The experimental results presented in [2] involved hot wire measurements on short cylinders suspended in a vertical wind tunnel, with comparable $\delta/a$ values.

Recently, an experimental towed array was used to investigate the wall pressure field beneath the cylindrical turbulent boundary layers at high Reynolds numbers and large ratios of boundary layer thickness to cylinder radius $\delta/a$ [3]. Measurements of the autospectra, cross-spectra, and wavenumber-frequency spectra of the wall pressure fluctuations were examined in detail for the purposes of characterizing direct wall pressure fluctuations and flow-induced vibrations. The current work augments that effort with details of the turbulent structure and distribution obtained on the same configuration. This information is required to develop empirical models of the turbulent boundary layer and flow noise.

Experimental investigations of high Reynolds number flows present unique difficulties due to the inherent small length scales and high frequencies involved. With respect to the array, this was a full scale measurement which required a large capture volume. The wide ranges of energy length and time scales were difficult to resolve. SPIV provides excellent spatial resolution over a large volume, but is limited in its temporal resolution, which is particularly problematic at low frequencies. The limit to spatial resolution was proximity to the fluid-solid interface; for this range of Reynolds numbers it was not possible to measure within the viscous sublayer. The measurements did, however, encompass the entire boundary layer, and the SPIV technique in no way disturbed the flow field. There were no transverse motions in the array which would result in boundary layer separation; however, the slight tow angle of the array resulted in the translation of the array downward within the field of view, complicating data processing.

**EXPERIMENTAL DESCRIPTION**

A towing tank investigation was conducted at the Carderock Division Naval Surface Warfare Center high-speed towing tank. The tank, which is 904 m long, is comprised of two adjoining sections: a deep-water section at the east end that is 4.9-m deep, 514-m long, and 6.4-m wide, and a shallow-water section at the west end that is 3-m deep, 356-m long, and 6.4-m wide. The fresh water in the tank was at a uniform temperature of 20°C throughout the duration of the tests, with a kinematic viscosity of $1.01 \times 10^{-6}$ m$^2$/s and a density of 998 kg/m$^3$. The water level in the tank was lowered slightly to allow the tow point to be raised above the surface of the water for rigging. The carriage is propelled by 16 weight-bearing vertical drive wheels and 16 horizontal drive guide wheels. The carriage speed is regulated to $\pm 0.03$ m/s with a feedback control system.

The towed model consisted of a long, pressurized, fluid-filled hose with internal strength members, ballasted to be nearly neutrally buoyant in fresh water. However, since the model was designed to emulate the flow on an actual fleet towed array, it is observed to move slowly downward in the field of view as it is towed through the laser sheet. The total vertical excursion decreases with tow speed. While this motion which had a negligible effect on the turbulent boundary layer development, it complicates the data analysis significantly. The model was 129.8-m long with an outer diameter of 3.8 cm. It was attached to a 4,450 N capacity load cell on the horizontal portion of the twin tow strut. The tow strut was designed to minimize form drag and vortex shedding. The total drag on the model during steady-state towing varied from 733.8 N at the lowest speed to 4,062.3 N at the highest speed. A control
volume analysis was then used to determine the momentum thickness $\theta$ at the end of the cylindrical model. Reynolds numbers $Re_\theta$ varied from $4.6 \times 10^5$ to $8.9 \times 10^5$.

Three-dimensional velocity field measurements were obtained with a stationary underwater SPIV system, as shown in Fig. 1. An underwater probe generated an 18 mm thick laser sheet oriented perpendicular to the direction of tow and the local fluid volume was seeded with micron-sized particles. Two high-resolution underwater cameras, positioned at angles to the measurement volume, and the laser probe were mounted on a platform attached to a hydraulically activated lift. This arrangement enabled optimization of the measurement volume depth and adjustments of the optics above the water surface. When the array was towed through the fixed laser sheet, the system was triggered to pulse the laser and the cameras collected the resulting images at known distances along the array. The image pairs were used to compute the mean and fluctuating streamwise and cross-stream velocities and vorticity in a 90 cm x 90 cm measurement plane. The SPIV measurements occurred at the photo pit located 488 meters from the west end of the tow tank, shown schematically in Fig. 2. The resulting vector resolution was approximately 3.6 mm. Data were collected for constant tow velocities ranging from 6.2 to 15.4 m/s.

Fig. 1: Underwater setup of SPIV instrumentation, showing laser sheet, high resolution cameras, seeding particle manifolds and hydraulic lift.

Plan View of Basin Test Configuration

Fig. 2. Layout of Experimental Components for the Tow Tank Tests at David Taylor Model Basin.
ANALYSIS APPROACH

To extract the most information from the acquired data, multiple steps of data processing are required. These steps include data pre-processing in Matlab™, vector-field composition and analysis in DaVis™, and boundary layer structuring in Matlab™. The three-dimensional vectors were computed with the commercial software package DaVis™. Significant effort was devoted to develop an appropriate image filter to suppress the array and enhance the particle images in the field of view. This algorithm reduced the number of erroneous vectors and facilitates tracking the array as it moves through the field of view. Sample raw images are shown in Fig. 3a and b. A Matlab script was created that organized the multiple sets of images into the format required by DaVis™ and enhanced them using several Matlab image processing tools, including an adaptive histogram equalizer, pixel intensity thresholds, unit8 function, pixel multiplication and the bit-wise inverse of the image.

The adaptive histogram equalizer enhances the contrast of the grayscale image by transforming the values using contrast-limited adaptive histogram equalization. This equalization operates on tiles, rather than the entire image. The contrast of each tile is enhanced so that the histogram of the output region approximately matches a specified histogram. The neighboring tiles are then combined using bilinear interpolation to eliminate artificially induced boundaries. These effects can be seen in Fig. 4a and b.
Pixel intensity thresholds were implemented to eliminate or separate certain pixels with a specified intensity. In this case, pixel intensities greater than the threshold were converted into unsigned integers. The highest value is 255 and the lowest is zero. Pixels with a lesser value than the threshold are set to zero. Once the values are reassigned, the intensities are multiplied by the initially enhanced image with the goal of defining the edges of the array and shadow regions and eliminating any bright reflections. Finally, the bit-wise compliment of the image is produced to yield the most effective image for computing the vector fields. The images as they are imported into DaVis are displayed in Fig. 5a and b.

A typical instantaneous vector field for a run at 18 kt (9.3 m/s) is shown in Fig. 6. This particular field was obtained at a streamwise location approximately halfway down the length of the array. The vectors represent the in-plane components of velocity and the color indicates the magnitude of the out-of-plane component \( V_z \). The dark regions correspond to the array as it appears in each off-axis camera and the shadow it casts. The displayed plane is orthogonal to the array and the direction of tow is into the page.
For flat plate zero pressure gradient turbulent boundary layers, estimates of the friction velocity may be obtained from measurements in the log law region, and viscous sublayer if possible. This method relies on established relationships for the velocity profiles. For the cylindrical geometry in this experiment, the form of the relationship is not well established at the outset. Furthermore, the very high Reynolds numbers precluded measurements in the sublayer within 10 viscous lengths from the array surface. Therefore, an independent measurement of the mean wall shear stress was extremely valuable and the values will be used to scale the velocity data. The velocity profiles will be compared to the log law relation for flat plate boundary layers given by [10] as:

\[ u^+ = \frac{u(y)}{u_\tau} = 2.44 \ln(y^+) + 4.9, \]  

where \( y^+ = y u_\tau / \nu \).

In addition, the momentum thickness values determined directly from the load cell measurements will be compared to values determined from the instantaneous velocity profiles. This comparison allowed the accuracy of the SPIV measurements to be evaluated, since temporal averaging to minimize the scatter in the data was not possible. Note that the definition of momentum thickness for a cylindrical geometry leads to a significant contribution from the outer region of the velocity profile:

\[ \theta^2 + 2a \theta = 2 \int_a^{\infty} \delta(y) \left( \frac{u(y)}{U_\infty} \right) \left( 1 - \frac{u(y)}{U_\infty} \right) y dy \]  

In contrast, for the flat plate case the majority of the momentum thickness contribution is closer the wall. Consequently, the value of momentum thickness in a cylindrical boundary layer is very sensitive to the range of integration away from the wall, and care must be taken when defining the boundary layer thickness for this class of flows.

Finally, the estimated boundary layer thickness values will be determined as a function of streamwise distance and compared to values predicted for the flat plate case using [11]:

\[ \delta(x) = 0.37 x (Re_x)^{-0.2} \]  

The results will evaluate the extent to which the boundary layer thickness departs from the predicted flat plate values when \( \delta/a \) is \( \gg 10 \).

**SUMMARY**
A full-scale tow tank experiment using experimental towed array modules was successfully completed in June 2007. Velocity and drag measurements were obtained at speeds between 6.2 m/s and 15.4 m/s (12 and 30 kts) at the NSWC Carderock High-Speed Tow Tank. Three-dimensional velocity field measurements were acquired over the length of the modules with a stationary SPIV system, and the total streamwise drag was measured with a strut mounted load cell. This is a unique application of this measurement technique to full-scale towed array models at operational Reynolds numbers. In addition, this investigation will provide details of the turbulent boundary layer velocity profiles on full-scale towed array models that are critical to the development of improved flow-noise and computational models. The measurement method is nonintrusive and allows extremely high spatial resolution of the turbulent flow field. The large field of view and vertical motion of the model through the field of view led to challenges in image processing and data analysis, requiring the creation of specific algorithms for this data set.

Related experiments [1, 3] and preliminary data analysis has established the existence of a cylindrical turbulent boundary layer on the towed model. A significantly higher mean wall shear stress was measured, up to twice that for the equivalent flat plate case at comparable values of $Re_\theta$. However, the boundary layer thickness values are estimated to be approximately equal to that predicted by flat plate theory. The results obtained for the towed array model will be compared with the laboratory results of Willmarth et al. for short cylinders suspended in a vertical wind tunnel, with comparable $\delta/a$ values. Further data analysis is required to determine the velocity profiles and growth of the boundary layer, as well as any Reynolds number effects. The higher wall shear stress accompanied by thick turbulent boundary layers implies higher levels of wall pressure fluctuations than would occur in a flat plate boundary layer. In addition, the thick turbulent boundary layers will significantly affect the cross flow drag during maneuvers.

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