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Artificial Thickening of Cavitation Tunnel Boundary Layers

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Abstract

Preliminary measurements of natural and thickened boundary layer mean velocity profiles on the ceiling of a cavitation tunnel test section are presented. The method of thickening tested is via an array of transverse injected jets. The array consisted of 252 equal diameter jets on a triangular grid on 8 spanwise rows. Several Reynolds numbers, jet flow rates and streamwise locations downstream of the thickening location were tested. Natural and thickened mean velocity profiles are compared with the laws of the wall and wake. At the most downstream location tested natural boundary layers with momentum thickness Reynolds numbers of 33000 could be thickened to over 73000 with minor but apparent remnant distortions from the artificial thickening.

Introduction

There is frequently the requirement in experimental facilities to artificially thicken test section wall turbulent boundary layers for simulation of a broad range of flows including those in atmospheric studies, wind engineering, aeronautical and naval hydrodynamics. Perhaps the earliest work in the field is that by Klebanoff and Diehl [9] from which they concluded it is possible to artificially thicken fully developed turbulent boundary layers free of distortion introduced by the thickening process. Various devices were trialled but only some produced boundary layers characteristic of those naturally developed over practical distances. Hence the most basic problem is conceiving devices or processes that produce fully developed boundary layers over the shortest possible distance.

For wind tunnel applications several studies have been carried out for flows ranging from subsonic to hypersonic [15, 11, 10, 12]. These studies used various obstructions, similar to [9], including rods, spires, and honeycombs to introduce the initial momentum deficit and turbulence to thicken the approaching boundary layer. More recently studies have been carried out investigating the use of an array of transverse injected jets to thicken wind tunnel boundary layers [13, 14].

In water tunnels studies have been carried out using relatively low profile saw toothed fences that are completely submerged within the natural boundary layer to minimise cavitation [1, 4, 2]. Injected fluid, or blowing, has also been used in water tunnel investigations but in this case for controlling the boundary layer about a streamlined body [7]. For water tunnels and in particular variable pressure water tunnels (or cavitation tunnels) the ceiling is frequently used for the testing of control and propulsion equipment or for mounting test objects generally. Reasons for this include ease of access to the test section, minimisation of the volume of fluid that must be emptied for access and the orientation of physical models for correct cavitation scaling [4, 2]. Depending on the test section Froude number, this may also be the location of the lowest local cavitation number and hence where cavitation can occur first [3].

For this purpose the recently completed Australian Maritime College, Cavitation Research Laboratory (CRL), cavitation tunnel was developed with a capability to artificially thicken (or thin) the test section ceiling boundary layer. The method chosen for the CRL tunnel was thickening via an array of transverse injected jets. Reasons for this include: previous work has shown this method to be at least as effective as the use of solid objects; this system may be used for thinning, via suction, as well as thickening; may be continuously adjusted; and potentially has improved cavitation performance over conventional solid devices.

A discussion of the specifications for the CRL tunnel is given in [6, 5] including the boundary layer control system. The basic requirement for the latter was to develop usable thickened boundary layers of nominally 0.1 m thickness within the test section length. Usable in this context being close approximations to flat plate, zero pressure gradient, high Reynolds number turbulent boundary layers.

The present work presents preliminary data acquired as part of testing and commissioning of the CRL tunnel boundary layer control system. Mean velocity measurements of the tunnel natural and thickened boundary layers at several Reynolds numbers and streamwise locations are presented. Comparisons are also made with the laws of the wall and wake.

Experimental Overview

CRL Cavitation tunnel

The CRL tunnel test section is 2.6 m long, 0.6 m square at entrance and 0.6 m wide by 0.62 m deep at exit. The test section ceiling is horizontal with the floor sloping 20 mm to nominally maintain constant speed and zero streamwise pressure gradient. The operating velocity and pressure ranges are 2 to 12 m/s and 4 to 400 kPa absolute respectively. The tunnel volume is 365 m^3 with demineralised water (conductivity of order 1 μS/cm). The tunnel has ancillary systems for rapid degassing and for continuous injection and removal of nuclei and large volumes of incondensable gas. A detailed description of the facility is given in [6, 5]. The test section velocity is measured from one of two (high and low range) *Siemens* Sitransp differential pressure transducers models 7MF4433-1DA02-2AB1-Zand 7MF4433-1FA02-2AB1-Z (measuring the calibrated contraction differential pressure) with estimated precisions of 0.007 and 0.018 m/s respectively.

Boundary layer control system

The boundary layer control system consists of an ancillary pipe circuit in parallel with the main tunnel circuit containing a pump and valves that enable the circuit to be configured for thickening or thinning of the test section ceiling boundary layer. Water is injected or ingested through a 0.6 m (spanwise) by 0.125 m, streamwise) penetration the trailing edge of which is located 0.115 m upstream of the test section entrance. The penetration may be fitted with a blank plate flush with the tunnel ceiling when not being used or with plates with nozzles, for either injection or suction, of various geometries as desired. Water is injected or ingested through the plate via a plenum in which the

x (m)	$C_{P_{inj}}$	Re	δ (mm)	δ^* (mm)	θ (mm)	C_f	U_τ (ms^{-1})	Re_θ	Re_τ
Natural BL									
0.7	0	2	21.3	3.22	2.42	0.00267	0.136	8054	2590
0.7	0	3	20.0	2.91	2.22	0.00261	0.201	11090	3601
0.7	0	4	19.8	2.80	2.16	0.00249	0.263	14376	4641
0.7	0	5	19.5	2.71	2.10	0.00241	0.323	17496	5616
0.7	0	6	19.3	2.65	2.07	0.00235	0.380	20625	6578
1.3	0	2	27.7	4.09	3.11	0.00259	0.130	10327	3313
1.3	0	3	26.7	3.80	2.93	0.00249	0.192	14595	4697
1.3	0	4	26.2	3.64	2.83	0.00239	0.251	18814	6015
1.3	0	5	25.9	3.55	2.77	0.00229	0.311	23010	7290
1.3	0	6	25.7	3.48	2.73	0.00223	0.369	27232	8564
1.9	0	2	34.1	4.92	3.77	0.00251	0.127	12531	4018
1.9	0	3	33.0	4.61	3.58	0.00242	0.188	17842	5725
1.9	0	4	32.6	4.46	3.48	0.00231	0.245	23203	7382
1.9	0	5	32.2	4.34	3.41	0.00222	0.301	28336	8925
1.9	0	6	31.9	4.24	3.34	0.00216	0.359	33335	10460
Thickened BL at several x values									
0.7	0.53	5	52.6	8.18	6.81	0.00195	0.273	51489	13703
1.3	0.54	5	66.1	8.42	6.72	0.00210	0.279	55913	17810
1.9	0.54	5	75.6	9.32	7.56	0.00208	0.284	62140	20056
Thickened BL for several $C_{P_{inj}}$ values									
1.9	0	5	32.2	4.34	3.41	0.00222	0.301	28336	8925
1.9	0.23	5	49.6	6.22	5.02	0.00219	0.281	41825	13661
1.9	0.54	5	75.6	9.32	7.56	0.00208	0.284	62140	20056
1.9	0.75	5	88.8	10.92	8.85	0.00203	0.280	73133	23357

Table 1: Summary of boundary layer parameters for natural and thickened measurements.

static pressure may be measured and compared with the tunnel dynamic pressure for real-time control. The plenum is connected to the ancillary circuit via a wide angle vaned diffuser and two honeycombs.

The plate used for thickening testing and commissioning is machined with an array of 252×5 mm diameter holes on a 16.8 mm triangular grid (8 spanwise rows). The plate is 15 mm thick and the holes have a 5 mm radius bellmouth entry.

For thinning, ingested flow is returned to the main circuit at the downstream tank used for separation of large bubbles. For thickening water is taken from the main circuit lower limb, where the flow is slow and has had any bubbles removed.

Experimental setup

All boundary layer mean velocities were measured on the test section vertical centre plane using a 0.7 mm outside, by 0.4 mm inside, diameter total head tube. The 1 mm diameter wall reference static tapping was located on the test section ceiling in the plane of the probe head 75 mm from the centre plane. The total head tube was traversed using an automated linear traverse incorporating a *THK* LM Guide Actuator Model KR26 with an estimated precision of 3 μm. Pressures were measured sequentially using a *Validyne* Model DP15TL differential pressure transducer via an automated pressure multiplexer incorporating a 7-way, Series 40 *Swaglok* valve. The estimated precision of the *Validyne* transducer is 0.1% of full scale.

Experimental procedure

Boundary layer traverses consisted of up to 50 measurements on a log distribution. All measurements were taken at 1024 Hz sampling rate for durations corresponding to at least 5000 boundary layer turnover times (TU_∞/δ), where T is the measurement duration, U_∞ the freestream velocity and δ is the boundary layer thickness corresponding to 99% of freestream velocity. A minimum of 5000 turnovers was chosen for mean velocity measurements on the basis of a convergence study comparing RMS deviations from the log law up to 25000 showing convergence after about 4000. The skin friction and wall friction velocity were determined from Preston tube measurement using the calibration by Head and Ram, as presented by Goldstein [8]. All traverses were carried out at constant static pressure of 200 kPa to prevent cavitation occurrence. The traversed probe position was offset for shear layer effects by 15% of the probe outside diameter (by MacMillan, as presented in [8]).

Results

Table 1 summaries the results presented. Measurements were made at three streamwise locations, x from the test section entrance. The natural boundary layers where measured at five test section based Reynolds numbers, $Re = U_\infty h/\nu$ where $h = 0.6$ m, is the nominal cross sectional dimension of the test section and ν the kinematic viscosity. For the thickened boundary layers, measurements were made at the three streamwise locations for a fixed Re and injection pressure coefficient $C_{p_{inj}} = P_{inj}/0.5\rho U_\infty^2$, where P_{inj} is the injection pressure relative to the free stream static and ρ the fluid density. Thickened measurements were also made for several $C_{p_{inj}}$ values a fixed Re and x values.

Results are compared with the law of the wall, $U^+ = (1/\kappa)\ln y^+ + B$ where $U^+ = U/U_\tau$, $y^+ = yU^+/\nu$, y is wall normal ordinate using the Karman constant, $\kappa = 4.1$ and the additive constant of 5.0. Results are also compared using the defect form of the following modified Coles law of the wake;

$$\frac{U_\infty - U}{U_\tau} = -\frac{1}{\kappa}\left(\ln\eta - 2\Pi\cos^2\frac{\pi\eta}{2} + \frac{1-\eta^3}{3}\right) \qquad (1)$$

where $\eta = y/\delta_c$ and δ_c is the boundary layer thickness. A value of the wake strength factor Π of 0.62 was used throughout to

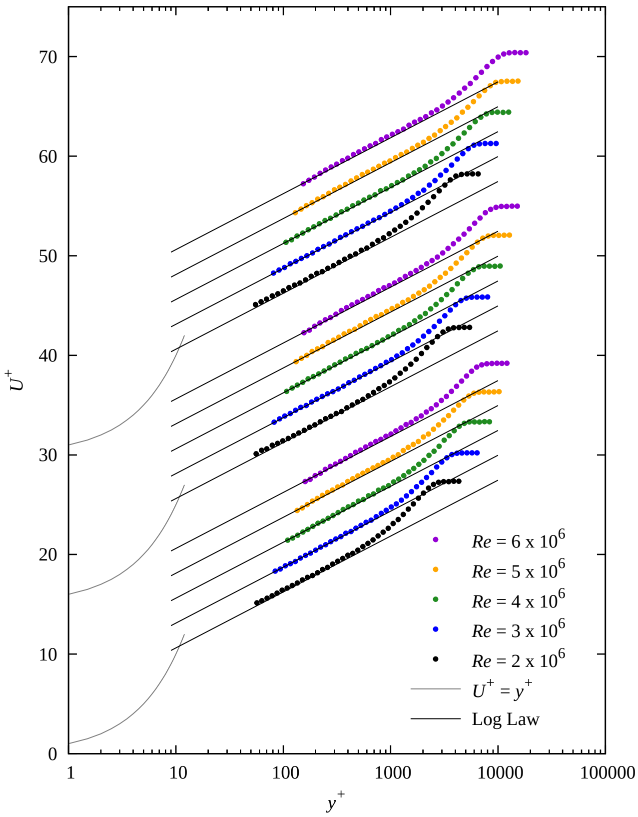

Figure 1: Mean velocity profiles of test section natural boundary layers at x = 0.7, 1.3 and 1.9 m and several Re values (plots staggered vertically in streamwise groups by $U^+ = 2.5$).

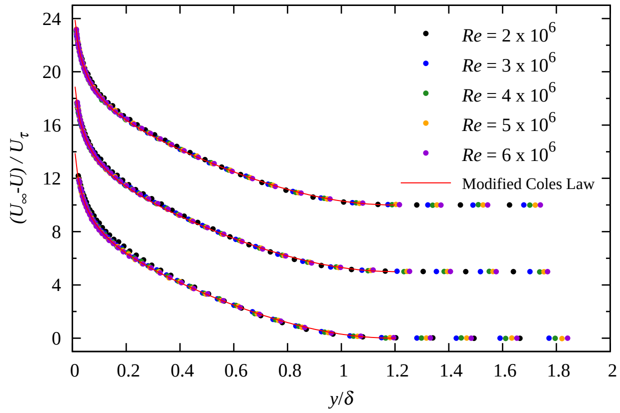

Figure 2: Data of Figure 1 replotted using outer scaling (plots staggered vertically in streamwise groups by $(U_1 - U)/U_\tau) = 5$.

compare the natural and thickened boundary layer mean velocity profiles. From least squares fitting of the entire profile for all the natural boundary layers Π was found to converge to about 0.62 for $Re_\theta = U_\infty \theta / \nu$ above 15000, where θ is the momentum thickness. An updated value of the thickness δ was obtained from a least squares fit to the outer 0.6δ for all the boundary layers using equation 1. From this it was found that for all cases $\delta_c = 1.2\delta$ to within less than 1%.

Figure 1 shows the inner scaled mean velocity profiles for the natural boundary layers. It can be seen that all profiles lie on the log law although some small trends with Re are apparent consistent for each x location. The diagnostic function $y^+ dU^+/dy^+$ does however show all data to have a mean close to $1/\kappa$. Figure 2 shows the outer scaled natural profiles compared with

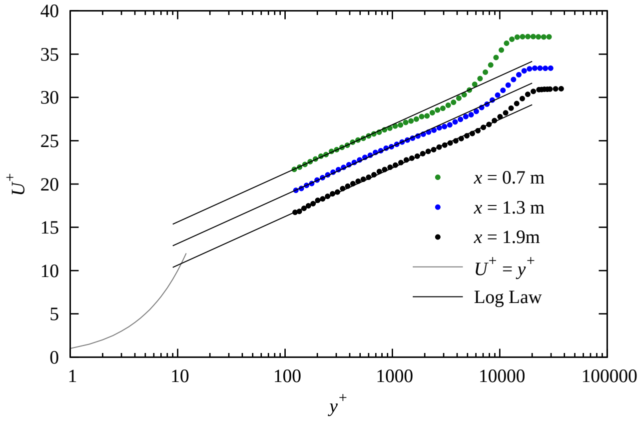

Figure 3: Mean velocity profiles of test section thickened boundary layers at x = 0.7, 1.3 and 1.9 m for $C_{P_{inj}} = 0.54$ and $Re = 5 \times 10^6$ (plots staggered vertically with streamwise location by $U^+ = 2.5$).

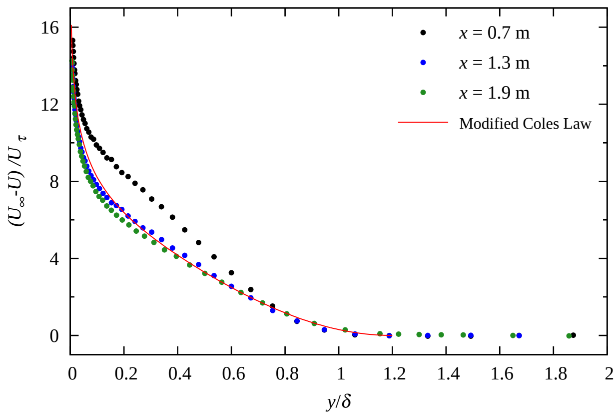

Figure 4: Data of Figure 3 replotted using outer scaling.

equation 1. All the data closely follow equation 1 for all but those for the lowest Re at the most upstream location. These data would suggest that for all but the lowest Re the natural boundary layers are fully developed regardless of streamwise location.

Figure 3 shows the evolution of the thickened inner scaled mean velocity profiles with x for a fixed $C_{p_{inj}}$ and Re. The profiles lie on the log law for $100 < y^+ < 1000$ but the deficit in the outer log region, for the larger turbulence scales, is apparent as is the redistribution with increasing distance downstream. The outer scaled data shown in Figure 4 exhibits the wake deficit more clearly and that by $x = 1.9$ m the profile has not converged with the law of the wake. The velocity excess for $y/\delta < 0.4$ being particularly apparent.

Similar behaviour occurs with varying $C_{p_{inj}}$ for a fixed streamwise position and Re as shown in figures 5 and 6 in which comparison is also made with the natural profile. For $C_{p_{inj}} > 0.23$ the deficit is noticeable and increases with $C_{p_{inj}}$ on the inner scaled profiles. Although the difference between the three $C_{p_{inj}}$ values is less apparent in the outer scaled profiles, all are clearly different from the natural profile. This tends to suggest that if more initial mixing can be imparted by the thickener then the rate of injection may not have a large influence. A simple jet arrangement was deliberately chosen for the commissioning array to gain basic information before trying more complicated jet arrangements.

The relationship between $C_{p_{inj}}$ and δ is shown in Figure 7 from

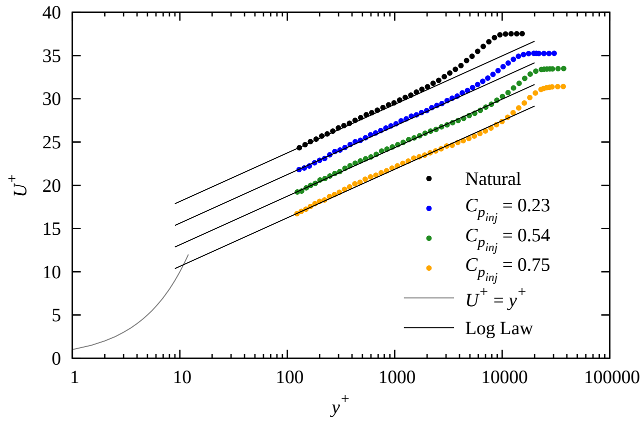

Figure 5: Mean velocity profiles of test section thickened boundary layers at streamwise location of 1.9 m for $C_{P_{inj}}$ values of 0 (natural), 0.23, 0.54 and 0.75 and $Re = 5 \times 10^6$ (plots staggered vertically with $C_{P_{inj}}$ by $U^+ = 2.5$).

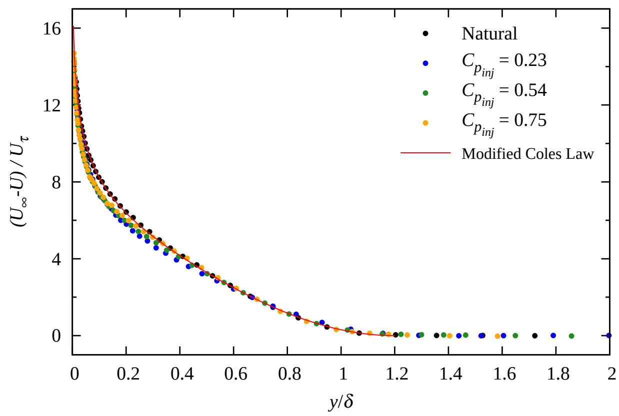

Figure 6: Data of Figure 5 replotted using outer scaling.

which, within estimated errors, is linear. The pressure used to derive $C_{p_{inj}}$ were measured with separate transducers and as such there is potential to reduce this error in future work using a single multiplexed transducer to eliminate span and zero errors.

Conclusions

Mean velocity profiles of the natural and thickened boundary layers on the test section ceiling of a cavitation tunnel have been measured. The method of thickening using an array of transverse injected jets was shown to increase the boundary layer thickness by about 3 times from the natural within the most downstream location investigated. However, small but apparent distortions remained in the profiles at this location. Future work will focus on alternative jet arrangements to optimise mixing to shorten the downstream length required to achieve profiles approaching fully developed.

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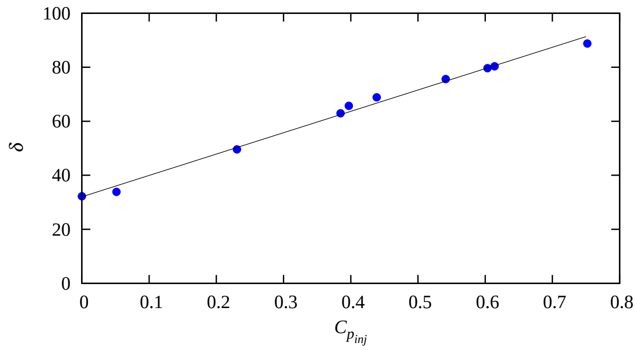

Figure 7: Boundary layer thickness at x = 1.9 m and $Re = 5 \times 10^6$ as a function of $C_{P_{inj}}$.

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