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Artificial thickening and thinning of cavitation tunnel boundary layers

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ABSTRACT

Measurements of natural, thickened and thinned boundary layer mean velocity profiles on the ceiling of a cavitation tunnel test section are presented. The method of thickening investigated is via an array of transverse injected jets and for thinning via ingestion of the natural boundary layer fluid through a perforated plate. Several jet arrays of different geometric configuration and open area were tested over a range of jet to freestream velocity ratios, Reynolds numbers and cavitation numbers. The thickened and thinned velocity profiles are compared with the laws of the wall and wake using parameters derived from the natural boundary layer profiles. The most significant parameter controlling the degree of thickening is the open area, as predicted by one-dimensional mass and momentum conservation, with improvements achievable depending on the jet array configuration. Of the configurations tested an array of intermediately spaced jets was found more effective for thickening than a single row or either sparsely or closely spaced arrays. The profiles of all configurations were found to compare favourably with the laws of the wall and wake to varying degrees, depending upon the geometry, jet velocity and the streamwise length in terms of the number of boundary layer thicknesses for profile development. The results showed that boundary layers could be artificially thickened from momentum Reynolds numbers of about 30,000 to values of about 100,000, or friction Reynolds numbers from about 10,000 to 35,000. Jet velocity was shown to have a significant effect on cavitation inception and generated noise, demonstrating this must be minimised to optimise cavitation limits. Overall the results suggest that a jet array of large open area, to increase thickness and minimise the jet to freestream velocity ratio, with jets distributed with sufficient spacing to promote mixing provides an idealised configuration.

1. Introduction

There is frequently the requirement in experimental facilities to artificially thicken test section wall turbulent boundary layers. Flow about objects immersed in wall bounded turbulence are of interest in a range of applications including those in atmospheric studies, wind engineering, aeronautics and naval hydrodynamics. Perhaps the earliest work in the field is that by Klebanoff and Diehl [1] from which they concluded it is possible to artificially thicken 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 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 [2–5]. These studies used various obstructions, similar to [1], 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 [6,7].

Studies have been carried out in water tunnels using relatively low profile sawtooth fences that are completely submerged within the natural boundary layer to minimise cavitation [8–10]. Injected fluid, or transpiration, has also been used in water tunnel investigations but in this case for controlling the boundary layer about a streamlined body [11]. 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 [9,10] 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. Depending on the test section Froude number, this may also be the location of the

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lowest local cavitation number and hence where cavitation can occur first [12].

For this purpose the tunnel in the Australian Maritime College, Cavitation Research Laboratory (CRL), 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 [13,14] including the boundary layer control system. The basic requirement for the boundary layer control 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. Preliminary results presented in [15] showed these basic requirements could be met. For thinning operation the minimum boundary layer thickness of appropriate velocity profile, achievable within the control system capabilities, was sought.

Mean velocity measurements for several nozzle array configurations for thickening and thinning operation are presented. For each configuration comparisons are made with the laws of the wall and wake and with those for the tunnel natural boundary layers. The relative merits of each configuration are evaluated in terms of similarity with the natural boundary layer properties depending on the Reynolds number and jet to freestream velocity ratio and the likelihood of cavitation occurrence. The results from this preparatory work will be used to develop an optimised nozzle array for which more detailed velocity and turbulence measurements will be made.

2. Experimental overview

2.1. 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 and the working fluid is 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 schematic of the tunnel circuit architecture and secondary pumping circuit for injection or ingestion of water for artificial thickening or thinning respectively of the test section ceiling boundary layer is shown in Fig. 1. The degassing process involves operating the tunnel at low velocity (2 m/s) and low pressure (4 kPa absolute) with large volume injection of microbubbles upstream of the contraction. The large surface area to volume ratio created by the injection of the microbubbles at such low pressure promotes rapid gas diffusion from liquid to gas phases. The injected microbubbles grow and coalesce and are ultimately removed via gravity separation in the downstream tank. By this process the tunnel volume of 365 m^3 may be degassed from 100% atmospheric saturation to 20% within 2 h. Shown in Fig. 1 are the arrays for injection of microbubbles (order 10 to 100 μm diameter) for artificially seeding the flow with nuclei for modelling the inception and dynamics of cavitation. Large volumes of injected incondensable gas or microbubbles (down to 10 μm diameter) are continuously removed through gravity separation in the downstream tank or through dissolution via extended residence and pressure. More detailed descriptions of the facility are given in [13,14].

The test section velocity is measured from one of two (high and low range) Siemens Sitrans P differential pressure transducers, models 7MF4433-1DA02-2AB1- Z and 7MF4433-1FA02-2AB1-Z (measuring the calibrated contraction differential pressure), with estimated precisions of 0.007 and 0.018 m/s, respectively. The test section absolute pressure is measured from one of two (high and low range) Siemens Sitrans P absolute pressure transducers, models 7MF4333-1FA02-2AB1 and 7MF4333-1GA02-2AB1, with estimated precisions of 0.13 and 0.48 kPa, respectively. The test section velocity and static pressure, or Reynolds and cavitation numbers respectively, are controlled real-time to set values using closed loop feedback control. The water temperature is measured real-time and used to calculate the fluid properties and hence the Reynolds and cavitation numbers.

A schematic of the cavitation tunnel test section and the boundary layer control system along with standard measurements and access locations at which the boundary layer velocity profiles were measured is shown Fig. 2. The tunnel contraction is 3 m long overall with an area ratio of 7.11 and has a stainless steel honeycomb, 0.15 m long with 6.35 mm hexagonal cells, at the entrance. The tunnel diffuser consists of a 1 m long, 2.4° (horizontal and vertical) pre-diffuser followed by a 14.15 m long 5° (horizontal and vertical) diffuser.

2.2. Boundary layer control system

The boundary layer control system consists of an ancillary circuit containing a pump and valves that enable the circuit to be configured for thickening or thinning of the test section ceiling natural boundary layer (Fig. 1). Water is injected or ingested through a 0.6 m (spanwise) by 0.124 m (streamwise) penetration, the trailing edge of which is located 0.115 m upstream of the test section entrance (Fig. 2). The penetration may be fitted with a blank plate flush with the tunnel ceiling when not being used or with plates with flush nozzles of various geometries for either injection or suction as desired. The blank plate (in common with all test section penetrations within the test section) is toleranced for ±0.04 mm to achieve steps of less than 0.1 mm. This is to prevent small vapour cavities forming on them at the lowest cavitation numbers and thinnest boundary layers to avoid production of unwanted microbubbles. Water is injected or ingested through the plate via a plenum in which the static pressure is measured and compared with the tunnel dynamic pressure for real-time control. The plenum pressure, relative to tunnel static pressure, is measured with a similar transducer to those used for measuring the contraction differential pressure described in Section 2.1. The plenum is connected to the ancillary circuit via a wide-angle vaned diffuser and two honeycomb flow conditioners. For thickening, water is taken from the main circuit lower limb, where the flow has low velocity and is devoid of bubbles. For thinning, ingested flow is returned to the main circuit at the downstream tank.

The nozzle array configurations tested are depicted in Fig. 3 with relevant parameters summarised in Table 1. All plates were investigated for thickening and plate *f* for thinning only. Plates *a* to *e* are all 15 mm thick, and the holes have a 5 mm radius bellmouth entry. Plate *f* is 8 mm thick and the holes have a 2 mm radius bellmouth entry. Plate *f* is reversed to have the bellmouth entry on the outside (or inside of the test section) when used for thinning. The thickening plates were conceived to test the effect of open area, jet to freestream velocity ratio and nozzle array geometry. The geometries were chosen to test the effect of major parameters including nozzle diameter to spacing ratios in the