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Development of a Fast Response Pressure Probe for Use in a Cavitation Tunnel

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Abstract

The performance of a prototype fast response probe designed for use in a cavitation tunnel is investigated. The probe consists of a total head tube with an embedded miniature pressure sensor. Miniaturisation allows installation of the pressure transducer close to the head of the head of the instrument and improves frequency response through reducing inertia of fluid in the connecting tube. Measurements made with the fast response probe are compared with those of a Pitot tube connected to a slow response transducer and a hot film probe in a thickened turbulent boundary layer on the tunnel ceiling. Measurements of both streamwise velocity and turbulence made with the probe were found to compare well with those of a Pitot tube and a hot film probe. A useful frequency response up to 2.5kHz in water was demonstrated without any frequency compensation for pressure tube response.

Introduction

Fast response probes, (FRPs) have been in use for some time for measuring velocity and turbulence in situations where thermal anemometry or other methods are either inappropriate or inconvenient. These include environments where hostile conditions exist or applied laboratories where cost and convenience of use can be a consideration such as transonic, combustion or cavitation test facilities [9]. In the cavitation tunnel environment relatively large ranges of pressure and velocity as well as the presence of cavitation are possible. These difficulties generally relate to model and equipment costs in terms of structural and mechanical design complexity and facility time required for experiments. At the Australian Maritime College (AMC) cavitation tunnel, Pitot and hot film probes have been used to date for velocity and turbulence measurements. Pitot probes with slow response pressure transducers, whilst very reliable and convenient for time-mean velocity measurement, cannot be used for turbulence measurement. The problems associated with the use of hot film probes are well known including their fragility and accuracy and stability of calibration.

For the reasons mentioned above and the desire for simultaneous measurement of both velocity and turbulence it was decided to develop a one-dimensional FRP for use in the cavitation tunnel. The design concept chosen is similar to other devices developed for aerodynamic [2, 6, 9, 10] and hydrodynamic measurements [1]. These are based on the measurement of unsteady pressures from which the velocity and turbulence components can be derived. The present investigation compares results from a prototype FRP with those from a Pitot tube and a hot film probe. The flow used to compare the probes is a thickened turbulent boundary layer in zero pressure gradient. Comparisons are made of streamwise mean velocity, turbulence intensity and wave number spectrum.

Experimental Overview

Fast Response Probe Design

The FRP has been conceived as a total head tube with an embedded pressure sensor similar to those used in transonic and combusting flow applications [2, 9]. The FRP general arrangement is shown in Figure 1. A modular design has been developed consisting of interchangeable probe head or tip, sensor housing and support stem. Each section can be changed depending on the flow to be investigated, range of velocity/turbulence to be measured and distance to be traversed. The sensor body is glued into the housing with epoxy resin and the periphery of the sensor head is surrounded by silicone filler as per manufacturer's suggestions.

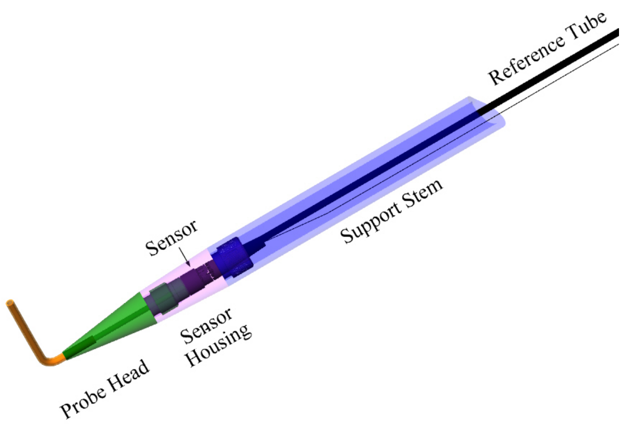

Figure 1. FRP General Arrangement.

The size of the probe head or tip for this application is based on considerations of spatial resolution and frequency response. Bradshaw [3] suggests that quasi-steady measurements in turbulent flows are possible provided the tube size is small compared with the size of energy containing eddies and that eddy traversal time is larger than the ratio of probe size to mean velocity. For the present application involving boundary layers and wakes of the order of 50 to 100mm thick and velocities up to 10m/s a probe head size of 1mm diameter has been chosen. For a velocity of 10m/s this gives a tube diameter to velocity ratio of the order of 0.1ms or frequencies of the order of 10kHz. The frequency response required for hydrodynamic measurements are generally much less those encountered in aerodynamic problems. Experience in the cavitation tunnel suggests that turbulent frequencies of interest for momentum transfer do not exceed 2kHz. The influence of yaw on a simple Pitot tube is insignificant for angles up to 15°; hence the use of a one dimensional probe for streamwise property measurement in the present study appears reasonable considering that the amplitude of incidence excursions should seldom exceed 15° based on typical zero pressure gradient boundary layer rms turbulent velocities.

Whilst there are a range of so called sub-miniature pressure sensors, of the order of 1mm diameter, available for applications in gases there are very few available for use in liquids. There are however so called miniature pressure sensors, of the order of 3mm diameter, available for use in liquids. These sensors must be embedded some distance from the probe tip to maintain a small head size, thus introducing problems of frequency response and viscous damping in the probe head. Estimations of acoustic natural frequencies derived from the speed of sound in water and the probe head length show that for this application frequencies of interest are significantly lower than the first acoustic natural frequency. However the added inertia of the contained water significantly reduces the natural frequency from that of the sensor alone. Damping involving viscous losses in the tube and at entry and exit is also significant. The tube length and sensor diaphragm can be modelled as a single degree of freedom system with the mass, damping and stiffness constants calculated or derived empirically. From this model, tube lengths and diameters have been chosen that provide satisfactory response. A tube with internal and external diameters of 0.8 and 1.2mm respectively was chosen for the present study. The chosen tube length of 32mm gives a natural frequency of mass oscillation of approximately 2.5kHz. This is sufficient to provide meaningful results for the present study, but is significantly lower than the 50 kHz natural frequency of the transducer.

For the present application an *Entran* EPB-B01-1.5B/Z2 miniature pressure sensor was chosen for the FRP. It has an overall diameter of 3.2mm, a pressure range of 150 kPa and is a differential sensor for which it is necessary to use an air reference due to exposed strain gauges that is incompatible with conducting liquids. The tunnel maximum speed is 12m/s, corresponding to a maximum mean dynamic pressure of 72 kPa, and the static pressure range is 4 to 400 kPa making a differential sensor necessary for acceptable resolution. To achieve an air reference the sensor is connected to a convenient static tapping via a volume containing a thin latex diaphragm separating the water and air. Through a process of design optimisation it was possible to size the diaphragm, adjacent volumes and connecting tubing such that the system responded quickly and only small deflections of the diaphragm resulted from static pressure changes.

Cavitation Tunnel Experimental Setup

All tests where performed in the Tom Fink Cavitation Tunnel, a closed recirculating variable pressure water tunnel. The test section dimensions are 0.6m x 0.6m cross section x 2.6m long. The velocity may be varied from 2 to 12m/s and the centreline static pressure from 4 to 400 kPa absolute. Studies may involve the investigation of steady and unsteady flows, two-phase flows including cavitation, turbulence and hydro-acoustics. Full details of the tunnel and its capabilities are given by Brandner and Walker [4].

Tests were performed in a thickened boundary layer created by a saw toothed device chosen from a range of tested devices as being the most efficient and that with the lowest inception cavitation number [4]. This thickener has been used in many studies in the cavitation tunnel and has been investigated in detail by wind tunnel tests of Sargison et al. [11]. The test section was set up with the thickener and probe located on the ceiling 0.3m and 1.15m from the test section entrance respectively. The thickener produces a nominally 50mm thick boundary layer equating to measurements being made at 17 boundary layer thicknesses downstream of the device. Measurements were made of the thickened boundary layer, on the test section vertical centre plane, with a Pitot tube, a hot film probe and the FRP. The probes were traversed using a computer controlled automated traverse with an estimated precision of better than 0.01mm. The wall static reference tap used for the Pitot tube and FRP was located on the test section ceiling in the plane of the probe head 75mm from the centre plane. The Pitot tube head diameter is 0.7mm and pressures relative to the tunnel static pressure (as well as tunnel instrument pressures) were measured sequentially using a slow response *Validyne* Model DP15TL differential pressure transducer via a Model 48J7-1 *Scanivalve* pressure multiplexer. The hot film probe used was *Dantec* R36 wedge probe with a *TSI* model 1750 constant temperature anemometer.

Parameters measured during testing include tunnel pressure, velocity, temperature and dissolved oxygen content. Online instrumentation is used for automatic control of tunnel pressure and velocity as well as real time data monitoring and acquisition. The test section pressure is measured using 2 *Rosemount* Model 3051C Smart absolute pressure transducers in parallel. Test section velocity is derived from the contraction pressure differential measured using 2 *Rosemount* Model 1151 Smart differential pressure transducers in parallel. One of each pressure transducer pair has a lower range to improve measurement precision at lower pressures and velocities respectively. The estimated precision of the absolute pressure measurement is 0.1 kPa for pressures up to 120 kPa and 0.5 kPa for pressures up to 400 kPa. The estimated precision of the velocity measurement is 0.05 m/s. Water temperature is measured to 0.5°C accuracy using a *Rosemount* Model 244 temperature transducer. Dissolved Oxygen content is measured using a *Rosemount* Model 499 Dissolved Oxygen sensor.

Experimental Procedure

The boundary layer traverses for each probe consisted of 50 positions up to 75mm from the wall graded with a log distribution. The Pitot tube and FRP where traversed onto the wall for Preston tube measurement of the wall skin friction and wall friction velocity (used for reduction of profiles to compare with the log law of the wall). The Preston tube calibration used is that by Head and Ram as presented by Goldstein [5]. The hot film probe was traversed to within 0.4mm from the wall and the wall friction velocity and wall skin friction were derived from a least squares fit to the log law of the wall using the 20 closest points to the wall.

Pitot tube traverses were performed at 9 Reynolds numbers between the test section minimum and maximum speeds. Hot film probe and FRP measurements were made at 5 and 6 Reynolds numbers respectively, limited by structural loading or electronic instrument considerations. All probe measurements were corrected for small temporal changes in test section velocity using the contraction pressure differential. The hot film was calibrated at the beginning and end of measurements using a non-dimensional relationship between the Nusselt number and the Reynolds number. The FRP was calibrated from measurements in the free stream using velocities derived from the contraction calibration. Data from slow response Pitot tube measurements was acquired at 800Hz over 6 s and hot film and FRP data was acquired at 16384Hz over 8s. Hot film and FRP turbulence data were both corrected for base electronic noise. For the present investigation instantaneous velocities for the FRP were derived from the unsteady total pressure measurements relative to the wall static reference assuming zero unsteady static pressure.

Results

Boundary Layer Parameters

A summary of boundary layer parameters measured with each probe are presented in Tables 1 to 3 and a comparison of derived skin friction coefficients are presented in Figure 2. The boundary layer thickness δ measured with the Pitot tube is that corresponding to 99% of the freestream velocity. The data generally compare favourably although the skin friction coefficients reflect the expected lack of accuracy of the hot film probe for mean data.

R_θ	δ, mm	δ*, mm	θ, mm	H	C_f
12400	51.7	6.32	4.94	1.278	0.00281
16200	51.5	6.26	4.94	1.268	0.00271
19200	50.3	5.94	4.69	1.268	0.00269
22800	48.5	5.87	4.63	1.267	0.00261
27400	51.3	5.98	4.76	1.258	0.00248
30900	51.0	5.90	4.69	1.258	0.00246
34400	50.4	5.80	4.61	1.258	0.00239
38400	50.4	5.81	4.63	1.257	0.00237
41700	50.0	5.79	4.62	1.252	0.00232

Table 1. Boundary Layer Parameters Measured Using Pitot Tube, where R_θ=momentum thickness Reynolds number, δ=boundary layer thickness at 99% of freestream velocity, δ*=displacement thickness, H=shape factor and C_f=wall friction coefficient.

R_θ	δ*, mm	θ, mm	H	C_f
12400	6.64	5.33	1.245	0.00301
16200	6.66	5.38	1.239	0.00278
19200	6.56	5.32	1.234	0.00267
22800	6.95	5.58	1.247	0.00250
27400	6.27	5.04	1.244	0.00243

Table 2. Boundary Layer Parameters Measured Using Hot Film Probe.

R_θ	δ*, mm	θ, mm	H	C_f
19200	6.14	4.95	1.240	0.00255
22800	6.10	4.94	1.234	0.00248
27400	5.95	4.83	1.232	0.00244
30900	5.86	4.77	1.228	0.00240
34400	5.88	4.80	1.226	0.00235
38400	5.82	4.76	1.222	0.00232

Table 3. Boundary Layer Parameters Measured Using FRP.

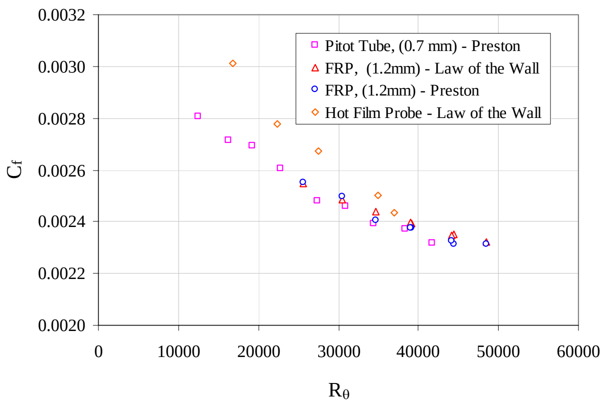

Figure 2. Comparison of Thickened Boundary Layer Wall Friction Coefficient Measured Using a Pitot Tube, Hot Film Probe and FRP.

Boundary Layer Velocity Profiles

The measured boundary layer profiles for each probe are presented as staggered plots in Figure 3. A comparison of each probe at a common Reynolds number is also shown. The data from all the probes show that the thickened boundary layer closely follows the law of the wall although a there is a slight undershoot in the outer part, also reported in [11]. These data also show little change with Reynolds number. The Pitot tube and FRP data show better overall agreement with the law of the wall compared with the hot film which, as mentioned above, can be attributed to less accuracy in velocity determination and hence the wall friction estimate.

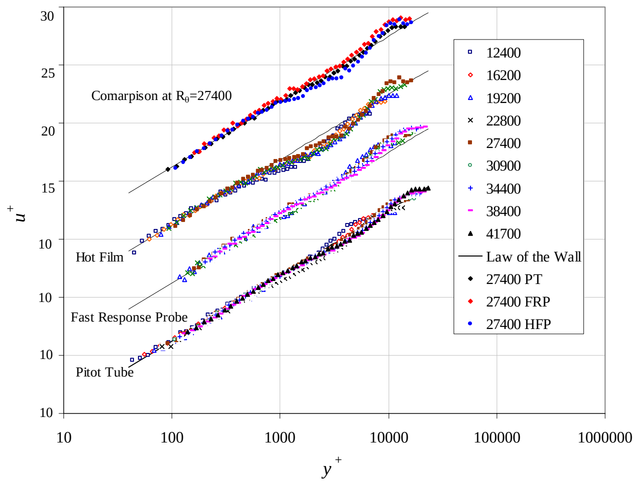

Figure 3. Comparison of Thickened Boundary Layer Velocity Profiles Measured Using a Pitot Tube, Hot Film Probe and FRP.

Boundary Layer Turbulence Profiles

Turbulence profiles measured with the hot film probe and FRP, for the range of Reynolds numbers tested, are shown as stagger plots in Figure 4, together with the profile by Klebanoff [7]. The profile from [7] appears to be based on a boundary layer thickness definition for 100% of the freestream velocity and has been adjusted by 15% for a compatible definition in this case of 99%. The difference in the magnitude of the profiles can in part be due to differences in Reynolds numbers. From [7] the experiments in [8] were performed at a much lower momentum thickness Reynolds number - approximately one order of magnitude less than the current measurements. There may also be some slight increase in turbulence intensity in the centre of the boundary layer as a result of boundary layer thickener. Higher freestream turbulence intensity of about 0.6% in the water tunnel as compared to 0.02 to 0.04% for [7] would have contributed to the higher boundary layer turbulence level observed in present study.

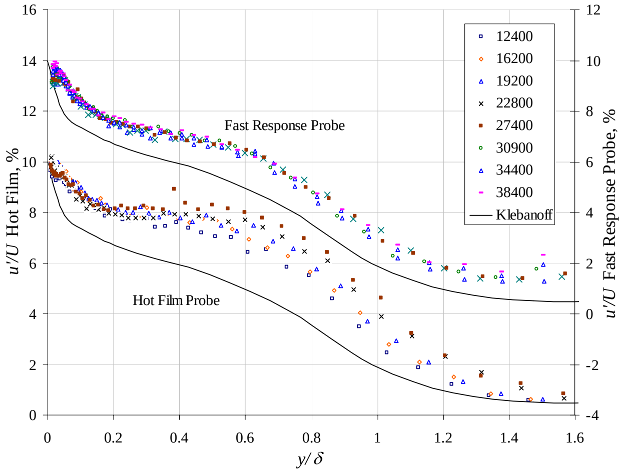

Figure 4. Thickened Boundary Layer Turbulence Intensity Profiles Measured Using a Hot Film Probe and FRP.

The FRP data shows a small monotonic increase of turbulence intensity with Reynolds number increase whereas the hot film data displays a much greater increase. Both the lack of variation with Reynolds number and the overall reduced value of the turbulence intensity for the FRP results, compared with the hot film, can be attributed to filtering of higher frequency turbulent energy. In the wake region the FRP over predicts the turbulence intensity, compared with the hot film probe, and examination of spectra shows that the outer most 3 points were affected by probe stem vibration and are therefore unreliable. The data at the lower Reynolds numbers agree overall to within few percent growing to a maximum of 15 to 20 % at the higher Reynolds Numbers. The greatest difference being through the middle of the boundary layer with excellent agreement near the wall for all cases.

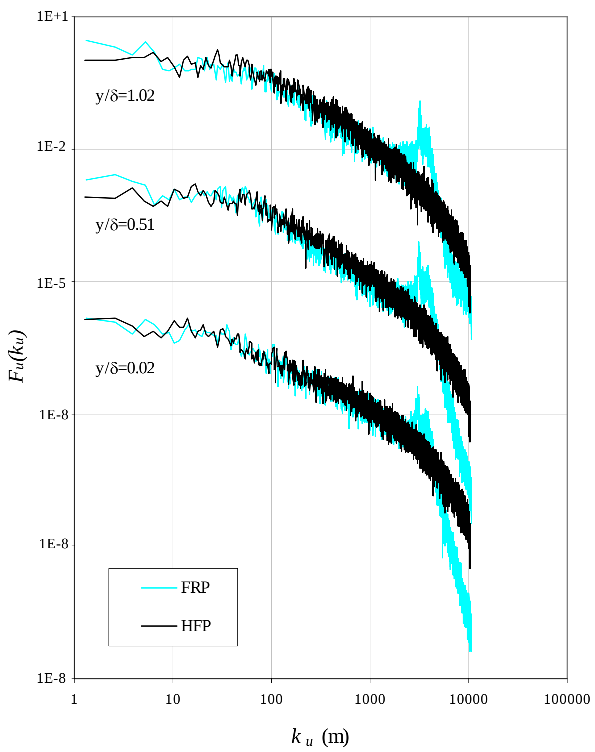

Figure 5. Comparison of Thickened Boundary Layer Wave Number Spectra at y/δ = 0.02, 0.50 and 1.02 Measured Using FRP and Hot Film Probe.

Wave Number Spectra

Wave number spectra for 3 positions across the boundary layer at R_θ = 27400, measured with the hot film probe and FRP, are shown in Figure 5. The spectra are presented using the quantities described in [7, 8]. The spectra for the two probes match closely for wave numbers up to approximately 2000 m^{-1} (~2.5 kHz) after which two resonant peaks at approximately 3500 and 3900 m^{-1} develop. The first peak is possibly due to head resonance in a torsional mode while the second is attributable to response of the sensor combined with the mass of water contained in the probe head. The straight line roll-off of the curve clearly demonstrates the effects of damping due to the viscous loss of the water contained in the head. As discussed above the typical frequency range of interest in the cavitation tunnel does not exceed 2 kHz which is well within the normal response range of the FRP. The attenuation at high frequencies probably explained the slight reduction in turbulence intensity measured by the FRP compared to the hot film data.

Conclusions

The present investigation has demonstrated the use of a prototype FRP for use in a cavitation tunnel. Streamwise velocity and turbulence measured with the FRP compare well with those measured with a Pitot tube and a hot film probe in a thickened turbulent boundary layer. The FRP exhibited resonance phenomena due to possible probe head vibration and mass oscillation of the water contained within the head combined with sensor diaphragm flexibility. The occurrence of damping beyond the resonance peak due to viscous losses associated with the movement of the water contained within the probe head was also discernable. A useful frequency response up to 2.5kHz in water was demonstrated without any frequency compensation for pressure tube response. This is an order of magnitude improvement over the performance of hydrodynamic probes reported in [1] and also exceeds the performance of frequency compensated aerodynamic probes reported in [6].

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