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EXPERIMENTAL DETERMINATION OF INGESTION STREAMTUBES FOR WATERJET PROPULSION INTAKES

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ABSTRACT

Surface flow visualisation and gas tracer studies were used to determine the extent of the bounding streamtube ingested by a waterjet propulsion system with a flush intake. While the results obtained for the limiting surface width of this streamtube are at the upper end of published data, independent validation of the results attests to their validity.

It appears that the amount of propulsive fluid originating in the vessel hull boundary layer has been under-estimated in some previous studies. This under-estimation will result in an under prediction of propulsive thrust.

INTRODUCTION

General Information on Waterjets

Waterjet propulsion systems are a means of propelling high speed marine vessels. They overcome the cavitation problems associated with conventional screw propellers at high speeds by using a duct to decelerate the propulsive fluid before delivery to the impeller. Other significant advantages of waterjet propulsion systems include the high manoeuvring force available at low/zero boat speed, shallow draft, reduced noise radiation, reduced vibration, reduced magnetic signature and reduced engine wear.

Allison (1993) provides a comprehensive introduction to waterjets, including information on their operation, practical design considerations and details on many of the commercial producers.

The most significant parameter describing a waterjet propulsion system's operating state is the intake velocity ratio (IVR) which is the ratio of average fluid velocity in the intake to free stream velocity. As the intakes are diffusing this is a number less than unity and typically around 0.6-0.7 for cruise operation.

Hull Boundary Layer Ingestion

The ingestion of hull boundary layer fluid augments the propulsive thrust and increases the efficiency of the propulsion system (Kruppa et al., 1969). For large displacement ships, hull boundary layer ingestion will appreciably affect the waterjet performance (Arcand and Comolli, 1968). As a result, many researchers (e.g. Dyne and Lindell (1994), Steen and Minsaas (1995), Svensson (1991) and Haglund et al. (1982)) have investigated the hull boundary layer ingestion problem.

The present paper is concerned with determining the origin of the propulsive fluid streamtube for a flush intake typical of current industrial practice.

Steen and Minsaas (1995) discussed boundary layer ingestion in terms of inflow momentum and concluded that assuming a rectangular ingestion cross section with a width of 1.3 times the physical intake width (such as assumed by Dyne and Lindell (1994) and Iannone and Rocchi (1993)) may seriously underestimate full scale thrust as the ingestion streamtube width is approximately twice the physical width of the intake. This paper presents results agreeing with the latter width. Assuming an ingestion streamtube width of 1.3 times the physical width of the intake (or even worse 1.0 times as in Kruppa et al. (1969) and Manins (1970)) will underestimate the amount of propulsive fluid originating in the hull boundary layer and therefore overestimate the inflow momentum.

Ingesting the hull boundary layer may also result in performance penalties, as the intake is subjected to less energetic flow and separation problems already present may worsen. Results presented in Roberts (1998) indicate that the influence of this lower flow energy is confined to a reduction in static pressure at the impeller face with no significant reduction in intake efficiency. The reduced static pressure will, however, have an adverse influence on cavitation.

METHODS

Experimental Equipment

Waterjet Intake Model

The experimental testing was based around a 1:7.67 scale model intake (see Figure 1 for full scale primary dimensions) mounted vertically (as a side wall panel) on the working section of a recirculating wind tunnel. A secondary flow circuit extracted air through the intake via a secondary pump which expelled to atmosphere. Make-up air was introduced by natural suction upstream to the low-speed return working section through a cover plate (of area 0.363 m^2) which was removed for this purpose.

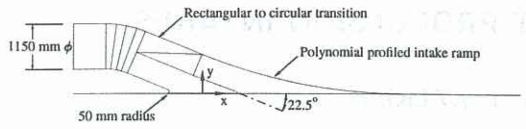

Figure 1: Centre-line cross-section of full-scale waterjet geometry showing principal dimensions.

Figure 2 shows the wind tunnel model which was hand constructed in acrylic with an intake diameter of 150 mm. The Reynolds number based on intake diameter and free stream velocity was around $1.7 * 10^5$ for the model compared to a full scale value of $2.2 * 10^7$. While this mis-match in Reynolds number is not ideal, the test value is high enough to avoid the most significant scale effects. A much more important issue is the boundary layer thickness upstream of the intake, and this is discussed later.

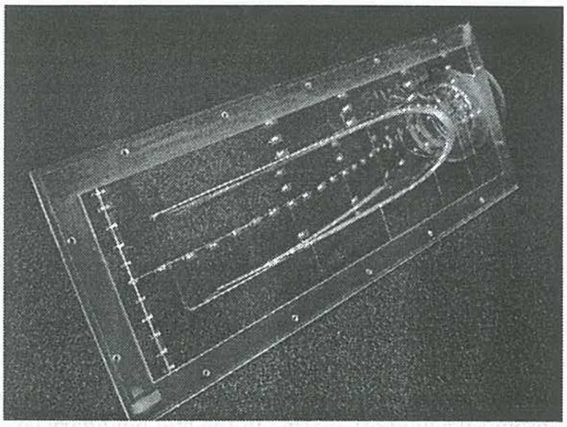

Figure 2: Waterjet intake model used in wind-tunnel testing

The intake roof of a flush type waterjet intake is typically a circular arc. However, this results in curvature discontinuities at both ends of the arc which produce pressure spikes detrimental to overall performance. For the model intake the circular arc was replaced by a fifth order polynomial enforcing continuous curvature at the intersection with the straight line segments. Figure 3 shows the polynomial profile overlayed with the more traditional circular arc profile. The fuller shape of the polynomial curve results from the gradual increase in curvature, compared to the step change for the circular arc.

Wind Tunnel

The wind tunnel used for this study has a working section of 0.61x0.61x1.22 m. Corner chamfering of the working section reduces the effect of corner vortices and reduces the working cross section to 0.34 m^2. Flow uniformity (within ± 0.5%) and low turbulence (less than 0.2% free stream turbulence) are achieved by a 6.2:1 contraction and upstream honeycomb with wire gauze screens.

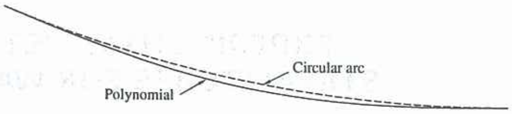

Figure 3: Comparison of intake ramp profiles showing the polynomial curve and the more common circular arc profile.

Tunnel Blockage

Ideally the waterjet model should be tested in a wind tunnel large enough to approximate the operation in deep water, i.e. a semi-infinite medium. The wind tunnel used here has a working section area of 0.34 m^2 compared to the model intake area of 0.0177 m^2. Clearly the removal of fluid from the working section by the intake produces an adverse pressure gradient on the wind tunnel walls which does not correctly represent the true operating conditions with an infinite unconfined stream. This problem can be overcome by varying the working section area with streamwise position to compensate for the flow removal from the tunnel. The natural growth in the wind tunnel wall boundary layer partly provides the requisite area variation.

The negative blockage created by the withdrawal of fluid from the waterjet model has a value of 2.6% at an inlet velocity ratio of 0.5. For IVRs around this value the natural growth in the wind tunnel boundary layer (experimentally measured at 2.5%) compensates for the flow removal by the waterjet. Therefore, the wind-tunnel flow is a fair approximation to a semi-infinite medium. Roberts (1998) gives more detailed information on all aspects of tunnel blockage.

Boundary Layer Thickening

The natural boundary layer in the wind-tunnel working section is too thin by approximately a factor of five for correct kinematic similitude at testing scale. Therefore, it was necessary to artificially thicken the wind-tunnel boundary layer for experimental testing. Tests were carried out with both the wind tunnel's naturally thin wall boundary layer (as done with most tunnel testing of waterjet intakes) and an artificially thickened boundary layer. This thickening was achieved by blowing through a perforated plate with the perforate size distribution selected to give realistic velocity and turbulence profiles. Details of the technique are given in Roberts (1998).

Measurement Techniques

Flow Visualisation

A fluorescent mini-tuft technique based on a fluorescent dye impregnated spun polyester sewing thread of diameter 0.1 mm (manufactured by Birch) and a standard 35 mm camera was used to determine surface streamline vectors. Roberts (1998) provides further details.

Carbon Monoxide Gas Tracer

Ingestion streamtube cross sections are required for momentum balances and the calculation of wake fractions. Griffith-Jones (1994) experimentally measured ingestion stream tubes using smoke photography. However the spatial resolution was limited and the probe size (9 mm diameter) was large compared to the inlet (215 mm diameter).

Roberts (1998) describes the carbon monoxide tracer gas technique used herein. This technique utilises the desirable features of studies by Wisler et al. (1987) and Wagner et al. (1985), namely the suppression of buoyancy effects by the selection of a gas with minimal difference in molecular mass compared to air, and the detection of the tracer gas using relatively inexpensive non-dispersive infrared (NDIR) detectors.

Spatial resolution is enhanced by fitting a sigmoidal function of the form

$$\mathrm{PCOC} = a\left(1 - \frac{1}{1+e^{-b(x-c)}}\right) \tag{1}$$

to the pseudo carbon monoxide concentration (PCOC) for traverses in the x direction with a intra-traverse spacing of 5 mm (see Figure 4). a and b provide scaling while c indicates the offset from the x origin of the 50% concentration point. In the absence of diffusion and turbulent mixing the measured concentration traverse would be a step function, with the bounding ingestion streamtube clearly determined. Diffusing and turbulent mixing "smear" out this step function into a sigmoidal function with the bounding ingestion streamtube being given by the 50% concentration point. Thus c is the position of the bounding ingestion streamtube for that traverse.

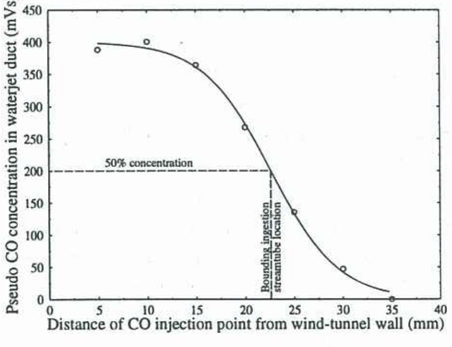

Figure 4: Typical carbon monoxide concentration traverses.

RESULTS

The flow visualisation results (see Figure 5) permit the approximate identification of the width of the ingestion streamtube at the model surface. An ellipse was fitted to the surface streamline vectors that would just be ingested by the intake. The minor axis gives an approximate width of the ingestion streamtube at the model surface. As shown in Figure 5 the width was around 1.8 intake diameters.

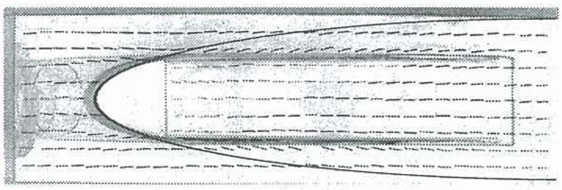

Figure 5: Surface mini-tuft flow visualisation results. Limiting surface streamtube is also shown (solid line).Case shown is for a thin hull boundary layer and an IVR of 0.66.

Gas tracer studies allow for the direct measurement of the ingestion streamtube. Figures 6 and 7 present ingestion streamtube cross-sections measured 1.8 intake diameters upstream of the start of the intake ramp.

The flow rate through the propulsion system can be calculated from two independent measurements, one based on the ingestion stream tube measurement and free stream velocity, the other a direct measurement of flow through an orifice plate downstream of the intake. These measurements agree within 10%, with the flow rate from the orifice plate reading being consistently higher.

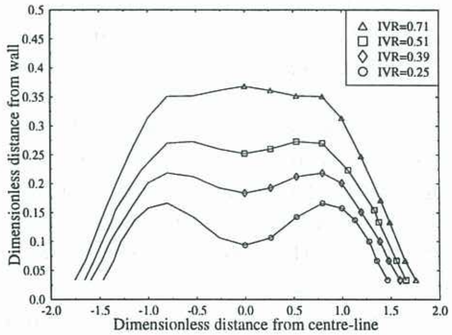

Figure 6: Bounding ingestion stream-tube cross sections, distances non-dimensionalised by the intake diameter. Thin boundary layer operation.

DISCUSSION

The width of the ingestion stream tube is approximately 1.7 intake diameters wide for the thin boundary layer work (Figure 6) increasing to approximately

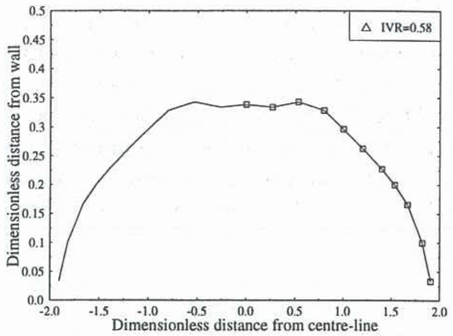

Figure 7: Boundary ingestion stream-tube cross section, distances non-dimensionalised by the intake diameter. Thick boundary layer operation.

2.0 in the thick boundary layer case (Figure 7). Steen and Minsaas (1995) agree with these results, citing an ingestion streamtube width around 2 times the physical width. This is substantially larger that the factor of 1.3 quoted in Dyne and Lindell (1994). Also, the cross section is rather elliptical and not rectangular as assumed in many papers on thrust prediction. The measured ingestion streamtube width in the present study is at the upper end of published values, but the high spatial resolution of the measuring technique and cross checking of flow rates provide firm evidence of the validity of these results.

The thrust produced by waterjet propulsion systems results from the forced change in momentum of the propulsive fluid stream. An incorrect calculation for the momentum at inflow will therefore result in a mis-prediction of produced thrust. As the measured ingestion streamtube width is substantially larger than the physical width of the intake a large proportion of the propulsive fluid originates in the hull boundary layer. This hull boundary layer fluid has a reduced momentum (compared to free stream fluid) and hence has the potential to produce more thrust for the same energy expenditure. However, if thrust calculations are based on a thinner ingestion streamtube width than reality, the thrust will be under predicted which may result in a waterjet propulsion system larger than optimum being selected at the vessel design stage.

The ingestion streamtube cross-section is roughly elliptical in shape for the highest IVR tested. This is in agreement with other published data (e.g. Griffith-Jones (1994)). However as shown in Figure 6, the cross-section develops two peaks positioned at the physical width of the intake at low IVRs. These twin peaks are possibly indicative of vortical flow structures developing along the waterjet-hull intersection. At high IVR's the depth of the streamtube is sufficient to "bury" these vortical structures inside the ingested fluid.

CONCLUSION

Waterjet propulsion systems offer an elegant and natural way to achieve thrust augmentation through re-energisation of the hull boundary layer. The quantity of propulsive fluid originating in the hull boundary layer appears to have been under-estimated in some previous studies. This under-estimation may lead to excessively conservative thrust predictions for a given hull-waterjet installation.

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