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PERFORMANCE OF WATER JET PROPULSION SYSTEMS WITH BOUNDARY LAYER INGESTION

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ABSTRACT

The problem of boundary layer ingestion for waterjet propulsion systems is briefly reviewed. A two dimensional theory is developed for waterjet propulsion systems, both with and without boundary layer ingestion. The theory is applied to two cases: a large semi-displacement vessel and a small planing hull vessel. Finally the effect of the nozzle drag on the propulsive efficiency is considered.

NOMENCLATURE

b	intake width
d	duct diameter
h	depth of stream-tube ingested
l	total wetted length of hull
n	index for power law velocity profile
r	dimensionless position $= 1 - s/l$
s	wetted length of hull from bow
u	x component of local velocity
w	wake factor $= (V_b - V_{mn})/V_b$
x	coordinate in direction of boat motion
y	coordinate normal to hull surface
A_{duct}	area of propulsor duct
A_j	area of jet
D	total drag
D_f	frictional drag
D_{nozzle}	drag force due to nozzle
P_{in}	power input by impeller
P_{out}	useful propulsive power $= TV_b$
Q_j	volumetric jet flow rate
T	net thrust from propulsor duct
T_{imp}	pressure force imposed by impeller
V_b	boat velocity
V_{in}	x component of local intake velocity
$\overline{V_{in}^2}$	mass averaged value of V_{in}^2 $= \int_0^h (\rho u)u^2 dy / \int_0^h (\rho u) dy$
V_j	jet velocity relative to the boat
V_{mn}	average velocity to provide same inlet momentum flux as actual flow
α	intake flow angle (relative to hull)
δ	boundary layer thickness
η	efficiency $= P_{out}/P_{in}$
ν	kinematic viscosity
ρ	density
θ	momentum thickness

Superscript

$'$	case without boundary layer ingestion

INTRODUCTION

Most published momentum theories for waterjet propulsion systems, such as Svensson (1991), Fujisawa and Ogawa (1992) and Savitsky (1987), use the ingestion stream-tube as the control volume. The problem with this approach is that the pressure distribution acting on the ingestion stream-tube is not precisely known and therefore usually neglected. This is obviously incorrect, as dynamic effects will significantly influence the static pressure along this stream-tube.

This simplified model gives a thrust equal to the difference in outlet and inlet momentum fluxes for the ingested stream-tube. The International Towing Tank Conference (Savitsky (1987)) adopt this as a first estimate for the thrust, called "gross thrust". The actual thrust is then obtained by applying an empirical "thrust deduction factor". Besides taking into account the pressure forces on the stream-tube boundary, this factor also allows for interaction effects such as changes in dynamic displacement and trim produced by the waterjet propulsion system.

A more rigorous approach is taken by van Terwisga (1991), van Terwisga (1992), van Terwisga (1993) and Alexander et al. (1994) who explicitly consider the pressure forces acting on the stream-tube boundary. According to van Terwisga (1993), for most practical intakes the net momentum flux passing through the control volume is less than the vessel drag. Alexander et al. (1994) state that the pressure force component acting on the exterior part of the ingestion stream-tube will react on the hull for large vessels; for smaller hulls a component may appear as a momentum change in the wake.

Førde et al. (1991) modify the above control volume by taking a plane parallel to the hull as the inlet surface. This eliminates the problem of estimating the pressure force on the surface of the ingestion stream-tube exterior to the hull. However, it introduces a new uncertainty in the distribution of flow angle α across the intake plane.

The present paper overcomes these problems by defining a control volume large enough so that the inflow and outflow are parallel and there is a hydrostatic pressure distribution on the boundaries.

The matter of boundary layer ingestion is handled differently by many authors. Savitsky (1987) recognises the importance of properly evaluating the inlet momentum and kinetic energy fluxes. Svensson (1991) assumes the local velocity variations are relatively small and uses the mean velocity value to calculate these fluxes. Coop et al. (1992) develop theory for the case without boundary layer ingestion; they then extend this to cover boundary layer ingestion by introducing the wake factor. The importance of the boundary layer is recognised by Fujisawa and Ogawa (1992); however, they only give results for the case without boundary layer ingestion.

Another interaction effect ignored to date is the growth of a new hull boundary layer downstream of the inlet, which introduces a drag penalty. This has been quantified in the current analysis.

The new theory is applied to typical cases of a small planing hull vessel and a large high speed semi-displacement vessel, typical of modern catamaran ferries. The relatively thicker boundary layers compared to the waterjet duct size (for Case A in this paper $\delta/d = 0.53$) and high installed power on large high-speed catamarans make them an important test case.

THEORY

The theory is developed for two dimensional flow situations, using the control volume shown in Figure 1, which also provides a schematic of a typical waterjet propulsion system.

Two cases are considered:

(a) the case of a pitot-type intake with no boundary layer ingestion is first examined to provide a reference case for comparison;

(b) the theory is then extended to the case with boundary layer ingestion as with a flush intake.

The limiting results for both cases are identical when the intake is positioned at the bow ($r = 1$).

To provide a consistent basis for comparison, the boat velocity and jet area are kept constant while all other parameters are allowed to vary.

The propulsor is modelled by an actuator disk with an increase in static pressure equal to that required for compatibility with the specified inlet and outlet conditions for the propulsor duct.

(a) No boundary layer ingestion (pitot-type intake)

Consider the control volume in Figure 1. The control surfaces are chosen such that the pressure distribution on (1) and (2) is hydrostatic and there is no significant pressure variation on (3). In this case the frictional drag is given by

$$D'_f = \rho b V_b^2 \left(\theta'_2 - \theta'_1\right)$$

where subscripts refer to the corresponding control surfaces. Assuming that the drag is totally frictional, conservation of

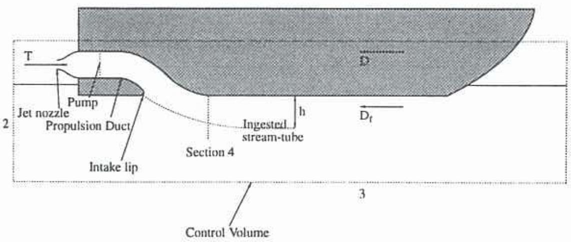

FIGURE 1: Schematic of waterjet propulsion system and control volume for momentum theory.

momentum gives

$$T' - D' = \rho b V_b^2 \left(\theta'_1 - \theta'_2\right) + \rho Q'_j \left(V'_j - V_b\right)$$

from whence

$$T' = \rho Q'_j \left(V'_j - V_b\right)$$

The useful propulsive power is

$$P'_{out} = T' V_b$$

and the input power (with uniform inflow velocity V_b and negligible change in stream-tube elevation) is

$$P'_{in} = \frac{1}{2}\rho Q'_j \left(V'^2_j - V_b^2\right)$$

This leads to the familiar Froude propulsive efficiency

$$\eta' = \frac{2V_b}{V_b + V'_j}$$

(b) Boundary layer ingestion (flush intake)

For the case with boundary layer ingestion a new boundary layer is grown from the cut-water or intake lip. This results in an increase in the frictional drag for the section of hull downstream of the cut-water. Assuming a completely turbulent hull boundary layer with velocity distribution following a power law $u/V_b = (y/\delta)^{\frac{1}{n}}$ the frictional drag for the hull is given by

$$D_f = D'_f \left(r^{\frac{n-1}{n}} + (1-r)^{\frac{n-1}{n}}\right)$$

The drag for this case is increased due to the higher shear stress associated with the new boundary layer growing from the intake lip as shown in Figure 2.

The thrust is now given by

$$T = \rho Q_j \left(V_j - V_b\right) + \rho b V_b^2 \theta_4$$

and the new input power is

$$P_{in} = \frac{1}{2}\rho Q_j \left(V_j^2 - \overline{V_{in}^2}\right)$$

CASE STUDIES

Table 1 summarises results for two case studies corresponding to extreme ends of the waterjet propulsion spectrum:

(a) a large semi-displacement catamaran;

(b) a small planing hull vessel.

Calculation of the frictional drag for the catamaran has assumed that the boundary layer is the same as that on a smooth flat plate in zero pressure gradient. The total drag for the catamaran is assumed to be 45% frictional. To adapt the two-dimensional theory to the real three-dimensional

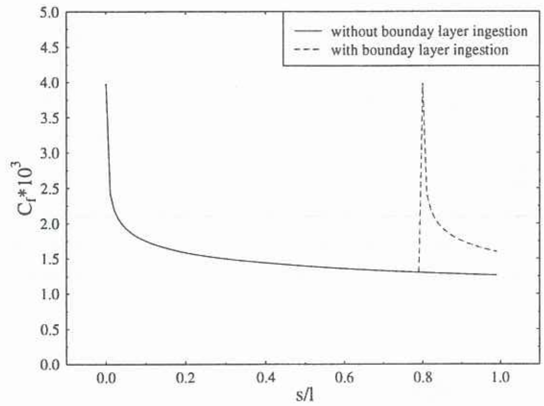

FIGURE 2: Typical variation of shear stress with distance along hull. Frictional drag is given by area under curve.

TABLE 1: Summary of case studies.
Constant parameter values:
$\nu = 1.04{*}10^{-6} m^2/s$, $\rho = 1026 kg/m^3$, $V_b = 20 m/s$

	Case A		Case B	
	Catamaran		Planing hull	
	without b/l ingestion	with b/l ingestion	without b/l ingestion	with b/l ingestion
$l(m)$	63		1.8	
n	10		7.5	
r	0.1		0.5	
$\delta(m)$	0.406		$7.0 * 10^{-3}$	
$A_j(m^2)$	0.3		$4.0 * 10^{-3}$	
D	92.13 kN	92.62 kN	178.2 N	182.0 N
$V_j(m/s)$	29.98	28.97	21.98	21.80
P_{in}	2.30 MW	2.19 MW	3.740 kW	3.743 kW
$\eta(\%)$	80.0	84.5	95.3	97.2
w	—	0.071	—	0.012

situation it is assumed that there is a total of three metres wetted hull perimeter for every metre of inlet width ($D = 3D_f/0.45$). The increase in frictional drag with boundary layer ingestion is only applied to the section of hull where the new boundary layer grows, ie. the zone of influence downstream of the inlet.

For the planing hull, the boundary layer thickness is assumed to be 60% of that of a smooth flat plate at zero pressure gradient to allow for the favourable pressure gradient. Again there is three meters of wetted hull perimeter for every meter width of intake but now the frictional drag accounts for 60% of the total drag.

Resulting performance predictions with zero intake and duct losses are shown in Table 1. The results indicate that boundary layer ingestion increases the drag for both vessels while reducing the required jet velocity. However this is not always beneficial as can be seen from the required input power curves for the planing hull vessel.

Graphs of efficiency and required input power as a function of intake position are shown for the semi-displacement catamaran (Figure 3) and the planing hull vessel (Figure 4). At the bow ($r = 1$) the boundary layer thickness is zero and the performance values with and without ingestion are identical.

Figure 3 shows, for the catamaran, the importance of the positioning of the intake, with the propulsive efficiency reducing and input power increasing as the intake is moved

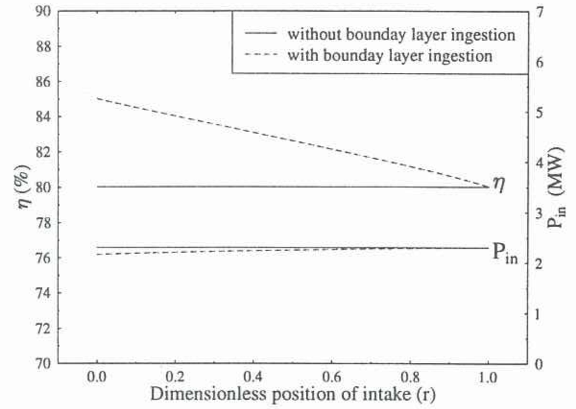

FIGURE 3: Variation of propulsive efficiency and input power with position of intake. Case A: semi-displacement vessel; zero intake and duct loss; r=0 corresponds to intake at stern.

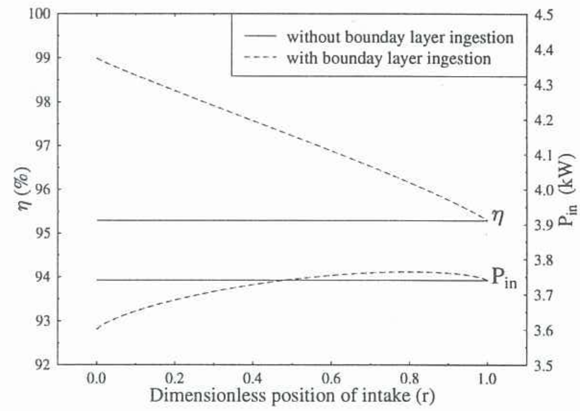

FIGURE 4: Variation of propulsive efficiency and input power with position of intake. Case B: planing hull vessel; zero intake and duct loss; r=0 corresponds to intake at stern.

forward. For this case the increased efficiency is accompanied by corresponding decrease in input power.

The performance variation for the planing hull vessel is more complex. Figure 4 indicates that boundary layer ingestion can increase or decrease the required input power depending on the relative position of the intake.

The favourable influence of boundary layer ingestion on propulsive efficiency arises from the smaller amount of energy addition required for a given momentum increase when the inlet velocity is lowered. This produces in turn a lower kinetic energy flux at the jet outlet. In the limiting case, an ideal propulsive efficiency of 100% could be achieved by re-energising all of the boundary layer fluid so that the jet exit velocity relative to the vessel was V_b and the velocity defect in the wake was everywhere zero. A detailed discussion of this phenomenon has been given by Smith (1993).

Figure 5 shows the effect of including intake and duct losses for the semi-displacement case detailed in Table 1. The duct loss was calculated assuming fully developed pipe flow with friction factor corresponding to a relative roughness of 0.001, whilst the intake loss was found from a curve fit to data presented in Fujisawa and Ogawa (1992) . The offset in the curves with the intake at the stern ($r = 0$) is due

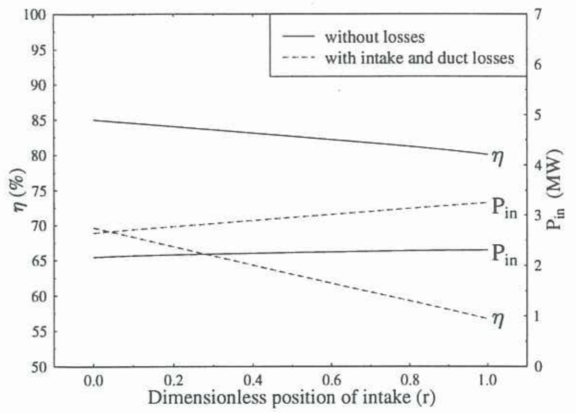

FIGURE 5: Influence of intake and duct losses on propulsive efficiency and input power. CASE A with boundary layer ingestion; r=0 corresponds to intake at stern.

to the intake loss, as the duct loss is zero at this point. The duct loss accounts for almost all of the variation with intake position, as the intake loss varies by less than three percent.

NOZZLE DRAG

It is also possible to apply momentum theory to individual sub-sections of the propulsion system, and this is especially useful for the nozzle. Considering a control volume consisting of the physical nozzle surface and the inflow and outflow areas, for the case of uniform inflow and outflow the total force acting on the nozzle can be derived:

$$D_{nozzle} = \frac{A_{duct}\rho V_j^2}{2}\left(1 - \frac{Aj}{A_{duct}}\right)^2$$

Note this is a drag force and as such the pressure force developed across the impeller must overcome this. The magnitude of drag force acting on the nozzle is quite significant: for example, using the semi-displacement vessel data given in Table 1 for the case with boundary layer ingestion and a duct diameter of $0.76m$, the nozzle drag is $22.93kN$ whilst the vessel drag is $92.13kN$.

Considering the simple case of no boundary layer ingestion, zero duct loss and a constant area inlet duct so that $A_j/A_{duct} = V_b/V_j'$, it can be shown that the force acting on the impeller is

$$T_{imp} = \frac{A_{duct}\rho V_j'^2}{2}\left(1 - \frac{A_j^2}{A_{duct}^2}\right)$$

Taking the ratio of the nozzle drag to impeller force gives

$$\frac{D_{nozzle}}{T_{imp}} = 1 - \frac{2V_b}{V_b + V_j'} = 1 - \eta'$$

so that the nozzle force accounts exactly for the variation of the Froude efficiency from unity.

CONCLUDING DISCUSSION

Most published work concerning waterjet propulsion systems assumes that boundary layer ingestion is always beneficial. It has been shown here that this is not necessarily true, when the drag increment due to removal of the hull boundary layer is taken into account. In practice boundary layer ingestion would produce even further decrements in efficiency due to adverse effects of flow non-uniformity on the pump performance which have been neglected here.

These results highlight the important and complex influence of the thickness and velocity distribution of the ingested hull boundary layer on the overall performance of a waterjet-propelled vessel.

The effect of intake positioning was examined across its entire possible range (from the bow to stern). In general, the performance was found to be enhanced by placing the intake further rearward. Practical considerations of reducing the mass of entrained water and providing adequate space for machinery placement also dictate an intake near the stern.

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