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## Water Jets

### 1 PURPOSE OF PROCEDURE

The method should ensure that the predicted full scale power is as accurate as possible.

### 2 POSSIBLE POWER PREDICTION METHOD FOR WATERJET SYSTEMS

The prediction method for waterjet systems presented below is based upon momentum flux considerations and has many elements in common with earlier methods, among them the one discussed in the Report of the High Speed Marine Vehicles Committee (18<sup>th</sup> ITTC, 1987). There are, however, some differences, the following ones being the most important:

- The gross thrust concept as defined at the 18<sup>th</sup> ITTC (1987) has been replaced by a change in momentum flux  $\Delta M$ , balancing the thrust from the pump and the internal ducting force, plus the change of hull resistance caused by the action of the propulsion unit, including trim effects.
- The change in momentum flux  $\Delta M$  and the shaft power  $P_D$  are calculated using the local energy velocity  $V_E$  defined by

$$\frac{V_E}{V} = \sqrt{\left(\frac{u}{V}\right)^2 + C_p},$$

where  $u$  and  $C_p$  are the local total velocity and the static pressure coefficient


$$C_p = \frac{p - p_o}{\frac{1}{2} \cdot \rho \cdot V^2}$$

measured at some distance in front of the in-take. The energy velocity is a measure of the reduced local total head inside the boundary layer caused by frictional forces along the hull. Therefore, it takes both the kinetic and the potential energy into account. Outside the boundary layer one obtains  $V_E = V$ . The relation between  $V_E$  and the local total head  $H$  is given by

$$H = \frac{V_E^2}{2 \cdot g}$$

Station No.	Location
0	in undisturbed flow far ahead of the vehicle
1	far enough in front of the intake ramp tangency point, before inlet losses occur
2	normal to the internal flow at the aft lip of the intake
3	just ahead of the pump
4	between pump and stator or between stages
5	behind stator
6	at the nozzle outlet plane
7	behind the nozzle outlet plane where the static pressure coefficient in the jet is zero (vena contracta)

Table A1

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- The torque  $Q$  and the rate of revolutions  $n$ , measured in self-propulsion tests, are monitored to check some of the uncertain quantities in the prediction procedure.
- Since the prediction method for waterjet systems differs so much from that for conventional propellers the use of the same nomenclature in the two cases has been abandoned wherever this may lead to confusion.

In the description given below the different stations of the stream tube through the waterjet-system (see Fig. A1) are numbered as given in Table A1. The prediction method is developed for flush intakes but can also be used for Pitot intakes by setting  $V_{E1} = V$ . It will be described for a body-fixed coordinate system  $x-z$  in the following.

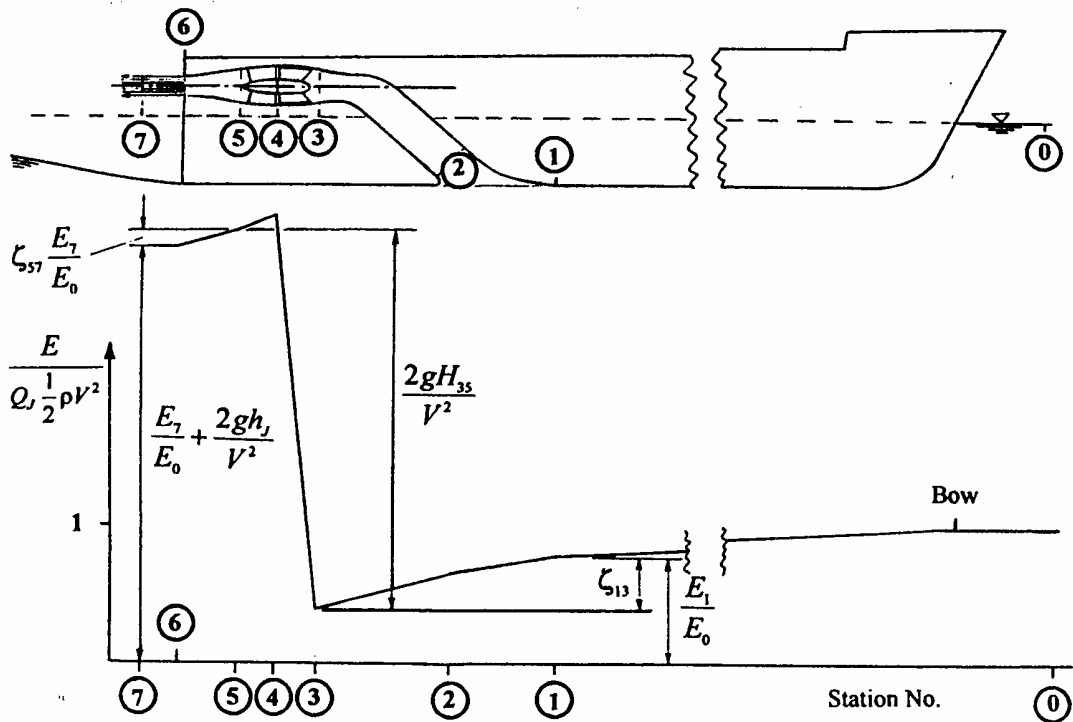



Figure A1. Definition of Station Numbers and Normalised Energy Flux

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## 2.1 Tow Rope Force

A tow rope force  $F_D$  is computed from the estimated difference in resistance coefficient  $C_T$  at model and full scale. Thus  $F_D$  includes differences in skin friction  $C_F$ , hull roughness and air drag. It also allows for the drag of appendages not present at model scale, etc.

## 2.2 Measurements During Self-Propulsion Tests

At the self-propulsion test the following quantities are determined apart from running trim and sinkage:

- the volume flow rate  $Q_J$ ,
- the torque  $Q$  and the rate of revolutions  $n$ ,
- the velocity distribution  $u_1(z)$  at the intake using the difference between the total pressure and the static pressure of a Prandtl tube located at Station 1 (observe that a Prandtl tube is rather insensitive to flow inclinations which means that it is measuring the total velocity  $u_1(z)$  and not the component  $u_{1x}(z)$ !),
- the static pressure coefficient  $C_{p1}(z)$ , obtained from the difference between the static pressure  $p_1$  at Station 1 and the static pressure  $p_0$  in undisturbed flow, measured by a second Prandtl tube located ahead of the vehicle, at Station 0,


- the local energy velocity  $V_{E1}(z)$ , calculated from  $u_1(z)$  and  $C_{p1}(z)$ , as defined above,
- the velocity component  $u_{1x}(z)$  in the  $x$ -direction, which in many cases can be assumed to be equal to  $u_1(z)$ ,
- the velocity distributions  $u_{7x}(A_7)$  and  $u_{7\phi}(A_7)$  in the jet, using a Pitot tube or multi-hole probe at Station 7, if the jet velocity distribution is irregular (the static pressure coefficient is computed).

## 2.3 Size Of Intake Area

The maximum height  $h_1$  of the intake area  $A_1$  is determined from the law of continuity using the flow rate  $Q_J$ , the velocity profile  $u_{1x}(z)$  and assuming the maximum width  $b_1$  and the intake area to be known. The shape of the intake area is assumed either to be rectangular or half-elliptic, as proposed by Alexander et al. (1994). Thus  $h_1$  and  $A_1$  are determined implicitly from

$$Q_J = \int_{A_1} u_{1x}(z) \cdot dA_1 \quad .$$

The velocity  $u_{1x}(z)$  is assumed to vary only in the direction of  $z$  until a better knowledge of three-dimensional inflow effects may permit more realistic approaches. The need for a better knowledge was stressed in the Report of the High Speed Marine Vehicles Committee (20<sup>th</sup> ITTC, 1993), largely with regard to quality control aspects of any power prediction method.

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## 2.4 Momentum Flux

The momentum flux at Station 1 used for force calculations, see Item No. 6, is obtained by integrating the local energy velocity  $V_{E1}$  as follows:

$$M_1 = \rho \cdot \int_{Q_J} V_{E1} \cdot dQ_J,$$

where

$$dQ_J = u_{jx} \cdot dA_j.$$

At Station 7, the „momentum flux“ is instead computed from

$$M_7 = \rho \cdot \int_{Q_J} u_{7x} \cdot dQ_J + \int_{A_7} (p_7 - p_0) \cdot dA_7,$$

where  $p_7 - p_0$  is the pressure reduction caused by tangential velocities  $u_{7\phi}$  of the jet

$$p_7 - p_0 = -\rho \cdot \int_r^{R_J} \frac{u_{7\phi}^2}{r} \cdot dr.$$

$A_7$  is the jet cross sectional area and  $R_J$  is the radius of the jet.  $A_7$  may be smaller than the geometrical nozzle area ( $A_6$ ) due to jet contraction.

The name „momentum flux“ for  $M_7$  is strictly not correct in cases when the jet is rotating, since  $M_7$  will then contain a pressure term.

## 2.5 Energy Flux

The energy flux used to calculate the power and the internal losses is obtained by integrat-

ing the local energy velocity  $V_{Ej}$  at Station  $j$  as follows:

$$E_j = \frac{1}{2} \cdot \rho \cdot \int_{Q_J} V_{Ej}^2 \cdot dQ_J.$$

In the undisturbed flow ahead of the vehicle, Station 0, the energy flux is:

$$E_0 = Q_J \cdot \frac{1}{2} \cdot \rho \cdot V^2.$$

## 2.6 Change Of Momentum Flux

The change of momentum flux  $\Delta M$ , for corresponding stream tubes in resistance and self-propulsion tests, can be written as

$$\Delta M = M_7 \cdot \cos \alpha - M_1,$$


where  $\alpha$  is the angle between the centreline of the jet and the horizontal plane. Since  $\Delta M$ , as mentioned, is supposed to be equal to the sum of the horizontal forces on the pump and the internal ducting plus the change of hull resistance due to the action of the waterjet system, it is equal to the effective model resistance minus the tow rope force. The effective full scale resistance can therefore be computed from

$$R_s = \frac{\rho_s}{\rho_M} \cdot \Delta M \cdot \lambda^3,$$

where  $\lambda$  is the scale factor and  $\rho_M$  and  $\rho_s$  are the water densities at model and full scale.

## 2.7 Effective Jet System Power

It is now possible to compute the effective jet system power  $P_{JSE}$ , from the increase of energy between Station 1 and Station 7:

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$$P_{JSE} = E_7 - E_1.$$

## 2.8 Elevation Power

The power needed to lift the water to a height  $h_j$  above the undisturbed water surface is computed from

$$\rho \cdot g \cdot Q_j \cdot h_j.$$

## 2.9 Internal Losses

Power is also needed to overcome the inlet and outlet losses. If  $\zeta_{13}$  and  $\zeta_{57}$  are the loss coefficients for the intake and diffuser on one hand and for the outlet nozzle on the other hand, one obtains

$$\zeta_{13} \cdot E_0 + \zeta_{57} \cdot E_7.$$

These coefficients can also be expressed as follows:

$$\zeta_{13} = \frac{E_1 - E_3}{E_0},$$

$$\zeta_{57} = \frac{E_5 - E_7}{E_7}.$$

## 2.10 Effective Pump Power

The effective power  $P_{PE}$  is the sum of the contributions described in Items No. 7-9 (see also Fig. A1), i.e.

$$P_{PE} = P_{JSE} + \rho \cdot g \cdot Q_j \cdot h_j + \zeta_{13} \cdot E_0 + \zeta_{57} \cdot E_7,$$

or

$$P_{PE} = \rho \cdot g \cdot Q_j \cdot H_{35},$$

where  $H_{35}$  is the increase of the mean total head across the pump:

$$H_{35} = \frac{l}{\rho \cdot g \cdot Q_j} \cdot [E_7 \cdot (1 + \zeta_{57}) - E_1 + E_0 \cdot \zeta_{13}] + h_j,$$

## 2.11 Model Shaft Power

If one knows the pump efficiency  $\eta_P$ , determined in a conventional pump test rig and the pump installation efficiency  $\eta_{inst}$ , taking care of the inflow non-uniformities to the pump in the waterjet system, one can determine the power  $P_{DM}$  needed to propel the model:


$$P_{DM} = \frac{P_{PE}}{\eta_P \cdot \eta_{inst}}.$$

## 2.12 Check Of Model Shaft Power

The shaft power can also be determined from the torque measurements. If  $P_{DM}$  is not equal to  $2 \cdot \pi \cdot Q \cdot n$ , then the estimate of internal loss coefficients ( $\zeta_{13}$ ,  $\zeta_{57}$ ) or efficiency values ( $\eta_P$ ,  $\eta_{inst}$ ) should be reconsidered.

## 2.13 Scale Effect Considerations

To be able to compute the full scale power one must determine full scale values of volume flow rate, size of intake area and energy veloci-

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ties at Stations 1 and 7. Due to the scale effects of the boundary layer profile at the intake these quantities can not directly be converted from corresponding model values but the following procedure must be followed.

- First, the full scale boundary layer thickness and velocity profile at the inlet are predicted, also considering that the full scale vehicle has a certain hull roughness. The static pressure coefficient is assumed to be the same as in the model test.
- Second, full scale values of  $Q_J$ ,  $M_1$ ,  $h_1$  and  $M_7$  are computed from the momentum theorem, using the full scale velocity profile and maintaining the change of momentum flux

$$\Delta M_s = R_s = \frac{\rho_s}{\rho_m} \cdot \Delta M_m \cdot \lambda^3.$$

- Third, full scale values of  $E_1$  and  $E_7$ , appropriate internal loss coefficients  $\zeta_{13S}$  and  $\zeta_{57S}$ , pump and installation efficiency figures  $\eta_{PS}$  and  $\eta_{instS}$  are estimated.

#### 2.14 Predicted Full Scale Power

Using the figures estimated in Item No. 2.13, the full scale effective pump power  $P_{PES}$  is computed as described in Item No. 2.7 – 2.10 together with the increase of mean total head across the pump  $H_{35S}$  as shown in Item No. 2.10. The pump shaft power, finally, will be:

$$P_{DS} = \frac{P_{PES}}{\eta_{PS} \cdot \eta_{instS}}$$

### 3 PARAMETERS

#### 3.1 Parameters to be Taken into Account

tow rope force  
size of intake area  
energy flux  
effective jet system power  
elevation power  
internal losses  
duct and nozzle losses

#### 3.2 Recommendations of ITTC for Parameters

None.

### 4 VALIDATION

#### 4.1 Uncertainty Analysis

None

#### 4.2 Test – Calculation

None

#### 4.3 Test - Full Scale

None

#### 4.4 Benchmark Tests

- 1) ITTC Database of Seakeeping Experiments (21<sup>st</sup> 1996 pp.43)  
S-175, High Speed Marine Vehicle