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# Propeller-hull interaction coefficients: classic vs alternative system *

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## ABSTRACT

Propulsion performance of icebreakers moving in ice fields, as well as of the ships towing various objects, is hard to assess because propeller-hull interaction coefficients are not always possible to determine as per the classic system. To overcome this difficulty, an alternative system of propeller-hull interaction coefficients is suggested.

This paper shows that the method of self-propulsion tests with tow force $F_D$ and the method of captive self-propulsion tests adopted by KSRC yield the same results.

It is noted that the classic system of propeller-hull interaction coefficient does not work in the processing of self-propulsion test data for the propellers under high loads.

The paper suggests an alternative, "bollard-pull" system of interaction coefficients that remains workable in self-propulsion data processing for heavily loaded propellers.

## INTRODUCTION

To calculate propulsion performance of a ship, it is necessary to have propeller-hull interaction coefficients. Propulsion performance of icebreakers moving in ice fields, as well as of the ships towing various objects is hard to assess because propeller-hull interaction coefficients cannot be determined as per the classic system. To overcome this difficulty, an alternative system of propeller-hull interaction coefficients is suggested.

## SELF-PROPULSION TESTS WITH TOW FORCE $F_D$

To determine propeller-hull interaction coefficients, most of hydrodynamic centres perform self-propulsion tests with tow force $\boldsymbol{F_D}$. These self-propulsion tests are performed with the model towed at speed $V_M$ corresponding to the specified speed $V_S$ of the ship.

$$V_M = {V_S}\Big/{\sqrt{\Lambda}} \qquad (1)$$

Here, tow force $\boldsymbol{F_D}$ is determined as follows:

$$\boldsymbol{F_D} = \rho_M \frac{V_M^2}{2} S_M (C_{TM} - C_{TS}) \qquad (2),$$

where:

*M* and *S* subscripts denote "model" and "ship" respectively;

$\rho$ - mass density of water, kg/m$^3$;

$\Lambda$ - model scale;

V - ship speed, m/s;

S - wetted surface area of the hull, m$^2$;

$$C_T = R_T / (\rho V^2/2 * S) \qquad (3)$$

$C_T$ - total resistance coefficient;

$R_T$ - towing resistance of the ship.

Output data of the self-propulsion tests with tow force $F_D$ for specified speed $V_S$ of the ship are the three following values:

Wake fraction $w_{TM}$;

Thrust deduction fraction *t*;

Relative rotative efficiency $\eta_R$.

These three values correspond to uniform straight movement of a ship at speed $V_S$. For details on the method of self-propulsion tests with tow force $\boldsymbol{F_D}$, see, for example, [1].

## CAPTIVE SELF-PROPULSION TESTS

KSRC applies the method of captive self-propulsion tests, which is a combination of the test runs performed at constant towing speed and variable propeller RPM, and the test runs performed at constant propeller RPM and variable towing speeds.

Thrust *T* and torque *Q* of the propeller are measured by a screw dynamometer installed inside the model hull. Force ***Z*** arising between the model and the towing carriage during self-propulsion tests is measured by a towing dynamometer. During self-propulsion tests (at different test runs), force ***Z*** varies, starting from positive values (propeller loads are heavy), then passing the zero level (self-propulsion point), and then becoming negative (propeller loads are small). Useful thrust $T_E$ is calculated as a sum of force ***Z*** measured by the towing dynamometer and model resistance $R_{TM}$ at given towing speed:

$$T_E = R_{TM} + \mathbf{Z} \qquad (4)$$

Calculation of propeller-hull interaction coefficients requires open-water model test data for the propeller.

Useful thrust coefficient is determined as:

$$K_E = \frac{T_E}{Z_P \rho n^2 D^4} \cdot \quad (5),$$

where:

$Z_P$ – number of propellers, $Z_P$=1 or $Z_P$=2;

$n$ – propeller rotation rate, rps;

$D$ – propeller diameter, m.

## ANALYSIS OF CAPTIVE SELF-PROPULSION TESTS: CONSTANT SPEED

Output data of self-propulsion tests with the speed remaining constant for each advance

$J_V = V/(n\,D)$ are the following four values:

$w_{TM}(J_V)$ – wake fraction;

$t(J_V)$ – thrust deduction fraction;

$\eta_R(J_V)$ – relative rotative efficiency;

$K_{DE}(J_V)=J_V/\sqrt{K_E}$ – useful-thrust loading coefficient.

Thus, the following three relationships are determined:

$$w_{TM} = w_{TM}(K_{DE}) \quad (6);$$

$$t = t(K_{DE}) \quad (7);$$

$$\eta_R = \eta_R(K_{DE}) \quad (8).$$

The values of $w_{TM}$, t, $\eta_R$ are calculated as per the classic procedure described in [2,3].

For the ship, the load coefficient with respect to the useful thrust is determined as:

$$K_{DES} = V_S \cdot D_S \Big/ \sqrt{\frac{R_{TS}}{\rho_S}} = D_S \Big/ \sqrt{\frac{S_S}{2} \cdot C_{TS}} \qquad (9),$$

where

$$R_{TS} = \rho_S \frac{V_S^2}{2} \cdot S_S \cdot C_{TS} \qquad (10)$$

For the model tested with tow force $\boldsymbol{F_D}$, the load coefficient with respect to the useful thrust can be expressed as

$$K_{DEM} = V_M \cdot D_M \Big/ \sqrt{\frac{R_{TM} - \boldsymbol{F_D}}{\rho_M}} \qquad (11),$$

where

$$R_{TM} = \rho_M \frac{V_M^2}{2} \cdot S_M \cdot C_{TM} \qquad (12).$$

Then, it has to be considered that

$$R_{TM} - F_D = \rho_M \frac{V_M^2}{2} \cdot S_M \cdot C_{TM} - \rho_M \frac{V_M^2}{2} S_M (C_{TM} - C_{TS}) = \rho_M \frac{V_M^2}{2} S_M \cdot C_{TS},$$

so

$$K_{DEM} = \frac{V_S}{\sqrt{\Lambda}} \frac{D_S}{\Lambda} \Big/ \sqrt{\frac{V_S^2}{2 \cdot \Lambda} \frac{S_S}{\Lambda^2} C_{TS}} = D_S \Big/ \sqrt{\frac{S_S}{2} C_{TS}} \quad (13).$$

Consequently, at the calculation point for the ship as per (9), the load coefficient with respect to the useful thrust coincides with the load coefficient for the model tested with tow force $F_D$ (13).

$$K_{DES} = K_{DEM} \qquad (14).$$

Expression (14) means that these two methods of self-propulsion tests yield the same results.

## ANALYSIS OF CAPTIVE SELF-PROPULSION TEST DATA: CONSTANT RPM

Self-propulsion tests at constant RPM and variable towing speed are performed to investigate the effect of Froude numbers upon propeller-hull interaction coefficients. The value of constant RPM is selected so as to correspond to the value of the useful-thrust loading coefficient, as determined by Formula (9). If the effect of Froude numbers is significant, additional tests at constant speed are performed.

## ANALYSIS OF CAPTIVE SELF-PROPULSION TEST DATA: CONSTANT RPM CORRESPONDING TO BOLLARD-PULL OPERATION OF PROPELLERS

For icebreakers, ice-going ships and tugs, additional self-propulsion tests at constant RPM are performed. The RPM is selected so as to correspond to the bollard-pull condition. The tests are performed at several low speeds of the ship. Here, the effect of Froude numbers is negligible. Figs. 1 and 2 provide self-propulsion model test data for an ice-going twin-shafter, where constant propeller rotation rate (n= 14.6 rps) corresponds to the bollard-pull condition.

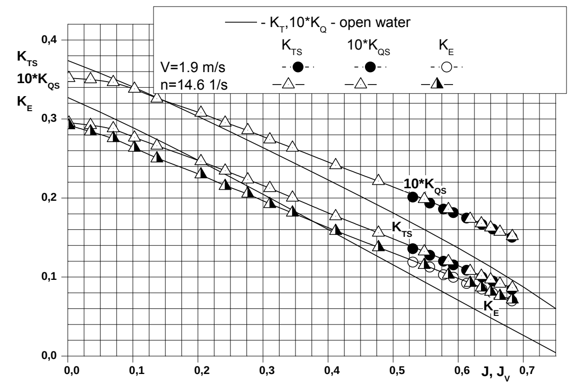


Fig. 1 – Performance curves of the starboard propeller No. 8369 in open water and behind the hull of model No. 11765.Outward rotation. Ahead running. Draught $T_F$= $T_A$=0.286 m.

In Fig. 1 above, the curves without the experimental points show the open-water model test results for the starboard propeller No. 8369, J = $V_A$/(n D) being the open-water propeller advance ratio, $V_A$ – speed of the propeller advance. The curves with the experimental points in the same Figure 1 show the following hydrodynamic parameters of propeller No. 8369 model behind the model hull:

$K_T = T/(\rho\, n^2 D^4)$ – propeller thrust coefficient;

$T$ – propeller thrust, N;

$n$ - propeller rotation rate, rps;

$K_Q = Q/(\rho\, n^2 D^5)$ – propeller torque coefficient;

Q - propeller torque, N*m;

$K_E = \dfrac{T_E}{2\,\rho n^2 D^4}$ - useful thrust coefficient;

Subscript *S* means “starboard”.

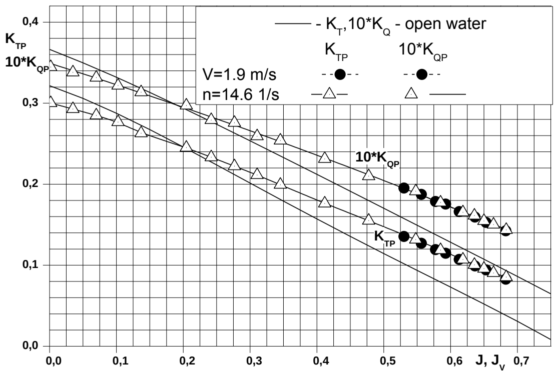


Fig. 2 – Performance curves of the port side propeller No. 8370 in open water and behind the hull of model No. 11765.Outward rotation. Ahead running. Draught $T_F$= $T_A$=0.286 m.

In Fig. 2 above, the curves without the experimental points show the open-water model test results for the port side propeller No. 8370, J = $V_A$/(n D) being the open-water propeller advance ratio.

For behind-the-hull operation conditions, the nomenclature in Fig. 2 is the same as in Fig. 1, except *p* (port side) subscript.

Processing of the self-propulsion test data provided in Fig. 1 and 2 above, intended to obtain relationships 6-8, yields the results shown in Fig. 3 below:

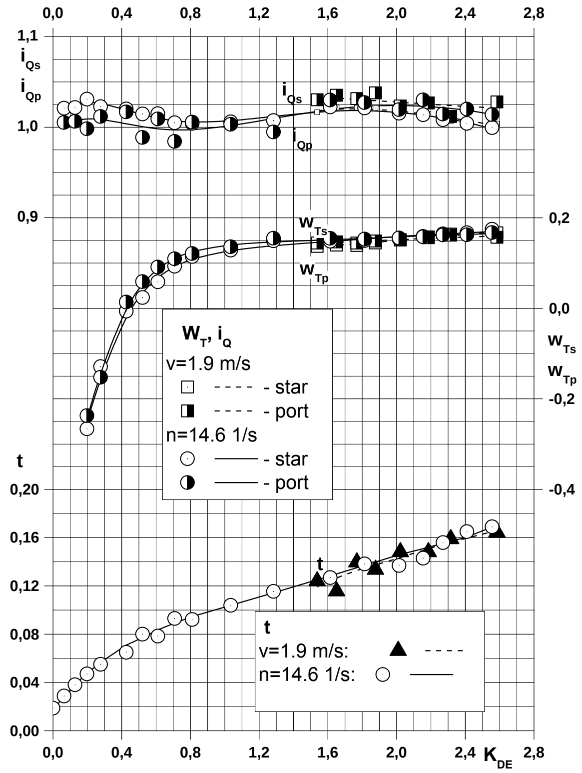


Fig. 3- Interaction coefficients of propeller models with the hull of model No. 11765 (classic system). Ahead running. Draught $T_F$= $T_A$=0.286 m.

Instead of Expression (8), Fig. 3 provides the following coefficient:

$$i_Q = 1/\ \eta_R \quad (15).$$

So for classic interaction system we have three functions:

$$t = t\,(K_{DE}) \qquad (7);$$

$$w_{TM} = w_{TM}\,(K_{DE}) \quad (6);$$

$$i_Q = i_Q(K_{DE}) \qquad (16).$$

For classic interaction system we have following connection for hull efficiency coefficient:

$$\eta_H=(1-t)/(1-\ w_{TM})*1/\ i_Q \quad (17)$$

Analysis of the data in Fig. 3 shows that thrust deduction fraction *t* is determined for all the values of useful-thrust loading coefficient $K_{DE}$. Along with it, wake fraction $w_{TM}$ at $K_{DE}$ < 0.45 becomes negative and tends to infinity as $K_{DE}$ tends to zero, which means that at $K_{DE}$<0.45 the classic system of propeller-hull interaction coefficients does not work.

It shall be noted that operational conditions of the icebreakers moving in the ice field correspond to $K_{DE}$<0.45. Operational conditions of the ships towing various objects also correspond to $K_{DE}$<0.45. So propulsion and net thrust calculations of these ships require an alternative system of interaction coefficients.

This paper suggests the alternative, “bollard-pull”, system of propeller-hull interaction coefficients, consisting of the following three relationships:

1. Thrust deduction fraction coinciding with the one adopted in the classic system:

   $t= t(K_{DE})$ (7).

2. Coefficient of hull effect upon the thrust:

   $$i_{TB}(K_{DE})= K_T\,(J_V)/K_{To.w.}(J) \quad J=J_V \qquad (18).$$

3. Coefficient of hull effect upon the torque:

   $$i_{QB}(K_{DE})= K_Q\,(J_V)/K_{Qo.w.}(J) \quad J=J_V \qquad (19).$$

For alternative interaction system we have following connection for hull efficiency coefficient:

$$\eta_H=(1-t)*\ i_{TB}\ /\ i_{QB} \quad (20)$$

Here, *o.w.* subscript means “open-water”.

Fig. 4 provides the results of the same self-propulsion tests as those in Fig. 1 and 2 above, processed as per the “bollard-pull” system of propeller-hull interaction coefficients.

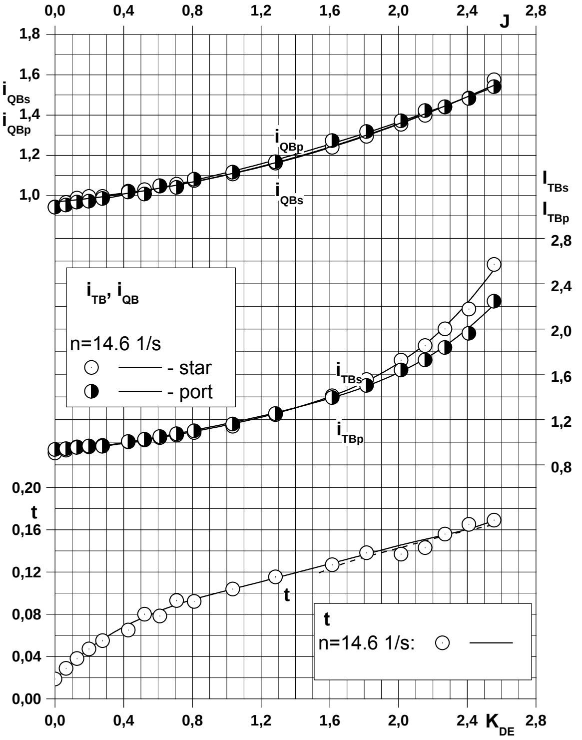


Fig. 4 – Interaction coefficients of propeller models with the hull of model No. 11765
(bollard-pull system). Ahead running. Draught $T_F$= $T_A$=0.286 m.

Analysis of the data provided in Fig. 4 above shows that the bollard-pull system of propeller-hull interaction coefficients remains workable at low values of useful-thrust loading coefficient, $K_{DE}$<0.45, i.e. at $K_{DE}$<0.45 propeller-hull interaction coefficients $i_{TB}$, $i_{QB}$ are possible to determine.

It was decided to fulfil investigation of data of ice trial of icebreaker 'Vladivostok' to show the results of use of alternative interaction coefficients system. The ice trial environment is shown in table 1. The resultant ice thickness was varied from 0.81 to 1.68 m for the different runs.

Table 1: The ice trial environment.

| № of run | Ice thickness, m | Snow thickness, m | Resultant ice thickness, m | Bending strength, kPa |
|---|---|---|---|---|
| 2.1 | 0,63 | 0,18 | 0,81 | 280 |
| 3.1 | 128 | 30 | 1,58 | 420 |
| 3.2 | 138 | 23 | 1,61 | |
| 3.3 | 128 | 40 | 1,68 | |

The ice trial results for icebreaker 'Vladivostok' are shown in table 2. The icebreaker speed was varied from 0.63 to 10.3 knots for the different runs.

Table 2: The ice trial results for icebreaker 'Vladivostok'.

| № of run | Speed, knots | Power, kWt | | RPM | |
|---|---|---|---|---|---|
| | | star | port | star | port |
| 2.1 | 10,3 | 8964 | 8964 | 156 | 156 |
| 3.1 | 2,28 | 8964 | 8964 | 140 | 140 |
| 3.2 | 2,54 | 8964 | 8963 | 141 | 140,5 |
| 3.3 | 0,61 | 7228 | 7279 | 128 | 127 |

The prediction of the ice propulsion for icebreaker 'Vladivostok' is shown in table 3.

Table 3: The ice propulsion for icebreaker 'Vladivostok'.

| № of run | Speed, knots | Power, kWt | RPM | Ice resistance or towing force of propellers, kN |
|---|---|---|---|---|
| 2.1 | 10,3 | 2×9000 | 151 | 1080 |
| 3.1 | 2,28 | | 139,2 | 1654 |
| 3.2 | 2,54 | | 139,5 | 1643 |
| 3.3 | 0,61 | 2×7250 | 128,1 | 1495 |

It may be note that for given speed and power predicted RPM are close to measured ones. Beside that the ice ship resistance is also determined.

## CONCLUSION

1. It has been shown that the method of self-propulsion tests with tow force $\mathbf{F_D}$ and the method of captive self-propulsion tests adopted by KSRC yield the same results.
2. It has been noted that the classic system of propeller-hull interaction coefficients does not work in the processing of self-propulsion test data for heavily loaded propellers.
3. An alternative, "bollard-pull" system of interaction coefficients has been suggested. This alternative system remains workable in the processing of self-propulsion test data for heavily loaded propellers.

## REFERENCES


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3. W.P.A. Van Lammeren, L. Troost, J. G. Koning 'Resistance, Propulsion and Steering of Ships'. A manual for designing hull forms, propellers and rudders. The Technical Publishing Company H. Stam-Haarlem-Holland, 1954.