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METHODS OF DETERMINATION OF FRICTIONAL RESISTANCE FOR PREDICTION OF TOTAL RESISTANCE OF INLAND WATERWAY VESSELS

Jan Kulczyk
Wrocław University of Technology, Poland

ABSTRACT

In the present paper presented are the results of prediction of total resistance of inland waterway vessels based on model test data. In scaling the resistance from model to full scale the extrapolation with two-dimensional frictional resistance formulation (without form factor) was applied, combined with different methods of determination of frictional (viscous) resistance coefficient. There were used the equations that include the effect of water depth, with and without account for pressure gradient. It was shown that limited depth of water substantially affects the frictional resistance. The results of example calculations are compared to resistance prediction made using the ITTC 1957 model-ship correlation line. Example calculations take into account the limited depth of water. Depending on the applied method of determination of frictional resistance coefficient the resultant total resistance of inland waterway vessel is higher or lower than the resistance based on the ITTC 1957 correlation line. The effect of water depth depends on the ratio of water depth to ship draught (h/T), on ship speed, and on the composition of a convoy. The extrapolation of resistance was made without including the form factor. Computations are made based on model test data for an inland waterway cargo vessel, for a kombi-type convoy of an inland waterway cargo vessel and a dumb barge, and for a convoy of two dumb barges without a pushboat.

Keywords: inland waterway vessel, extrapolation of hull resistance, coefficient of frictional resistance

INTRODUCTION

In design of inland waterway vessels the prediction of ship resistance is made based on model tests and using the Froude hypothesis and extrapolation techniques. For determination of frictional resistance the ITTC-1957 model-ship correlation line or the Schoenherr formula are usually applied. In the range of Reynolds numbers that can be encountered in resistance prediction, i.e. $10^5 \le Re \le 10^9$, the values of frictional resistance coefficient determined using above formulae differ merely slightly. The difference is about 2% for low Reynolds numbers and less than 1% for $Re \ge 10^8$.

Above methods of determination of frictional resistance are based on the resistance of flat plate and do not account for finite water depth in the case of shallow water. In comparison to deep water the finite depth of shallow water is related to specific phenomena in ship motion:

- significantly higher resistance at the same ship speed,
- change in position of hull in relation to undisturbed surface of water, i.e. trim and sinkage.

The back flow appears and the velocity in flow around the hull is higher than ship speed.

The study of ship motion in shallow water reveal the rapid growth of hull resistance, trim and sinkage when approaching the critical speed. Critical speed is related to the velocity of energy transportation in wave motion. The critical speed in shallow water amounts:

$$V_{kr} = \sqrt{g \cdot h} \tag{1}$$

where g is the acceleration due to gravity, and h is the depth of water.

In practice, merchant ships in restricted waters are operated at speeds lower than the critical speed. The hydrodynamically economic speed limit for inland waterway vessels [1] was determined as [3]:

$$V_{gr} = (0,5 \div 0,65) \cdot V_{kr} \tag{2}$$

The upper value applies to motor cargo vessels and the lower value applies to pushed barge trains composed of two or three rows of dumb barges and a pushboat.

The rapid growth of hull resistance at speeds above the economic speed limit V_{gr} is the effect of increase of wave resistance. The share of viscous resistance in total hull resistance of an inland vessels has not been recognized in details. Based on data from model tests one may assume that at speeds around the economic speed limit the contribution of viscous resistance amounts about 30÷40% of total resistance. This share is higher at speeds below V_{gr}, and is lower at speeds higher than V_{gr}. Because the share is considerable the error in determination of viscous resistance may cause significant error in power prediction for a full scale vessel.

In this paper the results of prediction of total resistance of inland waterway vessels are presented based on model test data and extrapolation procedure. In scaling the resistance from model to full scale the extrapolation with two-dimensional frictional resistance formulation (without form factor) was applied combined with different methods of determination of frictional (viscous) resistance coefficient. There were used the equations that include the effect of water depth, with and without account for pressure gradient. It was shown that limited depth of water substantially affects the frictional resistance. The results of example calculations were compared to resistance predicted using the ITTC-1957 model-ship correlation line. The resultant total resistance of inland waterway vessel is higher or lower than the resistance based on the ITTC-1957 correlation line depending on applied method of determination of frictional resistance coefficient. The ratio of predicted values depends on the proportion between water depth and ship draught (h/T), on ship speed, and on the composition of a convoy of vessels. The extrapolation of resistance was made without account for velocity of back flow and roughness (no roughness allowance). It was assumed that the contribution of above components in any case would be the same, independent from the method of determination of frictional resistance coefficient. Computations were made based on model test data for an inland waterway cargo vessel sailing alone or coupled with a single dumb barge (a kombi-type train) [5], and for a convoy of two dumb barges without a pushboat [2].

FRICTIONAL RESISTANCE IN SHALLOW WATER

The conditions of sailing in shallow water are determined by finite distance between ship bottom and the bed of waterway. Turbulent boundary layer in ship flow is confined. In very simple terms one may assume that the flow is similar to the flow between two parallel flat surfaces where one surface is motionless and the other moves at velocity corresponding to ship speed. Such model of flow does not include the variable gradient of pressure that is the case in actual ship motion in shallow water. One assumes that flow in space between surfaces is a fully developed turbulent flow, and that the distribution of velocity is logarithmic. Accordingly, the following relationship has been derived [4]:

$$\frac{1}{\sqrt{c_F}} = 1,768 \cdot \ln\left(\sqrt{c_F} \cdot \mathrm{Re}_h\right) + 1,509 \tag{3}$$

where:

c_F -coefficient of frictional resistance,

Re_h -Reynolds number based on distance between surfaces:

$$\mathrm{Re}_h = \frac{V_S \cdot h}{\nu} \tag{4}$$

where:

h -distance between surfaces,

ν -kinematic viscosity of water.

The relationship between the coefficient of frictional resistance c_F and the Reynolds number Re_h is illustrated in Fig.1. It has been approximated using the cubic polynomial:

$$C_F = -6.541\text{E-}05(\log Re_h)^3 + 1.466\text{E-}03(\log Re_h)^2$$
$$- 1.138\text{E-}02 \log Re_h + 3.195\text{E-}02 \tag{5}$$

Zawiślak [6] has completed the formula (3) with the term that accounts for pressure gradient:

$$\frac{1}{\sqrt{c_F}} = 1,768 \cdot \ln\left(\sqrt{c_F} \cdot \mathrm{Re}_h\right) + ST + 1,326 \cdot f(c_F, \mathrm{Re}_y, y_n) \tag{6}$$

where:

ST = 0.68 for model ship,

ST = 1.509 for full scale ship.

The term $f(c_F, \mathrm{Re}_y, y_n)$ takes into account the averaged pressure gradient between the bottom of vessel and the bed of waterway. The Reynolds number Re_y is based on local distance between the bottom of 'averaged' hull and waterway bed:

$$y_n = h - \frac{Ax(x)}{B} \tag{7}$$

where:

Ax(x) -local sectional area of hull,

B -ship beam.

In the case of flat surface the last term in equation (6) equals zero and the equation is identical to eq. (3). Two values of term ST in equation (6) were introduced based on numerical computations of flow between the ‘averaged’ two-dimensional hull and waterway bed [6]. One may consider it as a partial equivalent of form factor commonly used in extrapolation of ship resistance.

Frictional resistance coefficient c_F calculated according to equation (6), without the effect of pressure gradient ($f(c_F, Re_y, y_n) = 0$), is presented in Fig.1.

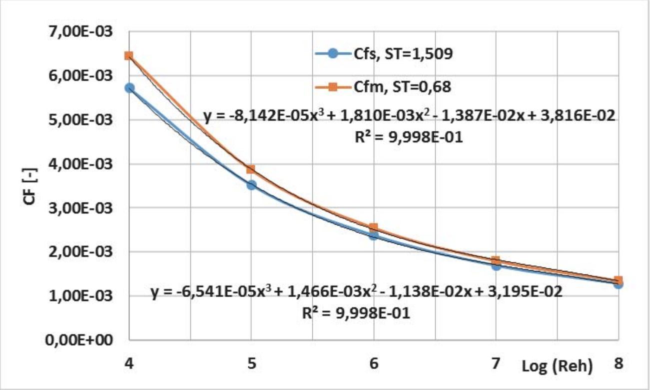

Fig.1. Coefficient of frictional resistance c_F calculated according to equation (6) with $f(c_P, Re_y, y_n) = 0$

The effect of shallow water on resistance prediction was investigated using frictional resistance coefficient calculated according to equation (3), approximated with formula (5). The effects of scale factor and pressure gradient (according to eq. (6)) are presented for one test case of the OBM motor cargo vessel.

RESULTS OF CALCULATIONS AND THE ANALYSIS

The effect of the method of determination of frictional resistance coefficient on resistance prediction was investigated for two vessels that were extensively tested in model scale including the variation of draught and water depth. There are conventional ships operated on inland waterways: the motor cargo vessel (OBM) operated alone or as a kombi-type convoy i.e. coupled with a dumb barge (OBM+BP), and two dumb barges coupled in a single-row convoy without a pushboat (2xT170). Model tests of the motor cargo vessel were carried out in Ship Design and Research Centre in Gdańsk [5]. The convoy of two dumb barges was tested in Development Centre for Ship Technology and Transport Systems (DST) in Duisburg, in the framework of RTD project INBAT [2]. Hull forms of considered vessels are presented in figures 2 and 3. Main particulars are as follows:

OBM
Length between perpendiculars LPP = 67.83 m
Draught T1 = 1.60 m; T2 = 2.36 m
Length at waterline LWL1 = 67.83 m; LWL2 = 69.27 m
Beam B = 8.92 m
Dumb barge (BP)
Length between perpendiculars LPP = 44.12 m
Draught T = 1.60 m
Test conditions
Water depth h = 2.00; 2.25; 2.50; 2.75 m
Model scale 1:16

Dumb barge T170 (INBAT)
Length over all LOA = 48.75 m
Length between perpendiculars LPP = 48.28 m
Design draught T = 1.70 m
Beam B = 9.00 m
Conditions of model tests
Draught T = 0.6; 0.9; 1.4; 1.7 m
Water depth h = 1.2; 2.0; 3.6; 5.0 m
Model scale 1:14

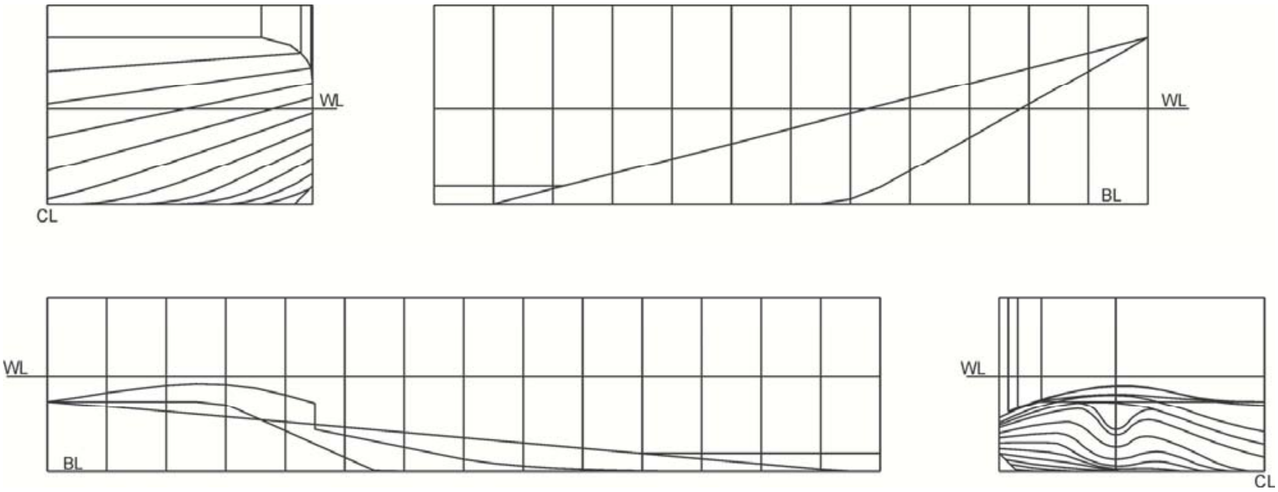

Fig.2. Hull form of motor cargo vessel OBM

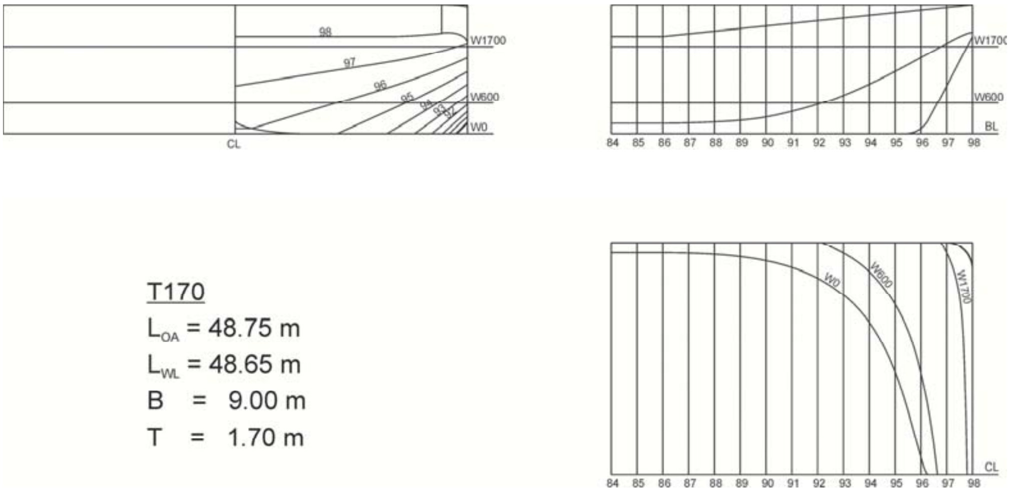

Fig.3. Hull form of dumb barge T170

OBM - THE RESULTS OF CALCULATIONS

The ratio of ship resistance predicted with coefficient of frictional resistance calculated according to eq. (3) (Rths) to ship resistance predicted with coefficient of frictional resistance determined using the ITTC-1957 model-ship correlation line (Rts57) is presented in figures 4, 5 and 6. Resistance predicted with account for restricted depth of water Rths is higher (Fig.4). The differences are within 0.5% to 3% and depend on water depth and ship speed. At lower depths of water these differences are smaller. The increase of ship speed causes that the differences decrease. The trends at ship draught T = 2.36 m are similar (not presented in this paper).

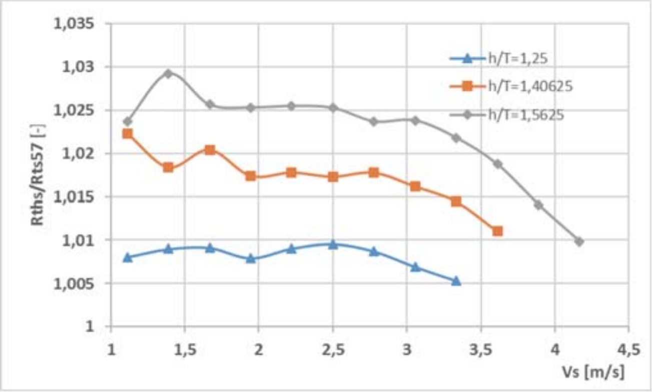

Fig.4. The effect of water depth on resistance prediction, OBM at T = 1.60 m

When the coefficient of frictional resistance is calculated using eq. (3) with term ST adjusted to model ship and full scale ship, as in eq. (6), then the predicted ship resistance is lower than resistance predicted with application of the ITTC-1957 correlation line (Fig.5). The differences amount from 6% to 1%. The effect of depth to draught ratio h/T is not distinct. The effect of ship speed is clear.

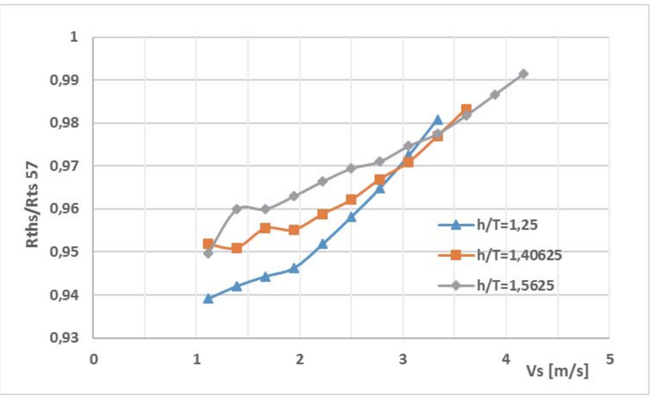

Fig.5. The effect of account for scale factor (last term in eq. (3) adjusted to model ship and full scale ship during extrapolation) on resistance prediction, OBM at T = 1.60 m

The effect of ship length on resistance prediction is shown in Fig.6. In the case of kombi arrangement (OBM+BP) the resistance predicted with account for restricted depth of water is lower. The differences do not exceed 3% and at higher speeds are smaller.

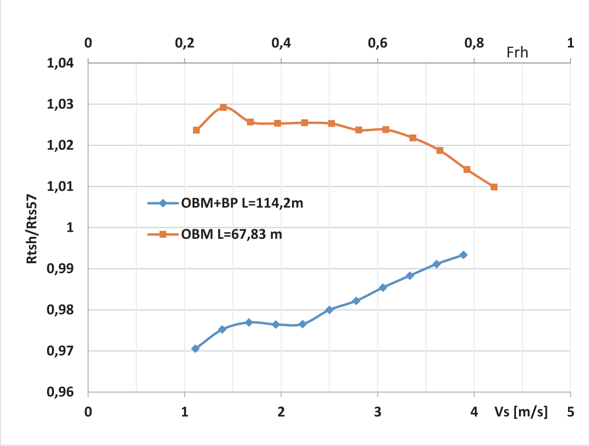

Fig.6. The effect of ship length on resistance prediction, OBM at T = 1.60 m, h = 2.5 m

The coefficient of frictional resistance c_F calculated according to eq. (6), i.e. with account for scale factor α and pressure gradient dp/dx, for the motor cargo vessel OBM are presented n fugues 7 and 8. The values calculated with non-zero pressure gradient (dp/dx ≠ 0) were originally published in [6].

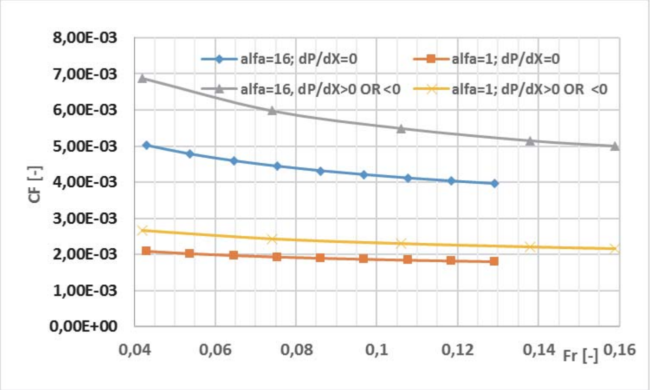

Fig.7. The effect of scale factor α and pressure gradient dp/dx on coefficient of frictional resistance cF calculated according to eq. (6), OBM at T = 1.60 m, h/T = 1.25

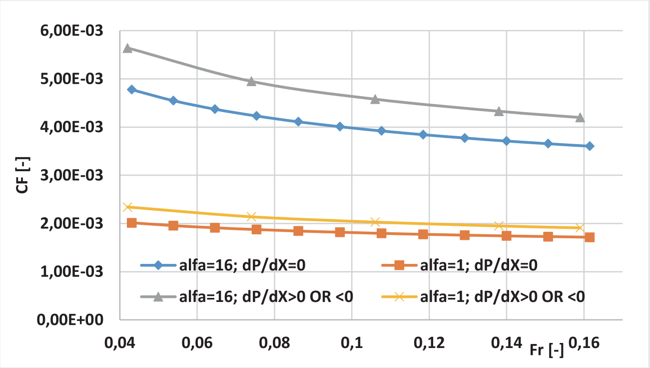

Fig.8. The effect of scale factor α and pressure gradient dp/dx on coefficient of frictional resistance cF calculated according to eq. (6), OBM at T = 1.60 m, h/T = 1.56

The neglect of pressure gradient (dp/dx = 0) makes the difference in frictional resistance coefficient in full scale lower than in model scale. Similar is the effect of increased water depth.

THE CONVOY OF TWO DUMB BARGES T170

Resistance prediction was made for typical convoy of two dumb barges coupled stern to stern in one row. Example results of calculations for the convoy at two settings of ship draught: T = 1.70 m and T = 0.90 m, are presented in figures 9 and 10, respectively. For the different ranges of speed the ratio Rths/Rts57 is drawn versus depth Froude number Fr_h.

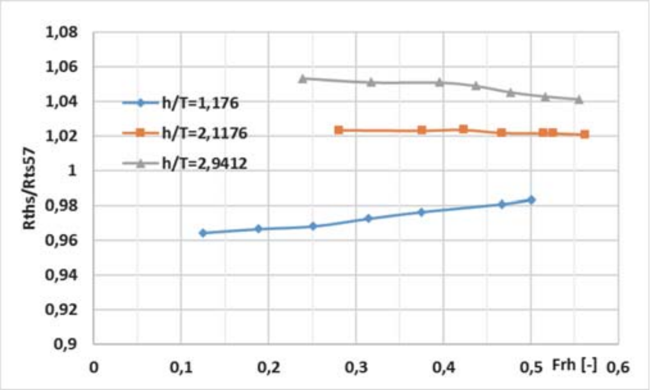

Fig.9. The effect of water depth, 2xT170 at T = 1.70 m

In comparison to OBM the effect of water depth is opposite. For very shallow water ship resistance predicted with application of eq. (3) (Rths) is lower than with ITTC-1957 correlation line, wherein apparent is the effect of ship draught. The differences in ship resistance range from 14% at T = 0.90 m to less than 4% at T = 1.70 m.

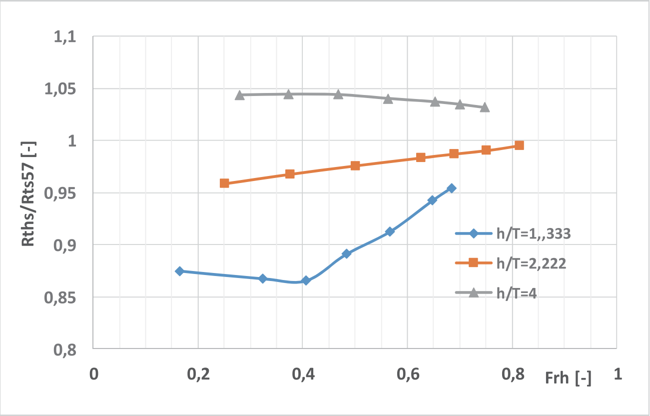

Fig.10. The effect of water depth, 2xT170 at T = 0.90 m

At increased water depth the resistance predicted with eq. (3) becomes higher than resistance predicted with application of ITTC-1957 correlation line. This trend is especially apparent at T = 1.70 m. However, the difference does not exceed 5%.

SUMMARY AND CONCLUSIONS

The ratio of ship resistance predicted using the coefficient of frictional resistance calculated with account for restricted depth of water, to ship resistance predicted using the ITTC-1957 model-ship correlation line (Rths/Rts57) is within 0.95 through 1.05. Considering highly variable conditions of ship operation on inland waterways, the results presented in this paper show that the application of frictional resistance coefficient calculated with account for restricted depth of water has little effect on power prediction. However, the application of frictional resistance coefficient calculated according to equation (3) or (6) enables to determine the influence of important operating parameters as:

- depth of water,
- ship draught,
- composition of convoy.

The neglect of pressure gradient may have a significant effect on resistance prediction based on model tests only at very shallow water.

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