A method of predicting main propulsion power for inland waterways push trains

Jan P. Michalski, Assoc. Prof.
Gdańsk University of Technology
Polish Naval University

ABSTRACT

This paper presents a method of predicting effective power demand (brake horse power – B.H.P.) for propulsion of inland waterways push train, useful in the preliminary design stages. By using it, on the basis of known main particulars of a given push train, i.e. its length, breadth, draught and speed, a generalized Admiralty formula can be determined and then the pusher propulsion power can be preliminarily predicted by making use of the elaborated structure of the formula. Application of the method is illustrated on the example of a two-segment push train of inland waterways passenger ship designed in the frame of the Eureka INCOWATRANS E!3065 project.

Keywords : inland waterways ships, ship design, brake horse power of push trains

INTRODUCTION

Parametric methods used both for determining hull resistance and predicting propulsion power demand belong to the basic tools applied in ship design theory. Many parametric methods elaborated for and adjusted to sea-going ships are as a rule hardly applicable to designing inland waterways ships – because of :

- different values of ratios of hull main dimensions
- different ranges of Froude number design values
- significant influence of limited dimensions of navigation waters on hull resistance.

The subject-matter literature comprises a few methods for determining resistance of inland waterways ships, such as e.g. : that of Graff-Schlichting-Landweber [8], Karpov [8], Apuchtin [1,2], Baranov [3], or Wróblewska-Sirotina [4] – which are often useful in designing the ships of a small value of the draught T and large values of B/T (breadth/draught) ratio. More up-to-date proposals of such methods have been presented by Howe (given in [5]), Kulczyk [5] and Marchal [6]. However only several parametric methods strictly concern the predicting of brake horse power demand for push trains, as it is in the case of the Wróblewska's –Sirotina's method given by Pospielov [7].

The method of predicting the brake horse power demand for push trains, presented in this paper, was elaborated on the basis of an idea a little different from that used in the Wróblewska-Sirotina method where propulsion efficiency was determined separately on the basis of estimation of maximum permissible diameter of screw propeller and its load factor.

STRUCTURE OF FORMULA FOR BRAKE HORSE POWER OF MAIN PROPULSION

The structure of the parametric formula expressing relation of the brake horse power P_B demanded for inland waterways push train and quantities of its design parameters $\overline{x}$ which are identifiable already at early design stages, was assumed in the form constituting a generalization of the Admiralty formula :

$$P_B(\overline{x}) = \frac{D(\overline{x})^{\alpha} v^{\beta}}{A(\overline{x})} \tag{1}$$

where :
D – push train displacement
v – its speed
$A(\overline{x})$ – effect function determined on the basis of statistical sample data of push trains of a considered type.

The original Admiralty formula elaborated in 19th century, was initially used for estimating the indicated power of steam machines used for ship main propulsion. The formula may be also applied to estimating brake horse propulsion power if only the factor A (called „Admiralty constant") is properly defined, as at low speeds of the then ships their hull resistance is mainly composed of friction resistance dependent on the ship speed v, hull wetted surface area Ω and friction resistance coefficient c_f .

The hull wetted surface area can be expressed by using the Taylor's formula :

$$\Omega = c\sqrt{VL} = cV^{2/3}\left(\frac{L}{V^{1/3}}\right)^{1/2} = cV^{2/3}l^{1/2} \tag{2}$$

where :
L – ship length
V – volumetric displacement of underwater part of ship hull
l – ship hull fineness ratio.

At small Froude numbers, hence at a negligible small wave resistance, the hull resistance R can be expressed as follows :

$$R(\overline{x}) = \frac{1}{2}c_f(\overline{x})\rho v^2\Omega(\overline{x}) = $$
$$= \left(\frac{1}{2}c_f(\overline{x})\frac{\rho}{\rho^{2/3}}cl(\overline{x})^{1/2}\right)(\rho V)^{2/3}v^2 = \frac{D(\overline{x})^{2/3}v^2}{a(\overline{x})} \tag{3}$$

where :

ρ – water density
a – proportionality factor.

The dependence, to the power of two,
of ship resistance on its speed results
from neglecting the wave resistance component.

The classical form of the Admiralty formula for estimating the tow-rope horse power, commonly used in the case of sea-going ships, is obtained by using the expression for ship hull resistance (3) :

$$P_E = R(\overline{x})v = \frac{D(\overline{x})^{2/3}v^3}{a(\overline{x})} \quad (4)$$

For similar ships the factor :

$$a(\overline{x}) = \frac{1}{\left(\frac{1}{2}c_f(\overline{x})\rho^{1/3}cl(\overline{x})^{1/2}\right)} \quad (5)$$

is a weakly changeable function, that justifies
its name – the „Admiralty constant".

The dependence of the effective propulsion power of inland waterways push trains on their dimensions and speed is more complicated since it additionally expresses, apart from resistance, such phenomena as :

- Effect of limited draught on permissible diameter of screw propeller and its efficiency
- Effect of small draught and large breadth of ship on values of wake and thrust deduction factors as well as rotative coefficient which expresses influence of distribution of water inflow velocity to propeller on its efficiency.

The data concerning parameters of existing push trains, derived from the subject-matter literature, were used as a statistical sample in elaborating the presented method.

As information concerning displacement values of the above mentioned ships was incomplete the following parameter (module) W was assumed instead :

$$W = LBT \quad (6)$$

The parameter W is strongly correlated with ship displacement, that results from low variability of hull block coefficients of push trains.

By applying the approximation method of least-squares of deviations were determined the values of the power exponents α, β of the formula (1), which provide the best approximation of the considered statistical sample. The approximation was achieved for the exponent values equal to :

$$\alpha = 3/5 \text{ and } \beta = 2 \quad (7)$$

The obtained result is different from the original Admiralty formula, which can be explained by small values of Froude numbers corresponding with low speed values of inland waterways push trains. Moreover in the relation (1) are contained the complex hydrodynamic interaction of hull, propeller and shores of water area – at a small draught of train, small depth of waterway and limited diameter of screw propeller.

PARAMETRISATION OF ADMIRALTY FORMULA

The parametrisation of the quantity to be determined was performed by assuming that the factor $A(\overline{x})$ is a function of the selected design parameters $\overline{x} = (L, B, T, \dots, v)$ of the train, i.e $A = A(\overline{x})$. Various forms of the function $A(\overline{x})$ were tested by using the prior assumed relation:

$$P_B = \frac{W^{3/5}v^2}{A(\overline{x})} \quad (8)$$

By examining the statistical sample of push trains such form of the function $A = A(\overline{x})$ was determined as to achieve approximated values of the brake horse power P_B possibly close to the relevant values for the sample in question – in the sense of the assumed measures of approximation accuracy.

The best approximation was obtained – by applying the procedure of making research hypotheses about a form of the searched analytical relation, and next by performing their numerical verification – in the case when the weighting function $A(\overline{x})$ was of the following polynomial form :

$$A(\overline{x}) = c_1 + c_2L + c_3L^2 + c_4B + c_5B^2 + c_6T + c_7T^2 + c_8v + c_9v^2 \quad (9)$$

where :

- v – train speed [km/h]
- L – train length [m]
- B – train breadth [m]
- T – train draught [m]
- c_i – structural constants of the formula.

The parametric formulas (8) and (9) make the designer free from necessity of having at his disposal data on a standard push train, hence the formula can serve as a useful tool in the preliminary stage of ship design. The determined values of the structural constants in the formula (9) are contained in Tab.1.

Tab. 1. *Values of the structural constants in the formula (9) .*

Constants c_i	Value
c_1	0.138887366
c_2	6.8508735E-005
c_3	-2.04243698E-007
c_4	-0.0246879704
c_5	0.00163608016
c_6	-0.00530335023
c_7	-0.000538558047
c_8	-0.00228835285
c_9	9.11419602E-005

The following measures were used
to assess accuracy of the approximation :

⇨ ΔP_B – relative error of approximation
⇨ E – relative percentage error of approximation
⇨ E_S – global average percentage error of approximation.

The obtained values of the approximation accuracy measures are presented in Tab.2. In Tab.2, Col. 2 contains the real values of brake horse power, Col. 3 – the brake horse power values determined by using the presented method, and in the last column are given the values of the factor $A(\overline{x})$ determined for the statistical sample elements.

EXAMPLE OF APPLICATION OF THE PROPOSED METHOD

The presented method was applied to predict brake horse power demand for the push train of hotel-passenger ship intended to operate in inland shallow waterways between Berlin and Królewiec (Koenigsberg), designed in the frame of the Eureka INCOWATRANS E!3065 project. The predictions were made for various draughts of the train operating in deep waters.

The main parameters of the push train in question :

- pusher length L = 55.0 m
- length of pusher and barge together L = 110.0 m
- breadth of pusher and barge B = 9.0 m
- draught of pusher and barge T – varying, equal to : 0.8 m; 1.0 m and 1.2 m.

Tab. 2. Assessment of approximation accuracy of the method for determining brake horse power of push trains .

No	P_B [kW]	$P_B(\bar{x})$ [kW]	ΔP_B [kW]	E [%]	E_S [%]	$A(\bar{x})$[-]
1	102	84.2	17.8	17.4	1.0	2.199073
2	132	149.2	-17.3	13.1	1.8	2.988848
3	176	171.1	4.9	2.7	1.9	2.576852
4	236	239.5	-3.5	1.5	2.0	2.562530
5	294	280.1	13.9	4.7	2.3	2.440841
6	294	271.2	22.8	7.7	2.7	2.394053
7	144	187.3	-43.3	30.1	4.5	3.463092
8	588	581.4	6.6	1.1	4.6	3.056463
9	588	629.3	-41.3	7.0	5.0	3.266292
10	566	558.9	7.1	1.2	5.1	1.527448
11	294	311.6	-17.6	6.0	5.4	2.514442
12	368	353.2	14.7	4.0	5.7	2.641990
13	294	291.4	2.5	0.8	5.7	2.774303
14	147	146.7	0.3	0.2	5.7	1.646277
15	1382	1410.7	-28.7	2.0	5.9	1.663954
16	2120	2047.3	72.7	3.4	6.1	2.514117
17	808	794.2	13.7	1.7	6.2	2.231999

Results of the elaborated predictions are presented in Fig.1, where the brake horse power demanded either for the push train consisted of pusher and barge or the pusher alone, versus speed are given in the form of diagrams for different train draughts, as follows :

- *L110 T08 curve* : for the train at its draught T = 0.8 m
- *L110 T10 curve* : for the train at its draught T = 1.0 m
- *L110 T12 curve* : for the train at its draught T = 1.2 m
- *L55 T08 curve* : for the pusher alone at its draught T = 0.8 m
- *L55 T10 curve* : for the pusher alone at its draught T = 1.0 m
- *L55 T12 curve* : for the pusher alone at its draught T = 1.2 m

Brake horse-power preliminary prognosis of INCOWATRANS push train type passenger ship

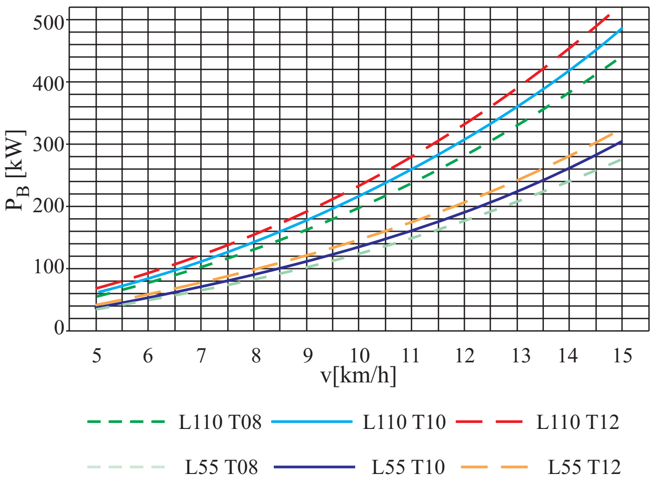

Fig. 1. Preliminary design predictions of the brake horse power demanded for push trains versus train speed .

The method was preliminarily verified by making comparisons of the results obtained for the push train *Eureka* at the design draught T = 1.0 m, designed in the frame of the INCOWATRANS project, with those obtained by using the method of Zwonkow [8] as well as that of Leningrad Design Office [8], which consisted in approximate estimations of ship propulsion efficiency, that made it possible to determine approximate curves of brake horse power demand. The calculations were performed for the pusher alone as well as the pusher-barge train. The obtained results of the calculations are presented in Fig.2 in the form of the diagrams where :

- *Zwon55 curve* shows the BHP demanded for the pusher alone, achieved by applying the Zwonkow method
- *Lenin55 curve* shows the BHP demanded for the pusher alone, achieved by applying the Leningrad Design Office method
- *JM55 curve* shows the BHP demanded for the pusher alone, achieved by applying the presented method
- *Zwon110 curve* shows the BHP demanded for the pusher--barge train, achieved by using the Zwonkow method
- *Lenin110 curve* shows the BHP demanded for the pusher--barge train, achieved by using the Leningrad Design Office method
- *JM110 curve* shows the BHP demanded for the pusher-barge train, achieved by applying the presented method.

Pusher brake horse-power prognosis confrontation (deep water L = 55 m and L = 110 m)

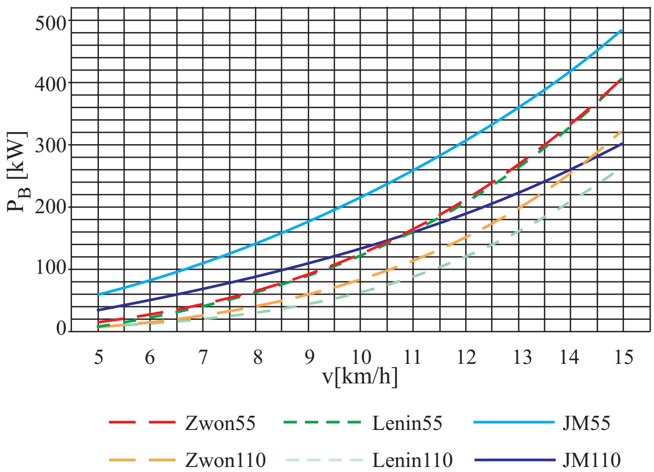

Fig. 2. Comparison of the brake horse power demand for the pusher and push train, calculated by using various methods .

From an analysis of the achieved results it can be concluded that in the case of the pusher alone the proposed method provides results only slightly different from those obtained by means of the remaining method. Whereas in the case of the pusher-barge train the brake horse power calculated by using the presented method is greater than that obtained from the comparative methods. The comparative tests which have been made so far, indicate the method to be correct. To perform a more thorough verification it would be necessary to carry out the tests based on a more ample comparative material, namely data on push trains of various ratios of main dimensions and various Froude numbers.

The following electric energy consumers, apart from the propulsion system, are provided on the designed ship :

- air-conditioning systems for ship accommodations
- drive systems of thrusters
- drive systems of steering gear
- drive systems of shipboard devices
- drive systems of auxiliary devices of ship power plant
- ship lighting system
- other electric appliances.

It was preliminarily estimated by using an index method that the demanded electric power for the designed ship amounts to about 200 kW. The demanded power for the ship's electric devices is only slightly smaller that that for its propulsion system, that speaks for application, to the ship in question, of the combustion-electric propulsion system consisted of several combustion-electric generating sets and electric motors. Such system makes it possible to obtain a high flexibility in using the installed power output at full load imposed onto particular generating sets working then at their maximum efficiency. Moreover such solution makes it possible – in emergency situations, e.g. in order to refloat the ship after its stranding – to use an electric power surplus for temporary supporting the main propulsion system.

RECAPITULATION AND CONCLUSIONS

- The elaborated method makes it possible to determine the generalized Admiralty formula, which enables – together with the formula for determining the brake horse power (BHP) – to predict in an approximate way the BHP demanded for main propulsion system of the pusher – on the basis of the assumed main parameters of the push train, namely : its length, breadth, draught and speed. The elaborated formula differs in its structure from that of the original Admiralty formula, which is supposed to result mainly from small values of Froude numbers characteristic for push trains
- From the test investigations it results that in the case of the pusher alone the obtained BHP values only slightly differ from those achieved by applying the remaining methods. However in the case of the pusher-barge train within the whole investigated speed range the BHP values are greater than those obtained by using the other methods
- The determined simple analytical relations model the brake horse power which expresses the complex hydrodynamic interactions of ship hull, propeller and shores of water area, characterized by limited hull draught, small depth of waterway as well as limited permissible diameter of screw propeller.

NOMENCLATURE

$a(\overline{x})$ – effect function of push train parameters
$A(\overline{x})$ – approximating function of „ Admiralty constant”
B – push train breadth
BHP – brake horse power
c – proporcionality constant
c_f – friction resistance coefficient
c_i – structural constants of a formula
D – push train displacement
E – relative percentage error of approximation
E_S – global average percentage error of approximation
l – push train fineness coefficient
L – push train length
P_B – brake horse power of push train
P_E – tow rope power of push train
R – hull resistance
T – push train draught
v – push train speed
V – volumetric displacement of push train underwater part
W – module of push train dimensions
$\overline{x}$ – vector of push train parameters

α, β – constant power exponents
ρ – water density
Ω – wetted surface area of push train
ΔP_B – absolute error of approximation.

BIBLIOGRAPHY

1. Kobyliński L.: *Ship resistance. Part I. Theory of resistance and model testing* (in Polish). State Scientific Publishers, (Państwowe Wydawnictwo Naukowe). Łódź-Warszawa-Poznań, 1961
2. Kobyliński L.: *Ship resistance. Part II. Approximate calculation methods of resistance and hull form effects on ship resistance* (in Polish). State Scientific Publishers, (Państwowe Wydawnictwo Naukowe). Łódź-Warszawa-Poznań, 1960
3. Żylicz A.: *Inland waterways ships* (in Polish). Maritime Publishing House (Wydawnictwo Morskie). Gdańsk, 1979
4. Wróblewska L.N., Sirotina G.N.: *Opriedielenie moszcznosti energeticzeskoj ustanowki w naczalnoj stadji projektirowania gruzowych sudow wnutriennevo i smjeszanovo pławania*. Trudy GIIWT, no.144, 1975
5. Kulczyk J., Winter J.: *Inland waterways transport* (in Polish). Publishing House of Wrocław University of Technology (Oficyna Wydawnicza Politechniki Wrocławskiej). Wrocław, 2003
6. Marchal J.L.J., Shen Y.D., Kicheva D.: *An empirical formula to estimate the resistance of a convoy in a restricted waterway*. Journal of Ship Research. No. 2, June 1996
7. Pospiełov W.I.: *Wybor na EWM optymalnych elementow gruzowych sudow wnutriennowo pławania*. Sudostrojenie (Publishing House). Leningrad, 1978
8. *A Handbook for Naval Architects, Vol. II, Ship Theory* (in Polish), Maritime Publishing House (Wydawnictwo Morskie), Gdynia, 1960

Photo : Arkadiusz Łabuć