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STATISTICAL EVALUATION OF PROPRIETY OF MEASUREMENTS OF SHIP'S MOVEMENT PARAMETERS

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Abstract

The paper presents some problems of carrying out measurements of energetic characteristics and vessel's performance in the conditions of sea examinations. As the object of propulsion characteristic determination was selected the ship with fixed pitch propeller. In order to formulate models of power characteristics, in first, known physical aspect were taken and subsequently statistic theory was implemented. Models of propulsion performance were built basing on two theoretical methods of determination of required shaft power and torque at a hub, as the function of propeller's revolutionary speed and sailing condition represented by dimensionless coefficients. Model number one, based on Silukov method presents function with variable power index, of shaft power in domain of revolutionary speed. The second one presents model of torque variations, based on Silovic – Fancev method. For verification of models were taken presented in available bibliography, results of researches of ship's propulsion systems [6].

We also discuss the manner of reducing the results of measurements to the standard conditions. We present the way of preparing propulsion characteristics and the analysis of examination uncertainty for the measurement of torque. Statistical analysis of deviation of results, using three models, proposed in the paper. As a result of analysis, one point from primary data set was rejected due to its unreliability, what was resulting with higher adequacy of characteristics.

Keywords: *diagnostics, vessel's propulsion systems, ship propulsion characteristics for ships with fixed propeller, modelling and determination of power characteristics*

Introduction

Measurements performed on vessels are aimed at determining the up-to-date technical condition of the elements of the main propulsion or the evaluation of the operating elements of a vessel. The diagnostic measurements should be performed in a continuous manner, and the measurements to determine propulsion characteristics should be performed at specified time points, e.g. after completing the construction works on the vessel, after construction phase, repairing elements of the propulsion system, etc. The measurements are performed on a vessel to develop propulsion forecast for a new built ship, or to evaluate current operating parameters of an exploited vessel. At design stage of the ship, propulsion characteristics are determinate basing on towing tank tests of the model, calculation of basic dimensions of a hull and selection of propellers and their hydrodynamic characteristics considering all coefficients related to collaboration of the system hull – propeller [3, 6, 8]. All characteristics evaluated above way are only approach with certain level of probability of description of real behaviour during exploitation at sea. It is caused among others:

- technology of hulls manufacturing and sustainment of accuracy of main dimensions and hull coefficients during construction,
- technology of making a propeller,
- similarity of assumed sailing condition, especially wake fraction and thrust deduction coefficients and hydro meteorological impact.

Contemporary technologies of hull's element production and propellers manufacturing guarantee high level of recurrence of dimensions, what finally lead to conclusion that basic impact at deviation of characteristics is coming from outer conditions.

Irrespective of the aim of the measurements, it should be noted that a vessel always works in different conditions and the conditions may affect the quality and reliability of measurements. The change of the conditions for vessel movement is induced by parameters linked:

- with the vessel, i.e. vessel loading, use of reserves (change in displacement), change in the condition of hull, propellers, engines, etc.,
- with hydro meteorological conditions,
- with vessel operation region.

The evaluation of factual propulsive characteristics in exploitation is performed during vessel sea trials [4, 5].

In order to evaluate fully the propulsive characteristics, the following should be measured: torque on propulsion shafts; propeller thrust; rotational speed of shafts, vessel speed and the use of fuel by particular engines.

Variability, even in short time, condition of measurement of propulsion parameters, has impact at its reliability and has influence at evaluation of comparative parameters and at evaluation of propulsion characteristics.

Different methods of elaboration of propulsion characteristic are based at making several groups of measurements, but do not includes statistical analysis of their credibility.

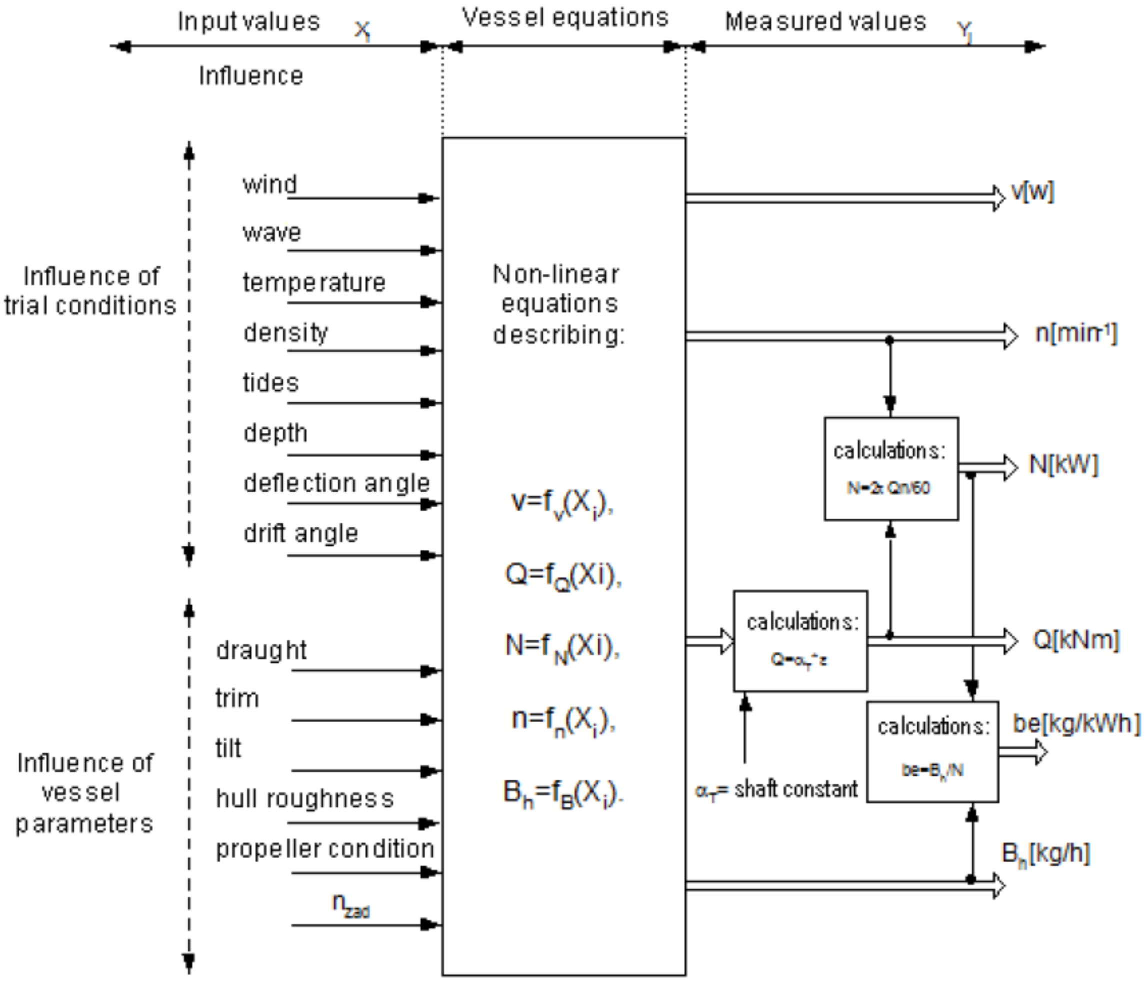

Fig. 1. Block diagram of a vessel

1. Modelling of propulsion characteristics

Analysis of modelling correctness of propulsion characteristics of a ship with FPP (Fixed Pitch Propeller) was carried out basing on available results of research carried out during ship sea trials [6]. Models of produced power were built up basin on knowledge about determination of propulsion characteristic [3, 5, 7, 9] following well-known general physical aspects of characteristic modelling [8].

Tab. 1. Data from propulsion characteristic study of ships [6]

Serial number	Measurement number	[rev./min]	**v** [kn]	N [kW]
1	1	75	9.5	542
	2	95	12	1144
	3	115	14	2124
	4	125	14	2911
	5	135	16	3946
2	6	48	3.5	270
	7	72	6	694
	8	95.6	9.2	1535
	9	116	12	2701
	10	128	12	3700
3	11	128	12	3844
	12	49	6,5	158
	13	72	9.1	462
	14	93.1	11.5	972
	15	115.4	14	2131
	16	125.9	15	2628
	17	137.2	16	3570

1.1 Modelling of propulsion characteristic based on Silukov method

First model taken for consideration was model resulting from the method called Silukov method basing on measurements in three conditions including bollard pull [6, 8, 9]. In that method, the power function model in form of formula (1) was applied:

$$N = c_f n^p, \tag{1}$$

where:

N – shaft power,

n – revolutionary speed of the shaft,

c_f – coefficient of sailing condition,

p – power index depending on sailing condition and ship speed, coming out from research results.

Function c_f was defined as follow:

$$c_f = -a_f v + c_u, \tag{2}$$

where:

a_f – coefficient which is the function of n,

v – ship speed,

c_u – constant assuming condition of bollard pull.

Function a_f was defined as follow [6]:

$$a_f = \frac{b}{n^z} \tag{3}$$

where:

b – constant,

z – function power index.

Doing adequate substitutions relation (3) to relation (2) and subsequently to (1), one obtains the formula of power in form:

$$N = c_f n^p = \left(-\frac{b}{n^z} v + c_u\right) n^p. \tag{4}$$

After transformation, formula (4) can be presented in form:

$$N_P = d_1 n^{w_{1n}} v + d_2 n^{w_{2n}}, \tag{5}$$

where:

d_1, d_2, w_{n1}, w_{n2} – constants determined by minimum mean square method.

In order to statistic confirmation of model correctness (5), the model was developed to the form:

$$N_P = d_1 n^{w_{n1}} v^{w_{v1}} v + d_2 n^{w_{n2}} v^{w_{v2}}, \tag{6}$$

where:

$d_1, d_2, w_{n1}, w_{n2}, w_{v1}, w_{v2}$ – constants obtained by minimum mean square method.

For designation of coefficients, model (5) requires at least four measurement points (case of interpolation), and model (6) at least six measurement points.

In Silukov method, which is interpolation method, are required three measurements points, because, in result of additional assumptions, number of designated constants was reduced to three, wherein at least one measurement must be done at bollard pull.

Shall be noticed that problem of mean square approximation by models (5) and (6) appears as nonlinear issue.

It seems to be correct to assume, that in case of research conducted under different sea condition, not necessary with bollard pull trial, such information is included among measurements data. In such case, the range of measurements must fulfil the propulsion system-working layout. When number of information would be sufficient, data collecting from bollard pull are not necessary, what let reject that complicated and difficult for carrying out trials.

1.2 Modelling of propulsion characteristic based on Silovic – Fancev method

After transformation of the formula of torque coefficient, torque at hub of screw propeller can be written as follow [5, 9, 10]:

$$M = cK_M n^2, \tag{7}$$

where:

c – constant,

K_M – torque coefficient,

n – revolutionary speed of a propeller.

Linear model of Silovic – Fancev considered in [9] assuming linear relation between torque coefficient K_m and advance coefficient J, in our method was assumed relation by square value of coefficient J, presented by relation (8):

$$K_M = b_1 + b_2 J + b_3 J^2, \tag{8}$$

where:

$b_1 \div b_3$ – constants from aproximation.

Taking under consideration that advance coefficient can be presented in form of formula (9) [1-3, 7]:

$$J = d\frac{v}{n}, \tag{9}$$

where:

d – constant,

v – ship's speed,

n – propeller's revolutionary speed.

Replacing J in formula (9) by formula (8) and subsequently placing obtained K_M into formula (7) and after processing of variables and constants, finally one achieve formula of torque characteristic presented by formula (10):

$$M = g_1 n^2 + g_2 nv + g_3 v^2, \tag{10}$$

where:
g_1-g_3 – constants from approximation.

Additionally, model was supplemented with constant value g4, what resulted with final model of characteristic described by formula (11):

$$M = g_1 n^2 + g_2 nv + g_3 v^2 + g_4. \tag{11}$$

Using relations between power, torque and revolutionary speed in form of:

$$N = 2\pi \cdot 60^{-1} Mn = c_\omega Mn \text{ [kW]}. \tag{12}$$

Replacing torque M in (12) by formula (11) and adding new constants $c_1 - c_4$ and c_5, extended model based on Silovic – Fancev assumption takes the form:

$$N = c_1 n^3 + c_2 n^2 v + c_3 nv^2 + c_4 n + c_5. \tag{13}$$

Constants $c_1 \div c_5$ are determined using method of minimum mean square supported by analysis values from measurements database.

2. Determination of characteristics of propulsion system's power

In first step, was considered approximation-using model (13), implementing stepper method of unwrapping of optimum model with criteria of lower mean square error for subsequently revealed elements of approximation function presented below:

$$N_k = a_k \cdot n^{m_k} \cdot v^{p_k}, \tag{14}$$

where:
m_k, p_k – exponents given and formed in step *k*.

In first step all elements of model (13) were checked and results obtained are presented in Tab. 2

Tab. 2. Results of selecting polynomial model ship propulsion power characteristics

$k = 1$ (step 1)					
$m_1; p_1$	3; 0	2; 1	1; 2	1; 0	0; 0
S	1.38E6	4.22E6	8.18E6	1.04E7	2.89E7
s	293	514	715	808	1343
$k = 1$ (step 2)					
$m_2; p_2$		2; 1	1; 2	1; 0	0; 0
S		3.13E5	3.13E5	1.37E6	1.37E6
s		144.4	144.6	302	302
$k = 3$ (step 3)					
$m_3; p_3$			1;2	1;0	0;0
S			3.13E5	3.10E5	3.11E5
s			149.5	148.7	149.1

Finally was formed polynomial with parameters $m_1 = 3$; $p_1 = 0$, for which value S was the lowest. In second step of approximation were created linear combinations of monomial built in first step with subsequent monomials presented in Tab. 2. As was shown in content of Tab. 2, in second step were created two polynomials giving practically even results in aspect of minimum square error value *S*. There are models:

$$N_{W1} = a_1 n^3 + a_2 n^2 v, \tag{15}$$

$$N_{W2} = b_1 n^3 + b_2 n\, v^2. \tag{16}$$

Model (15), which is Silovic- Fancey model, was adopted for doing step number 3, as attempt to find subsequent segment of approximation.

Extension of polynomial of approximation by adding the segment in step 3 does not diminish significantly the mean square S. The value of standard deviation s rather rise when little descent of S occurs, what can be observed comparing resylts of approximation of step 3 and results obtained in step 2. For other models, the same regularity was observed. It was because of diminishing of steps of freedom with parallel relatively small reducing mean square sum value S in subsequent step.

Lack of repetition of measurements in experimental points makes impossible standard evaluation statistical adequacy of the model.

In the case of mean square approximation of measurement data using the model (6) one has got following results: $S = 3.1\text{E}5$; $s = 143.7$ kW and values of exponents: $w_{n1} = 1.42$; $w_{n2} = 2.71$; $w_{v1} = 1.00$; $w_{v2} = 0.00$. Thus justification for implementation of the model (5) was confirmed statistical way, moreover developing of model to the form (6) was not necessary.

Comparing obtained results with results of approximation for models (15) and (16), one has to conclude that model (5) is the equivalent, from statistical point of view. Value S is higher than for other models but span of differential is small and can be omitted.

Of course one has to remember, that in the case of implementation of model (5) total number of determined parameters was 4 (four), when in case of model (15) or (16) were only 2 (two).

3. Verification of measurement data set and values of model's parameters

As can be observed, determined models present almost identical results of approximation. Coefficients of correlation WK of deviations between models are close to 1.0 and their values are as follow:

$$WK\{DN_{w1}; DN_{w2}\} = 1.00,$$
$$WK\{DN_{w1}; DN_p\} = 0.98,$$
$$WK\{DN_{w2}; DN_p\} = 0.98.$$

In Fig. 2 are presented results of comparison of differences between measurement and calculation using approximation models for 17 measurements. Additionally line of minimum square error $\mp 2s$ is presented.

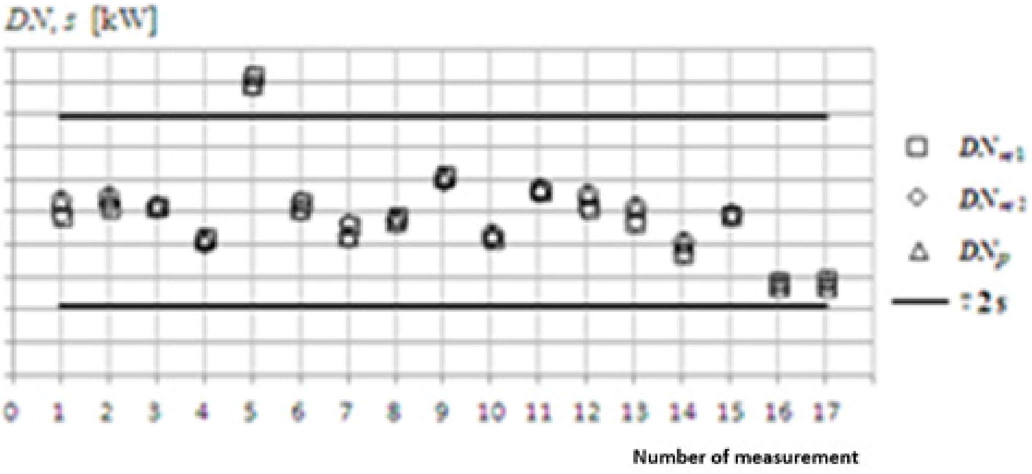

Fig. 2. Comparison of differences DN values of measured power and calculated from the approximation models, (15); (16) and (5)

As can be spotted in Fig 2, measurement point number 5 oversteps value $2s$, what requires verification. After exclusion of data coming from point 5, calculation was conducted again and final results are presented in Fig. 3. In result of recalculation, diminishing of standard deviation value and rise of power deviation in point 5 were obtained.

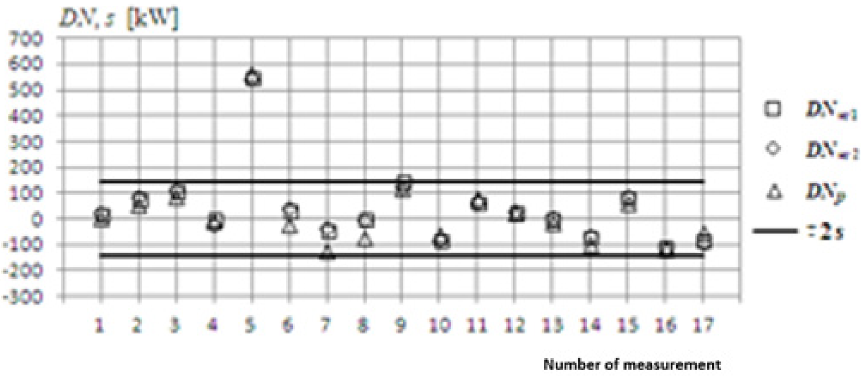

Fig. 3. Comparison of differences DN values of measured power and calculated from the approximation models, excluding point 5

Carrying out the analysis of results presented in Fig. 3, one concludes that extraction of point's 5 data was justified, and values of deviation of that point after rejection of point's 5 measurement data overstep significantly the value $3s$.

4. Conclusions

Following general knowledge regarding physical nature of propulsion characteristics and statistical methods, three models of power characteristics were elaborated. It were one nonlinear model based on power function (5) and two polynomial models (15) and (16)

All models are equal in statistical aspects, because determined values of power are close to each other.

Analysis of measurement data coming from research of propulsion system (Tab. 1) pointed that measurement number 5 carried mayor error. That measurement was excluded from data set for further analysis what resulted with improvement of confidence level of obtained results.

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