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Experimental determination of propulsion characteristics of a ship with controllable pitch propeller by applying a standardization method of input parameters

SUMMARY

In the paper a practical method of determination of propulsion characteristics of a ship with controllable pitch propeller is presented. The method is based solely on the results of the energy measurements performed onboard the ship. Therefore it is not necessary to make use of any results of ship hull model tests and engine bed tests. Planning of the experiment with the use of standard values of input parameters makes it possible to considerably lower the number of measurement points and this way to shorten time and cost of the measurements.

INTRODUCTION

Ship propulsion characteristics are one of the basic tools for analyzing load and service performance of her main propulsion system. Their usefulness for ship current operation or scheduling exploitation tasks is unquestionable. However, the usual, work-and-time consuming methods of their determination are inconvenient. Moreover changeable features of ship's operation and her propulsion system during exploitation make the characteristics becoming outdated in a relatively short time. The successive propulsion energy measurements to obtain actual data for their determination are costly and requiring to exclude the ship from service for 15 ÷ 25 h. Next, the methods based on results from engine tests on test bed, and ship hull model tests or those in which simplified approximation methods are assumed, are not adequate to working conditions of the ship propulsion systems. Especially tedious is determination of propulsion characteristics of ships fitted with controllable pitch propellers (CPPs), in result it leads to important content-related simplifications [2], [6].

Preferring elaboration of the characteristics on the basis of data from measurements onboard the ship in real conditions, the authors proposed a method of choosing measurement points and approximation of measurement results in such a way as to considerably increase effectiveness of the investigations due to decreasing amount and time of measurements as well as decreasing loss of ship exploitation cost and time.

This can be obtained by standardizing input parameters of the propulsion system operation [4] and approximation of results by solving a Chebyshev's polynomial set for standard values of the parameters, at saving required adequacy of resulting approximation functions.

The standardization of input parameters consists in substitution of their real values by standard ones in accordance with a relevant algorithm. The number and standard values of input parameters depend on a kind of scheme of the experiment to be realized and on number of input variables. The experiment planning is crucial as it can lead to reduction of number of measurement points.

THE METHOD APPLIED TO A SHIP FITTED WITH CPP

In the case of determining the propulsion characteristics of a ship fitted with CPP the input parameters are :

- the rotational speed of her engine or propeller, n [rpm]
- the propeller pitch related to maximum set pitch H [%]

The output parameters are :

- ★ the ship speed v [knots]
- ★ engine rated power N_e [kW]
- ★ fuel consumption B_e [kg/h].

If the object (engine + CPP + ship hull) is to be described by a number of models equal to that of input parameters it can be done by using three object functions of the following forms :

$$\left.\begin{array}{l} f_v(n, H, v) = 0 \\ f_{Ne}(n, H, N_e) = 0 \\ f_{Be}(n, H, B_e) = 0 \end{array}\right\} \text{ or } \left\{\begin{array}{l} v = f_1(n, H) \\ N_e = f_2(n, H) \\ B_e = f_3(n, H) \end{array}\right. \quad (1),(1a)$$

The approximation method in question consists in substitution of the set of discrete values of the experiment output parameter, $\{z\}$, by the function (2) :

$$\breve{z} = \breve{f}(x) \approx z = f(x) \qquad (2)$$

Measurements are performed in compliance with a determined, selective, multi-factor, rotary scheme of technical experiment [4]. It is assumed that a point location measure within the space of input parameters, R^i, is the radius ρ of a sphere concentric with the centre of reference system :

$$\rho^2 = \sum_{i=1}^{k} \hat{x}_{i,m} \qquad (3)$$

where, for the standard values of input parameters $\hat{x}_{i,m}$:

$$i = 1, 2, \ldots, k \qquad m = 1, 2, \ldots, u$$

spheres of different radiuses ρ ,
concentric with the system centre ($\hat{x}_{i,m} = 0,\ \rho = 0$) are obtained.

In the considered case the two-dimensional space R^2, i.e. the circle in the coordinate system $\hat{n}, \hat{H}$, is obtained, where :

$\hat{n}$, $\hat{H}$ - standard values of standardized input parameters n, H
$\hat{n}_P$, $\hat{H}_P$ - standard values of above parameters in P-th point of the considered experiment.

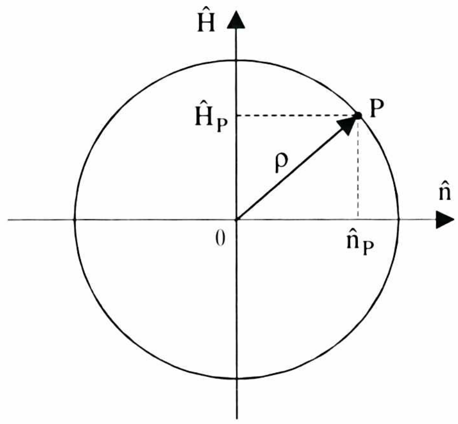

Fig.1.

An advantage of the method is possible reduction of number of measurement points in experiment scheme, as follows :

a) points being the scheme core, corresponding to the standard values of input parameters : ± 1 in the number of $m_c = 2^i$, where : i – number of input parameters
b) points called „star points" corresponding to the standard values of input parameters : ± α in the number of $m_\alpha = 2i$, where : α – „star arm" (for i = 2 , α = 1,414)
c) points in the scheme centre, corresponding to the standard values of input parameters : 0 in the number $m_o > 1$ (for i = 2, $m_o = 5$).

Therefore the total number of measurement points in the considered case is equal to :

$$u = m_c + m_\alpha + m_o = 2^i + 2i + 5 = 4 + 4 + 5 = 13 \qquad (4)$$

By applying the method algorithm it is possible to determine approximation polynomials for the searched functional relationships :

$$v = f_1(n, H) \qquad N_e = f_2(n, H) \qquad B_e = f_3(n, H),$$

in the form of the 2nd order polynomials as follows :

$$z = a_o + a_1 \cdot n + a_2 \cdot H + a_{12} \cdot n \cdot H + a_{11} \cdot n^2 + a_{22} \cdot H^2 \qquad (5)$$

In the case of energy investigations of a ship propulsion system containing CPP, aimed at determination of its propulsion characteristics the assumption of 2nd order approximation polynomials has been proved very useful which was confirmed by many so far performed investigations.

In the example in question the standard input parameters take the following values :

$$\hat{n} = -\alpha, -1, 0, +1, +\alpha$$
$$\hat{H} = -\alpha, -1, 0, +1, +\alpha \qquad (6)$$

which can be presented graphically as follows :

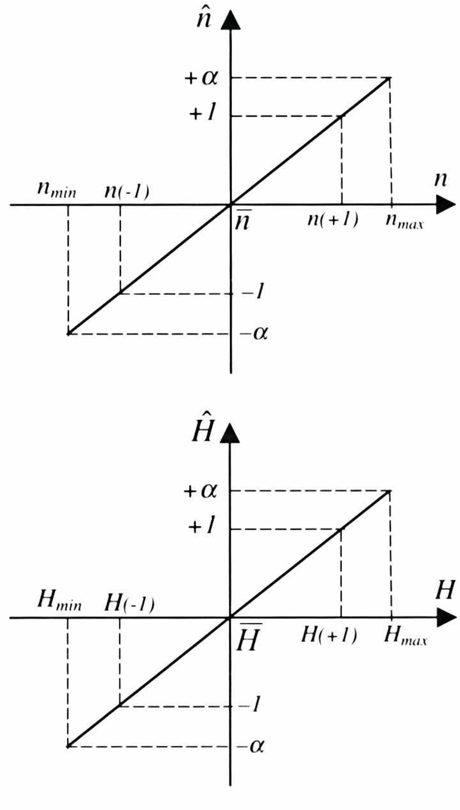

Fig.2.

and algebraically as follows :

$$\hat{n} = \frac{n - \overline{n}}{\Delta n} = \frac{\alpha(n - \overline{n})}{n_{max} - \overline{n}} = \frac{2\alpha(n - \overline{n})}{n_{max} - n_{min}}$$

or (7)

$$n = \overline{n} + \hat{n} \cdot \Delta n = \overline{n} + \frac{\hat{n}}{\alpha}(n_{max} - \overline{n})$$

where :

$$\Delta n = \frac{n_{max} - \overline{n}}{\alpha} = \frac{n_{max} - n_{min}}{2\alpha} \quad \text{and} \quad \overline{n} = \frac{n_{max} + n_{min}}{2} \qquad (8)$$

as well :

$$\hat{H} = \frac{H - \overline{H}}{\Delta H} = \frac{\alpha(H - \overline{H})}{H_{max} - \overline{H}} = \frac{2\alpha(H - \overline{H})}{n_{max} - n_{min}}$$

or (9)

$$H = \overline{H} + \hat{H} \cdot \Delta H = \overline{H} + \frac{\hat{H}}{\alpha}(H_{max} - \overline{H})$$

where :

$$\Delta H = \frac{H_{max} - \overline{H}}{\alpha} = \frac{H_{max} - H_{min}}{2\alpha} \quad \text{and} \quad \overline{H} = \frac{H_{max} + H_{min}}{2}$$

(10)

In order to verify suitability of the method relevant measurements were carried out onboard the research-training ship HORYZONT II. During sea voyage the ship's propulsion system operated within the following value ranges of the input parameters n, H :

$$n_{min} = 660 \text{ rpm} \quad \text{and} \quad H_{min} = 60\ \%$$

$$n_{max} = 1000 \text{ rpm} \quad \text{and} \quad H_{max} = 100\ \%$$

therefore their values calculated from (7), (8), (9) and (10) are respectively :

$$\begin{aligned} \overline{n} &= 830 \text{ rpm} \\ \overline{H} &= 80\ \% \\ \Delta n &= 120.2 \text{ rpm} \\ \Delta H &= 14.14\ \% \end{aligned}$$

The experiment measurement points corresponding to the standard values of input parameters (6) are assumed as follows :

$$\begin{aligned} n(-\alpha) &= \overline{n} - \alpha\Delta n = 660 \text{ rpm} \\ n(-1) &= \overline{n} - \Delta n = 710 \text{ rpm} \\ n(0) &= \overline{n} = 830 \text{ rpm} \\ n(+1) &= \overline{n} + \Delta n = 950 \text{ rpm} \\ n(+\alpha) &= \overline{n} + \alpha\Delta n = 1000 \text{ rpm} \\ H(-\alpha) &= \overline{H} - \alpha\Delta H = 60\ \% \\ H(-1) &= \overline{H} - \Delta H = 66\ \% \\ H(0) &= \overline{H} = 80\ \% \\ H(+1) &= \overline{H} + \Delta H = 94\ \% \\ H(+\alpha) &= \overline{H} + \alpha\Delta H = 100\ \% \end{aligned}$$

The measurement scheme contains 13 combination of the values of the input parameters in u = 13 measurement points :

Measurement number	Measurement place	Standard values of input parameters		Real values of input parameters corresponding to their standard values	
m		$\hat{n}$	$\hat{H}$	n	H
		-	-	rpm	%
1	scheme core	-1	-1	710	66
2		-1	+1	710	94
3		+1	-1	950	66
4		+1	+1	950	94
5	star points	+α	0	1000	80
6		-α	0	660	80
7		0	+α	830	100
8		0	-α	830	60
9	scheme centre	0	0	830	80
10		0	0	830	80
11		0	0	830	80
12		0	0	830	80
13		0	0	830	80

Location of the measurement points within the operation field of the ship's main propulsion system is shown in Fig.3.

The 2nd order approximation polynomials for functions (1a) related to the standard values of input parameters were obtained on application of regression analysis of the measurement results of the engine rotational speed, propeller pitch, ship speed, engine rated power, and fuel consumption, performed in compliance with the above mentioned experiment scheme and method algorithm :

$$\bar{z} = \hat{a}_o + \hat{a}_1 \cdot \hat{n} + \hat{a}_2 \cdot \hat{H} + \hat{a}_{12} \cdot \hat{n} \cdot \hat{H} + \hat{a}_{11} \cdot \hat{n}^2 + \hat{a}_{22} \cdot \hat{H}^2 \qquad (11)$$

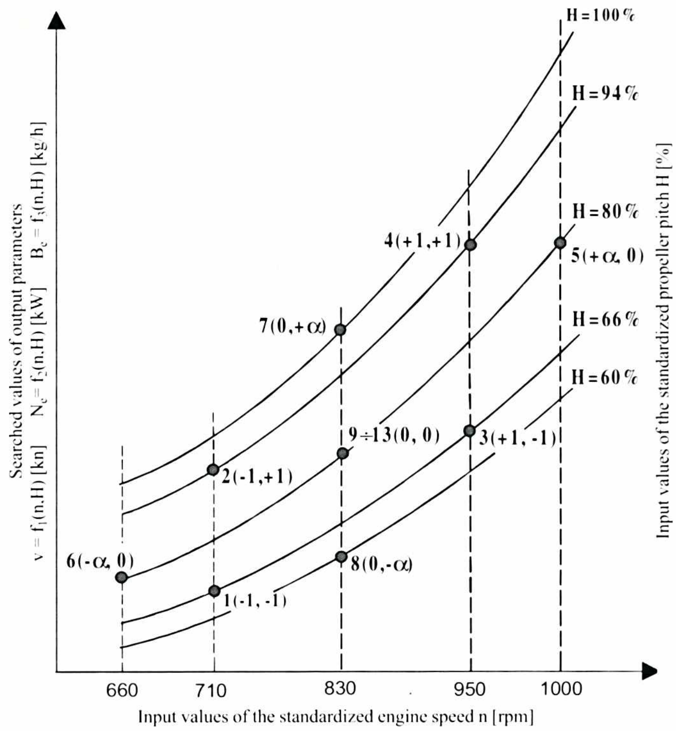

Fig.3. Scheme of ship propulsion characteristics with indicated location of measurement points (1÷13)

The relevant coefficients of the approximation polynomials for the standard values of input parameters were calculated according to the method algorithm as follows :

$$\hat{a}_o = D\sum_{m=1}^{u}\bar{z}^{(m)} + E\left(\sum_{m=1}^{u}\hat{n}_m^2\bar{z}^{(m)} + \sum_{m=1}^{u}\hat{H}_m^2\bar{z}^{(m)}\right) \qquad (12)$$

$$\hat{a}_1 = \frac{\sum_{m=1}^{u}\hat{n}_m\bar{z}^{(m)}}{e} \qquad (13)$$

$$\hat{a}_2 = \frac{\sum_{m=1}^{u}\hat{H}_m\bar{z}^{(m)}}{e} \qquad (14)$$

$$\hat{a}_{12} = \frac{\sum_{m=1}^{u}\hat{n}_m\hat{H}_m\bar{z}^{(m)}}{m_c} \qquad (15)$$

$$\hat{a}_{11} = (F-G)\sum_{m=1}^{u}\hat{n}_m^2\bar{z}^{(m)} + G\left(\sum_{m=1}^{u}\hat{n}_m^2\bar{z}^{(m)} + \sum_{m=1}^{u}\hat{H}_m^2\bar{z}^{(m)}\right) + E\sum_{m=1}^{u}\bar{z}^{(m)} \qquad (16)$$

$$\hat{a}_{22} = (F-G)\sum_{m=1}^{u}\hat{H}_m^2\bar{z}^{(m)} + G\left(\sum_{m=1}^{u}\hat{n}_m^2\bar{z}^{(m)} + \sum_{m=1}^{u}\hat{H}_m^2\bar{z}^{(m)}\right) + E\sum_{m=1}^{u}\bar{z}^{(m)} \qquad (17)$$

where :
for two input parameters (i=2) :

$\alpha = 1.414 \quad D = 0.2 \quad E = -0.1 \quad F = 0.1437 \quad G = 0.0187$

$e = 8 \quad m_c = 2^i = 4$

$\bar{z}^{(m)}$ - mean value of the output parameter in m-th measurement point

Next, by using (7) and (9) the form of the approximation polynomial (5) of the coefficients a_o, a_1, a_2, a_{12}, a_{11}, a_{22} was determined for real values of the input parameters.

For the average North Sea sailing conditions, namely : 1÷2°B sea state, 2°B wind force from ±15° bow sector, 5.1÷5.4 m mean ship draught, moderate ship motion in waves, the following equations were obtained for the ship speed, main engine rated power and fuel consumption within the operational field of the main propulsion system :

$$v = -2.174 + 0.01195\ n - 0.008727\ H + 0.000125\ nH - 0.000007574\ n^2 - 0.0001725\ H^2\ [\text{knot}]$$

$$N_e = 2470 - 4.355\ n - 33.72\ H + 0.04058\ nH + 0.001829\ n^2 + 0.06657\ H^2\ [\text{kW}]$$

$$B_e = 363.89 - 0.6959\ n - 4.545\ H + 0.006214\ nH + 0.0003259\ n^2 + 0.00648\ H^2\ [\text{kg/h}] \qquad (18)$$

On their basis any optional form of the propulsion characteristics can be drawn for the sailing conditions observed during the measurements. In Fig.4 example propulsion characteristic of fuel consumption in the above given sailing conditions, is presented.

Detail information on measurement errors, voyage conditions and limitations due to ship main engine load at low rotational speed and large propeller pitch values can be found, among other literature, in [5].

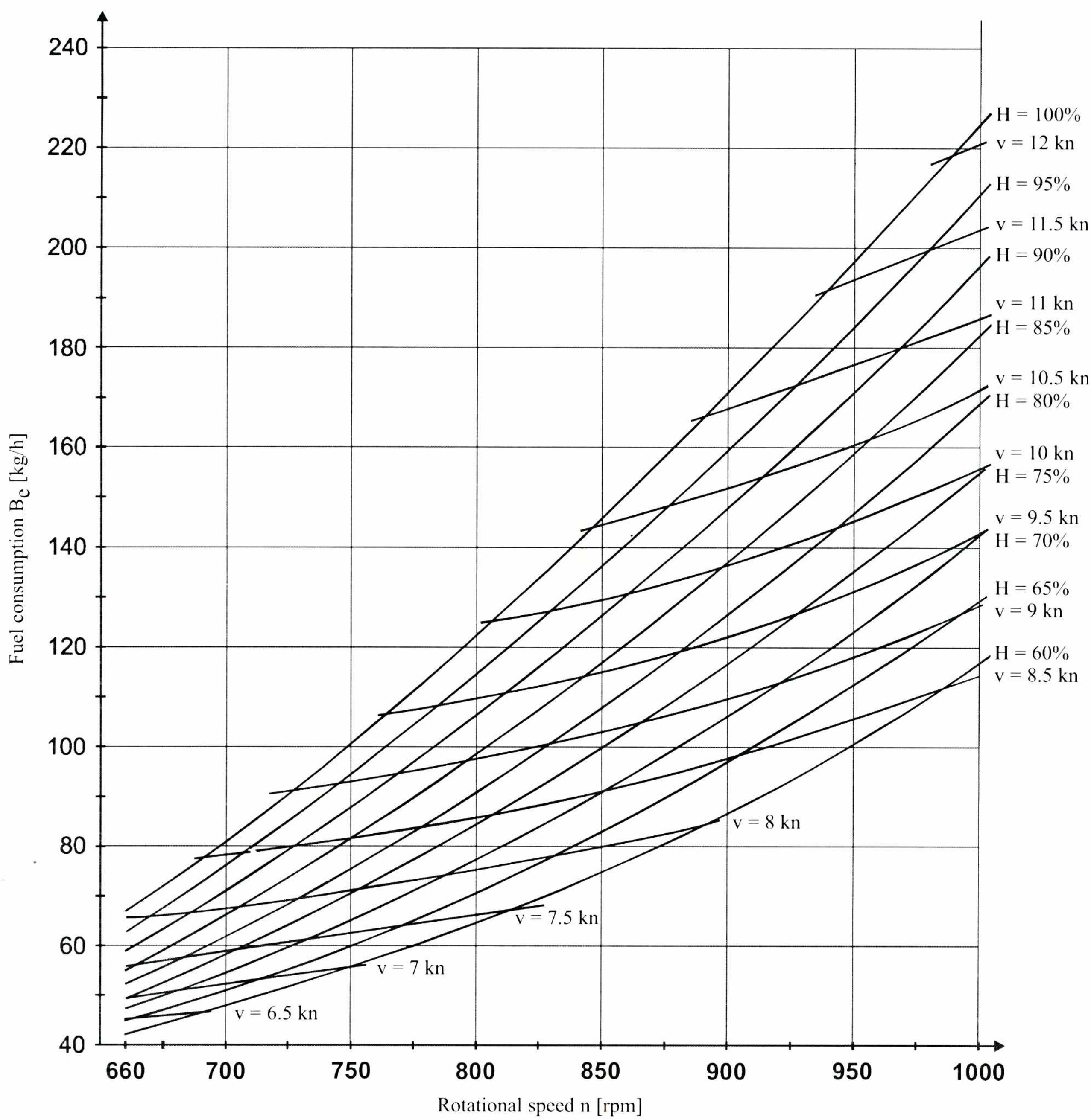

Fig.4. Propulsion characteristic of fuel consumption for m/s HORYZONT II (in average North Sea sailing conditions)

Correctness of the presented method has been confirmed by results of approximation error analysis of values of the output parameters, obtained from the polynomials (18). For instance, for the propulsion characteristics of fuel consumption :

- the variance of the approximated values $\sigma^2(z) = 4.33$
- the standard deviation $\sigma(z) = 2.08$
- the variation coefficient $\sigma = 1.98\%$

calculated respectively from (19) , (20) and (21).

$$\sigma^2(z) = \frac{1}{u(r-1)} \sum_{m=1}^{u} \sum_{j=1}^{r} (z_j^{(m)} - \bar{z}^{(m)})^2 \tag{19}$$

$$\sigma(z) = \sqrt{\sigma^2(z)} \tag{20}$$

$$\sigma = \frac{\sigma(z)}{\bar{z}_{pop}^{(m)}} \cdot 100\% \tag{21}$$

where :

u	–	total number of measurement points
r	–	number of measurement repetitions in a measurement point
$z_j^{(m)}$	–	result of a single measurement
$\bar{z}^{(m)}$	–	mean value in a measurement point
$\bar{z}_{pop}^{(m)}$	–	mean value of a results population.

CONCLUSIONS

- The presented simple approximation method of calculations can be easily implemented with the use of a PC thus making it possible - after performing relevant measurements - to determine current ship propulsion characteristics e.g. for a changed ship draught resulting from a new loading condition.
- Necessary measurements can be performed by means of the standard measurement instruments used onboard the ships.
- It is not necessary to make use of and analyze design data on the ship propulsion system; this is an advantage of the presented method, apart from possible reduction of amount of measurements and time of their performance.
- Implementation of the method on ships would contribute to spreading rational exploitation techniques of the ship propulsion systems.

Appraised by Andrzej Balcerski, Prof.,D.Sc.

NOMENCLATURE

a	–	approximation polynomial coefficient
a	–	approximation polynomial coefficient of a standard form
B_e	–	hourly fuel consumption of ship main engine
D	–	auxiliary coefficient
e, E	–	auxiliary coefficients
f_{1-3}	–	functions
f_{Be}	–	fuel consumption funcion of ship main engine
f_{Ne}	–	rated power function of ship main engine
f_v	–	ship speed function
F	–	auxiliary coefficient
G	–	auxiliary coefficient
H	–	CP propeller pitch related to maximum set pitch
$\hat{H}$	–	standard value of propeller pitch
$\hat{H}_P$	–	propeller pitch standard value at P-th experiment point
H_{max}	–	maximum propeller pitch
H_{min}	–	minimum propeller pitch
$\bar{H}$	–	mean propeller pitch
i	–	number of input parameters
k	–	total number of input parameters
m	–	number of measurement points
m_c	–	number of measurement points in experiment scheme core
m_o	–	number of measurement points in experiment scheme centre
m_α	–	number of „star points" of experiment
n	–	propeller or main engine rotational speed
$\hat{n}$	–	standard value of rotational speed
$\hat{n}_P$	–	rotational speed standard value at P-th experiment point
n_{max}	–	maximum rotational speed of propeller
n_{min}	–	minimum rotational speed of propeller
$\bar{n}$	–	mean rotational speed of propeller
N_e	–	main engine rated power
r	–	number of measurement repetitions in a measurement point
R^i	–	space of i input parameters of experiment
u	–	total number of measurement points
v	–	ship speed
x	–	experiment input parameter
$\hat{x}$	–	standard value of input parameter
z	–	output parameter value
$\hat{z}$	–	standard value of output parameter
$z_j^{(m)}$	–	result of a single measurement
$\bar{z}_P^{(m)}$	–	mean value of output parameter at P-th experiment point
$\bar{z}_{pop}^{(m)}$	–	mean value of population of results
α	–	star arm
ρ	–	sphere radius
σ	–	variation coefficient
$\sigma(z)$	–	standard deviation
$\sigma^2(z)$	–	variance of approximated values
0, 1, 11, 2, 22, 12	–	indices of polynomial coefficients

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Conference

3RD FORUM OF YOUNG SCIENTISTS

On 13 and 14 June this year a conference of young scientists was held in Borówno near Bydgoszcz. It was already 3rd scientific meeting called Forum of Young Scientists initiated by Regional Group of Utility Foundations Section, Mechanical Engineering Committee, Polish Academy of Sciences and arranged by Mechanical Department, Bydgoszcz University of Technology and Agriculture. Such conferences are held under the following main slogan :

Scientific problems in Construction and Exploitation of Machines

and they are an important element of raising qualifications of young scientific workers from Polish technical universities and research institutes. Every second year the conferences gather a large number of participants who make preparation to obtain D. Sc. degree in engineering under supervision of their promotors. During the conference the participants have an oportunity to present their scientific achievements both in theory and practical applications of engineering sciences. Simultaneously, by presenting prepared papers they gain experience in putting their scientific thesis under public jugement, and in defending them.

The educational character of the meetings is so much important that many invited well-known scienists take part in them, who friendly comment and discuss presentations of the young scientists. This year they came from among participants of the scientific conference, held in the same time, on Diagnostics of work machines and vehicles.

During the 3rd Forum of Young Scientists 17 papers were presented which were prepared by 22 young representatives of 7 Polish universities and institutes and one Lithuanian university. The largest number of the papers (8) was prepared by young scientists from the Bydgoszcz University of Technology and Agriculture.