Journal of POLISH CIMAC
Faculty of Ocean Engineering & Ship Technology
GDAŃSK UNIVERSITY OF TECHNOLOGY

IDENTIFICATION OF SHIPS PROPULSION ENGINE OPERATION BY MEANS OF DIMENSIONAL ANALYSIS

Jan Rosłanowski

Gdynia Maritime Academy
Faculty of Marine Engineering
81-87 Morska str.
81-225 Gdynia Poland
e-mail: rosa@am.gdynia.pl

Abstract

The following article presents the metod of determining the ship´s propulsion engine operation basing on the engines work parameters by means of dimensional analysis .The ships propulsion engine activity, as noticed by J. Girtler in his works [4,5], can be used for its diagnostics. of ship propulsion. Diagnostics engines increases safety of ships movement and at the same time protects the sea environment from pollution in case of its sinking. According to Girtler engine operation can be considered as, a new physical quantity of dimension Joul multiplied by second $\left[J \cdot s\right]$*. This quantity can be determined on the basis of algebraical diagram of dimensional analysis constructed by S. Drobot. This diagram allows to control the correctness of conclusion rules, in respect of mathematics, used in numerical functions of ship propulsion engine operation.*

Keywords: *ship propulsion engine operation dimensional analysis, diagnostics of ship engine*

1. Introduction

The Basic operating problem of ship propulsion systems is diagnostics of ship propulsion engines. Loss of operational capability of ship propulsion engine endangers the ships movement and in case of ship´s sinking may cause dangerous pollution of sea environment. Diagnostics of ship propulsion engines, as noticed by J. Girtler in the works [1,2,3], can be carried out by means of engine operation. Engines operation is interpreted as energy transmission in form of work or heat to the surroundings and expressed by the product of Joul and second [1,2].

Identification of engine operation by means of dimensional analysis in aspect of its usability to diagnostics has been carried out in the present article. The engine operation has been treated according to J. Girtler Works [1,2,3] as a new physical quantity to be used in diagnostics of ship propulsion engines.

2. Forms of dimensional functions of ship propulsion engine performance

Engine operation as dimensional quantity together with other quantities of his type characterizing the movement of ship propulsion system belongs to dimensional space elements. Products of dimensional space elements create abelian group together with involution of real exponent. It allows to describe dimensional space by means of positive real numbers. These numbers create the underspace of dimensional space. It means that both dimensional and nondimensional quantities belong to dimensional space. Out of dimensional space elements we can select, a determined by space dimension, amount of dimensionally independent quantities called the space base [4,5,6].

Elements of the same dimensional space can be arguments of the function defined as not an ordinary function and called a dimensional one. A dimensional function must equally well describe engines operation in each configuration of units and automatically fulfill the condition of invariance. Apart from this condition it must fulfill the condition of dimensional homogeneity. If in dimensionally invariant and homogeneous function there are independent and dependent arguments so an the basis of Buckingham theorem we can express the last by means of numerical function. Such information can be obtained only by means of experiment.

Analysis of ship engine activity in conditions of its operating creates great difficulties as it requires the knowledge of defining functions and also the knowledge of dynamic features of ship propulsion system.

The activity of ship propulsion engine in the course of its operation is defined by the following parameters:

-the effective Power of the engine **N,**
- torque of the engine **M,**
- rotational speed of the engine **n**,
- fuel volume consumed by the engine $\dot{V}$
- supercharging air compression **p**,
- time of engine activity **t**.

The function form of ship engine propulsion operation **D** can be determined on the basis of functional dependence among the above mentioned parameters. They have adequate dimensions in an accepted system of measure units. Besides on the basis of measurement we can attribute to them defined numerical values. Taking into account the above mentioned premises quantities we can write the following dimensional functions of ship propulsion engine operation **D** as below:

$$D = \Phi\left(M, n, \dot{v}, p, t \right) \tag{1}$$

$$D = \Phi\left(N, n, \dot{v}, t \right) \tag{2}$$

where:

Φ - symbol of dimensional function,

M – torque of the engine in $\left[\frac{kg \cdot m^2}{s^2} \right]$,

n – rotational speed of the engine in $\left[\frac{1}{s} \right]$,

$\dot{v}$ - fuel volume consumed by the engine in $\left[\frac{m^3}{s} \right]$,

N – effective power of the ship propulsion engine in $\left[\frac{kg \cdot m^2}{s^3} \right]$,

p – supercharging air pressure in $\left[\frac{kg}{m \cdot s^2} \right]$,

t- time of engine activity in $[s]$,

D – activity of ship propulsion engine in $\left[\frac{kg \cdot m^2}{s}\right]$.

Functions of ship propulsion engine operation (1) and (2) are described in dimensional space of the third grade, which means that among function arguments there are three dimensionally independent argument creating so called dimensional base. All possibilities of their choice in given functions (1) and (2) are presented in tables 1 and 2. Forms of numerical function of ship propulsion engine operation can be determined on the basis of measurements carried out in the course of its operation.

Tab. 1. Choice possibilities of arguments dimensionally independent, so called dimensional bases, in function of ship propulsion engine operation $D = \Phi\left(M, n, \dot{v}, p, t\right)$

Ordinal number	Form of dimensional function	Dimensional base	comments
1	$D = f\left(\phi_v, \phi_t\right) \cdot \frac{M}{n}$ $\phi_v = \frac{\dot{v} \cdot p}{M \cdot n}, \cdots\cdots \phi_t = n \cdot t$	M,n,p	
2	$D = f\left(\phi_p, \phi_t\right) \cdot \frac{M}{n}$ $\phi_p = \frac{p \cdot n \cdot \dot{v}}{M}, \cdots\cdots \phi_t = n \cdot t$	$M,n,\dot{v}$	
3	$D = f\left(\phi_M, \phi_t\right) \cdot \frac{\dot{v} \cdot p}{n^2}$ $\phi_M = \frac{M \cdot n}{p \cdot \dot{v}}, \cdots\cdots \phi_t = n \cdot t$	$n,\dot{v},p$	
4	$D = f\left(\phi_M, \phi_n\right) \cdot \dot{v} \cdot p \cdot t^2$ $\phi_M = \frac{M}{\dot{v} \cdot p \cdot t}, \cdots\cdots \phi_n = n \cdot t$	$\dot{v},p,t$	
5	$D = f\left(\phi_n, \phi_t\right) \cdot \frac{M^2}{\dot{v} \cdot p}$ $\phi_n = \frac{n \cdot M}{\dot{v} \cdot p}, \cdots \phi_t = \frac{\dot{v} \cdot p \cdot t}{M}$	$\dot{v}, p,M$	
6	$D = f\left(\phi_n, \phi_{\dot{v}}\right) \cdot M \cdot t$ $\phi_n = n \cdot t, \cdots\cdots \phi_{\dot{v}} = \frac{p \cdot t \cdot \dot{v}}{M}$	p,t,M	
7	$D = f\left(\phi_n, \phi_p\right) \cdot M \cdot t$ $\phi_n = n \cdot t, \cdots \phi_p = \frac{p \cdot t \cdot \dot{v}}{M}$	$M,t,\dot{v}$	

Tab. 2. Choice possibilities of arguments dimensionally independent so called dimensional bases in function of ship propulsion engine operation $D = \Phi\left(N, n, \dot{v}, t\right)$

Ordinal number	The form of dimensional function	Dimensional base	comments
1	$D = f\left(\phi_t\right)\cdot\frac{N}{n^2}$ $\phi_t = n \cdot t$	$N, n, \dot{v}$	
2	$D = f\left(\phi_n\right)\cdot N \cdot t^2$ $\phi_n = n \cdot t$	$N, \dot{v}, t$	

3. Determination of numerical function form of ship propulsion engine activity on the basis of dimensional argument measurements

To measure work parameters of propulsion engine of general cargo vessel with displacement of 5500 DWT all devices and measurement apparatus installed as ships standard equipment have been used. All measurements the results used in this work were taken during normal 17 days long voyage. Those measurements were taken at the time of engines steady work (excluding maneouevres) four times, a day at 8,11,14 and 20 o′clock of ship′s time. The general cargo vessel was propelled by 5RD68 engine made by H. Cegielski – Sulzer. The measurement results concerning the arguments of dimensional function of ship propulsion engine performance in the course of its operation in nondimensional form have been presented in drawing 1. Dependence of variable dependent on independent ones allows, in the domain of real numbers, to determine the numerical form of operational function by means of multiple regression and define its constant coefficients.

Drawing 1 presents measurement caordinates of numerical function of ship propulsion engine activity with sharply outlined linear dependence. These coordinates have been fitted to multiple regression which helped to obtain the equation of the following form:

$$\frac{D}{M \cdot t} \cdot 10^6 = 10^{-6} \cdot \frac{p \cdot \dot{v} \cdot t}{M} + 6{,}27 \cdot 10^6 n \cdot t - 0{,}001 \qquad (3)$$

or

$$D = 10^{-12} p \cdot \dot{v} \cdot t^2 + 6{,}27 n \cdot t^2 \cdot M - 10^{-9} \cdot M \cdot t \qquad (3a)$$

where:-
symbols like in formula (1).

Correlation coefficient of the above fitting to the straight line amounts to:

$$r = 0{,}99999572 \Rightarrow r^2 = 0{,}99999144 \text{ and after correction } r^2 = 0{,}99999092$$

which gives a standard estimation error equal to 0,00952.
Calculations that fit the straight line to measurement data included in table 4 were carried out by means of the programme STATISTICA

Tab. 3. Parameters measurements results of ship propulsion engine opetration which are arguments of dimensional function of its operation

Number	time of operation $t \cdot 10^6$ $[s]$	rotational speed $n\left[\frac{1}{s}\right]$	torque $M\left[\frac{kg \cdot m^2}{s^2}\right]$	fuel volume consump. $\dot{v}\left[\frac{m^3}{s}\right]$	effective power $N \cdot 10^6$ $\left[\frac{kg \cdot m^2}{s^3}\right]$	engine operation $D \cdot 10^{12}$ $\left[\frac{kg \cdot m^2}{s}\right]$	Super charging air compres. p $\left[\frac{kg}{s^2 \cdot m}\right]$
1	0	2,0833	22094	0,0209	2,8471	0	39226,8
2	0,0648	2,0900	22511	0,0194	2,9104	1240,65	41188,14
3	0,1512	2,0733	22094	0,0215	2,8339	6576,57	41188,14
4	0,1620	2,0650	22511	0,0224	2,8751	7661,34	43149,48
5	0,1728	2,0733	22511	0,0229	2,8868	8751,93	41188,14
6	0,1944	2,0833	22094	0,0224	2,8471	10923,92	41188,14
7	0,2376	2,0633	22094	0,0215	2,8199	16161,78	41188,14
8	0,2484	1,9900	21052	0,0192	2,5919	16241,63	34323,45
9	0,2592	1,9867	21052	0,0194	2,5875	17655,32	35304,12
10	0,2808	2,0567	22084	0,0231	2,8111	22502,09	41188,14
11	0,3240	2,0633	22094	0,0203	2,8199	30068,14	39226,80
12	0,3348	2,0633	22094	0,0203	2,8199	32106,10	39226,80
13	0,3456	2,0633	22094	0,0202	2,8199	34210,87	38246,14
14	0,3672	2,0683	22094	0,0203	2,8265	38714,45	39226,80
15	0,4104	2,1017	22719	0,0222	2,9538	50530,61	41188,14
16	0,4320	2,1200	22511	0,0208	2,9523	55960,04	43149,48
17	0,4536	2,1217	23136	0,0215	3,0361	63459,73	41188,14
18	0,4968	2,1067	22511	0,0213	2,9332	73542,86	41188,14
19	0,5076	2,1017	22511	0,0214	2,9266	76592,92	41188,14
20	0,5184	2,0967	22511	0,0212	2,9192	79696,81	41188,14
21	0,5400	2,1083	22302	0,0228	2,9089	86147,68	42168,81
22	0,5616	2,0667	22511	0,0244	2,8780	92194,77	42168,81
23	0,5616	2,0950	22511	0,0219	2,9170	93457,23	41188,14
24	0,5832	2,1200	22302	0,0238	2,9251	101040,29	47072,16
25	0,5832	2,1233	22928	0,0227	3,0111	104038,10	46091,49
26	0,6264	2,1283	22928	0,0227	3,0185	120304,64	45110,82
27	0,6372	2,1317	22928	0,0226	3,0229	124102,79	45110,82
28	0,6480	2,1300	22928	0,0222	3,0207	128847,40	45110,82
29	0,6696	2,1317	23343	0,0223	3,0413	140182,41	45110,82
30	0,7128	2,1283	23553	0,0221	3,1001	160027,39	45110,82
31	0,7236	2,1267	23553	0,0232	3,0979	164789,47	47072,16
32	0,7344	3,1733	24595	0,0247	3,3053	181138,80	52956,18
33	0,7560	2,0917	22928	0,0229	2,9663	172222,16	46091,49
34	0,8208	2,0967	23344	0,0219	3,0273	207188,73	43149,48
35	0,8424	2,1283	22928	0,0224	3,0185	217578,31	44130,15
36	0,9288	2,1300	23553	0,0222	3,1023	271925,61	45110,82

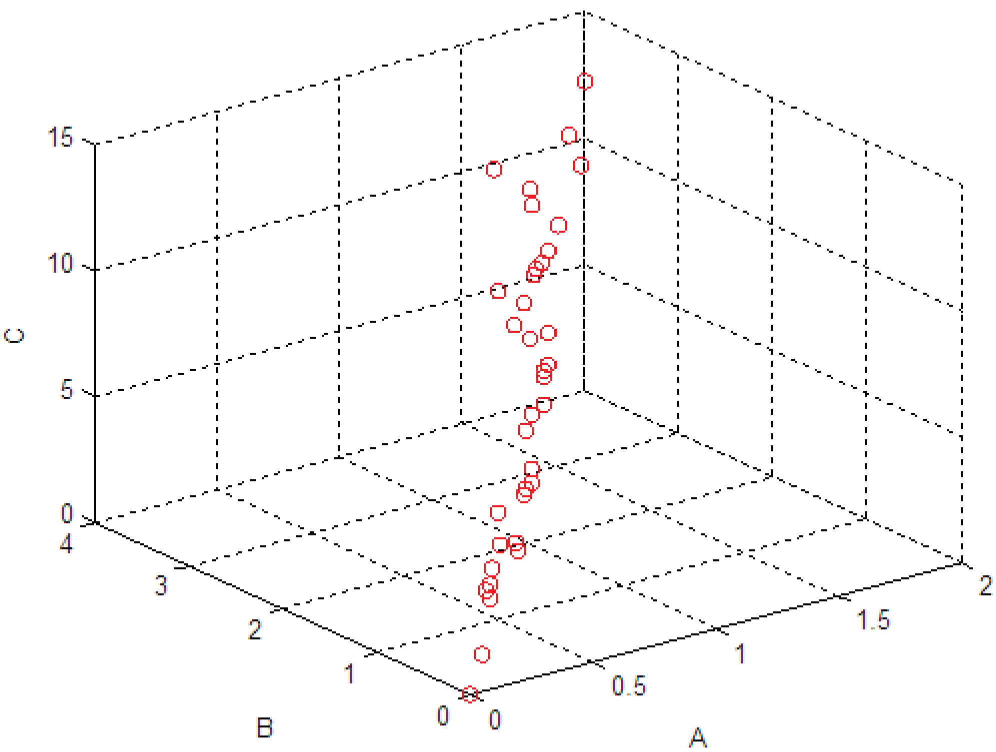

Fig. 1. Measurement coordinates of numerical function of ship propulsion engine activity in an established dimensional base p,t,M of the form C=f (A, B). (table1- position 6). Explanations: $C = \frac{D}{M \cdot t} \cdot 10^6$ *-nondimensional index of engine operation,* $A = n \cdot t \cdot 10^6$ *- similarity invariant of engine rotational speed,* $B = \frac{p \cdot \dot{v} \cdot t}{M}$ *-similarity invariant of fuel volume consumed by the engine, the rest of symbols like in formula (1)*

In dimensional function of ship propulsion engine defined by the formula (2) one can select four different dimensional bases , but only two are correct, in respect of dimensional structure. Structures of numerical functions obtained from formula (2), were given in table 2, position 2, similarity invariable of numerical function concerning engine operation is independent of its rotational speed as shown in drawing 2. On the other hand its value depends on engine work parameters in established conditions.

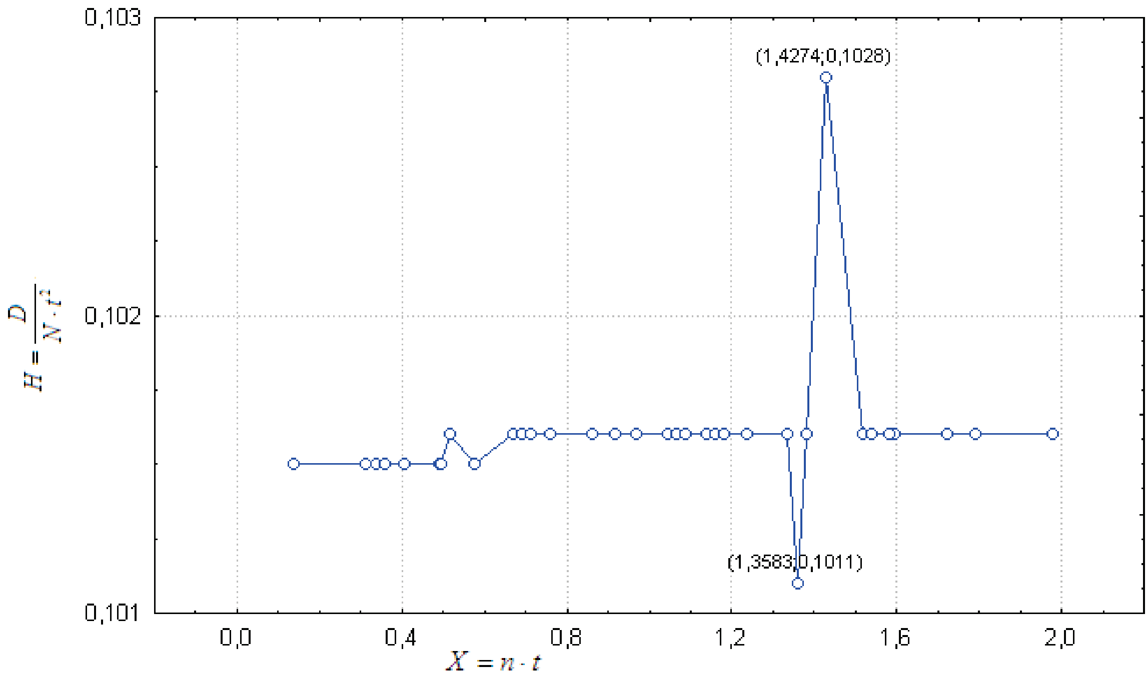

Fig. 2. Probability invariant measurements of numerical function concerning ship engine operation in an established dimensional base $N, \dot{v}, t$ *of the form* $H = f(X)$ *(look table 2 position 2). Explanations:* $H = \frac{D}{N \cdot t^2}$ *- nondimensional index of ship engine operation,* $X = n \cdot t$ *- similarity invariant of engine rotational speed, the rest of symbols like in formula (2)*

Peak occurence taking place in similarity invariant in numerical function of engine operation shown in drawing, is caused by the average of propulsion engine. After twelve days of the ship′s voyage broke the liner of engine cylinder head on third unit. First it caused, a decrease of operation value brought about by a faulty action of the third system and next an increase of operation value as a result of augmentem work of the remaining systems. Numerical structure given in table 2 position 2 on the basis of invariant changes of the engine operation similarity (numerical function dependent variable) can be recorded in the following way, drawing 2.

$$\left\{ \begin{aligned} \frac{D}{N \cdot t^2} &= 0{,}1015 \Rightarrow 0 \le n \cdot t \le 0{,}5775 \cdot 10^6 \\ \frac{D}{N \cdot t^2} &= 0{,}1016 \Rightarrow 0{,}5775 \cdot 10^6 \le n \cdot t \end{aligned} \right\} \tag{4}$$

or

$$\left\{ \begin{aligned} D &= 0{,}1015 \cdot N \cdot t^2 \Rightarrow 0 \le n \cdot t \le 0{,}5775 \cdot 10^6 \\ D &= 0{,}1016 \cdot N \cdot t^2 \Rightarrow 0{,}5775 \cdot 10^6 \le n \cdot t \end{aligned} \right\} \tag{4a}$$

where:
symbols like in formula (2).

4. Conclusions

Two different forms of numerical functions concerning propulsion engine operation (1) and (2) are possible to obtain, by means of algebraic diagram of dimensional analysis given by S. Drobot. Different numerical structures are given in tables 1 and 2.

These structures allow us to define superficially, dependence among dimensional quantities describing ship operation. Obtained on their basis numerical functions estimators of engine operation are their models can be defined accuratelly according to the established coefficients determined on the basis of engine work parameters.

Formulas (3) and (4) which define the ship engine operation can be treated only as correct proposals is respect of dimensional aspect. Forms (1) and (2) of dimensional function of engine operation differ one from another due to number of explanatory variables.

Reducing one explanatory variable [function form (2)] make it possibile to obtain numerical function structure of one variable. In case of five explanatory variables (form 1) one can obtain numerical function structures of two variables.

The best numerical function model of ship propulsion engine is the one of a simple form and easy to interpret physically. Numerical function models of operation distinquish themselves by the fact that they take into account the essential quantities which describe the work of an engine depending on the time of its operation. So they are of dynamic character and due to this can be used for diagnostic and prognostic purpose.

The form of numerical function models of ship propulsion engine operation can be defined on the basis of engine operation parameters. They can be true only for the engine at which the measurements were carried out.

5. References

[1] Girtler, J., *Energy-based aspekt of machine diagnostic*, Diagnostyka 1 (45), pp. 149-155, 2008.

[2] Girtler, J., *Work of a compression-ignition engine as the index of its reliability and safety,* II International Scientifically-Technical Conference Expo-DIESEL & GAS TURBINE”01 Coference Proceedings, pp.79-86, Gdańsk- Międzyzdroje-Copenhagen, 2001.

[3] Girtler, J., *Identyfication metod of technical state of othe objects on the Grodnu of estimation of their work*, Diagnostyka 2 (46), pp. 126-132, 2008.

[4] Drobot, S., *On the foundation of dimensional analysis*. Dissertation Mathematic, vol. XIV, 1954.

[5] Rosłanowski, J., *Modelling of ship movement by means of dimensional founction*, Transport No 3 (23), pp.443-448, Radom University of Technology, 2005.

[6] Rosłanowski, J., *The methodology of energetical process model construction in ship propulsion systems by means of dimensional analysis defining their dynamical features*, International Conference Technical economic and environmental aspects of combined cycle power plants, pp. 59-66, Gdańsk University of Technology, 2004.