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PARAMETRIC FUNCTIONS OF SHIP PROPULSION ENGINE OPERATION

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Abstract

The following article presents the method of determining the ship's propulsion engine operation basing on the engines work parameters by means of dimensional analysis.

The operation of engine is considered as effective energy transfer to ship propeller in the form of work during its operation. According to Girtler engine operation can be considered as, a new physical quantity of dimension Joul multiplied by second [2, 3].

A random type of combustion in engine cylinders makes possible to deal with engine operation as a random variable vectors in the Hilbert space isomorphic with dimension space. The analysis of stochastic engine work process is alternatively used as a set of determinist time functions by means dimension analysis.

Parametric functions of engine work were determined on the basis of algebraic analysis scheme designed by S. Drobot. This scheme makes possible to control the correctness of conclusion rules regarding mathematics in digital functions describing operation of ship propulsion engine. Additionally the parametric form of function makes possible to investigate the influence of function parameters on correctness of engine operation.

It makes possible to forecast the engine operation i given sailing conditions and to estimate steerability of ship during the voyage. It improves the safety of ship operation propelled by single engine propulsion plant.

Keywords: *transformation of energy, operation of the engine, dimensional space, dimensional functions*

1. Introduction

The basic problem in merchant ships operation is running of propulsion engine. It requires analysis of ship propulsion engine operation which consists in conversion and transfer of energy.

Transformation of chemical energy contained in fuel, into thermal energy takes place in engines during heat generation process in engine cylinders. The heat generation process in combustion engine cylinder takes place during filling the cylinder with a charge of fresh air, injection, then burning of fuel followed by exchange of heat between working medium and walls of combustion chamber. Generation of heat in engine cylinders is transformed into mechanical energy in the form of indicated work. Part of mechanical energy is lost during realization process of working medium exchange, except work recovered in a turbine.

Separation of work indicated and performed by gases in cylinders takes place in piston-connecting rod system of the engine. One part of this work is lost for propulsion of timing gear mechanisms, for overcoming of friction resistance in bearings, then resistance of piston friction against cylinder walls and ventilation resistance. However the second part of indicated work is transmitted to a screw-propeller as effective work during engine operation i.e. power. Such work creates the torque of the crankshaft at a definite revolution speed of the engine.

Therefore effective work of an engine being the form of converted in it energy, determines its performance. Engine operation interpreted as conversion of energy in the form of useful work can be described by the following formula:

$$D = 2\pi \int_0^t n(\tau) \cdot M_0(\tau) \cdot \tau \cdot d\tau \qquad (1)$$

where:

D - propulsion engine operation in [Js],
$n(\tau)$ - function of engine rotational speed from time τ in [1/s],
$M_0(\tau)$ - crankshaft torque function from time τ in [Nm],
τ - time of propulsion engine operation in [s].

Amount of effective work depends on quantity of exergue loss on the basis of which one can estimate heat generation process in engine cylinder. Each transformation of thermal energy into a mechanical one, causing the torque, can be treated as realization of stochastic process dependent on time, which is not random variable, but the parameter of this process. It has been shown in the paper [4] that time realizations of the engine torque during steady work of the engine create stationary stochastic process, partly ergodic, containing definite periodic constants. It allows treating stochastic process of the torque as the set of deterministic and dimensional functions of engine operation during work.

The ability to transform energy into a useful one is limited. The reason for this can be explained by the fact, that energy in irreversible process cannot be transformed into exergue. Process of generating heat in engine cylinder is of irreversible character which causes loss of exergue i.e. its transformation into energy. On the basis of the above of energy exchange can be divided into one part being able to do some work (exergue) and the other which cannot be transformed into work (energy).

In connection with this, engine operation understood as release of energy can be estimated. Estimation consists in comparing engine operation with dimensional physical quantity with a unit of measure, called by J. Girtler [2, 3] Joulesecond.

For this purpose one can take advantage of dimensional analysis which makes possible to pass from qualitative to numerical specifications. Thereby it enables to carry out analysis of ship propulsion engine operation by means of many variable functions. It is necessary to know here regularities taking place among dimensional quantities characterizing engine operation. One function of operation is not useful to can out analysis of all cases concerning engine performance. It is connected with the fact that it has been created for a definite goal of selecting specified quantities.

To be able to determine functional dependence of engine operation, if of course such dependence can be determined, the quantities must fulfil definite conditions:

1) significant influence on propulsion engine operation,
2) determination on the basis of measurement ,
3) dimension determining in an accepted system of measurement units,
4) descriptions in a commonly used system of measurement units SI.

If should be noticed that dimensional analysis does not determine and cannot determine of what kind the quantities are and how many of them are there? It depends exclusively on the energetic process under examination, taking place in an engine and on the knowledge about it.

2. Ship propulsion engine operation as dimensional function

Engine operation as dimensional quantity and other quantities of this type, characterizing ships motion, belongs to the elements of dimensional space. Elements products of dimensional space create abelian group together with involution of real exponent. It allows describing dimensional space of engine operation by means of positive real numbers. Those numbers from subspace of engine operation are dimensional space. It means that dimensional space of engine operation includes both no dimensional and dimensional quantities, which can be dimensionally independent.

Each system of no dimensional quantity with any dimensional quantity cannot be dimensionally independent. It is possible to choose out of dimensional space elements, a defined by space dimension, amount of dimensionally independent quantities called a space base. All bases of a given dimensional space are equipotent.

Dimensional space is of isomorphism character with vector space above the field of real numbers [1, 5-7]. In connection with this, theorems concerning vector space can be used in adequate transcription in dimensional space.

Elements of the same dimensional space can be arguments of engine operation function determined in this space. In this way determined function of engine operation is not a common numerical function and is called a dimensional one. Dimensional function of engine operation must identically well describe its performance in each unit system and thereby to be invariant in relation to dimensional transformation. Apart from this condition it must fulfil the condition of dimensional homogeneity i.e. it must not change a dimension of its value, in the situation when its arguments do not change them. Not in all cases dimensional functions of an engine are correct. Correctness condition of determined function with arguments creating configuration dimensionally independent in **n** dimensional spaces is fulfilled by exactly one solution of **n** equation set with a number of unknowns being equal to its arguments. This condition allows to check if the structure of described propulsion engine operation was put correctly or not [5-7].

In a general case function arguments of engine operation can be dimensionally independent and dependent. On the basis of Buckingham theorem [1] the last one can be expressed by means of numerical function. Numerical function of engine operation can be determined on the basis of an experiment exact to a constant parameter.

Dimensional analysis does not deliver any information about numerical form of engine operation function. Such information can be obtained only on the examination basis of propulsion engine performance during the ship motion.

3. Ship propulsion engine functions and their parametric structure

Analysis of ship propulsion engines during its operation deliveries many difficulties because it requires dependence knowledge between the quantities determining engine performance. Besides it requires also the knowledge of dynamic features of ship propulsion system.

Ship propulsion engine operation during its work is determined by the following dimensional quantities:

- torque of the engine M,
- rotational speed of the engine n,
- consumption of fuel volume by the engine G_v,
- pressure of charging air p,
- time of engine performance t.

Dimensional function form of ship propulsion engine **D** can be determined on the basis of functional dependence between the above mentioned quantities. They have adequate dimensions in a normalized measurement units set SI.

Taking into account the above mentioned premises, one searches for numerical forms of the following dimensional functions of ship propulsion engine operation **D**:

$$D = \Phi(M, n, G_v, p, t) \tag{2}$$

where:

Φ - symbol of dimensional function,
M - torque of the engine in $[(\mathrm{kg}\cdot \mathrm{m}^2)/\mathrm{s}^2]$,
n - rotational speed of the engine in [1/s],
G_v - consumption of fuel volume by the engine in $[\mathrm{m}^3/\mathrm{s}]$,
p - pressure of charging air in $[\mathrm{kg}/(\mathrm{m}\cdot \mathrm{s}^2)]$,
t - time of engine operation in [s],
D - propulsion engine operation in $[(\mathrm{kg}\cdot \mathrm{m}^2)/\mathrm{s}]$.

Function of ship propulsion engine operation (2) is described in dimensional space of the third grade. It means that among function arguments there are three dimensionally independent ones creating so called dimensional base. There are ten possibilities of their choice in a given function, but three of then are irregular. Chart 1 presents correct possibilities of argument choice dimensionally independent so called dimensional bases in propulsion engine performance [6, 7].

For a defined dimensional base presented in chart 1 it is possible to determine a general form of parametrical numerical function of ship propulsion engine operation exact to constant coefficients. Fixed coefficients can be determined on the basis of parameter measurement at steady work of ship propulsion engine, during normal voyage, by means of multiple regressions. To measure engine work parameters one should, best of all, take advantage of control and measuring apparatus and other devices installed as standard equipment of the ship. The way of carrying out such measurements was described in the paper [7] where exemplary results of parameter measurement of engine work were also presented. Measurements were carried out on the Sulzer engine 5RD68 which was a propulsion engine of General Cargo Vessel with displacement of 5500 DWT.

Operation of ship propulsion engine was calculated on the parameter measurement basis of engine work, basing on operation definitions presented in point 1. On the other hand steady coefficients taking place in a numerical function of engine operation were calculated on the basis of parameter measurement of engine work by means of formulas obtained from theorems of dimensional analysis.

Basing on the values determined in this way and presented in the paper [7] one can obtain three – dimensional diagram of dimensionless numerical function of propulsion engine operation such exemplary diagram has been presented in Fig. 1 which was obtained basing on dimensional form of engine operation function recorded as dimensionless shape after the acceptance of the base: ***p, t, M*** (look chart 1, position 6). Drawn and chartered variable dependence dependent on independent parameters allows in the field of real numbers, to determine numerical function form of operation by method of multiple regression and define its constant coefficients.

Tab. 1. Possibilities of arguments choice dimensionally independent, so called dimensional bases, in operation function of ship propulsion engine $D = \Phi(M,n,G_v,p,t)$ [5, 6]

Ordinal number	Form of dimensional function	Dimensional base	Remarks
1	$D = f(\phi_G, \phi_t) \cdot \frac{M}{n}, \quad \phi_G = \frac{G_v \cdot p}{M \cdot n}, \quad \phi_t = n \cdot t$	M, n, p	
2	$D = f(\phi_p, \phi_t) \cdot \frac{M}{n}, \quad \phi_p = \frac{p \cdot n \cdot G_v}{M}, \quad \phi_t = n \cdot t$	M, n, G_v	
3	$D = f(\phi_M, \phi_t) \cdot \frac{G_v \cdot p}{n^2}, \quad \phi_M = \frac{M \cdot n}{p \cdot G_v}, \quad \phi_t = n \cdot t$	n, G_v, p	
4	$D = f(\phi_M, \phi_n) \cdot G_v \cdot p \cdot t^2, \quad \phi_M = \frac{M}{G_v \cdot p \cdot t}, \quad \phi_n = n \cdot t$	G_v, p, t	
5	$D = f(\phi_n, \phi_t) \cdot \frac{M^2}{G_v \cdot p}, \quad \phi_n = \frac{n \cdot M}{G_v \cdot p}, \quad \phi_t = \frac{G_v \cdot p \cdot t}{M}$	G_v, p, M	
6	$D = f(\phi_n, \phi_G) \cdot M \cdot t, \quad \phi_n = n \cdot t, \quad \phi_G = \frac{p \cdot t \cdot G_v}{M}$	p, t, M	
7	$D = f(\phi_n, \phi_p) \cdot M \cdot t, \quad \phi_n = n \cdot t, \quad \phi_p = \frac{p \cdot t \cdot G_v}{M}$	M, t, G_v	

Figure 1 presents coordinates of dimensionless numerical function arguments of ship propulsion engine operation with distinctly visible linear dependence. These coordinates were fitted to the straight line with the aid of multiple regression method, obtaining the equation of the form [5]:

$$\frac{D}{M\cdot t}\cdot 10^{6}=10^{-6}\cdot\frac{p\cdot G_{v}\cdot t}{M}+6.27\cdot 10^{6}n\cdot t-0.001, \tag{3}$$

where symbols as in the formula (2).

Correlation coefficient of the above fitting to straight line is: $r = 0.99999572 \Rightarrow r^2 = 0.99999144$ which results in standard mistake of estimation equal to 0.00952.

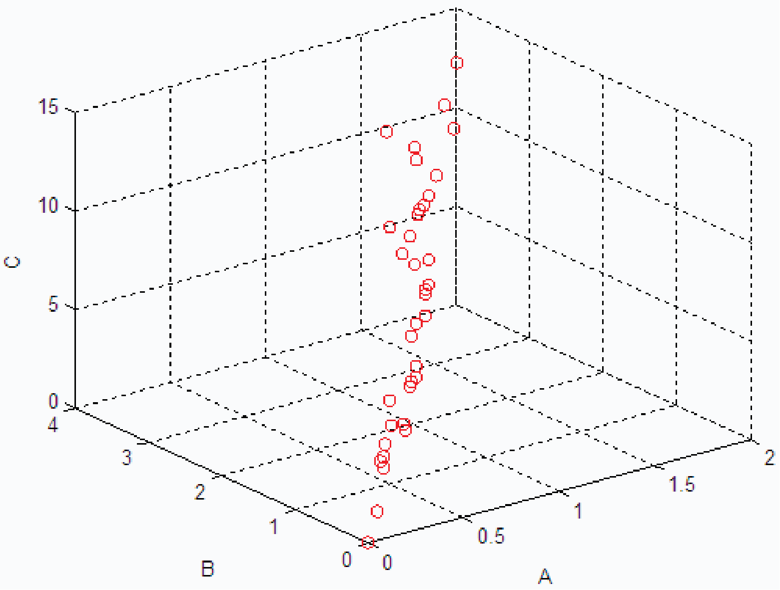

Fig. 1. Dimensionless arguments of propulsion engine operation function in an accepted dimension base p, t, M of the form C = f (A, B) [5, 6]. (look Tab. 1 position 6). Explanations: $C = [D/(M\cdot t)]\cdot 10^6$ – dimensionless indicator of engine operation, $A = n\cdot t\cdot 10^6$ – similarity invariant of engine rotational speed, $B = (p\cdot G_v\cdot t)/M$ – invariant of volumetric similarity for fuel consumption by the engine, remaining symbols like in the formula (2)

Acceptance of another dimensional base, for example *M*, *n*, *p* causes the following situation: corresponding with the base dimensionless arguments of dimensional function of engine operation in three- dimensional coordinates set are not so much linear as in the case of dimensional base equal to *p*, *t*, *M*.

No dimensional arguments of engine operation functions calculated on the basis accepted dimensional base *p*, *t*, *M* and of the same measurements as in the case of function determination (3) have been presented in Fig. 2. Fitting of no dimensional arguments of engine operation function presented in Fig. 2 has been carried out by means of nonlinear regression basing on STATISTICA program, obtaining the equation [5]:

$$\frac{D\cdot n}{M}=-0.01799+6.2985n^{2}\cdot t^{2}-0.0341n\cdot t+1.4752\frac{G_{v}\cdot p}{M\cdot n}, \tag{4}$$

where symbols as in formula (2).

Correlation coefficient of the above fitting is equal to r = 0.999996 which testifies good fitting of roller surface (4) to dimensionless quantities received on the basis of parameter measurement of engine operation. Structures of numerical functions (3) and (4) differ from each other because other argument choices dimensionally independent were used in them.

While determining numerical function forms of propulsion engine operation, one has taken advantage of dimensional quantities characterizing its work, which are however isomorphism with vectors. It means that treating them as scalars that is taking into account only these parts of them, which are dimensionless, is equally wrong as replacing vectors with scalars.

Figure 3 presents parametric numerical functions of propulsion engine operation during definite steady performance of its work obtained on the basis of dimensional function (2).

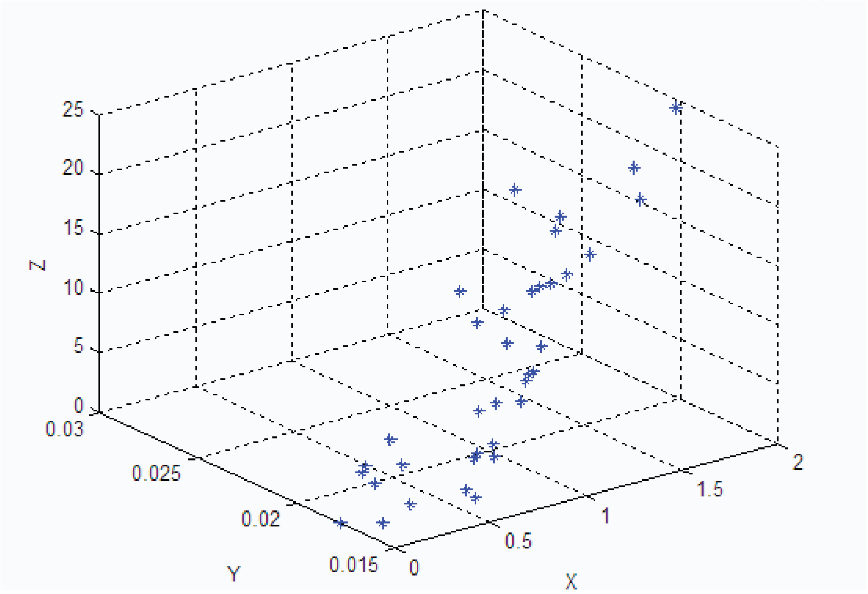

*Fig. 2. Dimensionless arguments of ship propulsion engine function in an accepted dimensional base M, n, p of the form Z=f (Y, X) [5,6]. (look Tab. 1, position 1). Explanations***:** *$Z = (D \cdot n)/M$ – dimensionless indicator of engine operation, $X = n \cdot t$ – similarity invariant of engine rotational speed, $Y = (G_V \cdot p)/(M \cdot n)$ – invariant of volumetric similarity of fuel consumption by the engine, the remaining symbols as in formula (2)*

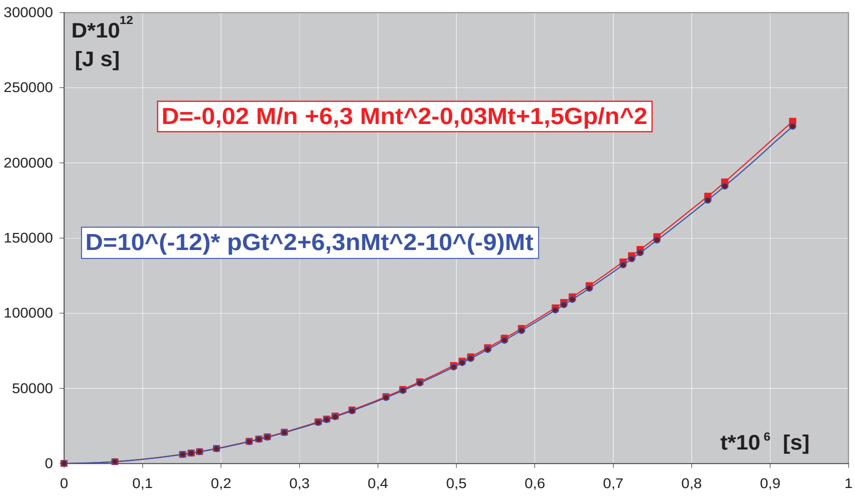

*Fig. 3. Numerical functions of ship propulsion engine operation during its steady work characterized by parameters: $n = 1.99$ [1/s], $M = 21052$ [(kg·m^2)/s^2], $G_v = 0.0192$ [m^3/s], $p = 34323.45$ [kg/(s^2·m)] obtained on the dimensional function basis. Explanations***:** *n – rotational speed of engine, M – torque on the propulsion shaft, G_v – consumption of fuel volume by the engine, p – pressure of charging air, t* 10^6 [s] – time of engine performance, D*10^{12} [(kg·m^2)/s] – ship propulsion engine operation*

Parametric numerical functions presented in Fig. 3 defining ship engine operation, can be treated only as correct proposals, considering dimensionality. The best numerical parametric function of ship propulsion engine operation is the one which has a simple form and easy physical interpretation.

Parametric forms of engine operation functions can be defined on the basis of parameter measurements of its work.

They are authentic only for the engine on which the measurements were carried out.

6. Summary

From dimensional function form of ship propulsion engine operation (2) one can, by means of algebraic diagram of dimensional analysis presented by S. Drobot, obtain different numerical structures presented in Tab. 1. These structures allow us to define dependence existing among dimensional quantities, describing propulsion engine operation during steady work.

Numerical parametric functions of propulsion engine operation, which have been obtained, are defined exact to constant coefficients, determined on the basis of the parameter measurements of its work.

Parametric numerical functions of propulsion engine operation are characterized by considering essential quantities describing its functioning depending on time. So they are of dynamic character and in connection with this, they can be used for diagnostic and prognostic purpose.

Possibility of using dimensional analysis depends on measurement of all quantities characterizing engine operation in an accepted set of units. Making use of this set of units in problems connected with engine operation description is obligatory in order to create, by all possible means, full description of mathematical specification connected with engine performance.

It also requires measurement of engine operation parameters in order to obtain exact parametric functions of its operation on the basis of useful dimensional quantities used for this purpose.

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