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Conditions of Carrying Out and Verification of Diagnostic Evaluation in a Vessel

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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. We present the influence of external conditions in the change of vessel's hull resistance and propeller characteristics as well as the influence of weather conditions in the results of examinations and characteristics of gas turbine engine. 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.

1 SYMBOLS

B –fuel consumption [kg/h];
b_e – unit fuel consumption [kg/kWh];
G_K –air consumption [kg/s];
D – propeller dimension [m];
J – advance of propeller;
K_Q – torque coefficient;
K_T – thrust coefficient;
L – work [kJ];
M – mass [kg];
N – power [kW];
n – rotational speed of a propeller [1/s];
p – pressure [Pa];
Q – torque [Nm];
R- Vessel resistance [N];
T – propeller thrust [N];
T – temperature [K];
t – temperaturę [^oC];
t – suction coefficient ;
w –wake fraction;
x – content relative to dry air mass;
v_p – propeller advance speed [m/s];
ρ – water density [kg/m^3];
η_p – freewheeling propeller efficiency;

Index's:
h – per hour;
m – concern measured parameters;
o – ambient parameters;
r – concern reduced parameters.

2 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 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. 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.
- hydrometeorological conditions
- vessel operation region.

The evaluation of factual propulsive characteristics in exploitation is performed during vessel sea trials [2].

In order to fully evaluate 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. Fig. 1 presents a block diagram of a vessel as the object of sea propulsion trials.

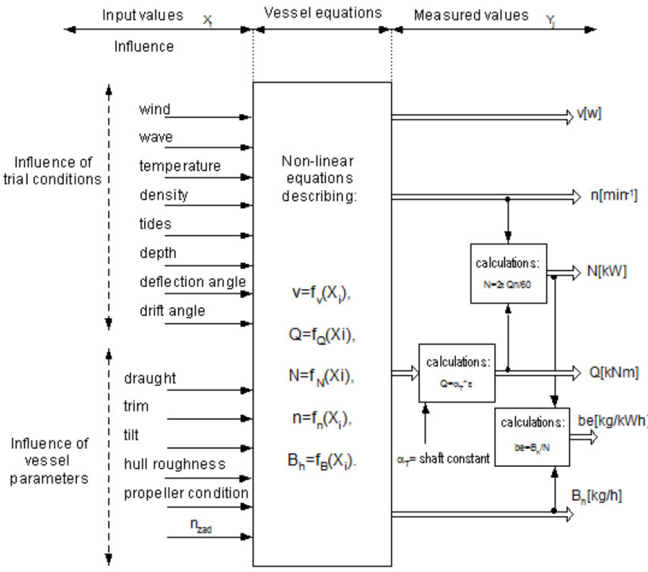

Figure 1. Block diagram of a vessel.

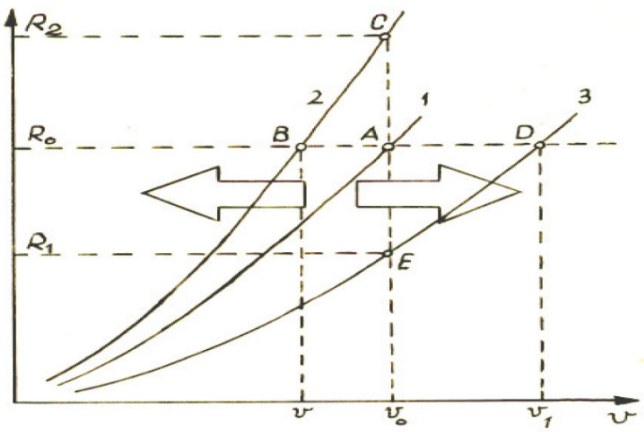

Figure 2. Resistance characteristics of a hull: 1. nominal ambient conditions (design); 2. degraded ambient conditions: 3. improved ambient conditions.

3 CHANGE IN VESSEL FLOATATIONAL RESISTANCE

Vessel resistance is determined at the design stage swith the use of computing methods and experimentally – with the use of model trials. They are the basis for selecting the propulsive system. At the design stage the resistance of a vessel is determined for standard navigational conditions. During exploitation, displacement, and consequently – draught, hull state, external conditions, etc. change continuously. This leads to a change (deterioration) in resistance characteristics and a change in the type of main engine load when the same vessel speed is developed. Thus, the information on resistance characteristics and the evaluation of the influence of particular conditions which, in turn, affect their values is significant in the diagnostic assessment of the state of propulsion system elements and of propulsive characteristics [3]. Fig. 2 illustrates exemplary resistance characteristics for a vessel operating in improved or worsened operating conditions.

4 CHANGE IN PROPELLER CHARACTERISTICS

Just like a hull, vessel propellers work in vastly varying conditions. It is especially applicable to changes in propeller draught resulting from displacement, permanent draught change and the angle of the incoming water during wave navigation, as well as deterioration in the condition of propeller blade surface (increased roughness). In order to evaluate the conditions in which a propeller operates at the rear of a vessel hull, it is important to know the cooperation relationship between the hull and propeller. Fig. 3 illustrates exemplary hydrodynamic characteristics of a propeller operating at the rear of a vessel hull.

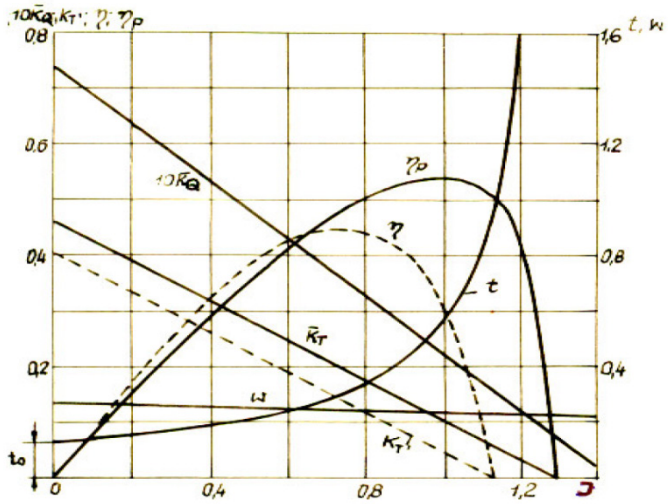

Figure 3. Hydrodynamic characteristics of a propeller: ------- free propeller characteristics in undisturbed water velocity field; - - - - characteristics of the working propeller after the ship's hull.

5 THE INFLUENCE OF EXTERNAL CONDITIONS ON ENGINE CHARACTERISTICS

The propulsive system of a vessel operates in vastly varying conditions. The change of conditions is caused by continuous change in displacement, and also draught, change of region where a vessel operates, change of hydrometeorological conditions, and changes in the condition of the hull, propeller and engines. In order to diagnose the propulsive system of a vessel in time, it is necessary to take changes in operating conditions into consideration.

5.1 *The influence of atmospheric parameters*

Atmospheric conditions affect the performance of each engine type, major influence, however, is observed in gas turbine engines [1]. In order to ensure adequate course of operation processes, gas turbine engines need considerable amounts of air. Excess air coefficient in the engine is 3,6–5. This accounts for unit air demand of 18 – 25 kg/kWh. The need for compressing large masses of air increases the importance of the influence of change in atmospheric conditions on engine functions, conditions for regulation, performance, etc. Significant influence is produced by changes in temperature, pressure and humidity of air, which cause changes in physical properties of the operating factor, such as density, viscosity, heat capacity, gas constant, etc.

Changes in engine performance resulting from atmospheric conditions may be considerable and sometimes may hinder the achievement of adequate engine performance, or the diagnosis due to the incomparability of measurement conditions.

5.1.1 *The influence of incoming air temperature*

Changes in incoming air temperature are due to the fact that vessels are exploited in various regions, or even climate zones, various seasons of the year, and day times.

The standard assumption is that ambient temperature is 288 K. And for the region of the Baltic Sea it may be assumed that ambient temperature fluctuates within the range of 238 –308 K. Such large fluctuations lead to considerable changes in engine work conditions, which needs to be taken into consideration while evaluating performance in an engine that operates in various conditions. The increase in incoming air temperature leads to reducing the air mass stream due to reduced density, and, as a result - decrease of engine power. What also changes are other figures that characterize the course of the working process of an engine and compressor efficiency. In the ranges of load that are close to those is calculations, the increase in air temperature leads to a minor increase in compressor efficiency. This is caused by an increase in sound speed and decrease of Mach number, as a result of which the conditions of transitional flow are improved, which translates to reduced hydraulic loss.

When incoming air temperature drops, the decrease of compressor efficiency leads to an increase in unit fuel consumption. Fig. 4 illustrates the properties of changes in compressor efficiency and its effective work depending on air temperature for various compression values. The presented relationships indicate that optimum compression is subject to linear changes both for compressor efficiency and work.

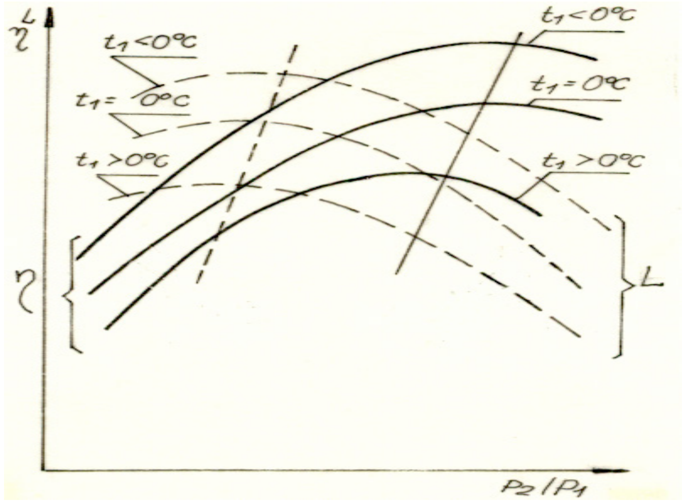

Figure. 4. The properties of changes in compressor efficiency and its effective work depending on air temperature and compression:

____ The optimum range of efficiency;

------ The optimum range of effective work.

The larger the difference in temperature, the larger the differences in the changes of optimum values.

5.1.2 *The influence of atmospheric pressure changes*

In comparison with temperatures, changes in atmospheric pressure are relatively minor. Changes in air pressure may be within the range 96 –104 kPa. Relative change of pressure in relation to standard pressure (101,3 kPa) is up to 10%. That is why the influence of pressure change on the properties of engine functions is not as significant, as the influence of temperature. Change of air pressure and the resulting change in air density at the engine inlet leads to proportional changes in all engine control cross-sections. An increase in atmospheric pressure leads to increasing air mass and, as a result, increase in engine power. What does not change is temperature, rotational speed, compression, efficiency and unit fuel consumption.

5.1.3 *The influence of change in air humidity*

Air humidity may be subject to a wide range of changes – from dry air to air containing saturated vapour. Humidity indeed affects gas engine performance. It is especially related to changes in air mass and with changes of air heat parameters, such as heat capacity and gas constant. An increase in humidity leads to an increase in gas capacity, leading to a decrease in incoming air density. That, in turn, leads to decreasing the volume of air flow through an engine. The influence of the decreased volume of air flow is larger than the increase in heat capacity, which leads to engine power drop. Apart from vapour, the incoming air also contains water drops in the form of sea spray. Moistening degree is determined based on water and vapour content relative to dry air mass.

$$X = \frac{m_{H2O}}{m_{ps}} \qquad (1)$$

where m_{ps} - dry air mass.

Fig. 5 illustrates an example of change in engine performance when the change in moistening degree is within the range 0,01 – 0,07

5.2 *Calculating the measured values to the so-called model atmosphere*

For changeable conditions during vessel engine exploitation, it is necessary to relate the test results to the so-called model atmosphere (po = 101,325 kPa and To =288,15 K).

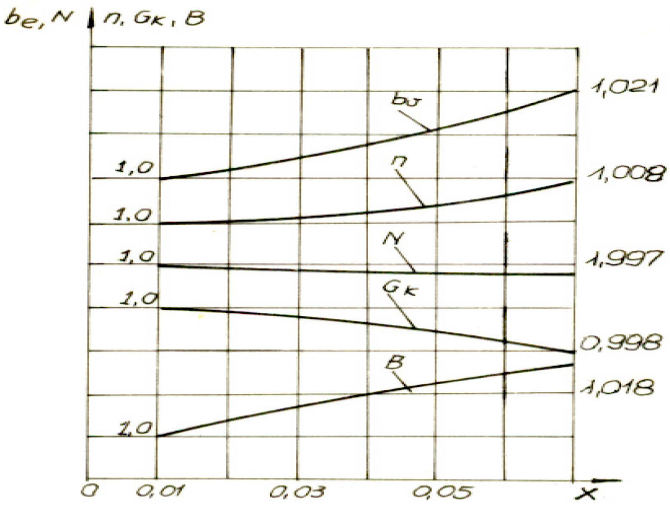

Figure 5. Influence of changes in incoming air humidity on turbine engine characteristics.

Changes in temperature, pressure, rotational speed and power relative to atmospheric conditions are presented in the following relationships:

– reduced engine power

$$P_{zr} = P_{zm} \frac{101325}{p_{ozm}} \sqrt{\frac{288,15}{T_{ozm}}} \qquad (2)$$

– reduced pressure

$$p_{zr} = p_{ozm} \frac{101325}{p_{ozm}} \qquad (3)$$

– reduced temperature

$$T_{zr} = T_{zm} \frac{288,15}{T_{ozm}} \qquad (4)$$

– reduced rotational speed

$$n_{zr} = n_{zm} \frac{288,15}{T_{ozm}} \qquad (5)$$

6 PROPULSIVE CHARACTERISTICS

In order to prepare propulsive characteristics, it is necessary to know the following:

– resistance characteristics of the hull R = f(v)..
– characteristics of freewheeling propellers
– characteristics of propulsive engines
– characteristics of elements transmitting the torque

Hydrodynamic characteristics of propellers in the form of K_T, K_Q, $\eta_p = f(J)$

where:

– thrust coefficient:

$$K_T = \frac{T}{\rho n^2 D^4} \qquad (6)$$

– torque coefficient:

$$K_Q = \frac{Q}{\rho n^2 D^5} \qquad (7)$$

– η_p – freewheeling propeller efficiency

$$\eta_p = \frac{K_T}{K_Q} \frac{J}{2\pi} \qquad (8)$$

– J - advance coefficient

$$J = \frac{\upsilon_p}{Dn} \qquad (9)$$

Coefficients which characterize hull and propeller cooperation

t – suction coefficient

$$t = 1 - \frac{R}{T} \qquad (10)$$

w –wake fraction

$$w = 1 - \frac{\upsilon_p}{\upsilon} \qquad (11)$$

The basis for propulsive characteristics is determining the area of possible operation for a freewheeling propeller on the grounds of hydrodynamic characteristics. The area is determined in coordinate systems T – n, Q – n, N – n with indicated lines of constant values of advance coefficient J and rotational speed of a propeller n. Next, resistance characteristics and propulsion engine characteristics are transferred onto adequate graphs and collated with the same measurement sites, e.g. propeller cone or output shaft clutch for torque and power, and vessel hull or propeller cone for resistance characteristics and propeller parameters. Collating the measurement results with appropriate sites is significant in order to consider the efficiency of particular elements that take part in transferring torque, and the efficiency of the hull and propellers. Propulsive characteristics offer the full presentation of the regularities in propulsion system element selection and make it possible to evaluate operating properties of a vessel. For vessels with combined propulsive systems, propulsion characteristics and the way in which they are presented are far more complicated. This is because:

- a combined propulsion system provides a number of ways to use diesel engines, e.g. propelling jet engines working on their own, peak engines working on their own, or both engine types working jointly;
- high navigation velocities result in high propeller strain; propellers usually work under highly developed cavitation, or supercavitation, hence, in addition to the advance ratio, the hydrodynamic characteristics of propellers must allow for the cavitation number.

Good results are achieved while presenting propulsion characteristics of combined systems as individual ones [4].

Fig. 6 illustrates an example of propulsive characteristics for classic vessel propulsion.

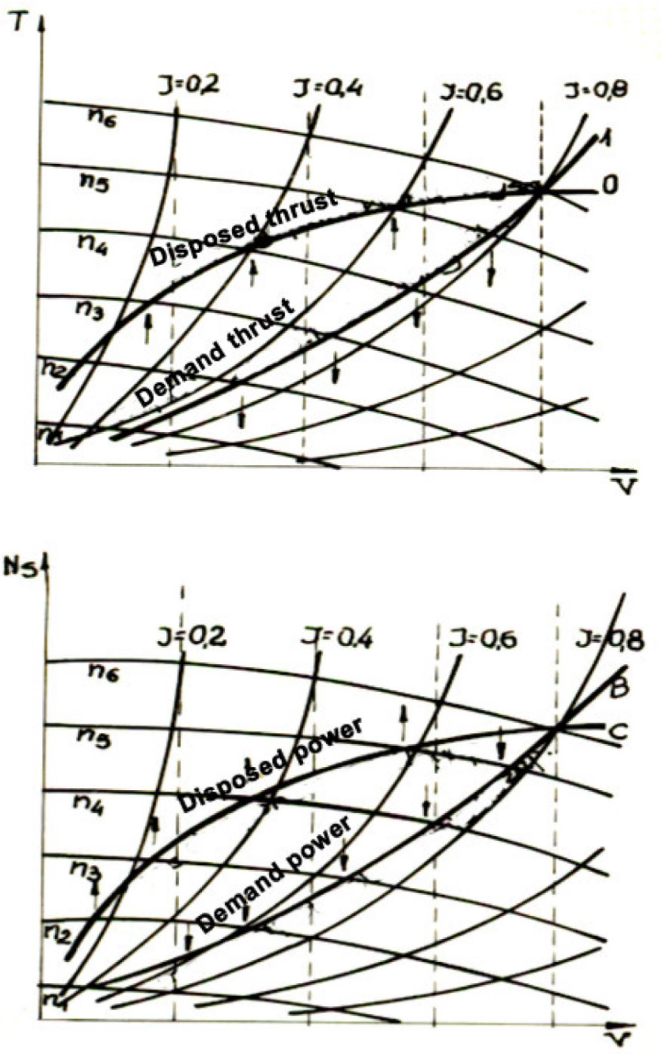

Figure 6. Propulsive characteristics of a propeller.

In order to properly evaluate propulsion characteristics achieved during sea trials, it is significant to estimate measurement uncertainty ranges for the measured and calculated values. Among the measured values, the largest measurement uncertainty is in measuring propeller thrust and torque.

Both values are measured by means of tensometry, with the use of contactless signal transmission from a rotating shaft.

The scope of measurement uncertainty for torque and thrust is mainly affected by the uncertainty of the evaluation of G shaft material resilience, which can be up to 4% and the error resulting from the failure to maintain parallel position relative to the axis of the shaft with tensometers, when propeller thrust is measured.

$$\frac{\partial Q}{Q \partial G} = \frac{1}{G}\frac{\partial Q}{Q \partial D} = \frac{3}{D}\frac{\partial Q}{Q \partial \varepsilon} = \frac{1}{\varepsilon} \tag{12}$$

The uncertainty for the measurement of torque measured by means of tensometry consists of two fraction components.

- u_1 standard uncertainty of the measuring apparatus
- u_2 standard constant uncertainty of the shaft α_T.

$$u_Q^{\ 2} = \left(\frac{u_Q}{Q}\right)^2 = \left(\frac{u_G}{G}\right)^2 + \rho\left(\frac{u_D}{D}\right)^2 + \left(\frac{u_\varepsilon}{\varepsilon}\right)^2 \tag{13}$$

The uncertainty of the measuring apparatus depends on the gauge used. Their borderline measurement error is 0,5%, thus the measurement uncertainty is

$$u_1 = \frac{0{,}5}{\sqrt{3}} = 0{,}289\% \tag{14}$$

with the assumption of even distribution.

For tensometric models of a measurement system a calibrated resistor R_{cal} is used; its borderline error is 0,01%. The measured stress of shaft ε are in the following relation to the model:

$$\varepsilon = \frac{1}{4K_t}\frac{R_t}{R_t + R_{cal}} \tag{15}$$

where:
R_t - tensometer resistance
K_t - tensometer constant

The influence of the model on measurement uncertainty for stress ε is determined according to relations like those for combined measurements

$$\frac{\partial \varepsilon}{\varepsilon \partial R_t} = \frac{1}{R_t}, \ \frac{\partial}{\varepsilon \partial K_t} = -\frac{1}{K}, \ \frac{\partial \varepsilon}{\varepsilon \partial R_2} - \frac{1}{R_2} \tag{16}$$

$$\left(\frac{U\varepsilon}{\varepsilon}\right)^2 = \left(\frac{V_{R_t}}{R_t}\right)^2 + \left(\frac{-U_k}{K_t}\right)^2 + \left(\frac{-V_{R_L}}{R_2}\right)^2 \tag{17}$$

With borderline errors of basic values $R_t \rightarrow \pm 0{,}2\%$, $K_t \rightarrow \pm 0{,}5\%$ and $R_2 \rightarrow \pm 0{,}01\%$, the uncertainty for models of shaft stress is 0,314%. Torque is calculated based on the variable shaft stress value

$$Q = \alpha T \varepsilon \quad (18)$$

where

$$J = \frac{\pi D^4}{32} \quad \alpha_T = \frac{4GJ}{D} \quad (19)$$

α_T – constant for a praticular shaft
J- moment of inertia; G- shear modules

Torque measurement uncertainty calculated like it is the case in combined measurements and with borderline errors

for G 3s = 3,45 % thus $u_G / G = 1{,}15\%$
for D ±0,1 mm D>200 mm and $u_{D/D}$ = 0,029%
for ε $u_\varepsilon / \varepsilon = 0{,}314\%$ is: *1,2%*

Measurement uncertainty is largely due to errors in estimating G resilience module. This error may be eliminated by running resistance tests on steel used for shafts or using special scale measurement middlebody in the shaft line segment

7 CONCLUSIONS

Vessel operating system trials conducted in real conditions, with effects affected by external factors, i.e. trial environment, broadly understood hull and propeller condition may enable estimation of the technical condition of the whole vessel, i.e. hull and propulsion system. Periodical tests make it possible to determine reciprocal relationships between fuel use, torque, rotational speed, and vessel speed. These relations may be used in ongoing exploitation in order to evaluate the condition of particular elements of a propulsion system while using theoretical propulsion characteristics calculated for the adequate hull and propeller. In diagnostic tests the following factors need to be taken into consideration every time: vessel loading, for warships – reserves, including fuel reserves, which account for a considerable share of the total mass of the vessel, as well as atmospheric and hydrometeorological conditions of measurements.

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