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Določanje vijačnih lastnosti motorja z merilnimi lističi in osebnim računalnikom v ustaljenih razmerah plovbe ladje

Determining the Propulsion Characteristics of an Engine Under the Conditions of a Standard Sailing Regime by Means of Strain Gauges and a Personal Computer

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V tem prispevku je z uporabo merilnih lističev in osebnega računalnika, z nedotikalno metodo, opisan postopek merjenja elastične deformacije osi ladijskega vijaka. Na podlagi znanega prečnega prereza in vrste materiala osi ladijskega vijaka, je določen vrtilni moment. Z znano frekvenco osi, kotno hitrostjo in vrtilnim momentom je mogoče določiti delež koristne moči, ki se prenaša od motorja do ladijskega vijaka. Vsa uporabljena oprema pri preizkusih, tako strojna kakor programska oprema, je bila izdelana v podjetju "HOTTINGER BALDVIN MESSTEHNIK" (HBM), Darmstadt, Nemčija. Preizkus je potekal na ladji Mornarice Srbije in Črne Gore pri ustaljeni plovbi.

(Ključne besede: ladijski motorji, dizelski motorji, vijačne lastnosti, merilni listič)

This paper describes the process of measuring a propeller shaft's elastic deformation by means of a non-contact method, strain gauges and a PC. By using the known cross-section as well as the propeller shaft's material type the torque was determined. Knowing the shaft frequency, that is the radial velocity and the torque, it is possible to determine the effective power transmitted from the engine to the propeller. The equipment, i.e., the hardware and the software, was produced by HOTTINGER BALDWIN MESSTEHNIK (HBM), Darmstadt, from the Federal Republic of Germany. The experiment was carried out on a ship belonging to the Navy of Serbia and Montenegro under the conditions of a standard sailing regime.

(Keywords: ship diesel engines, propulsion systems characteristics, strain gauges)

0 UVOD

Moč ladijskega motorja se v času njegove uporabe stalno spreminja, odvisno od priključenega porabnika. Pri potisku ladje z ladijskima vijakom z nepremičnimi krili, je koristna moč na ladijskem vijaku, odvisna od števila vrtljajev in geometrijskih lastnosti ladijskega vijaka. Pri nespremenljivem premeru in koraku ladijskega vijaka, je upor ladijskega vijaka, ki ga premaguje motor, sorazmeren kvadratu števila vrtljajev ladijskega vijaka.

0 INTRODUCTION

During the exploitation of a diesel engine, the changes of engine power always depend on connected devices. When a ship is propelled by a screw, the power that the engine delivers to the fixed thread screw depends on the number of turns and the geometrical characteristics of the screw. When the screw diameter and the thread are fixed, the resistance of the propeller, which is suppressed by the engine, is proportional to the square of the number of revolutions.

$$M = k_0 \cdot n^2 \quad (1).$$

Delež koristne moči motorja na ladijskem vijaku se lahko izrazi v odvisnosti od vrtilnega momenta, ki se prenaša od ročične osi prek spojke na ladijski vijak, ta se vrti s kotno hitrostjo ω.

The effective power that an engine transmits to the screw can be expressed by the torque that the clump transfers from the crankshaft to the screw, while it revolves at angular velocity ω.

$$P_e = M \cdot \omega \quad (2).$$

V primeru, ko motor poganja ladijski vijak z določenim korakom kril, bo moč motorja, ki jo absorbira ladijski vijak pri različnih vrtljajih [1]:

In the case when the engine drives the fixed thread screw, the power of the engine that the screw absorbs, at different numbers of revolutions, is [1]:

$$P_e = M \cdot \omega = k_0 \cdot n^2 \cdot \frac{\pi \cdot n}{30} = k_1 \cdot n^3 \quad (3).$$

Enačba (3) pove, da se moč motorja spreminja po kubni paraboli v odvisnosti od spremembe števila vrtljajev ladijskega vijaka. Krivulja se imenuje vijačna lastnost motorja (sl. 1, krivulja 1).

Pri uporabi ladijskega motorja je zelo pomembno določiti preneseno moč na ladijski vijak pri vseh vrtljajih. Na podlagi posnete vijačne lastnosti se da določiti, v katerem režimu motor deluje v področju možnih vrtljajev, oziroma ali deluje po proračunski lastnosti vrtilnega momenta pri plovbi, lastnosti vrtilnega momenta pri plovbi s "težkim ladijskim vijakom", ali po lastnosti vrtilnega momenta pri plovbi z "lahkim ladijskim vijakom".

V ladijskih razmerah običajno nimamo na voljo opreme za merjenje vrtilnega momenta motorja (ali njegove moči) in potisne sile ladijskega vijaka. Zato je v takšnih razmerah nujno treba izvajati neposredni nadzor trupa ladje, ladijskega vijaka in motorja.

Posadki ladje, ki upravlja pogonski sestav, znatno pomaga pri rešitvi takšne naloge uporaba ustreznih metod nadzora posameznih delov pogonskega sestava ladje, posebno pa nadzor delovanja glavnih potisnih motorjev.

Ena od učinkovitih metod, s katero se lahko meri vrtilni moment in tako tudi prenesena moč na

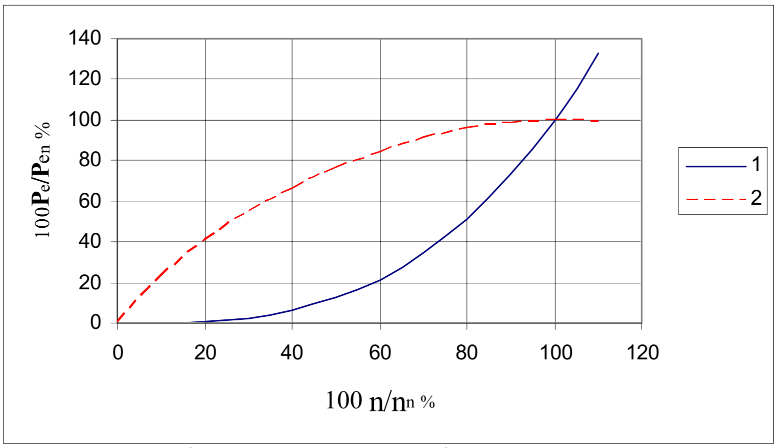
It is evident from Equation (3) that the power of the engine changes with cube parable, which depends on the number of screw revolutions. This curve is called the "screw characteristic of the engine" (Fig. 1, curve 1).

When an engine is used aboard a ship, it is very important to determine the power that the screw absorbs at different numbers of propeller revolutions, ranging from the minimum to the maximum. By using the transcribed characteristics we can determine the regime in which the engine is working at different numbers of propeller revolutions, i.e., whether it works with the forecast characteristic of the screw moment, the characteristic of the screw moment while sailing with a "hard propeller" or the characteristic of the screw moment while sailing with a "light propeller".

Ships usually do not have instruments for measuring the torque (engine power) propeller lifting, and so in this case it is necessary to perform direct control of the hull, the propeller and the engine.

To the members of the crew working in the engine room, using an appropriate method to control the functioning and condition of some of the elements in the engine room, especially of the main propulsion engine, can provide considerable help while executing this task.

One of the effective methods by which we can measure the torque and the power that the en-



Sl. 1. *Vijačna in zunanja lastnost motorja*

Fig. 1. *The screw characteristic and the outer characteristic of the engine*

ladijski vijak, je metoda z uporabo merilnih lističev in osebnega računalnika.

1 UPORABA MERILNIH LISTIČEV

Merilne lističe sta odkrila leta 1938 E.E. Simons in A.C. Ruge iz Kalifornije, ZDA, neodvisno drug od drugega. Prva tovarna za industrijsko izdelavo merilnih lističev je bila zgrajena leta 1941 v Baldwin-Southwark, ZDA. V Evropi je leta 1952 podjetje ''HOTTINGER BALDVIN MESSTECHNIK" (HBM) iz Darmstadta, Nemčija začelo izdelovati uporovne merilne lističe. Uporaba merilnih lističev je danes že zelo razširjena, unčinkovito se uporabljajo za analizo napetosti v konstrukcijah. Merilni lističi se lahko uporabljajo tudi za statična, navidezno statična in dinamična merjenja na konstrukcijah ali pa tudi na delih strojev.

Ko govorimo o merjenju pomikov in napetosti, se merilni lističi uporabljajo v področju elastičnih deformacij po Hookeovem zakonu. Merilni listič pomeni prevodnik določenega upora in je postavljen na površini merjenega predmeta. Vsaka deformacija merjenega predmeta, zaradi njegove obremenitve, povzroči sorazmerno deformacijo merilnega lističa, kar omogoča merjenje sprememb upora merilnega lističa.

V neobremenjenem stanju je upor merilnega lističa R_0, ko pa se obremeni, je po deformaciji $R_0 + \Delta R$ [2]:

gine transmits to the propeller is a method based on strain gauges and a personal computer.

1 APPLICATION OF THE STRAIN GAUGES

Strain gauges were discovered in 1938 by E.E. Simons and A.C. Ruge (working independently of each other in California, USA). The first company to begin the industrial production of strain gauges was founded in 1941 (Baldwin-Southwark, USA). In Europe, "HOTTINGER BALDWIN MESSTECHNIK" (HBM) from Darmstadt, Germany, began producing foil strain gauges in 1952. The use of strain gauges is widespread, and they can be used for the analysis of a stress measurement in a construction. Strain gauges can be used for static, quasi-static and dynamic measurements on constructions and machine parts.

When measuring dilatation and strain, strain gauges are used in the area of elastic deformations, according to Hooke's law. The strain gauge represents a conductor of defined resistance, fastened to the surface of a measuring object. Each deformation of the measuring object, due to stress, causes a certain deformation of the strain gauge and changes its electrical resistance.

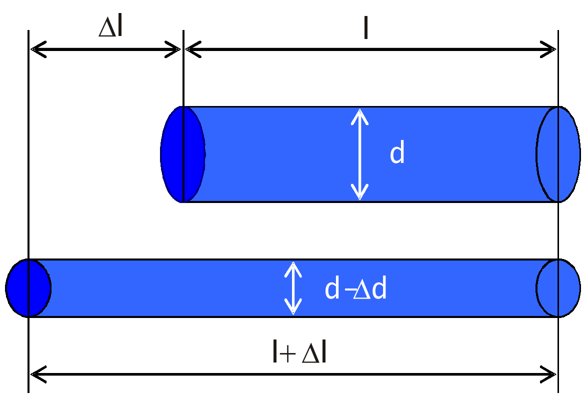
During a no-load state the strain gauge's resistance is R_0, and during a load state, i.e., after the deformation, it will be $R_0 + \Delta R$ [2].

$$R_0 = \frac{\rho \cdot l_o}{\mathrm{A}} = \frac{4 \cdot \rho \cdot l_o}{\pi \cdot d^2} \quad (4).$$

Skupna sprememba upora po deformaciji in spremembi mikrostrukture sestavnih materialov merilnega lističa je:

The total change of resistance, due to the deformation, and the change of the microstructure of the strain-gauge material is:

$$\frac{dR}{R_0} = \varepsilon \cdot (1+\nu) + \frac{d\rho}{\rho} \quad (5).$$



Sl. 2. *Deformacija predmeta ob obremenitvi*
Fig. 2. *Deformation of an object during a load state*

Odvisnost med mehanično deformacijo in spremembo upora na merilnem lističu za raznovrstne prevodne materiale je omejena z občutljivostjo merilnega traku k [2].

The relationship between the mechanical deformation and the strain gauge's electrical resistance for different conductors is determined from the strain gauge's response k[2].

$$k = \frac{\frac{\Delta R}{R_o}}{\frac{\Delta l}{l_o}} = \frac{\frac{\Delta R}{R_o}}{\varepsilon} \qquad (6).$$

Za nekatere zlitine, ki se uporabljajo pri izdelavi vlaken v merilnem lističu je občutljivost k tudi drugačna. Merilni listič naj bi spreminjal upor le zaradi napora v aktivni smeri (smer, v kateri se meri). Če je merilni listič obremenjen v svoji dejavni smeri, je občutljivost (k – količnik) definirana kot:

k is different for each alloy that is used for making the strain gauges. The strain gauge should change its resistance only due to the stress in the active direction (the direction of the measurement). If the strain gauge is loaded in its active direction, then the strain gauge's response is defined as:

$$k_l = \frac{\frac{\Delta R}{R_o}}{\varepsilon_l} \qquad (7).$$

Če je merilni listič obremenjen v prečni smeri, je k-količnik izražen kot:

If the strain gauge is loaded in a transverse direction, then the appropriate k factor is defined as:

$$k_t = \frac{\frac{\Delta R}{R_o}}{\varepsilon_t} \qquad (8).$$

Razmerje teh dveh količnikov določa prečno občutljivost:

The ratio of these two factors is defined as the cross response:

$$q = \frac{k_t}{k_l} \qquad (9).$$

Ta učinek se zmanjša z uporabo uporovnih merilnih lističev s prečnim odebelenjem omrežja. Odvisno od vrste merilnega lističa ter dolžine omrežja je prečna občutljivost q<0,01 do 0,02. Merilni lističi se na splošno uporabljajo za merjenje deformacij do 3000 μm/m. Največje podaljšanje merilnega lističa je odvisno od konstrukcije in materiala ter znaša od ± 2 cm/m do 15 cm/m. V primeru velikih deformacij, merilni lističi prikazujejo nelinearne lastnosti, ki niso zanemarljive.

Merilni listič pritrdimo na testirani predmet z lepljenjem, z uporabo različnih vezivnih materialov, kar terja zelo veliko natančnost. Električna vezava merilnih lističev se izvaja v obliki Wheatstonovega mostiča. Wheatstonov mostič se lahko uporabi za merjenje upora, in to:

- za merjenje absolutne vrednosti upora s primerjanjem znanega upora,
- za merjenje relativne spremembe električnega upora.

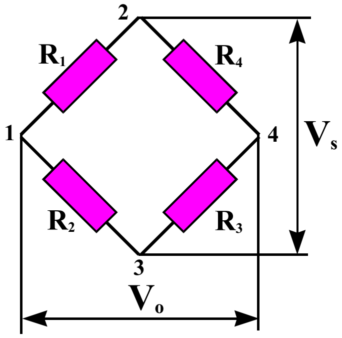
Ta način vezave merilnih lističev omogoča merjenje spremembe upora z zelo veliko natančnostjo, v mejah od 10^{-7} do 10^{-14} Ω/Ω. Merilni lističi so določeni upori, ki se povezujejo od R_1 do R_4, kakor

This effect is reduced by the use of a foil strain gauge with transversal wire thickening. The cross response is between q<0.01 to 0.02, depending on the strain-gauge type and the length of its grid. Strain gauges are normally used for measuring deformations up to 3000 μm/m. The maximum deformation of a strain gauge, which depends on its design and material, ranges from ±2 cm/m to 15 cm/m. In the case of extensive deformations, strain gauges show nonlinear characteristics that cannot be neglected.

The strain gauge is glued to the object of investigation using different binding materials, and it requires maximum attention. The electrical connection of the strain gauges is performed in the shape of a Wheatstone bridge. The Wheatstone bridge can be used for the resistance measurement, i.e.:

- for measurement of an absolute value of resistance by comparing it with a known resistance,
- for measurement of the relative alterations of resistance.

Strain gauges connected in this way provide a measurement of resistance alterations, ranging from 10^{-7} to 10^{-4} Ω/Ω, with a high accuracy. Strain gauges represent specific resistors, which



Sl. 3. *Wheatstonov mostiček*
Fig. 3. *The Wheatstone bridge*

je narisano na sliki 3. Točki 2 in 3 se povezujeta z virom električne napetosti V_s, bodisi z enosmernim ali z izmeničnim električnim tokom. V točkah 1 in 4 dobimo izhodno električno napetost V_0, ki izraža vrednost merjenega signala.

Načelo delovanja Wheatstonoevega mostiča se lahko predstavi s sliko 4.

Predvidevamo lahko, da je upor vira električnega toka R_G zanemarljiv ter da je notranji upor naprave za merjenje izhodnega električnega toka zelo velik. Električne napetosti V_1 in V_4 lahko izračunamo z uporabo znanih uporov R_1, R_2, R_3, R_4 in V_s.

are connected from R_1 to R_4 as shown in Figure 3. At points 2 and 3 there is the supply voltage V_s with alternating or direct current. At points 1 and 4 there is the output voltage V_0, that represents the measurement signal.

The basic functioning principles of the Wheatstone bridge can be explained with Figure 4.

It is supposed that the resistance of the source R_G is negligible, and that the inner resistance of the instrument for the measurement of the output voltage is infinite. If the resistances R_1, R_2, R_3, R_4 and V_s are known, voltages V_1 and V_4 can be calculated:

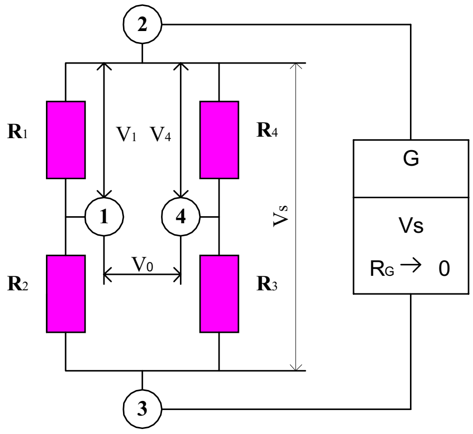
$$V_1 = \frac{R_1}{R_1 + R_2} \cdot V_s \tag{10}$$

$$V_4 = \frac{R_4}{R_3 + R_4} \cdot V_s \tag{11}$$

Razlika električnih napetosti V_1 in V_4 je izhodna električna napetost V_0:

The difference between V_1 and V_4 represents the output voltage V_0:

$$V_0 = V_s \cdot \left(\frac{R_1}{R_1 + R_2} - \frac{R_4}{R_3 + R_4} \right) \tag{12}$$



Sl. 4. *Načelo delovanja Wheatstonovega mosta*
Fig. 4. *The first principles of the Wheatstone bridge*

Neuravnoteženost mostiča je določena kot relativna izhodna električna napetost:

When the bridge is not balanced it is defined as the relative output voltage.

$$\frac{V_0}{V_s} = \frac{R_1}{R_1 + R_2} - \frac{R_4}{R_3 + R_4} \quad (13).$$

Obstajata dva primera uravnoteženosti mostiča:
- upori upornikov so v mostiču enaki ($R_1 = R_2 = R_3 = R_4$),
- razmerje uporov v obeh polovicah mostiča je enako ($R_1 / R_2 = R_4 / R_3$).

V obeh primerih, ko je vrednost električnih napetosti $V_0 / V_s = 0$, je mostič uravnotežen. Če se vrednosti uporov v mostiču $R_1...R_4$ spremenijo za določeno razliko ΔR, mostič ni uravnotežen, pojavi se določena izhodna električna napetost V_0. V tem primeru je relativna izhodna električna napetost:

There are two cases when the bridge is balanced:
- the electrical resistances of the bridge are equal ($R_1 = R_2 = R_3 = R_4$),
- the proportion of the electrical resistance on both sides of the bridge is equal ($R_1 / R_2 = R_4 / R_3$).

In both cases $V_0 / V_S = 0$, and the bridge is balanced. If the electrical resistances in the bridge, $R_1...R_4$, change their values by ΔR, the bridge is not balanced, and there is a certain output voltage, V_0. In this case the relative output voltage is:

$$\frac{V_0}{V_S} = \left(\frac{R_1 + \Delta R_1}{R_1 + \Delta R_1 + R_2 + \Delta R_2} - \frac{R_4 + \Delta R_4}{R_3 + \Delta R_3 + R_4 + \Delta R_4} \right) \quad (14).$$

Ko je $\Delta R_i << R_i$, se lahko relativna izhodna električna napetost izrazi tudi:

Because of fact that $\Delta R_i << R_i$, the relative output voltage can be expressed as:

$$\frac{V_0}{V_S} = \frac{1}{4} \left(\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2} + \frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4} \right) \quad (15).$$

Če pa je $\Delta R_i / R_i = k\varepsilon_i$, je relativna izhodna električna napetost:

Considering $\Delta R_i / R_i = k\varepsilon_i$, the relative output voltage is:

$$\frac{V_0}{V_S} = \frac{k}{4} \left(\varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4 \right) \quad (16).$$

Izhodna električna napetost z mostiča je torej funkcija:
- električne napetosti napajanja mostiča V_s,
- k-koeficienta merilnega lističa in
- deformacije ali spremembe električne napetosti v vejah ε_1 do ε_4.

The output voltage V_0 is a function of:
- the input voltage of the bridge V_s,
- the k strain-gauge factor,
- the deformation or change of voltage in the bridge's branches ε_1 to ε_4.

2 OPIS IN REZULTATI PREIZKUSA

Preizkus je izvajan v ustaljenih razmerah plovbe ladje. Pojem ustaljene razmere plovbe pomeni, da ladja pluje v določeni smeri in v mirnem morju. Eksperimentalno določanje vijačne lastnosti dvotaktnega ladijskega dizelskega motorja, z merilnimi lističi in osebnim računalnikom, z nedotikalno metodo smo izvedli na ladji Mornarice Črne Gore. Dolžina ladje je 96,5 m, širina 12,5m in standardni izpodriv 1470 ton. Vgrez ladje na premcu je 2790 mm, na krmi pa 3240 mm. Ladjo poganjajo dva glavna dizelska motorja in ena plinska turbina prek lastnih pogonskih osi. Na koncu vsake pogonske osi je trikrilni ladijski vijak z

2 DESCRIPTION AND RESULTS OF THE EXPERIMENT

The experiment was carried out under the standard sailing-regime conditions of a navy vessel. The standard sailing regime means that the ship is sailing on a given course and still at sea. The experimental determination of the screw characteristics of a two-stroke naval diesel engine by means of strain gauges and a personal computer, a no-contact method, was performed on a Serbian and Montenegrin Navy vessel. The length of the ship was 96.5 m, the width 12.5 m, and the standard displacement 1470 t. The drift on the prow was 2.79 m; the drift on the stern was 3.24 m. The ship is pronepremičnimi krili. Dizelski motorji so vrstni, vsak s po devet valji v dveh vrstah v navpičnem bloku. Motor je vrste 68B in je dvotaktni z močjo 5880 kW. Rabi dizelsko gorivo DS in olje SAE-50. Pri izvajanju preizkusa sta ladjo poganjala dva motorja, plinska turbina pa ni bila uporabljena. Os plinske turbine se je pri tem vrtela prosto. Položaj ladje, s katere se je začelo snemanje vijačne lastnosti je azimut pravi ω_p=047 °, oddaljenost d=0,3 M na otok Mamula. Smer plovbe ladje v času preizkusa je bila K_p=136 °. Morje je bilo 0 do 1 po Beaufortovi lestvici stanja morja, temperatura zraka 12 °C, barometrski pritisk 1005 mbarov, veter jugovzhodni 3 vozli, relativna vlažnost 68 % in temperatura morja 14 °C.

Merjenje je bilo izvedeno s postavljanjem merilnih lističev in merilne opreme na pogonsko os levega ladijskega vijaka. Mesto postavljanja merilnega lističa na osi je bilo med spojko motorja in odrivnega ležaja.

Del pogonske osi ladijskega vijaka, kjer so bili pritrjeni merilni lističi, je bilo v obliki obročastega prečnega prereza velikosti 260/80 mm. Pogonska os ladijskega vijaka je iz litega jekla z modulom elastičnosti E = 215 MPa.

Shematski prikaz postavljanja in vezave merilne naprave je prikazan na sliki 5. Na pogonsko os ladijskega vijaka sta bila pritrjena dva para merilnih lističev tipa "XY21-6/350" povezana v Wheatstonov mostič. Lističi so bili postavljeni pod kotom 180° drug na drugega. Napajanje merilnih lističev je izvajano z enosmernim električnim tokom 9 V. Merilni signal Wheatstonovega mostiča je potekal do predajnika in čez predajno anteno do sprejemnika merilnega signala. Vir električne energije, oddajnik in antena so bili postavljeni na obročasti disk iz plastične snovi, da bi izločili motnje, vse skupaj pa pritrjeno na pogonsko os ladijskega vijaka. Na pogonsko os ladijskega vijaka je bil pritrjen tudi temni listič s svetlim lističem čez njega, za registriranje števila vrtljajev pogonske osi ladijskega vijaka. Na pogonski osi ladijskega vijaka je bil na določenem razmiku postavljen sprejemnik merilnega signala in bralnik števila vrtljajev.

Sprejemnik merilnega signala in pretvornik števila vrtljajev sta bila povezana z elektronsko merilno napravo "SPIDER-8", ki je bila povezana z osebnim računalnikom. Programska oprema, ki omogoča merjenje in obdelovanje izmerjenih podatkov, se imenuje "CATMAN 3.0". Vsa ta oprema, strojna in programska je izdelana v podjetju "HOTTINGER BALDWIN MESSTECHNIK" (HBM), Darmstadt, Nemčija.

Računalniški program "CATMAN 3.0" deluje v delovnem sistemu MS Windows in omogoča

pelled by two diesel engines and one gas turbine via independent propeller shafts. On each shaft there are three bladed propellers with fixed blades. The diesel engines are linear, placed in two rows with nine cylinders each, and in a vertical block. The type of engine is a 68B, two stroke, with a rated power of 5880 kW. The engine uses diesel fuel, and SAE 50 motor oil. When the experiment was performed the ship was propelled by two diesel engines, and though the gas turbine was not used its shaft rotated freely. The position of the ship when the propeller characteristic was recorded was: azimuth real ω_p=047, distance from Mamula island d=0.3 M. The course was K_p=136. The sea conditions were 0 to 1, air temperature t=12°C, pressure p=1005 mbar, wind SE, 3 knots, humidity 68%, sea temperature 14°C.

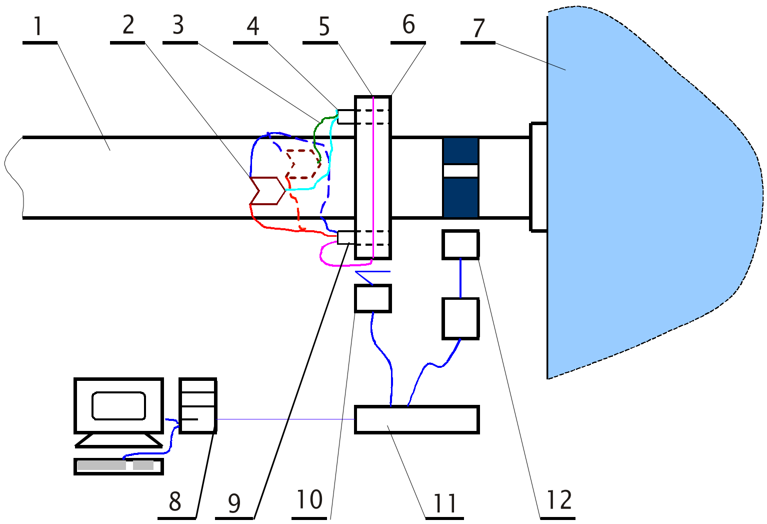
The measurement was performed by placing the strain gauges and the measuring equipment on the left shaft, between the clutch and the thrust bearing.

The strain gauges were placed on a shaft with an annular cross-section of 260/80 mm. The shafts were made of forged steel with elastic modulus E=215 MPa.

A schematic review of installing and connecting the measuring equipment is shown in Figure 5. Two pairs of strain gauges, type "XY21-6/350", were placed on the shaft and connected in the Wheatstone bridge. The strain gauges were installed at an angle of 180^0. The strain-gauge circuit feed was a DC voltage of 9V. The measuring signal from the Wheatstone bridge was carried to the emitter, and through an aerial delivered to the receiver. The circuit feed, emitter and antenna were placed on an annular disk (that has to be made of plastic to eliminate the backset) that was installed on the shaft. A dark ribbon with a light ribbon over it was also put all around the shaft to provide a measurement of the number of revolutions. Near the shaft, at a certain distance, a receiver and a transducer of the number of revolutions were installed.

The receiver and the transducer were linked to an electronic measuring device named "SPIDER-8"; the "SPIDER-8" was linked to a personal computer. The software that makes possible the measurement and data processing is "CATMAN 3.0". The hardware and software were produced by "HOTTINGER BALDWIN MESSTECHNIK" (HBM), Darmstadt, Germany.

"CATMAN 3.0" is software designed to work with MS Windows. It allows the user to focus his or



1 – pogonska os ladijskega vijaka, 2 - merilni lističi, 3 – el. prevodniki, 4 - vir el. energije, 5 - antena, 6 - obročast nosilnik, 7 – motor, 8 – osebni računalnik, 9 – oddajnik merilnega signala, 10 – sprejemnik merilnega signala, 11 – “SPIDER-8”, 12 – pretvornik števila vrtljajev osi ladijskega vijaka

1 – propeller shaft; 2 – strain gauge; 3 – conductors; 4 – power supply; 5 – antenna; 6 –annular disc; 7 – engine; 8 – personal computer; 9 – emitter; 10 – receiver; 11 – “SPIDER-8”; 12 – transducer

Sl. 5. *Shematski prikaz postavitve in povezave merilne opreme*
Fig. 5. *Diagrammatic view of the installation and the connections of the measuring equipment*

uporabniku popolno koncentracijo za merjenje. “CATMAN 3.0” je namenjen za uporabo interaktivne ali avtomatične merilne programske opreme, prav tako pa ga je mogoče uporabljati kot podlago za razvoj posebnih uporab [3].

“SPIDER-8” je elektronska merilna naprava za merjenje fizikalnih spremenljivk, to so delo, moč, pritisk, pospešek, hitrost ali temperatura. Prek osebnega računalnika je povezan na tiskalnik. Sinhronizacija se izvaja s pomočjo programske opreme in upravljanjem prek računalnika. Ima štiri digitalne ojačevalnike, ki delujejo na frekvenci 4,8 kHz in 8 kanalov oštevilčenih od 0 do 3 in od 4 do 7. Vsak kanal deluje z lastnim analogno-digitalnim (A/D) pretvornikom, ki dovoljuje merilne hitrosti od 1/s do 9600/s, kar zagotavlja popolno pokritost obsega mehaničnih merilnih opravil [4].

Merilni lističi, ki so uporabljeni pri merjenju deformacije pogonske osi ladijskega vijaka, so posebne serije Y, vrste XY21-6/350, izdelani iz dveh lističev, tako da oblikujejo dvojico merilnih lističev. Notranji upor merilnih lističev je 350 Ω, a njihova občutljivost je k = 2,07. Največja napetost električnega toka v merilnem lističu je 19 V. Videz merilnega lističa je prikazan na sliki 6.

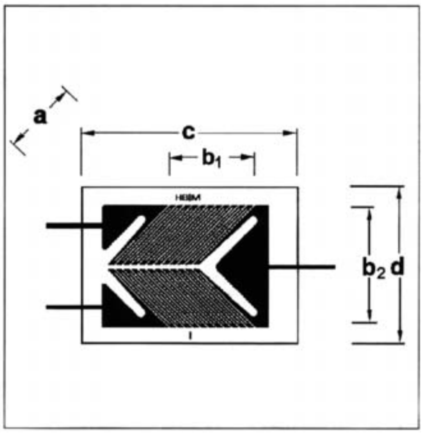
Izmere merilnega lističa na sliki 6 so: a=6 mm, b_1=7,8 mm, b_2=10 mm, c=17,5 mm in d=12,7 mm.

her attention primarily on the tasks of measuring. “CATMAN” is designed to work with interactive or automatic measuring software, but it can also be used as a matrix for special applications [3].

The “SPIDER-8” is an electrical measuring device for the measurement of changeable physical values like strain, force, pressure, acceleration and temperature. It is linked to a personal computer through the printer connection. All the adjustments of the device are performed by the software, i.e., by a personal computer. There are four digital amplifiers that work with a frequency of 4.8 kHz, and eight channels numbered from 0 to 3 and from 4 to 7. Each channel works with a separate analogue to digital converter (A/D) that allows a measuring rate from 1/s to 9600/s, which means that it covers the complete range of mechanical measuring tasks [4].

The strain gauges that were used for the shaft deformation measurement are from a specially shaped series Y, type XY21-6/350, made from two gauges that form the strain-gauge pair. The strain-gauge resistance is 350 Ω, and the sensitivity is k=2.07. The maximum voltage of the strain gauge is 19V. For details see Figure 6.

The dimensions of the strain gauge according to Figure 6 are as follows: a=6 mm, b_1=7.8 mm, b_2=10 mm, c=17.5 mm and d=12.7 mm.



Sl. 6. *Videz merilnega lističa* XY21-6/350
Fig.6. *Strain gauge* XY21-6/350

Za začetek postopka merjenja moramo v program "CATMAN" vnesti vse podatke, ki prikazujejo lastnosti pogonske osi ladijskega vijaka:
- modul elastičnosti *E*,
- strižni modul *G*,
- Poissonov količnik *í*,
- odpornostni moment prečnega prereza osi W_p,
- torzijski moment M_d.

V program je bilo še nujno treba vnesti podatke o sinhronizaciji merilne opreme po metodi kretnice. Pri takšni metodi sinhronizacije in glede na uporabljeno vrsto merilnih lističev, vrednost izstopne napetosti električnega toka mostiča 2 mV/V ustreza vrednosti deformacije merilnega lističa 1000 μm/m, kar se mora upoštevati pri določanju torzijskega momenta.

Odpornostni moment za obročasti prečni prerez se določa z enačbo [5]:

To start the measurement it is necessary to input the following initial shaft data in the "CATMAN" program:
- coefficient of elasticity, E (elastic modulus),
- shear modulus, G,
- Poisson's coefficient,
- moment of drag shaft's cross-section, W_p,
- moment of torsion, M_d.

Besides this data it is also necessary to input the calibration data of the measuring equipment. The "shunt" calibration method was applied in this case. With this method of calibration, considering the type of strain gauge used, a strain-gauge deformation of 1000 μm/m corresponds to a bridge output voltage of 2 mV/V, which must be taken into consideration when determining the moment of torsion.

The polar drag moment for an annular cross-section is defined as [5]:

$$W_p = \frac{D^4 - d^4}{16 \cdot D} \cdot \pi \qquad (17).$$

Strižni modul se določa z enačbo [5]:

The shear modulus is defined [5]:

$$G = \frac{E}{2 \cdot (1 + \nu)} \qquad (18).$$

Za jeklo je vrednost $\nu = 0{,}3$.
Torzijski moment se določi [2]:

For steel $\nu = 0.3$.
The moment of torsion is [2]:

$$M_d = \frac{1}{2} \cdot W_p \cdot G \cdot \varepsilon_i \qquad (19),$$

ε_i pomeni izmerjeno vrednost deformacije osi.

Moč, ki jo motor oddaja ladijskemu vijaku preko osi, znaša [1]:

ε_i represents the measured shaft-deformation value.

The power that the engine delivers to the screw through the propeller shaft is [1]:

$$P = M_d \cdot \omega \qquad (20).$$

Vrednost moči se vnese kot začetni podatek v program "CATMAN", ki v vsakem trenutku omogoča določanje moči, ki jo motor odda osi vijaka. Menjava vrednosti oddane moči motorja se lahko spremlja stalno v daljšem časovnem koraku ali pa v koraku nekaj sekund.

Tako je izvedeno merjenje vijačne lastnosti ladijskega motorja v celotnem obsegu vrtljajev ročične osi od 273 min^{-1} do 602 min^{-1}. Moč je snemana na 9 delovnih točk, in to za vsako točko v 10 sekundnem časovnem koraku merjenja. V vsakem 10 sekundnem časovnem koraku je izmerjenih po 250 vrednosti. Izmerjeni rezultati so prikazani v preglednici 1.

Na sliki 7 je grafično prikazana sprememba moči za vsak vrtljaj ročične osi na podlagi izmerjene vrednosti deformacije osi ladijskega vijaka v 10-sekundnem časovnem koraku.

Za pridobitev vijačne lastnosti ladijskega motorja so uporabljene srednje izmerjene vrednosti moči v vsakem časovnem koraku. Vijačna značilka ladijskega dizelskega motorja je grafično prikazana na sliki 8 (krivulja 3).

We input the formula for power, as initial data, into the "CATMAN" program, thus providing the determination of the power that the engine transmits through the propeller shaft to the screw at any moment. The power change can be observed continuously during a long period or during a period of a few seconds, depending on the requirements.

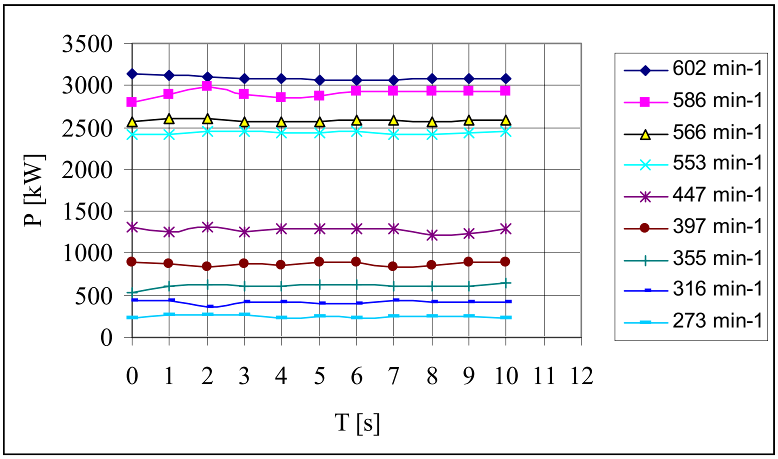
In this way, the propeller characteristic for the engine, from a minimum number of crankshaft revolutions, 273 min^{-1}, to 602 min^{-1}, achieved under the given conditions, was recorded. The power was recorded at nine working points, at an interval of 10 seconds for each point. During each of these intervals 250 values were measured. The measured values are shown in Table 1.

Figure 7 illustrates the change of power, for each number of crankshaft revolutions, based on the measured values of propeller deformation during an interval of 10 seconds.

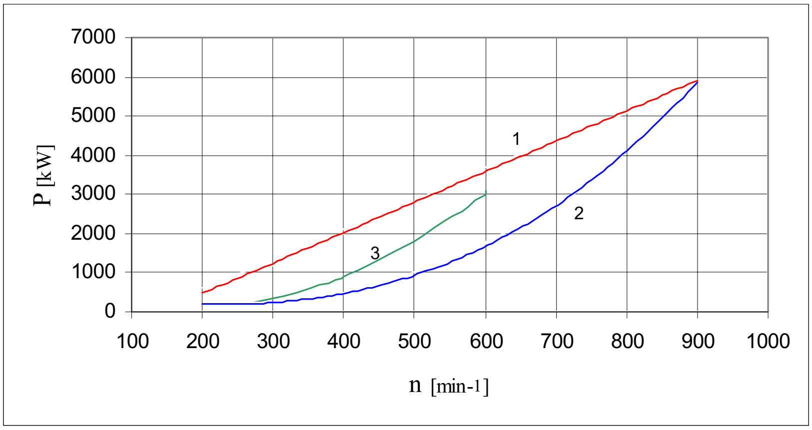
The mean values of the power at each interval were used to determine the screw characteristic. The screw characteristic of the diesel engine is illustrated in Figure 8 (curve 3).

Preglednica 1. *Izmerjeni rezultati moči za posamezna števila vrtljajev osi motorja*
Table 1. *Measured values of power for different numbers of shaft revolutions*

n min^{-1}	273	316	355	397	447	553	566	586	602
P_{sr} kW	241,27	414,28	612,22	870,33	1283,98	2432,64	2587,33	2902,47	3088,79



Sl. 7. *Grafični prikaz spremembe moči dizelskega motorja v 10-sekundnem časovnem koraku pri številu vrtljajev od 273 do 602 min^{-1}*
Fig. 7. *The change of diesel engine power during a 10-second interval for numbers of revolutions ranging from 273 min^{-1} to 602 min^{-1}*



Sl. 8. *Grafični prikaz vijačne značilke ladijskega motorja*
Fig. 8. *The screw characteristic (curve 3)*

Na sliki 8 je predstavljena zgornja mejna vijačna značilka motorja (krivulja 1) in vijačna značilka pri vožnji ‘’naprej’’ (krivulja 2), ki ji je dal proizvajalec v navodilu za uporabo motorja 68B, narisane pa so na podlagi izidov testiranja motorjev po vgradnji na novi ladji [6]. Pri testiranju sta ladjo poganjala dva dizelska motorja, plinska turbina pa je mirovala, pri čemer se je vrtela samo os ladijskega vijaka.

Na sliki 8 je vidno, da se z merilnimi lističi izmerjena vijačna značilka znatno razlikuje od vijačne značilke proizvajalca v navodilu ter predstavlja delo motorja pri ‘’težkem ladijskem vijaku’’. Razlaga je lahko naslednja:

- ladja ni bila na popravilu 4 leta ter so podvodni deli trupa in ladijski vijak ‘’obrasli’’, kar pomeni velik upor pri premikanju ladje.

Figure 8 shows the upper engine-power limit (curve 1) and the screw characteristics for driving “ahead” (curve 2), given in the manufacturer’s manual for the engine type 68B. These curves are based on the results achieved during an investigation of a diesel engine aboard a ship, after it was built. During the investigation the ship was propelled by two diesel engines, without a gas turbine, although its shaft rotated freely.

As you can see in Figure 8, it is obvious that the screw characteristic transcribed with the use of the strain gauges is different from the screw characteristic given in the manual by the manufacturer, and represents an engine working in the ‘’hard propeller’’ regime. We can find the explanation in the following:

- Because the ship was not at dock for four years the underwater parts of the ship were “overgrown” and this represents a large resistance to the movement of the ship.

3 SKLEP

Z metodo snemanja vijačne značilke pridobljeni eksperimentalni podatki na dejanski ladji so pokazali, da ladijski motor deluje po krivulji “težkega ladijskega vijaka”, kar nam pove, da ladja ne more razviti take hitrosti plovbe kakor ladja s čistim podvodnim delom. Da bi se dosegla nujna hitrost ladje, bi bilo treba povečati število vrtljajev motorja, to pa ima za posledico preobremenitev motorja. Iz diagrama je razvidno, da je že na 600 min^{-1} vrtljajev ročične osi, krivulja bližja zunanji mejni značilki motorja, to pomeni da so vsi parametri delovnega postopka blizu zgornjih meja. Ugotovimo lahko, da motor ne more delati na načrtovanem številu vrtljajev (n = 900 min^{-1}), ladja pa ne more doseči načrtovane

3 CONCLUSION

The experimental data acquired by this method of transcribing the screw characteristic, on a concrete ship, show that the engine is working in the “hard propeller characteristic”, and that this ship cannot achieve the same speed as a ship whose underwater part and propellers are clean. To achieve the necessary speed the number of engine revolutions must be increased, which would cause the engine to be overloaded. The transcribed screw characteristic shows that at 600 crankshaft revolutions per minute the curve is nearing the outer boundary of the engine’s characteristics, i.e., all the parameters of the process are near their upper limits. This means that the engine is not able to work with the projected number of revolutions hitrosti oziroma delo vsega pogonskega sestava je negospodarno.

Kakor vse znane metode, ima tudi ta svoje dobre in slabe strani.

Dobre strani te metode so:
- merilni lističi in pretvorniki po načelu merilnih lističev so zelo majhnih mas, kar pomeni, da nimajo vztrajnosti,
- merilni lističi ne delujejo na testirani predmet,
- merilni lističi so se pokazali kot zelo uporabni za dolgotrajna dinamična testiranja z velikim številom ponovitev (delo motorja),
- zaznavala po načelu merilnih lističev delujejo na zelo nizkih in zelo visokih tlakih (od 10^{-7} mbar do 10000 bar),
- glede na zgornje mejne frekvence nimajo omejitev, kar pomeni, če so merilni lističi pravilno postavljeni, sprejemajo vse dinamične spremembe na testiranem predmetu,
- ko so merilni lističi postavljeni na predmetu, se lahko po testiranju zaščitijo s posebno gumijasto zaščito in se nato lahko ponovno uporabijo.

Slabe strani metode so:
- največje še dovoljene temperature za uporabo merilnih lističev so do 350 °C,
- merilni listič je občutljiv na parazitske obremenitve,
- merilni lističi so občutljivi na vlago, zato jih je treba obvezno zaščititi s posebno gumijasto zaščito.

Povzamemo lahko, da se metoda z merilnimi lističi uspešno uporablja za nadzor trupa ladje in ladijskega vijaka ter nadzor ustreznosti vgrajenih ladijskih vijakov za dejansko ladjo oziroma ladijski motor.

(n_n=900 min^{-1}), and the ship is not able to achieve its projected velocity, and that the work of the propulsion complex is not economic.

Like other known methods, this one has both advantages and disadvantages.

The advantages of this method:
- Strain gauges and strain-gauge transducers are very light, which means that there is no inertia.
- Strain gauges have no influence on the object of the investigation.
- Strain gauges proved to be very convenient for long-term dynamic investigations of a large number of cycles (in this case engine work).
- Strain-gauge transducers can endure both low and high pressures (from 10^{-7} mbar to 10000 bar).
- There are no upper frequency limits, so if they are properly installed, strain gauges can record all the dynamic changes of the object of the investigation.
- Once the gauges are installed on an object they can be protected with a special rubber band, so the measurement can be repeated, when required, even after a long period of time.

The disadvantages of this method:
- Strain gauges can be used up to a maximum temperature of 350^{0}C, except for special strain-gauge transducers, which can stand higher temperatures;
- Strain gauges are sensitive to so-called parasite stress;
- Strain gauges are sensitive to moisture, so it is necessary to protect them with a special rubber.

The conclusion is that we can use this method successfully to check the condition of the hull and the screw, as well as to determine whether the screw is suitable for the particular hull and engine.

4 OZNAKE
4 INDEX

vrtilni moment	M	Nm	torque
stalnica	k_0		constant
število vrtljajev	n	min^{-1}	number of revolutions
nominalno število vrtljajev	n_n	min^{-1}	number of revolutions-nominal
moč	P	kW	power
koristna moč	P_e	kW	effective power
nominalna koristna moč	P_{en}	kW	effective power-nominal
kotna hitrost	ω	s^{-1}	angular velocity
azimut dejanski	ω_p	°	real azimuth
Ludolfovo število	π		Ludolf's number
stalnica	k_1		constant
dejanska smer	K_p	°	real course
električna upornost	R	Ω	electric resistance
specifična upornost materiala	ρ	Ωmm^2/m	specific resistance of material

dolžina	l	mm	length
premer	d	mm	diameter
površina	A	mm^2	surface
relativno podaljšanje	ε	mm/m	relative extension
relativno podaljšanje vzdolžno	ε_l	mm/m	relative along extension
relativno podaljšanje prečno	ε_t	mm/m	relative across extension
Poissonov količnik	ν		Poisson's coefficient
faktor občutljivosti	k		factor of sensitivity
prečna občutljivost	q		across sensitivity
električna napetost izhodna	V_o	V	outgoing voltage
električna napetost vhodna	V_s	V	voltage supply
odpornostni moment prereza	W_p	mm^3	polar moment of cross section resistance
premer	D	mm	diameter
strižni modul	G	kPa	shear modulus
modul elastičnosti	E	kPa	elastic modulus
torzijski moment	M_d	Nm	moment of torsion
čas	T	s	time

5 LITERATURA
5 LITERATURE

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