*Article citation info:*
RUDNICKI, J., KORCZEWSKI, Z. Diagnostic testing of marine propulsion systems with internal combustion engines by means of vibration measurement and results analysis. *Combustion Engines*. 2013, **154**(3), 308-313. ISSN 0138-0346.

*Jacek RUDNICKI*
*Zbigniew KORCZEWSKI*

**PTNSS–2013–SC–026**

# Diagnostic testing of marine propulsion systems with internal combustion engines by means of vibration measurement and results analysis

*Abstract: In this paper selected issues concerning vibration diagnosis of the mechanical system within marine propulsion units have been presented, carried out on the basis of experimental examinations of a real object in which an exceedance of the allowable vibration's level had been observed. Used diagnosing system has been characterised. A procedure of longitudinal and transverse vibrations shaft lines of the mechanical system within marine propusion measurement was presented, with use of portable vibration computerized data logger as well as on the method of vibrations spectral-correlation analysis as a basis of diagnostic process considering dynamic state of analyzed system. Analyzis that has been carried out enabled the selection of the most probable causes for the loss of mechanical system stability. The relevance of the diagnosis was confirmed by the workshop measurements of the torque transmission elements as well as visual inspection of the propellers while the ship was put on a dock.*

Keywords: *technical diagnosis, vibrations measurements, marine propulsion unit, dynamical state*

## Badania diagnostyczne okrętowego zespołu napędowego z tłokowymi silnikami spalinowymi na podstawie pomiarów drgań i analizy ich wyników

*Streszczenie: W referacie przedstawiono wybrane zagadnienia diagnostyki drganiowej okrętowego zespołu napędowego, na przykładzie eksploatacyjnych badań obiektu rzeczywistego, na którym zaobserwowano zwiększony poziom drgań. Scharakteryzowano zastosowany system diagnozujący. Zaprezentowano procedurę pomiaru drgań wzdłużnych i poprzecznych linii walów okrętowego układu napędowego, z zastosowaniem przenośnego rejestratora drgań oraz metodykę ich analizy widmowo-korelacyjnej, jako podstawę wnioskowania diagnostycznego o stanie dynamicznym rozpatrywanego układu. Przeprowadzona analiza pozwoliła na wskazanie najbardziej prawdopodobnych przyczyn utraty stabilności układu mechanicznego. Trafność postawionej diagnozy potwierdziła weryfikacja warsztatowa elementów transmisji momentu obrotowego oraz oględziny śrub napędowych podczas postoju okrętu w doku.*

Słowa kluczowe: *diagnostyka techniczna, pomiary drgań, okrętowy zespół napędowy, stan dynamiczny*

## 1. Introduction

One of the parameters which impacts on durability of the marine propulsion unit's mechanical system the most is a fatigue strength of material of which its structure is built. During an engine's operation on a sailing ship because of multifold changes of mechanical loads (caused by periodically changeable reactions of forces and torques generated by propulsion engines, propellers and a ship hull operating on waves) cyclic elastic and plastic shaftings deformations take place. They give rise to transverse, axial and torsional vibrations – Fig. 1. That means a loss of the mechanical system's stability as well as a resonance phenomenon to appear in a global and local sense. The increasing amplitudes of changeable internal stresses stand for the cause of a considerable limitation of the cycle number of load alterations, at which elements transmitting torque from the engine to the propeller are subject to the accelerated wear and tear process until the irreversible failures occur (cracks, deterioration of constructional material's strength characteristics) because of material fatigue. The loss of stability of the mechanical system within marine propulsion unit under operation results from an occurrence and development of the following detrimental phenomena: a slowly worsening unbalance state of shaftings and propeller resulting from sediments, erosion, corrosion and bent shafts or a loss of their alignment, a sudden increase of shafting unbalance state resulting from deformations or broken-off fragments of propeller blades, excess of allowable load of bearings, shafts seizing in slide bearings, failures within rolling bearings etc.

All the above specified factors worsen a dynamic state of the propulsion unit, enlarging a quantity of dissipated kinetic energy that has to be devoted to extort a vibration. However, the results of reliability investigations carried out on marine propulsion systems univocally show that the excessive load among the main engine cylinders represents the most frequent cause of the enlarged level of the shafting torsional and axial vibration. As far as the transverse and axial vibration is concerned - the loss of shaftings alignment as well as propellers' damages [4, 6].

In the operation practice the measurements of torsional vibration are performed only on the propulsion units which are especially prepared for this aim. The low supervisory susceptibility in this range of serial propulsion units considerably limits a credibility of the gathered measuring results [1, 2]. Hence, in case of affirming the raised vibration of the ship hull, first of all, the main engine cylinders indication should be done. Then, when the cylinders are eliminated as the potential source of the generated vibration, measurements and the analysis of transverse and axial vibration in the selected constructional points of the propulsion units are carried out. The main purpose of the conducted investigations is to claim whether the changeable transverse or axial stresses, caused by the vibration, exceed admissible values or not. The stresses, after achieving definite (for the given constructional material) cycles number lead to the fatigue damages.

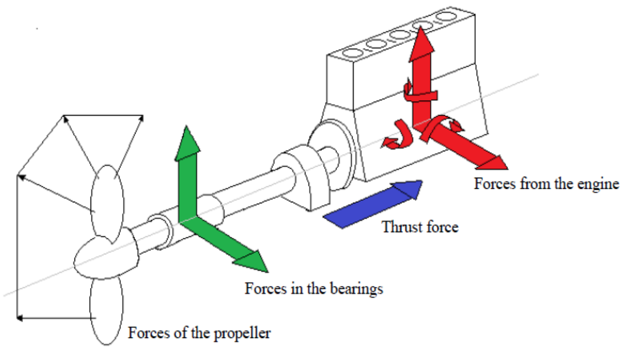


Fig. 1. Force and torque system that impels a marine shafting vibration [3]

The affected transverse and axial vibration occur within propulsion shafts practically in the whole range of rotational speed alterations. Nevertheless, the largest amplitudes appear at the resonance rotational speeds. In order to identify the resonance's sources vibration a spectral analysis of the registered vibration signal should be conducted. It consists in the signal decomposition into harmonic components of the determined resonance frequencies. The condensation of amplitude spectrum as well as the growth of amplitudes of the characteristic harmonic components testifies about the existence of local resonances and the deterioration of the propulsion unit's dynamic state threatening with the damages of elements which transmit a torque to the propeller.

The transverse and axial vibration issue in terms of their measurements and spectral-correlation analysis has been introduced in numerous publications in detail. However, there is still perceptible lack of bibliographic positions presenting this question in the aspect of the widely understood operation diagnostics. Just the Authors were guided by such a purpose during editing the present article.

## 2. Research object characterization

An experimental testing, carried out on the three shaft homogeneous drivetrain (Fig. 3) while the ship was operating, was designed to check a stability of the propulsion's mechanical system. To carry out the programme of testing it was necessary to put the ship to sea and several cycles of vibration measurements were made.

The diagnostic investigations were conducted on the Baltic Sea, at the sea state about 2÷3.

During the measurements, all the main engines were running simultaneously (a common work), and besides the vibration signals the additional control parameters were observed, as follows:

- rotational speed of the propeller shafts - 282 rev/min,
- steady load: the engines' rotational speeds n = 800 rev/min, the engines' load indexes: PS engine Wo=6.5, SB engine Wo=6.8 and Central engine Wo=7.0,
- floating speed: 14 knots,
- temperatures: tube stuffings 18 - 20$^0$C, radial bearings of the tunnel shafts 35 - 37$^0$C, gearboxes 47 - 50$^0$C.

Operation diagnostic measurements were worked out by means of SVAN 956 digital vibration measuring instrument of SVANTEK Ltd. production [http://svantek.com]. It gives a possibility of the following trends of values' alterations of the spectrum parameters in different characteristic frequency bands, for the well-known and recognizable states of operation unfitness.

SVAN956 is equipped with DYTRAN piezoelectric acceleration sensor 3185D type. A magnetic connection of the sensor makes a quick exchange of the measurement place possible, which has got the very essential meaning in case of variable and limited conditions of the measurement's realization. Three independent measuring profiles applied in the analyzer permit selecting three filter sets and time-constants for the simultaneous measurement of vibration's acceleration, velocity and displacement within the frequency range from 0.5 kHz to 20 kHz (limited with a transfer band of the applied transducer). Thanks to the large power of a signal processor the simultaneous narrow-band analysis FFT, the simultaneous frequency analyses within the octave- and tercial-bands as well as the simultaneous analysis of vibration envelope are possible during the measurements. There is also accessible the register's function of a whirling machine balancing, which requires a simultaneous rotational speed and vibration measurement.

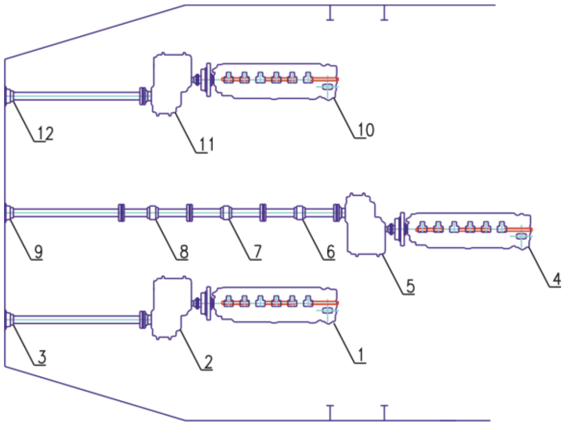


Fig. 3. Schematic diagram of the ship drivetrain: 1 – starboard side (SB) Sulzer main engine of 6ATL25D type, 2 – SB gearbox, 3 – SB stern tube stuffing - box, 4 – central Sulzer main engine of 6ATL25D type, 5 – central gearbox, 6 – radial bearing No. 3, 7 – radial bearing No. 2, 8 – radial bearing No. 1, 9 – central stern tube stuffing - box, 10 – port side (PS) Sulzer main engine of 6ATL25D type, 11 – PS gearbox, 12 – PS stern tube stuffing – box

## 3. Research procedure

The measurements of the vibration speed and acceleration generated through constructional joints of the marine propulsion unit were executed before the ship's repair on a dock in the Polish Shipyard "Nauta". The main aim of the measurement was to evaluate a reference state of dynamic balance and alignment within the propulsion shaftings. The registration of the transverse vibration was executed in vertical (V) and horizontal (H) plane of the tube stuffings, radial bearings and gearboxes by assembling the accelerometer in direct closeness of bearing joints by means of a magnetical connection. The registration of axial (longitudinal) vibration (L) enforced by an impact of the periodically variable trust force from propellers (3 impacts of the trust force per 1 revolution of the propeller shaft) was executed by assembling the accelerometer on the gearboxes in the vicinity of bearings, from the side of output shafts transmitting a power to the propellers. An example manner of the accelerometer sensor's assembly is shown in Fig. 5.

The vibration measurements were worked out in 19 measuring points (the points’ numbering is consistent with the measurement order) presented in Fig. 4

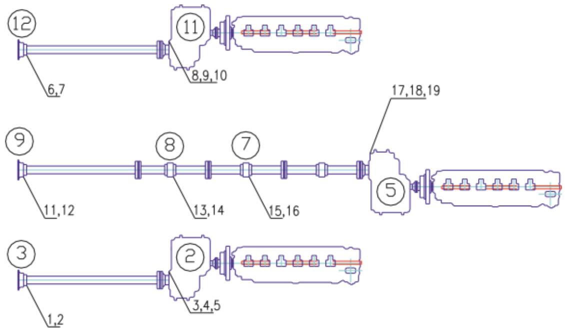


Fig. 4. The numbering of measurement points and spatial arrangement of the axis: 1. Stern tube stuffing - box (3) – „V”, 2. Stern tube stuffing - box (3) – „H”, 3. Gear (2) – „V”, 4. Gear (2) – „H”, 5. Gear (2) – „L”, 6. Stern tube stuffing - box (12) – „V”, 7. Stern tube stuffing - box (12) – „H”, 8. Gear (11) – „V”, 9. Gear (11) – „H”, 10. Gear (11) – „L”, 11. Stern tube stuffing - box (9) – „V”, 12. Stern tube stuffing - box (9) – „H”, 13. Bearing (8) – „V”, 14. Bearing (8) – „H”, 15. Bearing (7) – „V”, 16. Bearing (7) – „H”, 17. Gear (5) – „V”, 18. Gear (5) – „H”, 19. Gear (5) – „L”

*„V” – measurement on the vertical axis, „H” – measurement on the horizontal axis, „L” – measurement on the axial (longitudinal) axis*

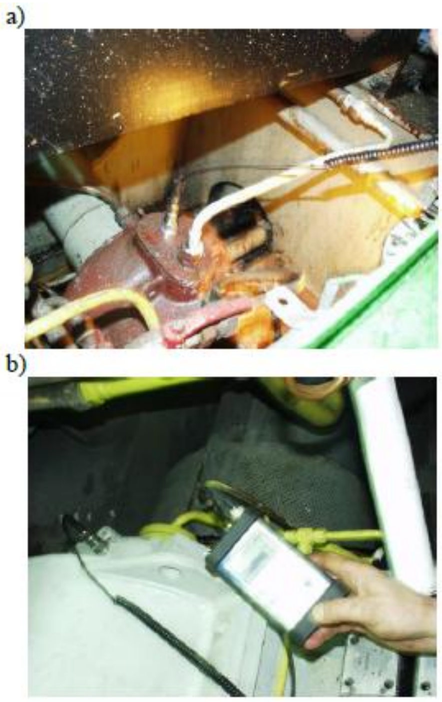


Fig. 5. Manner of DYTRAN 3185 D accelerometer sensor's assembly in the point of shaftings vibration speed and acceleration measurements: a) radial bearing – vertical plane, b) gearbox – vertical plane

## 4. Research results and their analysis

The analysis of the measurements results has been conducted in accordance with VDI 2056 guideline recommendations for machines of "T" Group as well as ISO 4868-1984 standard (PN-92 /W-01353 standard represents its Polish counterpart) within the following scope:

- root mean square (RMS) value of the vibration velocity - measured in the frequency range of 10Hz to 1kHz,
- amplitude spectrum of the vibration velocity and acceleration in relation to basic frequencies harmonics of the propeller shafts rotational speed as well as characteristic frequencies associated with the main engines work (3 gasdynamical cycles (extortions) per 1 crankshaft revolution), the shafting carrying bearings as well as the propellers (3 trust force extortions per 1 revolution of the propeller shaft), for every propulsion unit.

The gathered RMS vibration date is presented in Tab. 1. The results of FFT (Fast Fourier Transform) in the plot form of vibration amplitude vs. frequency are demonstrated in Fig. 7 ÷ 9. This is a basic analytical method most often used in diagnosing faults associated with unbalance, misalignment, eccentric components and damaged bearings, shafts or gears [1, 2].

The measurement results showed in Tab.1 confirm that the vibration parameters characterizing the stability of the mechanical system within the central and starboard propulsion units exceeded operational tolerance's borders, in accordance with VDI guideline 2056 (ISO-10816), which serve as the basic standards regarding execution of the measurements, selection of the measuring points and limits of machine dynamic state evaluation [www.iso.org/].

The highest RMS amplitude values of the vibration velocity were registered in the constructional joints as follows:

- on the casing of central shaftline's bearing No. 1 (the first one from the tube stuffing), in the horizontal axis - the amplitude YRMS = 12,4 mm/s;
- on the casing of central shaftline's bearing No. 2, in the vertical axis - the amplitude YRMS = 29,6 mm/s;
- on the casing of the starboard reductive gearbox, in the axial (longitudinal) axis - the amplitude YRMS = 25,1 mm/s.

Tab. 1. Vibration data spreadsheet

| RMS VALUE OF THE VIBRATION VELOCITY [mm/s] | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Engine speed – 800 rpm | Axis „V" | *Measuring point No.* | | | | | | | | |
| | | **1** | **3** | **6** | **8** | **11** | **13** | **15** | **17** |
| | | *Results* | | | | | | | | |
| | | 5,11 | 5,04 | 4,49 | 4,6 | 7,97 | 6,87 | 29,6 | 4,8 |
| | Axis „H" | *Measuring point No.* | | | | | | | | |
| | | **2** | **4** | **7** | **9** | **12** | **14** | **16** | **18** |
| | | *Results* | | | | | | | | |
| | | 3,3 | 5 | 3,19 | 4,15 | 4,2 | 12,4 | 4,9 | 8,88 |
| | Axis „L" | *Measuring point No.* | | | | | | | | |
| | | **5** | **10** | **19** | | | | | |
| | | *Results* | | | | | | | | |
| | | 25,1 | 7,44 | 5,3 | | | | | |

RMS amplitude represents an indication of the amount of vibration energy in the ship propulsion unit's mechanical system (the amount of dissipated kinetic energy within this system). One should be aware that the higher the vibration energy, the higher RMS velocity amplitude.

On the basis of vibration measurements and their analysis two possible causes of inadmissible dynamic state of the central and starboard shaftlines were pointed out: the shaftline misalignment or the worsened balance state caused probably by the shaft bending or propellers' damages. Such a formulated diagnosis confirmed results of technical state workshop verification carried out after the ship was undocked in the shipyard, when widespread damages of the ship propellers were detected - Fig. 6.

a)

b)

Fig. 6. Results of visual inspection of the propellers while the ship was put on the shipyard dock: a) damages of the port side propeller, b) damages of the starboard propeller

The port side propulsion unit does not reveal any symptoms of the worsened dynamic state.

The conducted frequency analysis of the registered vibration velocity spectrum in the vulnerable, neuralgic joints of the central and starboard propulsion units (Fig. 7) showed an undesirable condensation of the amplitude spectra in the vicinity of ranges of the propeller and propeller shaft proper vibration.

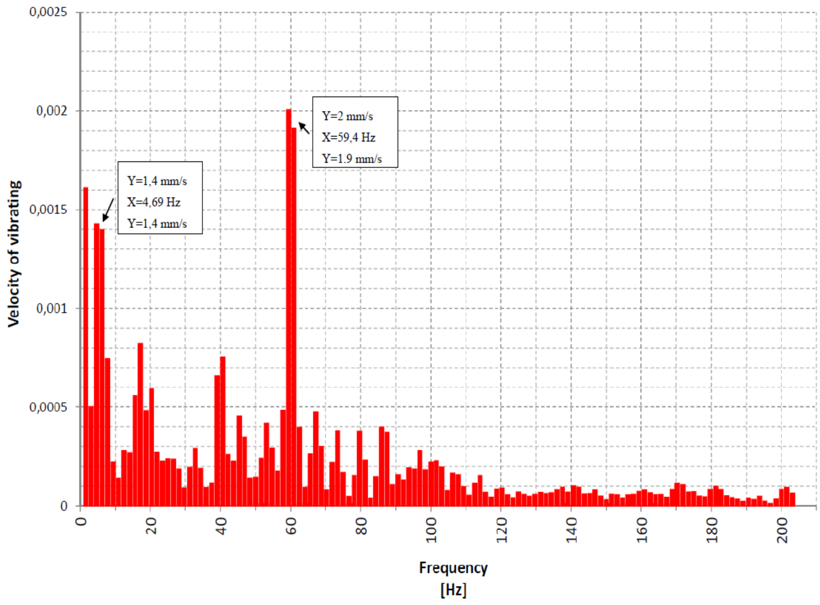


Fig. 7. Velocity spectrum of vibrating SB gearbox, registered in vertical plane – V axis, measuring point number 3

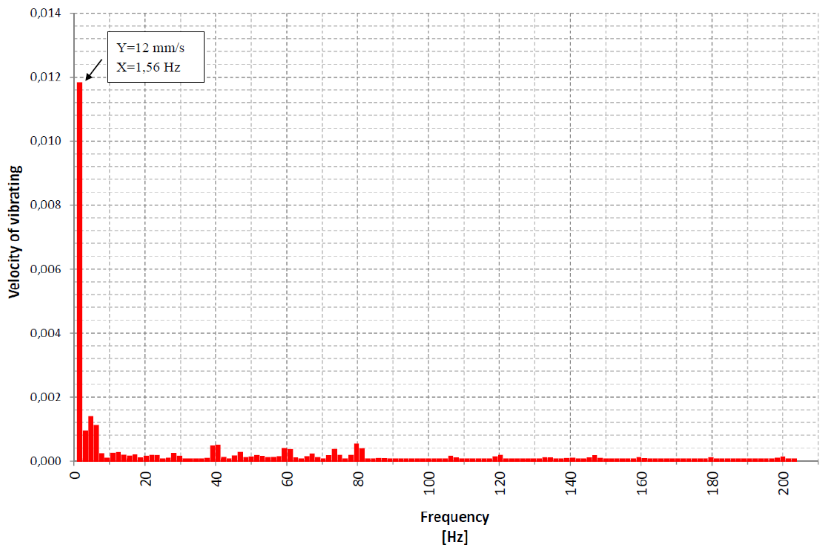


Fig. 8. Velocity spectrum of vibrating bearing casing No.1, registered in horizontal plane – H axis, measuring point number 14

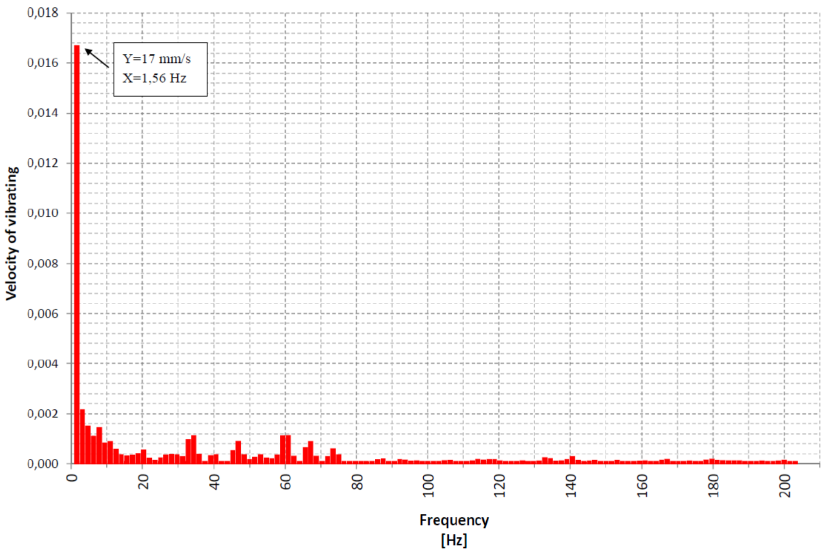


Fig. 9. Velocity spectrum of vibrating bearing casing No.2, registered in vertical plane – V axis, measuring point number 15

There was additionally observed was, that the amplitude of characteristic subharmonic frequency 1/3 $f_0$ equalled 1,56 Hz (94 rpm) predominated within the spectra. It usually represents the main source of vibration extortion in radial direction derived from the enlarged clearance of a slide bearing in the casing (Fig. 8 and 9)

## 5. Conclusions

Vibration measurements and analysis represent an important indicator of the current stability state of a marine propulsion unit's mechanical system. The authors aimed to prove that the operational vibration investigations can be conducted easily, effectively and successfully even by means of a very simple measurement apparatus.

The presented results of the diagnostic examination of three-shaft marine drivetrain confirm the importance of three distinct components of the complete vibration analysis: absolute vibration measurements, bearing condition measurements and FFT frequency analysis enabling diagnosing faults associated with the propulsion mechanical system, in this case – the propellers.

## Bibliography/*Literatura*


[1] ADAMS, M.L.: Rotating Machinery Vibration: From Analysis to Troubleshooting. New York: Marcel Dekker, 2001.

[2] BENTLY, D.E. and HATCH, C.T.: Fundamentals of Rotating Machinery Diagnostics. Minden: Bently Pressurized Bearing Press, 2002.

[3] CUDNY, K.: Linie wałów okrętowych. Gdańsk: Wydawnictwo Morskie, 1976.

[4] DRAGANTCHEV, H.: Control and Diagnostics of Ship Shafting. Proceedings of the IMAM 2000, Ischia, April 2-6, Session L, 115-122.

[5] KORCZEWSKI, Z.: Endoskopia silników okrętowych. Gdynia: AMW Gdynia, 2008.

[6] Gdansk University of Technology, Poland: Reports of diagnostic investigations of the marine propulsion systems – Research Reports, Gdańsk 2009 – 2011.



Prof. Zbigniew Korczewski, DSc, PhD – Head of the Department of Marine and Land Power Plants in the Faculty of Ocean Engineering & Ship Technology at the Gdansk University of Technology.

*Prof. dr hab. inż. Zbigniew Korczewski - Kierownik Katedry Siłowni Morskich i Lądowych na Wydziale Oceanotechniki i Okrętownictwa Politechniki Gdańskiej.*

*e-mail:* z.korczewski@gmail.com



Mr Jacek Rudnicki, PhD, MEng. – Doctor in the Faculty of Ocean Engineering and Ship Technology at Gdańsk University of Technology.

*Dr inż. Jacek Rudnicki – adiunkt na Wydziale Oceanotechniki i Okrętownictwa Politechniki Gdańskiej.*