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An analysis of cause and effect relations in diagnostic relations of marine Diesel engine turbochargers

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Abstract

The article justifies the need to analyse diagnostic relations for turbocharger operation purposes. Types of turbochargers most frequently used in modern marine engines have been presented. Turbocharger decomposition has been conducted on a selected example. The influence of typical inefficiencies in respect to symptom value changes has been worked out for each heat engine and sub-system. Validation of selected cause and effect relations has been based on operational experience in the technical scale.

Introduction

The reliability of evaluation of the technical condition of marine engine sub-systems and the adequacy of undertaken decisions poses a major task in the operation process of marine main engines. Regardless of the performance conditions, as well as the moment of the engine technical condition evaluation, the reliability of the functional diagnostic test, including the relations of parameter – symptom – inefficiency, is of primary significance.

Methods applied for the purpose of diagnosing the engines, including also the turbochargers, could utilise the parameters of the main working medium participating in energy conversion and the parameters of the accompanying processes.

Since a turbocharger is a marine engine subunit, influencing the power output, its dynamic properties and reliable operation, for the purpose of evaluation of the technical condition of the turbocharger unit operational and energy parameters, as well as vibration signals are used as a comprehensive and universal set of diagnostic parameters [1, 2, 3].

Turbocharger operation conditions, complexity of their construction and restricted controllability of their functional features impose the application of turbocharger parametric identification procedures [1, 4, 5]. In the majority of turbocharger constructions a complete diagnostic survey cannot be performed due to the limited measurement accessibility.

In marine conditions there is no possibility to simulate a degradation state in order to experimentally identify diagnostic relations and their effect on turbocharger functional features.

Thus, the obtained operational experience cannot be arranged into cause and effect relations and is not used in a systematic manner at the stage of diagnostic concluding and decision making on the scope of service. A limited access to manufacturer's information makes operational practice dependent on the authorised – ship owner's methods of proceeding. Therefore, the need to determine the nature of their mutual relations arises.

The purpose of this article is to make an attempt at recognising diagnostic relations in the evaluation of the technical condition of a marine main engine turbocharger using a method based on intuition modelling techniques, verified by the machinery personnel expert knowledge, based on the operational diagnostic experience in the technical scale.

Turbochargers of modern marine Diesel engines

Nowadays, marine Diesel engines are supercharged by means of turbochargers. Both, the two-

-stroke slow-speed engines, as well as the four-stroke, medium-and high-speed engines are manufactured as supercharged. Differences consist in the manner of their charging and the mode of turbine supply with the exhaust gas. In large, two-stroke, slow-speed engines the applied charging system is of the exhaust gas supply constant pressure, whereas in the four-stroke, medium- and high-speed engines pulsating charging is applied. In the constant pressure systems, the exhaust gas leaving the engine working spaces gathers in the exhaust gas manifold where its kinetic energy is transformed into potential energy which results in stabilisation of its pressure. An analysis of turbocharger applications in marine engine charging systems indicates the domination of marine turbocharger models contemporarily constructed by three manufacturers: MAN Diesel & Turbo, ABB and Mitsubishi [6, 7, 8, 9, 10, 11].

MAN Diesel & Turbo factory produces turbochargers of the following types: TCR, NR, TCA and NA differing from one another in rotor unit constructions (with radial or axial machines) and organisation of the inlet and outlet of the air and exhaust gas. They have been built as machines with the non-cooled housings, lubricated by the engine lubrication system, with high efficiency, reliable and durable, easy to use and operate. The materials of the rotor unit and turbine housing are adjusted to being supplied with the products of burning of marine distillate, residual fuels and natural gas. Turbochargers of the TCR type are provided with a single-stage radial compressor and a radial turbine supplied with exhaust gas of the permissible temperature of 700°C and the compression up to 5.4 [8, 12].

Constant pressure turbochargers also include turbochargers of the TCA type with single-stage axial turbines supplied with exhaust gas of maximum temperature of 500°C for the two-stroke engines and 650°C for the four-stroke engines and permissible compression up to 5.5.

Constant pressure turbochargers of the TPL and VTR types are also produced by ABB. Decomposition of the popular VTR model is presented in figure 1, whereas normal characteristics of the VTR type in the co-ordinate system compression – flux of charging air volume for the contractual engine operation point, identifying operational parameters of compressors are shown in figure 2 [7, 10].

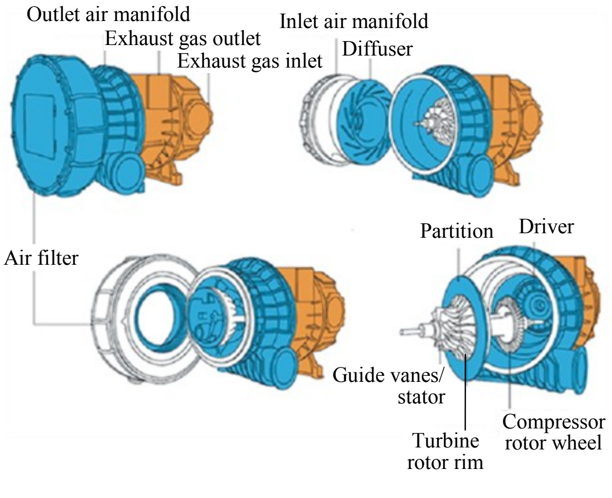

Fig. 1. Decomposition of a VTR type turbocharger manufactured by AB [7, 10]

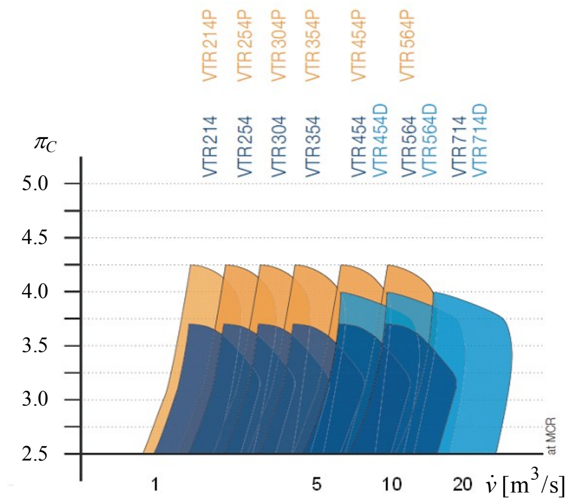

Fig. 2. Normal characteristics of the compressors of the VTR type [7, 10]

VTR turbochargers in the working medium exchange system of Diesel engines deliver air fluxes of compression up to 3.3 (the basic compressors) and up to 4.25 (P type) with the volume fluxes up to approximately 15 m^3/s and the compression up to 4.0 and mass flux up to 20 m^3/s (D type).

Symptoms of technical condition of the turbocharger sub-units

In a turbocharging system the turbocharger is connected with a piston engine in a gas-dynamic mode through an air exchange system, a combustion chamber and exhaust gas flow ducts. In their spaces interactions between engine and the turbocharging system take place. In some turbocharger constructions these relations refer also to the manner of bearing lubrication which is effected from the engine circulation.

Basic functional elements of the charging system includes: an air filter, an air inlet / outlet manifold, a rotor unit comprising a compressor wheel with a blade cascade and a single-stage axial turbine, an exhaust inlet/outlet manifold and an air cooler.

Inlet air filter and manifold

Turbochargers supply marine engines with a mixture of air, steam, precipitation droplets, sea aerosol containing salts and biological particles, oil and exhaust gas vapours and in port and land areas also industrial dust. Their penetration into the turbocharger and engine flow ducts significantly affects the quality of energy conversion and causes degradation of the technical condition of sub-units of the engine supercharging system [2, 13]. Therefore, ensuring the cleanliness of the air at the engine inlet remains an important operational task. Regardless of the construction, filters during operation display the following inefficiencies:

– increase of the flow resistance;
– loss of filtering properties;
– loss of tightness.

The increase of the flow resistance is caused by excessive filter contamination which causes an increase in flow resistance in the system.

Filter tightness loss may be caused by loosening of the housing, or cover fixing bolts or due to the cracking of any filter elements.

Loss of filtering properties of the filter is most frequently related with the break in the filtering system / package. This kind of damage leads to the fast contamination of the air inlet system. During the filtration process the filtering material constantly fills with the contaminants. As filter structures get contaminated, the flow resistance and filtering efficiency grows. Upon reaching a limiting value of the adhesion force of the agglomerates to the fibres, the range of filter stable operation ends. During the filter operation, aerodynamic resistance increases, in the effect of porosity decrease, particles are torn away from the fibres. When the filter structure gets incorrect, contamination gets through the filter, and then filtering efficiency drops.

As the filter gets contaminated, an active sectional area of the air through the filter gets smaller which leads to the reduction of the air pressure value before the compressor by the value of Δp_F. With the maintained compression degree π_S unchanged, the value of the air pressure behind the compressor p_2 is reduced. The quality- and quantity-oriented influence of the negative pressure of the inlet air before compressor on the engine operation depends on the charging manner. In the four-stroke engines with the single-stage charging by the turbocharger, with the increased negative pressure at the compressor inlet the pressure value is reduced by Δp_F. This causes the reduction of the air surplus coefficient and the increase of the temperature of the outlet exhaust gas T_4. The increase of the negative pressure at the compressor inlet, in order to keep the set value of the rpm of the engine, causes an increase of a fuel dose (resulting from speed regulator activation). Because the air mass flux through the engine is smaller, the increased fuel dose causes an increase in the temperature of the outlet exhaust gases and an increase of the specific fuel consumption b_e. The influence of the air filter and the inlet ducts contamination on the tendencies in the engine operational parameters changes is shown in figure 3.

Compressor

At the operation process, compressor flow ducts are subject to contamination with:

– vapours of their own luboils penetrating through the labyrinth sealing, more intensively in the case of slide bearing application than with the rolling bearings (the higher pressure of the oil supplied to these bearings at the 0.25 MPa level);
– vapours of oil and fuel contained in the air taken from the engine room, subject to condensation at the filter and in the compressor ducts.

In the turbochargers which suck the air from the engine room, the effective section of the compressor diffuser within approximately 7,000 operation hours may get reduced by 10–20% [12, 13]. Contamination of the flow-carrying parts and compressor blades changes its geometry, impairs the surface

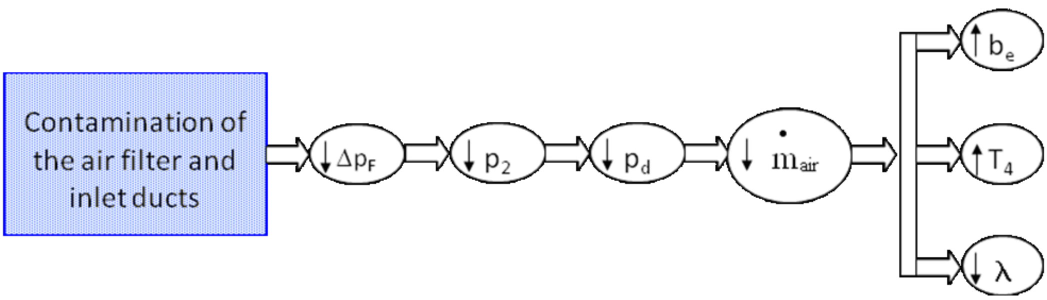

Fig. 3. The influence of the air filter / inlet ducts contamination on the tendencies of the engine operational parameters changes

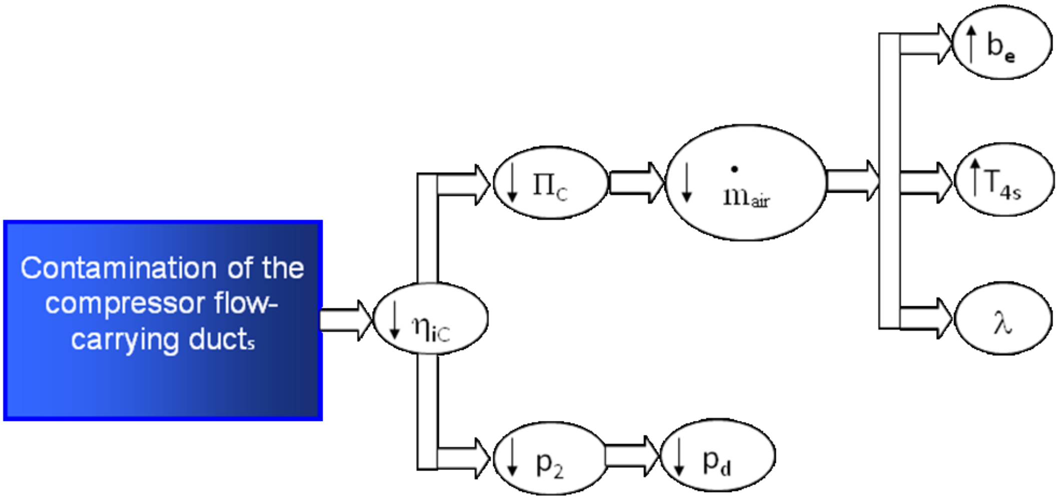

Fig. 4. The influence of compressor contamination on Diesel engine operational parameters

smoothness and thus the compressor throughput is lessened. The change in the geometry of the blade profiles and smoothness of their surface is caused by the erosive action of the sea aerosol. The change in the geometry of the blades caused by contamination leads in turn to the change in the angle of attack and downflow angle of the compressor blades which affects the aerodynamics of the flow. The conditions of the joint operation of the compressor and turbine with the flow tract are changed. With the diminished efficiency of the compressor a bigger turbine power output is needed in order to obtain the unchanged charging pressure p_d. With a constant engine specific fuel consumption the turbine power output increase is impossible to obtain, thus a reduction in the efficiency of the compressor leads to a decrease in the charging pressure and a decrease of the flux supplied by the air compressor m_{pow} which results in the decrease of the air surplus coefficient λ and the increase of the outlet exhaust gas temperature T_4. The influence of compressor contamination on Diesel engine operational parameters is shown in figure 4.

Turbine

Operational practice shows that damage to the turbine guide vanes / stator and rotor most frequently has the form of bends at the edges of attack, deformations, edge losses, cracks or corrosion pits. Extensive damage of turbine guide vane / stator blades and rotor is caused by fragments of broken piston rings and valves. Damage of this type occurs most frequently in engines of high power output, when there is no protection provided for the turbine inlet by using a protective net or if it is damaged or improperly adjusted. Turbine blade damage caused by stress increase brought about by vibrations due to pressure pulsation of the exhaust gas supplying the turbine [1, 3]. They occur more frequently as the engine is reversed. In such cases large volumes of cold starting air and hot exhaust gas flow alternately through the turbine, which in consequence increases the thermal strain of turbine blades and generates micro-cracks. Blade vibrations caused by the pulsating action of the exhaust gas flux supplying the turbine are likely to extend the cracks up to the point of blade breaking.

During turbocharger operation tarry substances and carbon deposit in the turbine flow ducts, at the guide vane / stator blades and rotor blades, as well as labyrinth sealings. They are particularly deposited at incomplete fuel burning in engine cylinders. Contamination of turbine blades leads to a reduction of the turbine throughput capacity – an active sectional area of the surface of the turbine inter-blade ducts. However, the contamination increase causes also the impairment of the conditions of the operation process course in the cylinder due to the deviations of the value of the ratio of the charging pressure p_d to the exhaust gas pressure before the turbine; the deviations being with respect to the optimum values which ensure the conditions for the correct course of the charge exchange process. Turbine surfaces covered with sediments cause an increase of the exhaust gas flow resistance, which in turn leads to a reduction of the turbine power and an increase of the specific fuel consumption.

Layers of carbon deposit on the turbine rotor disk infringe the dynamic balance which in turn is accompanied by the appearance of vibrations that accelerate the wear of the rotor unit bearings. Figure 5 shows the influence of contamination of turbine blade passages on engine operation parameters.

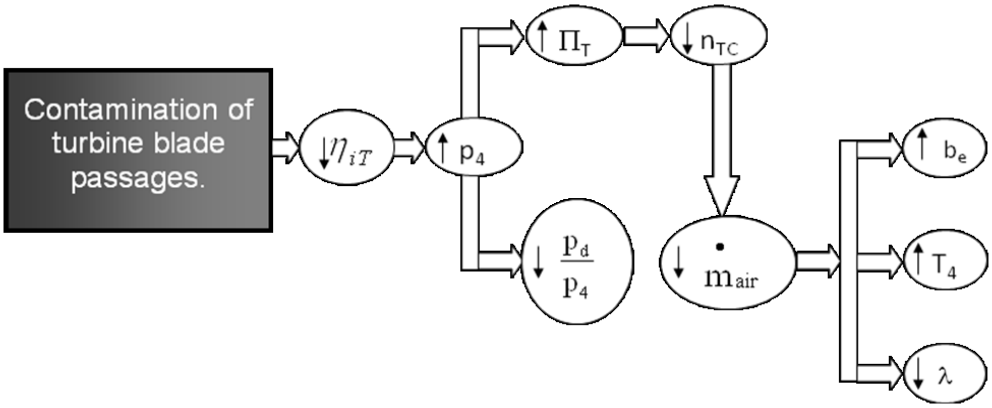

Fig. 5. The influence of contamination of the turbine blade passages on engine operational parameters

Bearings

The causes of failures of rolling bearings in turbochargers are:

– not disclosed early enough minor cracks and scaling of raceway surface and rolling elements;
– loss of the free passage capacity of the ducts carrying oil to turbocharger bearings and in consequence their seizure (the probability of the bearing damage grows when they are lubricated from the engine oil circuit);
– oil pump emergency shut-down or sudden drop in the oil pressure accompanied by an improper operation of the emergency lubrication of turbocharger bearings.

The frequently occurring damage to labyrinth sealings is caused by prior wear of the thrust bearings.

Charging air cooler

The following conditions play a major role in the charging air cooler damage mechanism:

– cooler operation conditions, particularly insufficient monitoring of the air flow resistance values and the temperatures of the coolant and the cooled medium that indicate the necessity of cooler cleaning;
– contamination of cooling water and filtration inefficiency, as well as the related speed of the cooling water in the cooler ducts due to their diminishing section caused by the sediments;
– an increase of the engine forced vibration amplitudes overlapping the cooler free vibration range;
– an increase of the cooler thermal loads connected with the engine higher loads.

The loss of the cooling efficiency of the cooler causes a decrease in the volume flux of the air, its temperature and pressure, thus causing a drop of the air surplus coefficient, which in consequence leads to an increase of fuel consumption and exhaust gas temperature. These phenomena generally occur simultaneously, and the set of the symptoms is the superposition of the air cooler technical condition degradation. The influence of the loss of the cooling efficiency of the air cooler on the engine operational parameters is shown in figure 6.

Exhaust manifold

The exhaust ducts, similarly like the inlet ducts, are chiefly expected to display possibly minor flow resistance values which is a necessary condition to obtain good filling of the cylinder with the fresh

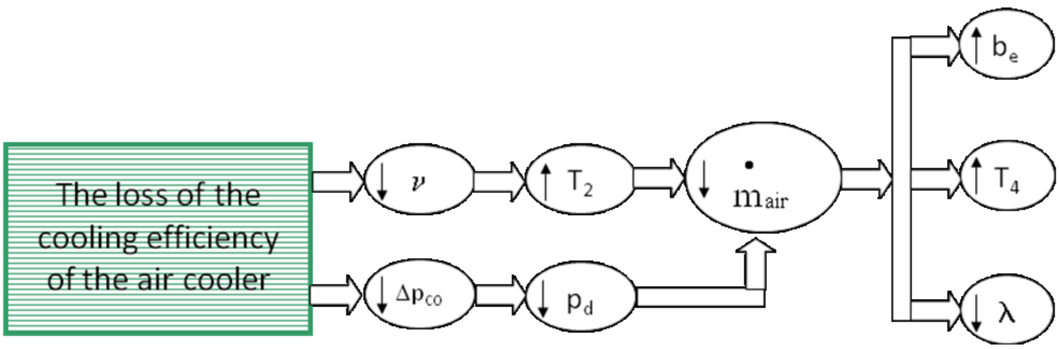

Fig. 6. The influence of the loss of the cooling efficiency of the air cooler on the change the engine operational parameters

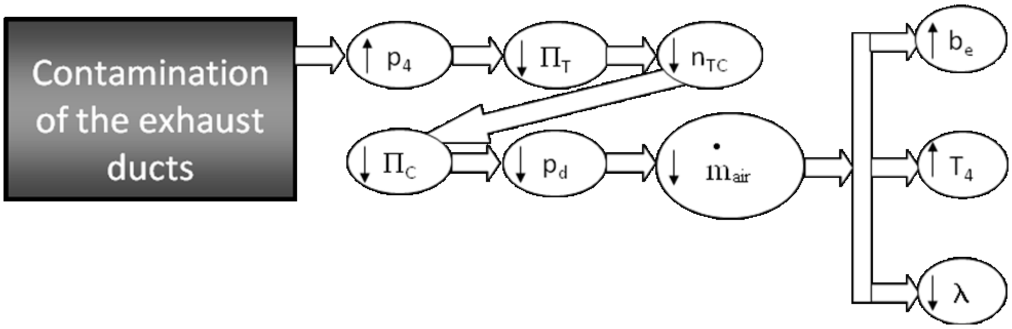

Fig. 7. The influence of contamination of exhaust ducts on engine operational parameters

charge and a complete removal of the exhaust gas from them.

Basic inefficiencies of the exhaust ducts comprise their contamination caused by tarry substances depositing there, which is the result of the incomplete fuel burning in the engine cylinders. Excessive contamination of the exhaust ducts brings about pressure increase of exhaust gas behind the turbine p_4. As a result, the gas expansion degree in turbine π_T is decreased, the turbocharger power output and rotor rpm are diminished.

Thus, the increase of the exhaust gas counter--pressure at the outlet of the manifold p_4 is accompanied by the reduction of the expansion degree in the turbine π_T, turbocharger rpm, compression degree in the compressor π_S, air surplus coefficient λ, whereas the outlet exhaust gas temperature T_4 and the specific fuel consumption b_e increase. The influence of contamination of the exhaust ducts on engine operational parameters is shown in figure 7.

Validation of the Turbocharger Technical Condition Degradation Symptoms

Operational conditions of turbochargers operating in conjunction with engines are determined by state parameters of exhaust gas leaving the exhaust duct. These comprise exhaust gas temperature and pressure, subject to the current load of the engine, its technical condition and the properties of supply fluxes – air and fuel. The degree of air humidification with droplets carrying sea salts and chemical composition of the fuel and its quality become of particular importance for the operation of a marine engine turbocharger.

Interactions of the previously mentioned factors in relation to the turbocharger flow duct surfaces cause:

- appearance of salt and oil sediments in the compressor;
- appearance of carbon deposits in turbines and exhaust gas ducts;
- corrosion of the materials of the rotor unit, shafts and sealings;
- loss of balance of the rotor unit and in consequence bearing damage.

Previous operational experience and procedures of turbocharger maintenance indicate the preference towards a two-stage qualification of machines for their being either fit or unfit for use, and the conducted repairs are inspired by the most frequently disclosed inefficiencies or damage which could be divided as follows:

1. Those which resulted from an improper operation and lack of care of the turbocharger technical condition.
2. Those which resulted from natural wear.
3. Those which resulted from the occurrence of the external chance causes which lead to the equipment exclusion from service.

Acquisition of information of the symptom – inefficiency type is extremely difficult due to natural causes – often the inefficiencies are not recorded during service. On the other hand, turbocharger emergency repairs provide a documented information source with respect to the likely occurring damage for a given type of turbochargers. For the purpose of the practice of machinery condition maintenance, as well as for the modern, open expertise systems, there is a need to establish a relation of the: symptom – cause – inefficiency / damage type [4, 5, 13].

Validation of diagnostic relations of the cause – symptom – inefficiency / damage type has been conducted on the basis of the selected cases of recorded inefficiency or failures, characteristic for turbochargers of the VTR-250, VTR-304-11 and VTR-454-11 type manufactured by ABB.

The recorded damage has been divided into:

1) damage resulting from an improper operation or the lack of care for the turbocharger technical condition connected with the construction of particular elements (Fig. 8 [13]):
   - housings of the compressors and turbines (e.g. damage to their protective coatings);
   - the inlet duct with filters;

a) b)

Fig. 8. Damage connected with the construction of turbocharger elements [13]; a) damage to the coolant flow ducts of the VTR-304-11 turbocharger, b) damage to the labyrinth sealings of the ABB VTR-304-11 turbocharger

a) b)

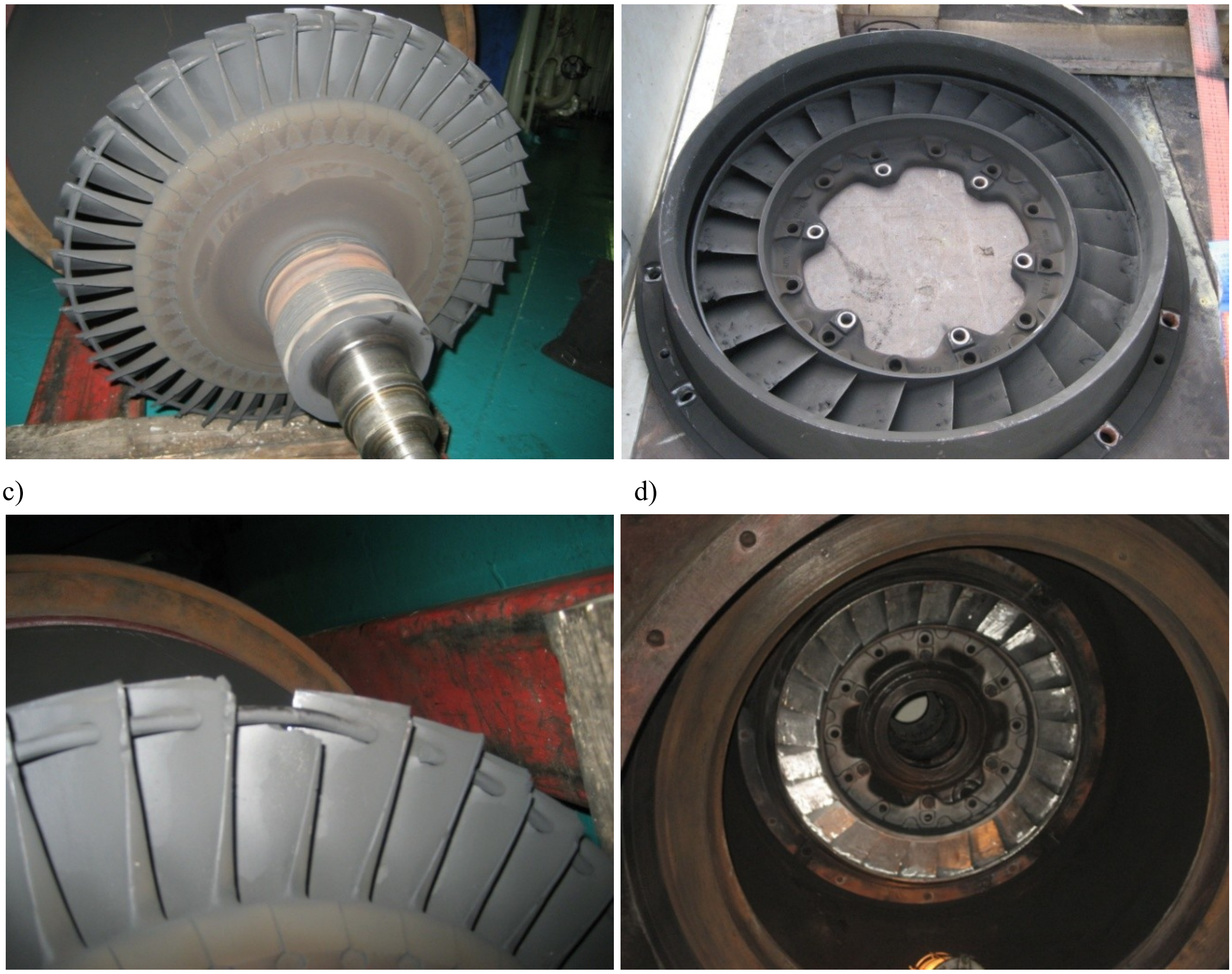

Fig. 9. Results of natural age-related wear of elements of the VTR-454-11 turbocharger; a) bearing journals including the labyrinth sealing of the turbocharger and the turbine blades covered with 0.2–0.5 mm thick layer of carbon deposit, b) turbocharger turbine guide vane / stator, c) turbocharger turbine rotor blade rim, d) contaminated turbine outlet guide vane / stator

– the own oil system or the engine oil installation of.

2) Damage resulting from the natural ageing / wear processes, related to the turbocharger active service time (Fig. 9).
3) Damage resulting from external chance causes (Figs 10 and 11).

These can be regarded as the random events, related to faulty functioning of an antropo-technical couple: human – engine (a nut left in the turbine, not renewed oil). The most frequently encountered damage of this type results from non-compliance with the assembly technology, e.g.: positioning of bearings incompatible with manufacturer's recommendations, application of the substitute sealings etc.

Conclusions

Relations between operational parameters of a turbocharging system and an engine, presented graphically in the figures 3–7, generally point to three values that inform about an impaired technical condition of the object: the increase of the specific fuel consumption b_e, the exhaust gas temperature T_4 and the decreasing air surplus coefficient value λ. The knowledge of the symptoms regarding individual sub- units or elements is required in order to locate the inefficiencies. For instance – as shown in figure 10a – the damage to the VTR-454-11 turbocharger turbine guide vane / stator due to a broken or torn injector pin, according to the Chief Engineer report, has been reflected in the following changes of the charging system operational parameters:

a) b)

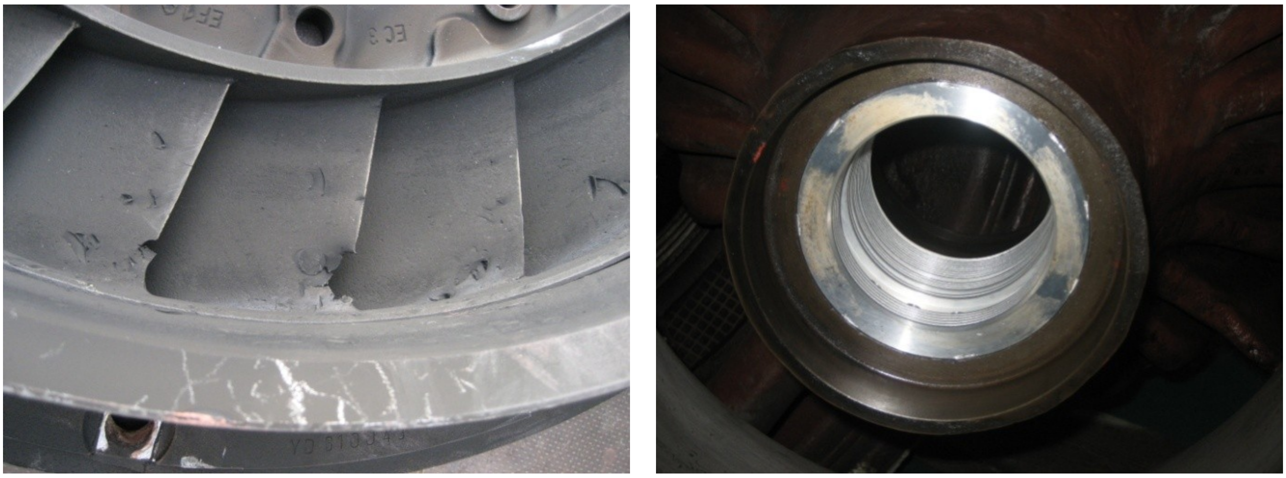

Fig. 10. Results of the random damage to the VTR-454-11 turbocharger; a) damage to turbine guide vane / stator blades due to a broken or torn injector pin, b) the damaged labyrinth sealing due to the shortage of an air barrier

a) b)

Fig. 11. Results of the random damage to the ABB VTR-250 turbocharger [13]; a) damage to the compressor rotor caused by the seizure of the bearings of the VTR-250 turbocharger, b) damage to the turbine rotor by a foreign body – the ABB VTR – 250 type turbocharger

– excessive temperature of the exhaust gas from the cylinders and before the turbocharger T_4;
– lowered charging air pressure p_d;
– lowered rpm of the n turbocharger rotor unit.

As turbine ducts had been washed, the described symptoms became more profound which was reflected by the change of the value of the operational parameters / symptoms in accordance with the tendencies shown in figure 5, and confirmed by operational measurements.

Any attempt to determine the technical condition of a turbocharger and the location of the operational fault, with a view to the compact nature of its construction, and its functional and critical features, is associated with putting the engine out of service with all the technical and economic consequences. While striving to eliminate this negative situation in the operation, one is forced to search for methods to conduct a reliable diagnostic test during the service, without disconnecting the turbocharger from the engine. Validation of the cause and effect relations in the diagnostic relations, acquired on the example of the VTR-454-11 turbocharger, justifies the need for establishing a diagnostic test based on previously studied relations.

References

1. ADAMKIEWICZ A., MICHALEC G.: General Diagnostic Model of a Marine Diesel Engine. Turbocharger, Marine Technology Transaction, Vol. 11, 2000, 25–40.
2. ADAMKIEWICZ A.; MICHALEC G.: Ocena stanu dynamicznego turbodoładowarki okrętowego silnika spalinowego. Problemy Eksploatacji, Zeszyty Naukowe Instytutu Technologii Eksploatacji, Nr 2/99, Radom 1999.
3. MICHALEC G., POLANOWSKI S., ŁUTOWICZ M.: Turbodoładowarka silnika okrętowego jako obiekt diagnostyki. Materiały Konferencji DIAGNOSTYKA'99 – ATR Bydgoszcz – Borówno, czerwiec 1999.
4. ADAMKIEWICZ A.: MICHALEC G.: Identyfikacja relacji diagnostycznych w turbodoładowarce okrętowego silnika spalinowego. Materiały konferencji DIAGNOSTYKA'99, ATR Bydgoszcz – Borówno, czerwiec 1999, t. I, 7–18.
5. MICHALEC G., ADAMKIEWICZ A., WITKOWSKI K.: Model Diagnostic Relations in a Marine Diesel Turbocharger System. II Internationally Technical Conference Explo-Diesel & Gas Turbine'01, Gdańsk – Międzyzdroje – Kopenhaga, April 23–27, 2001.
6. ABB Turbochargers TPL – B, ABB 2006.
7. ABB Turbocharging VTR, ABB 2009.
8. Exhaust Gas Turbochargers. Programme 2011. MAN Diesel & Turbo.
9. TurboNews TCS-PTG. 2007. MAN Diesel & Turbo.
10. www.abb.com/product
11. www.mhi.co.jp
12. The New Generation of MAN B&W Turbochargers, MAN B & W Diesel AG. Germany md 019705.
13. ADAMKIEWICZ A., MICHALEC G.: Problematyka eklsploatacji turbosprężarek okrętowych tłokowych silników spalinowych. Budownictwo Okrętowe i Gospodarka Morska, Nr 4 (501), Gdańsk, kwiecień 2001, 23–25.

Other

14. GIRTLER J.: Diagnostyka jako warunek sterowania eksploatacją okrętowych silników spalinowych. Studia Nr 28. WSM, Szczecin 1997.

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