Article citation info:
KORCZEWSKI, Z., RUDNICKI, J. "Shadow" vs. "Phase 3D" method within endoscopic examinations of marine engines. *Combustion Engines*. 2013, **154**(3), 302-307. ISSN 0138-0346.

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PTNSS–2013–SC–025

"Shadow" vs. "Phase 3D" method within endoscopic examinations of marine engines

Abstract: A visual investigation of surfaces creating internal, working spaces of marine combustion engines by means of specialized view-finders so called endoscopes is at present almost a basic method of technical diagnostics.

The surface structure of constructional material is visible during investigations like through the magnifying glass (usually with a precisely determined magnification), which makes possible a detection, recognition and if possible, quantitative evaluation of the failures and material defects appearing, and in result – an opinion of the waste degree and the dirt intensity of studied constructional elements. This is an especially important advantage while the failures do not generate observable values of diagnostic parameters.

Endoscopic investigation of the machine being switched off from motion enables evaluation of its constructional elements' waste and dirt almost at once.

The paper deals with diagnostic issues concerning endoscopic examinations of the working spaces within marine diesel and gas turbine engines. In the beginning, endoscopy apparatus being on laboratory equipment of the Department of Ship Power Plants of Gdansk University of Technology in Poland has been characterized. The endoscopy considerations have been focused on theoretical bases of a digital image processing and especially - on the "Shadow" and "Phase 3D" measurement method. There has been carried out a comparative analysis of these methods' efficiency and effectiveness in the real conditions of the diagnostic investigations performance of the engines built in the marine power plant.

Keywords: *technical diagnostics, endoscopic investigation, "Shadow" method, marine diesel and gas turbine engine*

Porównanie metod pomiarowych „Cienia" i „Fazowej 3D" w badaniach endoskopowych silników okrętowych

Streszczenie: Badanie wizualne powierzchni tworzących przestrzenie robocze silników okrętowych z zastosowaniem specjalistycznych wzierników tzw. endoskopów to obecnie niemal podstawowa metoda diagnostyki technicznej. Struktura powierzchniowa materiału konstrukcyjnego widoczna jest podczas badań jak przez lupę, zazwyczaj w pewnym powiększeniu, co umożliwia wykrycie, rozpoznanie i ewentualną ocenę ilościową występujących defektów i wad materiałowych, które zazwyczaj nie generują obserwowalnych zmian wartości parametrów diagnostycznych.

W artykule przedstawiono wybrane zagadnienia diagnostyki endoskopowej przestrzeni roboczych okrętowych turbinowych i tłokowych silników spalinowych. Scharakteryzowano endoskopową aparaturę diagnostyczną będącą na wyposażeniu bazy laboratoryjnej Katedry Siłowni Okrętowych Politechniki Gdańskiej. Przybliżono podstawy teoretyczne przetwarzania obrazu w endoskopii cyfrowej, ze szczególnym uwzględnieniem metody pomiarowej „Cienia" i „Fazowej 3D". Przeprowadzono analizę porównawczą efektywności i skuteczności zastosowania każdej z metod w rzeczywistych warunkach realizacji badań diagnostycznych silników zabudowanych w siłowni okrętowej.

Słowa kluczowe: *diagnostyka techniczna, badanie endoskopowe, metoda „Cienia" i „Fazowa 3D", okrętowy silnik spalinowy tłokowy i turbinowy.*

1. Introduction

A constant development and evolution of diagnostic systems applied in marine piston and turbine combustion engines enables an extension of the functions of the inspection systems by not only measurement of operating parameters but also image recording in the internal space of the engine by means of endoscopies. The surface structure of the constructional material is visible during investigations like through the magnifying glass (usually with a precisely determined magnification), which makes possible a detection, recognition and if possible, quantitative evaluation of the failures and material defects appearing, and in result – an opinion of the waste degree and the dirt intensity of studied constructional elements. This is an especially important advantage while the failures do not generate observable values of diagnostic parameters.

Contemporary piston engines are fitted with sophisticated control systems measuring load characteristics. The basis for routine diagnostic tests is indicating of the engine cylinders under steady operation at representative load ranges. A comparative statistical and content related analysis within the use of analyzers of fast changing values is performed as regards indicator graphs, courses of accelerations (generated by the operation of the mechanisms related to the piston assembly transmitted to the measuring point on the top of the cylinder head) and the courses of other values characterizing the operating processes in the engine cylinders throughout its cycle. So determined diagnostic measures: mean indicated pressure, indicated power output, maximum combustion pressure and the speed of in-cylinder pressure growth $dp/d\alpha_{OWK}$ etc. provide important information on the general condition of the elements of the combustion system. The test results are used to determine the trends, analyze the changes in the engine condition and make decisions as to further operation [Diagnostic Raports, 2009-2011].

Nevertheless, in practice, cases of serious engine damage are known caused e.g. by mechanical stability loss leading to a torsional resonance as a consequence of an excessive load spread whose sources were not identified in due time. The occurring torsional vibration of high amplitudes have a destructive impact on the engine and the whole drivetrain of a ship as they cause material fatigue and finally cracking of the constructional elements of the torque transmission to the propeller or the bearing nodes – Fig. 1a. Similarly, it is difficult to assess the condition of a piston engine based on the operating parameters if the operation of the fuel delivery system is improper. Frequently, the trend lines of the changes in the temperature of the exhaust from individual cylinders change their course to a small extent only and the effect of a failure of one of the injectors is that the piston crown is damaged – Fig. 1b.

The difficulties in damage diagnosis in the flow part of turbine engines based on the measured thermodynamic parameters that characterize the energy state of the flowing medium are dependent on appropriate interpretation of the symptoms of the defect which are often identified as consequences of constant and inevitable processes of fouling, ageing and deterioration determined by the period of operation. The external symptoms in such states are usually concurrent and difficult to precisely determine. A special case is the problem of diagnostic parameter analysis needed to assess the extent of fouling in the flow channels of the fan assemblies and the effectiveness of their cleaning. A classic mistake in interpretation of the symptoms is the incorrect differentiation of the operating foul of the flow part as a constant process accompanying the engine operation under marine conditions from the state of its inability to operate properly caused by e.g. burning of the edges of the turbine blades – Fig.2a.

a)

b)

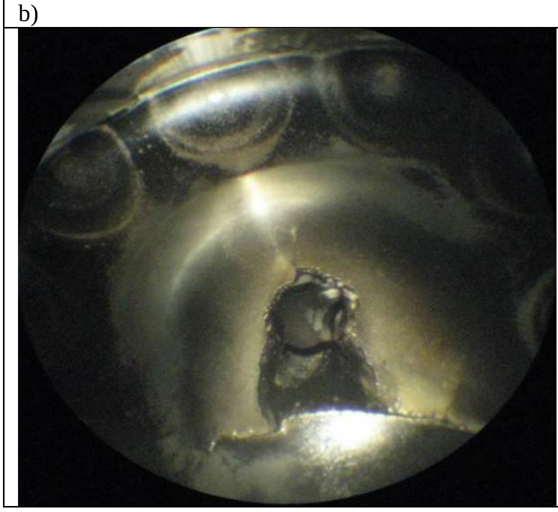

Fig. 1. Damages of the drivetrain and marine piston engine elements: a) broken output shaft, b) damaged piston crown [2]

Such a situation may take place as a result of a lack of cleaning of the flow part of the turbine, which, among other things, improves the cooling of the blades.

Another example of faulty diagnostic reasoning is the assessment of the condition of a turbine engine based on the distribution of the stream of enthalpy throughout the length of the flow part and the evenness of the temperature field of the exhaust on the circumference of the control cross-section downstream the exhaust generator.

Very often the slip in the turbine speed and the circumferential temperature distribution unevenness change only slightly and the effect of the injector failure leads to a burning or cracking of the flame tube in the combustion chamber – Fig. 2b. That is why, each time (if the technical conditions allow) on confirming the deformations of the gas dynamic characteristics an endoscopic inspection of the flow part is performed in order to finally validate the diagnosis.

a)

b)

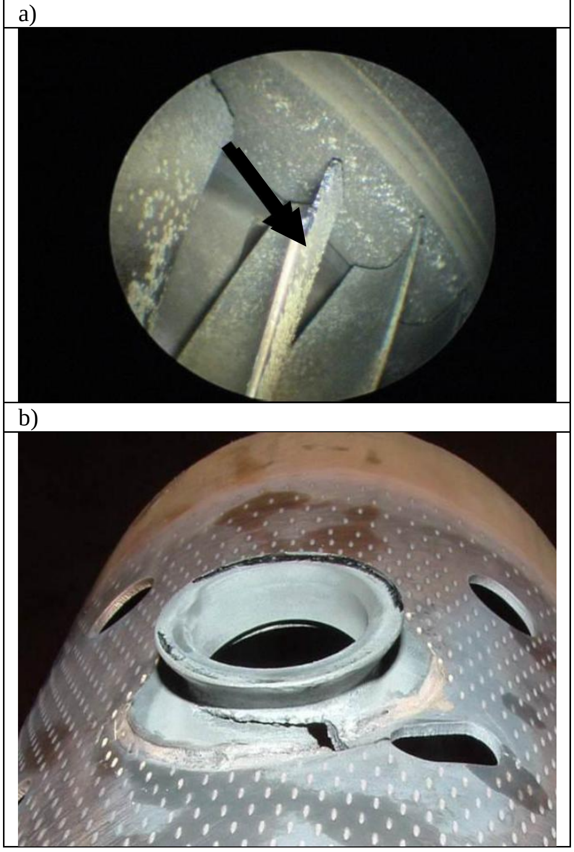

Fig. 2. Partly burned or cracked gas turbine elements: a) high-pressure turbine rotor blade tips,
b) flame tube [2]

2. Measurement methods applied in digital endoscopy

During an endoscopic inspection of the internal parts of machines we often lack reference for determining of the dimensions of the detected defects. The observed size is a function not only of the real dimensions of the defect but also of the distance of the lens from the examined surface. Since the machine manufactures provide the admissible values related to surface defects of the most susceptible constructional elements the identification of the actual dimensions of the defect is a key diagnostic issue. The traditional optical approach provides a comparison which is a calibrated reference frame fitted at the end of the fiberoscope [2]. Entirely new possibilities in this problem are brought by digital endoscopy. Digital image analyzers working with “Stereo”, “Shadow”, “Laser” or “Phase 3D” measurement heads, based on the theory of triangulation[1] are capable of precise determination of the distance of the lens from the examined surface, hence they determine the dimensions of the surface defects [2, Błachnio et al., 2007]. The measurement heads enable a digital processing of the stereoscopic effects which allows the images to give the impression of three-dimensional space (focus depth, layout and solidness).

2.1. “Shadow” method

A diagnostic team of Gdansk University of Technology in Poland disposes the most modern EVEREST measuring videoendoscopic set of XLG3 type, equipped with “Shadow” probe - Fig. 3. It creates the totally new diagnostic possibilities, including an accomplishment of the quantitative evaluation of the surface layer degradation (measurement possibility of the detected structural changes - defects, discolourings, contrasts etc.). The "Shadow" digital image processing method enables measuring the seen paintings in such way, to give

Fig. 3. EVEREST measuring videoendoscope XLG3: general view, b) magnification of the panoramic LCD projector

the quasi three-dimensionality impression, with its depth, the massiveness and the mutual distribution. The speculum of the „Shadow” probe is fitted with a specialized optics generating a shadow (projector) of a characteristic shape (most frequently a straight line) on the examined surface – Fig. 4. The shadow

[1] W. Snellius was the creator of triangulation theory (1615). The measurement method consists in division of the measuring area into adjacent rectangular triangles and marks on the plane the co-ordinates of points by means of application of the trigonometrical functions.

projection is performed while the angle of the speculum position against the observed surface and the angle of observation sector is known.

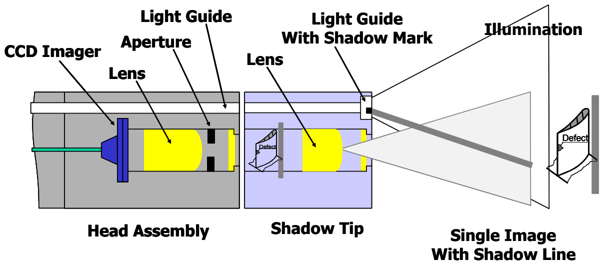

Fig. 4. Technology of image transformation in the "Shadow" method [by courtesy of EVEREST VIT]

A shadow generated near the defect is localized and recorded by a CCD camera placed in the head. The closer is the head to the examined surface the closer is the shadow line to the left side of the display. Since we know the position of the shadow generating the image on the display we can easily calculate the enhancement of this image, hence determine the linear distance between individual pixels and then the real dimensions of the surface defects [2].

In the "Shadow" method the following options are available: length, skew length, multi-segment length, broken line length (circumference), distance of the point from the base straight line, depth (protrusion), diameter of the marked area (taken by a gauge).

A very strong advantage of the "Shadow" method is the possibility of precise interpretation of whether we can see an attrition or a deposit. Such diagnostic problems occur in the examination of internal parts of piston or turbine combustion engines. Very frequently, due to optical and illuminative effects a simple foul of the surface of the air or exhaust flow channels (mineral deposits or products of fuel combustion – carbon) is interpreted as a corrosive or erosive attrition of the material. These doubts can be cleared by the nature of the deformation of the shadow line. If the surface is indented (larger distance from the head) the shadow line is refracted and shifted to the right on the display.

2.2. "Phase 3D" method

A key element in the design of the inspection probe of the measuring videoendoscope Everest XLG3 in the "PhaseProbe" option is the diffraction lens mounted in the inspection probe head – Fig. 5.

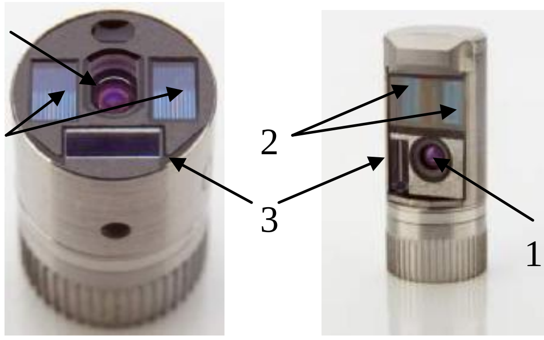

Fig. 5. Diffraction lens for measuring the phase shift with the aid of "PhaseProbe" of the videoendoscope Everest XLG3 [4]: a – straight-ahead direction of observation (field of vision angle "FOV" - 105^0, depth of field "DOF" - 8-250 mm, b – side direction of observation ("FOV" - 105^0, "DOF" - 7-250 mm); 1 – image processing optics – CCD camera, 2 – diffraction grating, 3 – window of standard illumination system

The standard illumination system of the videoendoscope works in the continuous mode only during routine observation of the examined surfaces. During the measurement the standard illumination system is automatically switched off to reach the maximal possible resolution of the interference fringe pattern generated by the diffraction gratings, which are illuminated in this time by electroluminescence diodes (LED) radiating the precisely defined light wave length.

When the distance of the "PhaseProbe" lens from the examined surface changes, the halftone screens of diffraction fringes also undergo relevant changes, according to the schematic diagram shown in Fig. 6. Therefore based on the records and analyses of the deformation pattern of particular diffraction fringes we can conclude about qualitative and quantitative surface deformations of the examined object. Since the observed dimensions of the surface defects are not only the function of their real dimensions but also of the distance of the inspection head lens from the examined surface, its precise determination is a basic metrological problem in 3D measurements. For this purpose we can apply the phase shift method, initially described by Thomas Young – what is precisely explained in the publication [Korczewski, 2013].

3. Advantages and disadvantages of the 3D measurement method

The videoendoscope Everest XLG3 is equipped with a 3D measurement probe bearing the name of "PhaseProbe" which is a „flexible three-dimensional eye" of the operator. These borescopes

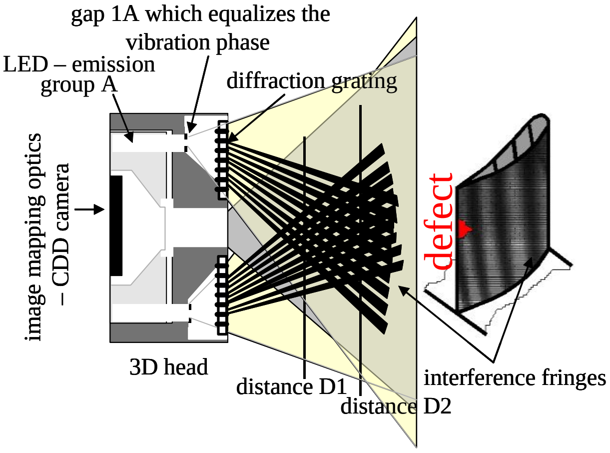

Fig. 6. Schematic diagram of the method of 3D measurement with the aid of the "PhaseProbe" inspection probe diffraction lens

reveal numerous advantages, which are the reason why they are in more and more frequent use. The basic advantage of the 3D measurement technology with respect to older measuring methods, such as "StereoProbe", "ShadowProbe", and "LaserDots" for instance, is its ergonomics.

Switching from the standard (qualitative) measurement mode to the measuring (quantitative) mode does not require withdrawing the inspection probe from the inside of the examined object and changing the optic lens. Apart from complicated manual work to be done to change the lens, a big problem in those cases was finding again the earlier detected surface defect, the more so that the measuring lens reveal, as a rule, low quality of image processing of the examined surface observed from a larger distance. For instance, the depth of field for "ShadowProbe" lens is within 7-30 mm, while for "PhaseProbe" it ranges between 7-250 mm!

On the other hand, "PhaseProbe" is very sensitive to image movements (vibration) and light reflection from highly reflective surfaces. The measurement cannot be performed, in practice, when the operator does not manage to keep the tip of a flexible and a number of meters long probe still and situated at a proper angle for at least two seconds. It is extremely difficult to reach this state, even if a special probe rigidiser with a tube gripper is used for this purpose [2,3]. From the practical point of view it is a serious disadvantage of the "PhaseProbe" based 3D measurement method and it should be eliminated in the future by its inventors.

Taking into account high cost of purchase of the measuring set, which, despite the decreasing trend, still remains at the level of 40-50 thousand Euro, each time a decision about its purchase should have strong rational background.

When discussing possible areas of application of the measuring videoendoscope with "PhaseProbe" in marine engine diagnostics, working spaces should be mentioned for which surface wear is decisive for the efficiency of the energy conversion processes taking place in the engine. Tasks to be done in those cases include precise determination of parameters characterising the roughness of the surfaces composing the borders of the working space. This should be done over a relatively large area, which from the point of view of endoscope diagnostics requires its full numerical mapping and dimensioning. In those cases the quantitative measure of wear of the examined surface is the arithmetic mean deviation of its profile from the average line determined along a normalised elementary line segment, or the roughness height calculated using ten points of this profile.

The research experience gained in the past by the author suggests that the phase shift method can be efficiently used for diagnosing the following constructional elements:

1. For working spaces of piston engines:
a) cylinder bearing surface – honing grooves,
b) valve seats – valve set faces, wear thresholds on valve heads,
c) air and exhaust gas flow ducts – shape and geometric dimensions, active flow sections, condition of inner surfaces,
d) turbo compressor rotor assembly - shape and geometric dimensions of blades, condition of blade profile surfaces and inter-blade passages;
2. For flow parts of turbine engines:
a) rotor assemblies of compressors and turbines – shape and geometric dimensions of stator and rotor blades, condition of blade profile surfaces and inter-blade passages,
b) combustion chamber - shape and geometric dimensions of blade systems in flame tube swirl vanes, condition of inner and outer surfaces of flame tubes.

The measuring "Shadow" method provides opportunities for digital processing of stereoscope effects, which makes it possible to dimension the observed objects in such a way that they give an impression of quasi three-dimensionality with its depth, massiveness and mutual distribution. Unfortunately, their application to full (sufficiently detailed), three-dimensional mapping of larger surfaces is very limited.

The "Shadow" method has a form of single-fringe scanning and brings useful three-dimensional information only with respect to one plane of the examined surface profile within a very limited area, as a result of optical limitations of the applied "Shadow" type lens („FOV" – 50^0, „DOF" - 7-30 mm). An additional difficulty in the realisation of the 3D measurement with the aid of the "Shadow" method is the need for very precise linear positioning of the fringe with respect to the examined surface, which requires some experience. If the surface is not ideally flat, or the inspection probe lens is not directed perpendicularly, then a relatively large error can be recorded in the measurements which require referring the baseline to the points situated off the line, the line-point distance measurement for instance. For these reasons, and bearing in mind the fact that, like in the “Stereo” method, a huge-capacity processor is to be installed in the videoendoscope to solve equations of the mathematical model describing the 3D profile of the examined surface in this technique, the application of the “Shadow” method is rather limited to only dimensioning the detected surface defects [2].

4. Final remarks and conclusions

A basic condition for formulating a reliable endoscope diagnosis of the technical state of working surfaces in a marine engine is an opportunity to perform not only qualitative but also quantitative assessment of the detected surface defects. New perspectives in this area are brought by digital endoscopy. Numerical image analysers cooperating with the measuring heads of “StereoProbe, “ShadowProbe”, “LaserDots” and here described “PhaseProbe” type provide opportunities for numerical processing of stereoscopic effects which in turn makes it possible to dimension the observed images in such a way that they give an impression of quasi three-dimensionality, with its depth, massiveness, and mutual distribution.

Recent years show that further development of the endoscopic diagnostics of marine engines is absolutely determined by increasing technical capabilities of the more and more perfect and faultless measuring equipment. Precise and ergonomically designed digital endoscopes open new prospects for developing the diagnostic knowledge on the kinetics of working space wear in engines in operation, leaving less and less space for traditionally used optical endoscopes [1]. However, there is one *sine qua non* condition: the diagnostician should study in detail technical capabilities of the owned measuring videoendoscope and be able to use them effectively in the environmental conditions in which the diagnostic examination is performed. He also should avoid operating mistakes which would lead not only to the decrease of the life time and reliability of the very expensive measuring endoscope equipment, but also to worsened reliability of the diagnosis of the examined engine.

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