“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

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 charac-
teristics. 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 \( \frac{dp}{d\alpha} \), 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.

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.

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 fiberscope [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 triangulation¹ 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 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 spec-
ulum position against the observed surface and the 
age of observation sector is known.

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 dis-
play. 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 (pro-
trusion), diameter of the marked area (taken by a 
gauge).

A very strong advantage of the “Shadow” meth-
od 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 en-
gines. Very frequently, due to optical and illumina-
tive 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 defor-
mation 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 videendoscope Everest 
XLG3 in the “PhaseProbe” option is the diffraction 

Fig. 4. Technology of image transformation in the “Sha-
dow” method [by courtesy of EVEREST VIT]

Fig. 5. Diffraction lens for measuring the phase shift 
with the aid of “PhaseProbe” of the videendoscope 
Everest XLG3 [4]: a – straight-ahead direction of ob-
servation (field of vision angle “FOV” - 105°, depth 
of field “DOF” - 8-250 mm, b – side direction of ob-
servation (“FOV” - 105°, “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 
videendoscope works in the continuous mode only 
during routine observation of the examined sur-
faces. During the measurement the standard illumi-
nation 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 electro-
luminescence diodes (LED) radiating the precisely 
defined light wave length.

When the distance of the “PhaseProbe” lens 
from the examined surface changes, the half-tone 
screens of diffraction fringes also undergo relevant 
changes, according to the schematic diagram shown 
in Fig. 6. Therefore based on the records and analy-
ses of the deformation pattern of particular diffra-
ction fringes we can conclude about qualitative and 
quantitative surface deformations of the examined 
object. Since the observed dimensions of the sur-
face defects are not only the function of their real 
dimensions but also of the distance of the inspec-
tion head lens from the examined surface, its pre-
cise 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 
publishation [Korczewski, 2013].

3. Advantages and disadvantages of the 
3D measurement method

The videendoscope 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
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 videendoscope 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 constrictional 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°, ”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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