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RECONSTRUCTING THE COMPLEX GEOMETRY OF THE INJECTION NOZZLE CHANNELS OF MARINE DIESEL ENGINES

Key word

Marine engines, complex elements, mapping geometry.

Abstract

This paper presents the application of modern methods to reproduce a model of selected features of the complex geometric components of present medium-speed marine diesel engines. Geometrical data was obtained in experimental investigations of new objects operating in natural conditions, where measurements of some structural features are very difficult and burdened with great uncertainty. To obtain data for modelling, the analyses of two-dimensional images were used. The aim was to study the geometrical features of the main elements of fuel injection equipment to develop relationships between diagnostic signals to determine the technical state. Such examinations are also useful for the evaluation of the wear and damages of elements when operating in extremely difficult conditions.

As a result of geometric measurements, it was possible to get a set of points and to produce digital images of objects.

Introduction

For structural elements of mechanical objects, such as marine diesel engines, the geometry is a very important issue, affecting the functioning of the engine, as well at the technical state and its reliability. During operation, individual elements undergo wear or fail, thus causing changes in their geometric features. Geometrical data was obtained in experimental investigations of new objects operating in natural conditions, where measurements of some structural features are very difficult to make with certainty.

Basic notions are useful for descriptions of the unevenness of an area. A geometric structure of an area may include a set of data representing the unevenness of the real profile (the shape, dimensions, the waviness, and coarseness, the directionality of signs of processing, breakages, and deformations) [15]. Surface roughness is the deviation of the actual profile from the mean line.

Based on measurements, it is possible to determine the surface roughness along with the deformation of an object.

Among the many geometric features, a distinguished group of the most important features can be measures, determining the technical condition, and consequently a malfunction of the entire system. Various difficulties in a particular item can be found using its basic dimensions, such as diameter, length, width, height, and thickness.

The profile of surfaces of machines includes the combined effects of roughness, waviness, and shape, as the result of imperfections and manufacturing processes of wear and damage. During measurement, it is recommended to eliminate unnecessary frequency components using a method of the analysis of the measurement signals in the digital filters.

1. Features of a mechanical object and the factors acting on them

For test simulations or some of the experiments, it is advisable to develop a virtual model based on the actual object that is made with tolerances and is subject to wear [6]. It may be preceded by making the appropriate measurements, as a way of solving the problem. The model must be credible and reflect the real geometry of the object, because then it can replace the real element enough to provide an additional amount of new information about the object. Quality is the set of features, which include the accuracy of the dimensions (length, thickness, diameter, and angles), correct shape (circularity, cylindricity, flatness, waviness, parallelism) surface quality (scratches, contamination, gloss, matt), etc. Defects are then categorized according to their importance to [8] faults, defects, major defects, and dangerous (critical) defects.

The resulting processing performance depends on the state of the workpiece material, machine technology, tools, operator, environment, etc. If the ratio of three standard deviations of the measurement of uncertainty is less than 25%, the impact of the error can be omitted [8]. The volumes of production xi(τ) are imposed tolerances to meet the following condition [8]:

$$d_{gi} \le x_i(\tau) \le g_{gi}, \qquad (1)$$

where d_{gi} – lower size limit, g_{gi} – upper size limit.

The technical state of the object can be described as adopted traits, which is divided into measurable C_m and immeasurable C_n. The state in the time τ determines the set of instantaneous values of features of the object:

$$S_{ti} = \{C_j(t)\} = C_j(t_i) \quad , \qquad (2)$$

where S_{ti} – i-th state of the object,C_j – (j = 1, ..., n), – value j-th features at time t_i. Features of the state are the set quantities that describe the composition and structure of the test object:

$$C = \{c_1, c_2, ..., c_i ..., c_n\}, \qquad (3)$$

where i – finite sequence of indices.

The set of characteristics that describe the element can be represented as a matrix, and the first three lines describe the primary features [8]:

$$C^p = [C_{kl}] = \begin{bmatrix} C_{11}, & C_{12} & .... & C_{1l1} \\ C_{21}, & C_{22} & .... & C_{2l2} \\ C_{31}, & C_{32} & .... & C_{3l3} \\ C_{41}, & C_{42} & .... & C_{4l4} \end{bmatrix}, \qquad (4)$$

where k = 1 macro geometric features, k = 2 micro geometric characteristics, k = 3 structural features.

Assessment of a technical object becomes the evaluation of its features. One of them is the structure, which is the set of ordered elements to perform the designed functions. The set of instantaneous values of all features adopted to describe it determines the state of the object at a given level of knowledge and technology. Features of the state of the internal combustion engine are the dimensions of components, clearances in joints, elasticity, wear, airtightness, density, surface state, etc.

2. Methods of measuring surface stereometry

To measure the surface stereometry, contact and optical methods are used, including the following [1, 2, 3, 6, 9, 11, 15]: a three-dimensional profile measurement gauge, scanning equipment, and special designs of measuring instruments. The basic factors that have a direct impact on the accuracy of contact measurements may include the following [11]: the dimensions of the apex and the apex angle of the stylus, the pressure of the measuring penetrator, kinematics motion, setting the measuring arm and the dimensions of the shoe, and interference from the environment. Surface topography can affect the fuel and oil consumption, and they are also parameters of an internal-combustion engine.

Over the past several years, this process has been the subject of intensive development mainly due to the development of techniques for measuring surface topography (contact measurement, optical, using scanning microscopy) by increasing the range of instruments (resolutions, different filters and speed of the travelling, measurements in 2D and 3D). It is possible to measure approximately 300 profile parameters and tens of topographic parameters, and many graphical presentations can be made [6, 8, 16]. Computed tomography is one of the contactless methods in reverse engineering, and it is currently the only non-destructive technique that enables the reproduction of the internal geometry of objects with appropriate accuracy [5].

Research on geometric structures in relation to time allows the analysis and modelling of the manufacturing and the operation of the engine [11]. On the cylindrical surfaces are smoothed scratches that are present after production and after a considerable operating period of an engine. The influence of the parameters of the micro geometry of cylindrical surfaces on reaching phases of wear is considered in some publications as a determination of the time before the danger of seizure.

Non-contact methods include optical or contactless, which are gaining increasing recognition in reverse engineering, thanks to their advantages. Definitely one of them is much cheaper than the purchase of an expensive instrument like a coordinated measuring machine. In contact methods, the most often used is a stationary machine, which is bulky and requires the adaptation of facilities [6]. The methods of non-contact measurements are less accurate than contact methods, but the accuracy offered by a specific device is often sufficient. Contactless methods can also make measurements and further analysis of objects made of soft materials, e.g., deposits. Optical methods are less common as standard methods in comparison to the contact methods [15]. The best seems to be a combination of contact and noncontact methods.

3. Geometry measurement of small injection holes of the injector nozzles

Measurements of diameters and shapes of spray holes were performed by optical [2], hydrodynamic [10], and aerodynamic methods. Optical measurements were carried out using a universal microscope on the basis of reflected light at a magnification of about 50 times and a resolution of about ±1 μm. Measurements of the outlet diameter of the holes does not reflect the actual state due to the discontinuity of their shapes and dimensions, the large surface topology on the influence of the functioning, and rays rounding edges on the course of the injection process. Charts of the deformation holes were enlarged and projected for visualization [2]. In this way, the changes resulting from the accumulation of deposits, erosion and cavitation wear can be observed and measured.

The attempt was made to transfer images from the microscope with a video camera to a computer for image analysis [6, 13], but it was only a comparative attempt. The surface of injector nozzles being covered with a layer of dark deposit significantly hinders the application of optical methods due to the absorption of light. These methods of the evaluation of the state spray holes were characterized by high labour consumption and a fragmentary nature of the evaluation of features of the state, which were not suitable for application.

Previous attempts to use the flow properties of various media did not satisfactorily explain occurring phenomena. Mass flow of the fuel can be determined using an injector nozzle after removing the injector needle, which determines the hydraulic characteristics at full lift of the needle, when throttling the fuel takes place on the spray holes. Because of the compact and complex shapes and an unfavourable location of the holes, the use of the mass flow of the medium seems promising to assess their condition. Including diverse geometrical features of holes into the global investigation of the stream of mass is useful in reflecting the functioning of the injector nozzle. It is simultaneously sensitive to changes in features of the holes and their wear.

The internal geometry of typical multi-hole injector nozzles were analysed by electron microscopy [1]. A detailed analysis of the geometry of standard serial products of multichannel injector nozzles was conducted using both optical and scanning microscopes, including the measurement of the internal geometry of the nozzle with the application the techniques of casting processes. Images from an electron microscope indicated a significant improvement in the surface of nozzles, due to the elimination of feathered edges and deposits on the inlet producing a smoother shape of the inlet. The geometry of the multi-hole injector nozzle of compression ignition engines was analysed using optical and scanning electron microscopic techniques in order to exactly identify the internal configuration and dimensions.

Measurements were made directly on the shape and roughness of the injector nozzle inside the holes without the necessity of sectioning the hole. A slender tactile sensor was used with dimensions that have been adapted to allow access to the millimetre deep and 100 μm diameter holes [12]. The vertical resolution offered nanometre and sub-micrometre lateral resolution at hundreds of microns in the vertical deflection range and a millimetre-per-second scanning velocity. Measurements of nozzles having injection openings of 170 and 110 μm in diameter were carried out with a different speed of scanning and sampling rate [12]. The characteristic outline and coarseness of the wall of the hole may be caused by the process of processing detected measurements with very good repetitiveness in the profilogram of the area at different speeds of scanning. Thus, the results indicated the innovative potential of the sensor in the metrology during the manufacturing process of injector nozzles.

The roundness measurement for the bores of micro-holes with diameters less than 0.500 mm is a challenge that cannot be addressed with conventional metrology, such as tactile measurement. Work [3] presents a setup for semi-automated positioning and roundness measurement of boreholes with diameters down to 0.160 mm (and even less) using fibre-optical probes and low-coherence interferometry. A fibre-optic measurement method has been developed that addresses fast measuring in confined spaces and allows the measurement of diameters and absolute hole geometry.

Work [7] presented the results of the measurements of the geometry of channels of one and multi-hole injector nozzles using optical microscopy, which was a high quality X-ray tomography of the area and X-ray phase contrast projection. The initial data was smoothed to develop a STL file, which is recommended for computational grid generation for ECN3. The authors argue that such measurements are not possible with optical instruments.

These various geometrical characteristics of the injector holes are difficult to measure with optical methods, especially in the exploitation phase. So far, a decision about the suitability of the injector nozzles has been subjective. These features of injector channels may be determined, if the holes are treated as pressure differential devices.

4. Objects of research

Marine engines injector nozzles operate in very difficult conditions due to the following effects [2, 4]: intense and random operating conditions, high thermal and mechanical loads, large dynamic loads, limited lubrication, chemical influence of fuels and combustion products, climatic zones of use, the unrepeatability of the process of compression and injection of the engine, and the like. Multi-hole injector nozzles are construction nodes of complex manufacture, and wear significantly affects the proper operation of internal combustion engines. Wear includes smoothing the edges of the holes and covering them with deposits causing deterioration in the quality of atomization.

The objects of research were injector nozzles of medium-speed marine diesel engines after manufacture and operating under natural conditions. During the production the holes of injector nozzles errors can be made in their shape and the location, and they can be damaged or wear in various ways during exploitation. Some injector nozzle was cut along the axis of the spraying holes.

5. Methods and means of research

In previous investigations, a workshop microscope, biological microscope MB30, and a microscope with a camera were employed with limited effect [2, 6, 10]. Problems resulted from the discontinuity of channel profiles and coverage by dark deposits. For this research, an optical-digital microscope of a new standard, automated, and with high-resolution was used. It is simple to operate and can control the analysis accuracy (Fig. 1). The microscope was used for observations of objects in reflected light. Applied optics and the digital system ensured good quality images.

Fig. 1. Image of an optical-digital microscope for contactless investigation

Injector nozzles were washed with extraction naphtha and flushed with compressed air to remove contaminants. Geometrical measurements were designed to determine the shape of the geometric elements, dimensions, and clearances between the mating surfaces. The test results were compared with the previous measurement techniques.

6. Examples of research results

Measurements were made of the spray holes of apertures of the outside and inside after cutting along the axis of the well and the longitudinal axis of injection channels. For comparison, Fig. 2 shows the hole in the field of the MB30 microscope at a magnification of 50 x, and the field of view of the optical-digital microscope (Fig. 1). There is a visible difference in the quality of images taken in the fields of view of microscopes.

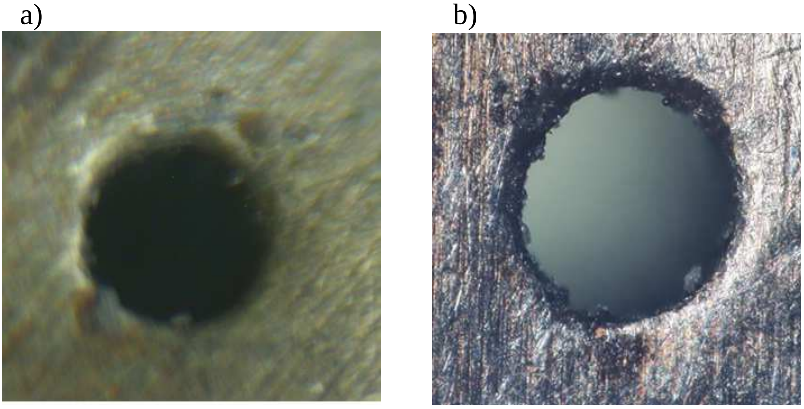

Fig. 2. The image spray holes of injector nozzle in the visual field of the biological microscope (a) and the optical-digital microscope (b)

Some surfaces have shapes that are fragments of the surface of curves, wherein the removal of curvature can be made by various methods. A wheel was inscribed into the hole (Fig. 2b) to determine the nominal shape (Fig. 3). Circularity errors of the hole are caused by the quality of workmanship, wear, and deposit particles covering the edges.

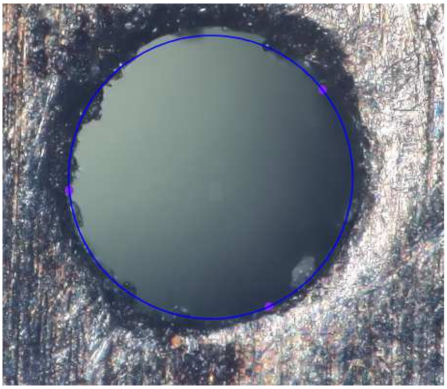

Fig. 3. Determination of the shape of the nominal injection hole with the diameter d = 259 219 nm

Figure 4 shows the images in the field of view of optical microscopes of the injector nozzle cut along the axis of the well (Fig. 4a) and along the spray hole (Fig. 4b). The channel shown in Fig. 4b is characterized by significant irregularity in the profile, which became like a truncated cone with the base on the outlet side, which was the product of manufacturing and wear. Figure 5 shows images from the optical-digital microscope of the cross section along the pivot of the sack volume of the injector. The average diameter of the channel was outlined (Fig. 5 b) equal to 272 150 nm with a ±3 σ standard deviation = ±109676 nm, which indicate a significant dispersion of dimensions.

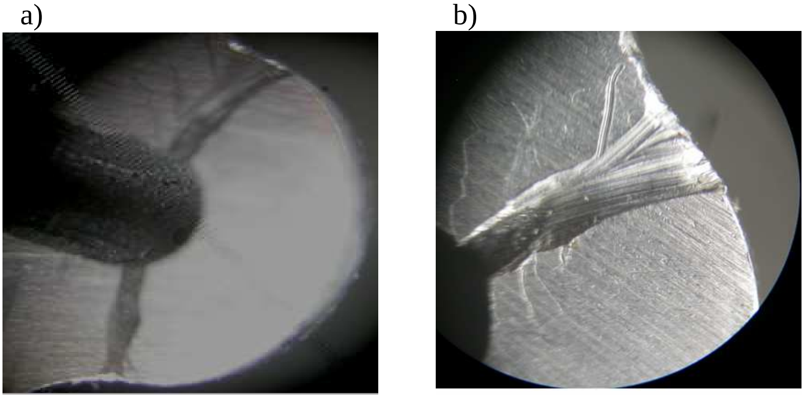

Fig. 4. The optical microscopy images of central cross-sections of the injector nozzles along axial of sack volume (a) and spray hole (b)

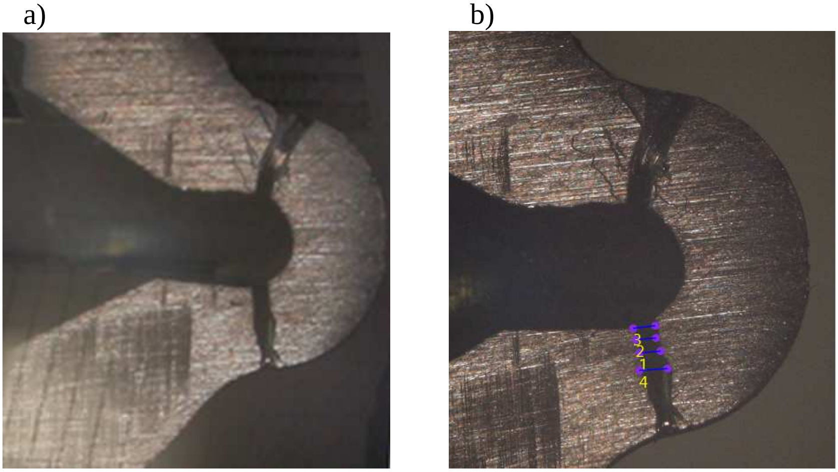

Fig. 5. Images from the optical-digital microscope of the cross section of the injector nozzle along well and the two spray holes (a), and the measurements at several places on the injection channel in the lower part (b)

Conclusions

This work presents geometry measurements of spray holes of a marine diesel engine's injector nozzles using optical and optical-digital microscopes. The resolution of contemporary measurements increased, but the labour consumption and the large uncertainty of measurements are like traditional measurement techniques.

Without cutting the injector nozzle, measurements only of the outlet hole diameter were made. However, studies have shown that the geometry of the aperture of the inlet side have a greater influence on the fuel flow, similarly, as for pressure differential.

Satisfactory results were obtained only by destructively cutting the injector nozzle along the axis of the jet well and along the axis of the spray holes.

Due to the lack of repeatability, it is advisable to examine the large sample of injector nozzles, to assess the extent of the changes and the representative shapes. Apart from the diameters of the spray holes, additional measurements of geometric features of injector nozzles are needed.

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Odtworzenie geometrii złożonych kanałów rozpylaczy okrętowych silników spalinowych

Słowa kluczowe:

Silniki okrętowe, złożone elementy, odwzorowanie geometrii.

Streszczenie

W pracy ukazano zastosowanie nowoczesnych metod do odtworzenia modelu wybranych cech geometrycznego złożonych elementów konstrukcyjnych współczesnych średnio-obrotowych okrętowych silników spalinowych. Dane geometryczne pozyskano w badaniach eksperymentalnych obiektów nowych i eksploatowanych w naturalnych warunkach, których pomiary niektórych cech konstrukcyjnych są bardzo trudne lub obarczone dużą niepewnością. Do pozyskania danych do modelowania wykorzystano również analizę obrazów dwuwymiarowych. Celem było ukazanie cech geometrycznych głównych elementów aparatury wtryskowej do opracowania relacji sygnał diagnostyczny – stan techniczny w diagnostyce. Badania takie również są przydatne do oceny zużycia i uszkodzeń obiektów pracujących w wyjątkowo trudnych warunkach eksploatacji.

W wyniku pomiarów geometrycznych możliwe było pozyskanie zbioru punktów i na ich podstawie opracowanie obszarów cyfrowych obiektów. Stosując program do modelowania w przestrzeni trójwymiarowej możliwe jest odwzorowanie badanych elementów.