

Measurements of the geometry of selected complex components of the injection subsystem of marine engines in terms of assessing the technical state and modeling

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ABSTRACT

The article presents the application of modern metrological measurement methods to reproduce the geometry of complex components of marine self-ignition engines. Geometric dimensions and shapes were obtained in the tests of new and operated marine self-ignition engine components. Cognitive aspects of two- and three-dimensional images were used to obtain data for modeling in design as well as technology development, diagnostics, and tribology. The scientific objective was to determine the geometry of the main components of the fuel injection subsystem after manufacture and operation for quality control and condition monitoring. Geometry tests were performed using a volumetric scanner, a laser scanner, an optical measuring machine, a high-precision coordinate measuring machine, digital microscopes with a resolution of 0.01 μm , and measurements of friction forces and the mass flow of oil and air on the constructed innovative test benches. The relative uncertainty of the fuel mass stream rate does not exceed $\pm 0.5\%$. Measurements were taken of surface micrometer readings, external and internal component dimensions, silicone castings, shape and position errors, and profile shapes that affect fuel injection. The geometric measurements of a set of points were obtained to elaborate digital images of structures for design modeling and noninvasive diagnostics. The author's scientific contribution is the evaluation of the geometry of small internal spaces of the fuel injection equipment using X-ray tomography, measurement of friction in precision pairs, and a method for estimating limit values. Multiple regression was used to select the optimal global state feature of the technical condition for quality control, with a coefficient of determination of 0.880.

Keywords: Marine engines, injection apparatus, selected components, complex geometry, state features, modeling.

INTRODUCTION

The description of the shape and spatial structure of components in marine internal combustion engines (ICEs) is a very important issue at both the manufacturing and operational stages. During production, there is significant variation in dimensions and quality, and in operation, individual components are subject to wear or damage, which can change their geometric features [1, 2]. This requires the use of scientific methods and tools.

The operation of the injection subsystem in diesel engines is determined by its design,

manufacturing technology, and operation. The technical state of the injection apparatus significantly affects engine performance, fuel consumption, harmfulness, and exhaust smoke. The most unreliable component of the injection subsystem is the injector nozzle. The design features of inside injector nozzles are most difficult to assess from geometric measurements, given their small size and limited availability [3]. Dimensions and surface conditions of spray holes were selected to influence the flow properties [4]. Measurement methods revealed weak points in the nozzles and indicated potential for optimized nozzle

geometry [5]. The multidimensional geometry of the injection subsystem's components necessitates the development of measurement methods and instruments to address measurement challenges scientifically.

The design of the injection nozzle in large marine two-stroke self-ignition engines (SIEs) differs significantly in size and in the asymmetry and eccentric arrangement of holes, compared to four-stroke engines [6]. Fuel flow studies showed significant differences between nozzle geometries with and without hydro-erosion grinding, which prompted evaluation using flow methods.

Li et al. [7] found that nozzles with smaller spray-hole diameters are more effective in improving fuel economy and reducing emissions, and that an injection angle of approximately 10° enhances engine performance. Muralikrishnan et al. [8] reported measurements of the diameter and shape of injector nozzle holes using a fiber-optic probe with very low contact force. The limitation in achieving greater measurement accuracy was mainly due to errors in the hole shapes determined by the manufacturing technology.

According to Macian et al. [9], the main reason for the lack of knowledge about the exact dimensions of injector nozzle holes is the small channel size and its excessive length. Currently, two main techniques available use nozzle geometry information: optical techniques and destructive techniques, which differ from the design values. Cutting open the nozzle is a good way to measure its internal dimensions, but it is destructive.

Guan et al. [10] determined the effect of asymmetric structural features on flow within the multi-hole injector nozzle of a marine engine. The mass flow rate and flow coefficients of the two holes on both sides were greater than those of the two holes in the center as the radius of the inlet hole corner, the diameter d_p , and the hole length increased.

Yang and Zhao [11] analyzed the effect of geometric parameters on transient flow inside asymmetric fuel injectors. Increasing the nozzle length reduces the outlet flow rate by 1.03–1.69%, and increasing the inlet rounding radius can optimize the flow structure, increase the flow velocity by 1.68–2.13%, and increase the flow coefficient by 19.30% [11].

The article [12] presented a new method for analyzing a controlled radius. The method involved analyzing the flatness of the curve under consideration and determining a measurement

characteristic. An advantage of the presented method was its ability to be implemented in the software of a coordinate measuring machine.

Monieta and Łukomski [13] presented methods and means of testing the condition features of injector nozzles. The selected state features were measured using geometric and flow tests. The majority of state features were outside the tolerance limits. Ning et al. [14] developed a 3D model to assess the effect of nozzle opening geometry on fuel flow.

The vast majority of SIEs are equipped with multi-hole injection nozzles. Manufacturing inaccuracies and nozzle geometry lead to differences in injection rates across individual nozzle holes, and this is influenced by the difficulty of producing and measuring the injector nozzle geometry [15].

Some features of the injection equipment can be measured directly using an optical microscope [13, 15]. However, difficulties arise when measuring small holes located inside the nozzle. The paper [15] demonstrated the use of modern geometric measurements to develop a digital model of complex structural elements in modern marine combustion engines (CEs). Geometric data were obtained in experimental studies of objects, and measurements of some structural features proved very difficult or prone to significant errors when using microscopy [15, 16].

In the mold technique, semi-liquid vinyl polysiloxane silicone was injected into the spray holes. The resulting mold can be measured after removal using an optical microscope or a scanning electron microscope. The accuracy was approximately 2% in measurements of the nozzle outlet diameter [2], but silicone models are prone to damage. Measurements of the nozzle geometry showed that all spray holes are offset from the needle and sack axes. Measurements showed a smaller diameter than the nominal value, with significant differences between injector nozzles.

Butmarasri et al. [17] investigated the body seat geometry and surface roughness; body seat hardness measurements were performed to determine textural and physical properties. Measurements were performed using optical microscopy and scanning electron microscopy to obtain microstructural information about the nozzle body seat. A new coordinate measuring machine method based on spatial analytical geometry theory for measuring the shape and position of camshafts [18] was published.

A linear laser measuring device and a laser displacement sensor were combined to achieve high accuracy and efficiency. Xu et al. [19] used the third-generation Shanghai Synchronous Radiation Light Source to record images of the internal structures of single- and multi-hole nozzles. The diameter and length of the nozzle holes, as well as the aperture angle, were measured. Assessing the technical condition of injector nozzles is difficult because they are sensitive to unknown geometric effects. The nozzle geometry was measured using X-ray tomography, phase-contrast X-ray imaging [19], silicone molding, and optical microscopy [21].

Wang et al. [22] obtained a three-dimensional structure of the nozzle, along with detailed information about its internal geometry, using phase-contrast X-ray imaging with synchrotron radiation. The nozzle model was verified against experimental data.

To investigate the nozzle flow during fuel injection in marine CEs, nozzle geometries were used [6]. The real nozzle geometry is more complex than that of this simplified model. The materials did not withstand the high pressures and temperatures involved in the fuel injection process.

Multidimensional simulations with varying nozzle geometries were performed, and the influence on spray characteristics was analyzed [9, 21]. It was found that nozzle sack volume, inlet hole curvature, hole inclination angle [15], the lift, and injector needle eccentricity affected the fuel flow in the nozzle.

Manufacturers of injection apparatus must control production tolerances, and researchers must assess the accuracy of the metrological techniques used in their studies. Technologies are sought to offer significant efficiency in mass production while maintaining high surface quality and geometric texture [23, 24].

Salvador et al. [2] investigated various experimental techniques to determine the geometry of a modern injector. The inlet and outlet ports, control volumes, and nozzle orifices were evaluated. Computed tomography (CT) scanning and silicone mold visualization techniques demonstrated the ability to characterize the complex shapes of internal injector components. A small-sized tactile sensor was used to measure holes with a diameter of 100 μm [24]. Characteristic signatures and roughness of the orifice walls were investigated by profiling injector nozzles with the sensor.

Jermak et al. [1] presented the application of modern methods to recreate the geometric

model of the injection subsystem components of marine SIEs. The geometric features of the injector nozzle were determined from measurements with an optical profilometer. A three-dimensional (3D) computer modeling program mapped the test component spaces. For a geometric model of a nozzle orifice, the most important parameter is the nozzle body diameter guiding the needle (D_k). Other parameters, such as the inlet radius and the length of the orifice, also affect the flow through the orifice.

Lim et al. [25] reported a study on the feasibility of predicting the attenuation of acoustic emission signals propagating in a complex solid body. The attenuation of these signals is influenced by the object's material properties and geometry.

Among the many technical state features, a set of the most important for assessing the technical condition should be selected. The most important groups of object characteristics include microgeometric and macrogeometric properties [1, 13, 18–21]. Macrogeometric features include length, width, thickness, diameter, perpendicularity, parallelism, and coaxiality, with associated permissible errors [13, 22]. Features describing microgeometry include parameters of the primary profile, waviness, and roughness [1, 8].

Mietlinski et al. [26] presented a review of existing test artifacts, classified based on geometric features. Measurement techniques such as stylus profilometry and CT were used. Existing geometries were critically assessed in surface metrology. Features were classified as [10, 13]: critical, essential, minor, or negligible. If the value of at least one essential feature exceeded its limiting value, the object was considered unusable [13].

The features of an object change during its existence and under the influence of forcing factors [13, 27]. The set of instantaneous feature values determines the object's state at a given level of knowledge and technology. A state for recognizing a CE component is a full ability technical state; its features lie within the range between the lower and upper limit values [13]. The state of knowledge described is fragmentary. Only a few publications were found on the measurement of the injection subsystem geometry and other essential components of the CEs. There are more publications on the effect of selected geometric features of injector nozzles on flow properties, engine performance, and exhaust emissions. The authors typically did not measure nozzle

geometry, but instead relied on manufacturer-provided dimensions [1, 13]. Image analysis and X-ray examinations were mainly used to assess atomization quality, rather than the technical condition. Literature rarely describes methods or devices for measuring small, discontinuous holes covered with dark carbon deposits during operation [13, 15]. In noninvasive diagnostics, on the other hand, signals are analyzed, typically without measuring technical condition parameters.

Catalucci et al. [28] presented a review of the current state of the art in intelligent optical metrology, discussing the latest advances in integrated intelligent optical solutions for measuring part geometry and surface texture. In this field, the use of a priori knowledge and the implementation of machine learning algorithms to optimize measurement planning were considered.

Few studies have examined the effect of overall nozzle geometry on the internal flow of a marine injector [10, 22], and even fewer have investigated its technical condition and artificial intelligence [29]. One of the most difficult applications of optical metrology is measuring the shape of the internal surfaces of fuel injector nozzles, due to their small diameters, long length, and the presence of deposits. The authors aimed to bridge this gap in the state of knowledge. Some authors have conducted measurements, typically using a single instrument and a single method to analyze part of the geometry. There is a lack of a comprehensive approach to mapping the geometry of the injection subsystem and linking it to diagnostic parameters and modeling.

METHODS

Selection of measuring equipment and methods

The measurements were performed in cooperation with the Department of Manufacturing Technology at the West Pomeranian University of Technology in the Surface Topography Laboratory and in Maritime University of Szczecin. The geometry values of the tested objects were measured and analyzed.

The primary scientific objective of this study was evaluation the geometry of injection system components in order to assess their manufacturing and operational quality, which are formed during manufacturing and changes during operation as a

result of wear, using selected measuring instruments and methods. The secondary objective was to develop geometric and mathematical models of the components under study for use in design and technology development, in modeling the working processes of ICEs, in diagnostics, and in tribology. The scientific objective of this study was to understand how the geometric structure develops during selected fuel injection subsystem components, dispersion in manufacturing, and change during operation as a result of wear, using selected measuring instruments and methods.

In accordance with the research objectives, the following hypothesis was formulated: It is possible to map the geometry of complex components of the injection subsystem in marine ICEs using selected measuring instruments and methods, as well as to apply these scientifically selected mapping features in diagnostics and modeling of the fuel injection process.

The research methodology consisted of the following stages:

- Microgeometric measurements of the surfaces of injection apparatus components manufactured using various methods;
- Comprehensive evaluation of the geometry of injection molding subsystem components using high-precision 3D metrology;
- Assess the geometric structure of tested objects using measurement techniques;
- Development of geometric models using reverse engineering tools;
- Measurements of microgeometric changes in friction pairs, such as roughness and waviness;
- Statistical analysis of the results and construction of geometric and mathematical models.

The following measuring devices were selected to solve the research problems: a Phoenix V|tome|x S volumetric scanner (tomograph) used in non-destructive testing of products, a Quick Vision Hyper 302WLI optical measuring machine with a WLI x25 interference lens, Mitutoyo Starto-Apex 574 coordinate measuring machine, and others. The surface topography was scanned with a MITUTOYO HYPER WLI device with a WLIx26 interference sensor. The results were processed using MCube MAP ULTIMATE 8, and the data were processed using DG/LTD LAB. The study also utilized a RIEGL VZ 2000i laser scanner and a state-of-the-art VHX-X1 optical digital microscope with fiber-optic transmission from Keyence.

For the structure geometric surface (SGS) Interferometric System on the MITUTOYO HYPER WLI, the values were determined based on the standard deviation of the measurement series σ_{sx} , increased by the expansion factor $k(\alpha) = 2.0$ (covering the $\alpha = 0.954$ confidence interval around the mean value), and were used to calculate the measurement uncertainty U_{sx} according to the relationship $U_{sx} = \sigma_{sx} \cdot k(\alpha)$, yielding the values. A measurement error is the difference between the measured value and the true value. In contrast, uncertainty is the estimated range (interval) within which the true value is likely to lie with a probability of at least $\alpha = 0.683$ (expansion factor $k(\alpha) = 1.0$). In some cases, the uncertainty is specified on the instrument's calibration certificate.

Uncertainty propagation for explicit multidimensional measurement models, it involves determining the relationship between the vector output $Y = (Y_1, \dots, Y_m)^T$ and the vector input $X = (X_1, \dots, X_j)^T$ in the form $Y = f(X)$, where $f = (f_1, \dots, f_m)^T$ is a multidimensional measurement function. Associated with the estimate $x = (x_1, \dots, x_j)^T$ of the input vector is a $j \times j$ covariance matrix of pairs:

$$U_x = \begin{bmatrix} u(x_1, x_1) & \dots & u(x_1, x_j) \\ \vdots & \ddots & \vdots \\ u(x_j, x) & \dots & u(x_j, x_j) \end{bmatrix} = \begin{bmatrix} u^2(x_1) & \dots & u(x_1, x_j) \\ \vdots & \ddots & \vdots \\ u(x_j, x) & \dots & u^2(x_j) \end{bmatrix} \quad (1)$$

since $u(x_i, x_i) = u^2(x_i)$ is the variance associated with the component x_i , $u(x_i, x_j)$ is the covariance associated with the components x_i and x_j , i and j are the numbers of the input and output variables.

The data on the equipment used, measuring devices, were selected to solve the research problems, as presented in Table 1. Geometric measurements were performed under reference conditions using air conditioning.

The root mean square errors of the measurements of macro- and microgeometric characteristics and flow parameters are presented in Table 2. An example of estimating the absolute error for the mass flow stream of oil is as follows:

$$\sigma(q_m) = \sqrt{\left(\frac{\partial q_m}{\partial m} \sigma(m)\right)^2 + \left(\frac{\partial q_m}{\partial \tau} \sigma(\tau)\right)^2} \quad (2)$$

where: $\sigma(m)$ – mass measurement accuracy,
 $\sigma(\tau)$ – time measurement accuracy.

The relative errors were estimated relative to the measured values and expressed as a percentage.

The relative uncertainty of the fuel mass stream rate, with an expansion factor $k(\alpha) = 2$, does not exceed $\pm k(\alpha)\sigma(q_m) = \pm 0.5\%$.

The AL20 II 7 injector nozzle was placed in the Quick Vision Hyper 302WLI, where the principle of measuring a series of profiles with an optical device is similar to that of a contact device. Light reflection and interference fringes occurred separately on the tested surface at the measurement point, and the SGS state was tested in the body's guide section and on the spire. A smaller fragment containing approximately 87 million points was cut out from the entire tested surface (approximately 9 GB of data) [23].

The QVPAK-Untitled program was used to measure roughness in accordance with the PN ISO 21920-1–3 standard. The roughness of the bodies and needles of the operated AL20 $9 \times 0.25 \times 159^\circ$ (Figure 1) was measured in planes

Table 1. Data on the selected measuring equipment

Measuring system	Maximum uncertainty [μm]	Resolution [μm]
Optical MITUTOYO HYPER WLI	$MPE_{EXY} = 0.8 + 2.5 \times L/1000$	0.1
Optical geometric structure MITUTOYO HYPER WLI	$U_{Ra} = 0.032$	0.1
Mitutoyo Starto-Apex 574 Mitutoyo Europe GmbH	$MPE_{EXY} = 0.7 + 2.5 \times L/1000$	0.1
Computer tomography Phonix V tome x	$U_{Lx} = 1.2$	0.1
Olympus DSX500 opto-digital microscope	$\pm 3\%$	0.01
VHX-X1 optical digital microscope Keyence	0.2	0.1
Keyence VR-6000 + VR-6200 measurement system	0.4	0.1
Marameter 844K Intramess Mahr	1.5	0.0

Note: MPE_{EXY} – maximal permission error.

Table 2. Absolute error values for the macro- and microgeometric characteristics of spray nozzles: $\sigma(D_k)$ – diameter of the needle guide body, $\sigma(d_i)$ – diameter of the needle guide, $\sigma(L_a)$ – average diametrical clearance, $\sigma(h_{max})$ – maximum needle stroke, $\sigma(\alpha_i)$ – needle apex angle, $\sigma(q_m)$ – mass flow stream of the fuel metered

Quantity	(D_k)	$\sigma(d_i)$	$\sigma(L_{sr})$	$\sigma(h_{max})$	$\sigma(\alpha_i)$	$\sigma(q_m)$
Unit	[μm]	[μm]	[μm]	[μm]	[$^\circ$]	[kg/s]
Error	± 0.2	± 0.01	± 0.15	± 0.3	± 1.5	± 0.02

P1, P2, and P3, and of the new L16/24 engine. The results of the surface topography measurements are presented as 2D and 3D images, along with surface roughness profiles, also in selected cross-sections. Cross sections of the elements were made to measure channels that are difficult to access and are covered with carbon deposits.

The injector nozzle body of the AL20 $9 \times 0.25 \times 159^\circ$ with a cutout along the well, is shown in Figure 1a, and the needle measurements are shown in Figure 1b. MITUTOYO MCubeMAP software was used to determine selected SGS indicator values that define the three-dimensional surface state.

When measuring roughness, the instrument head was too large, so this part of the measurements was performed using the PFF white-light lens focusing differentiation method. It was not possible to measure the roughness on the state surface of the cone by the interference method, nor by the white light lens focusing method.

The geometric accuracy and internal structures of the fuel supply system components were examined using CT. An X-ray beam was generated in a volumetric scanner at 200 kV and 400 μA . To ensure accurate measurements, the detector and voxel spatial resolutions were calibrated before the examinations. For this purpose, 4500 images of the reference standard were collected

and averaged during reconstruction to 1500 images. The calibration standard (TYPE VTX18CG00) consisted of ruby spheres with axes spaced at a calibrated value of 99.9347. To ensure accurate measurements, the detector and the voxel spatial resolution were calibrated before the actual examinations. After calibration, the overall dimension of the injector nozzle was measured at 76.0 mm.

The reconstruction of X-ray images into a 3D model was performed on an external computing unit connected online to the Phoenix V|tome|x S tomograph. VG Metrology 2024 software was used to calculate geometric errors and selected length values. This software uses recognized algorithms to determine length and angle values as well as shape, direction, and position errors, and is PTB and NIST-certified. After two repetitions of the calibration scans, a voxel volume of $0.2 \mu\text{m}^3$ was achieved at the lowest resolution of the tomograph. During the assembly of X-ray images (256 gray levels), the material of the tested object was determined from the median value at the peak. The entire material of the tested object fell within the gray-level values of $\pm 3\sigma$ (standard error) of the median. Contact scanning of the geometry of the delivery valve and a fragment of the camshaft was performed using an APEX STRATO 574 device, shown in Figure 2.

It is essential to determine the technical state of engine components during manufacture and

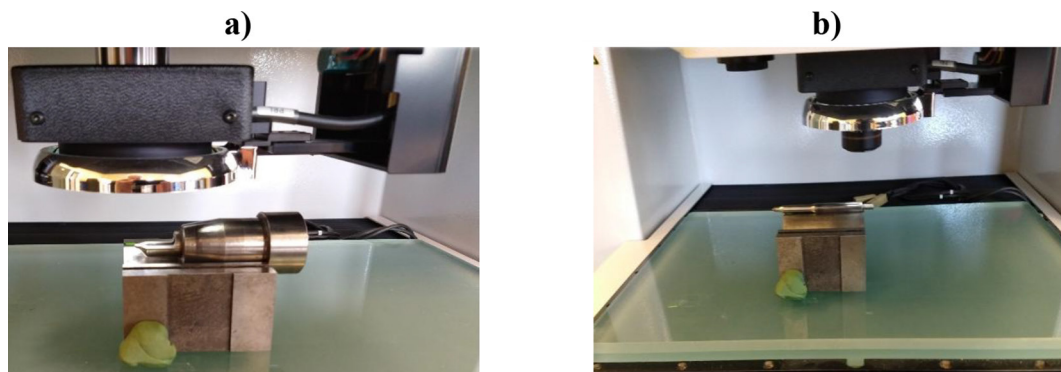


Figure 1. Measurement of the roughness of a partially cut AL20 injector nozzle body a) and the used needle b)

operation, and to identify how CE components wear. Using three-dimensional modeling programs, the geometry of the tested components can be mapped from measurement results.

A self-centering digital caliper with an 844K [13] expansion tip was used to measure the inner diameter of the nozzle body's guide section D_k . Before the measurement, the sensor was zeroed against a master ring, the dimensions and form errors of which were measured with even higher resolutions. Diameter measurements were performed in three planes perpendicular to the longitudinal axis and in four cross-sections passing through their axes at 45° intervals.

The measurement procedures for the other measuring instruments are analogous and described in their user manuals as well as in the following general instructions. Optical measurement technologies relate to photogrammetry and involve reconstructing a three-dimensional (3D) point cloud from two-dimensional (2D) images of the measured object. A three-dimensional point cloud consists of a set of Cartesian coordinates x , y , z . This is achieved through methods for characterizing and calibrating photogrammetric systems [28]. Software and techniques for analyzing results support hardware technologies. The procedures focus on developing new machine learning methods for data analysis [29] and new ways to search point cloud data.

Algorithms can be used to align and filter point clouds. Preliminary processing aims to improve aspects of the point cloud, such as part coverage and point sampling, as well as to develop and optimize methods for determining point features, surface model fitting, and point cloud registration. The knowledge gained from this research will enable the selection of the most reliable measurement methods and devices for various types of surfaces at the micro- and nano-scales.

Test objects

The selection of injection system components was based on reliability investigations, which found the fuel supply system and the injection subsystem to be the most unreliable system and components of marine engines fueled by distillate fuels [30]. The studies covered engine types widely used by the largest domestic shipowner, and in which problems had been encountered. The percentage shares of the most frequently tested engine types were as follows: 6AL20D 31.5%, L20D2 25.9%, and L16/24 16.7%. The types of engines tested varied as the shipowner renewed its fleet.

Geometric data were obtained during experimental tests of new and operated marine CE components, where measuring specific design features is very difficult or prone to significant errors and uncertainties. Measurements of the roughness of the injector nozzle bodies and needles of operated AL20 engines were carried out, some of which were partially cut along the well or along the longitudinal axis. A new L16/24 injector nozzle was also tested.

The nozzle of the electronically controlled main drive engine 50 ME-B9 was examined using a tomograph. Testing large products was limited by the high density of materials with high hardness [23]. The geometry of the MAN L16/24 auxiliary engine nozzle and the geometric state of a smaller nozzle from the H1LMK 148/1 common rail system with three spray holes were examined using a tomograph. Fitting diameter errors were checked using the contact scanning method, with 340 points per tested cross-section.

X-ray tomography was also used to perform geometric measurements of the AL20 delivery valve mushroom with a diameter of $\varnothing = 15$ mm. The same method was also used to examine a



Figure 2. View during scanning of the geometry of the delivery valve a) and a fragment of the camshaft b)

fragment of the A20 engine injection pipe with a threaded connection fitting.

Reliability investigations were conducted on marine engine injectors, which revealed that the majority of damages occurred during the initial period of operation, indicating an initial unreliability caused by inadequate quality control during manufacturing and maintenance.

Methods for testing the technical state of marine engine components

Based on a solid model, it is possible to develop a signal-technical state relationship and a technical drawing, and to produce a prototype with 3D printing [31] that would be difficult to purchase and transport to a ship. The methods used allow determination of the external and internal geometric dimensions, thereby obtaining condition-signal relationships in the object's diagnostic model [1, 13, 15].

The research involved measuring the geometric features of injector nozzles, injector valves, injection pumps, fuel injection pipes, and camshafts. The recorded measurement results were presented in tables, with the average value being the final value for many features. Some threshold values for technical state features were provided by the manufacturers, while others refused to disclose them; therefore, the author's patented method (PL 246619 B1) was used to estimate the lower and upper limits based on three standard errors of the mean (average $\pm 3 \frac{\sigma}{\sqrt{j}}$). For dimensions subject to general tolerances, the dimensional class tolerances in accordance with IT 6–IT 9 were adopted.

Such studies are also helpful for assessing wear and damage to objects operating under harsh conditions. The value of the friction force was also adopted as a technical state feature [15].

The recorded surface profiles allow the geometric structure of the surface to be described in three dimensions. The focus was on analyzing the primary (unfiltered) microstructure profile and the waviness of the macrostructure.

To classify the surface profile and verify design and technological requirements, a quantitative description was introduced using numerical parameters that characterize the profile state in accordance with standards EN-ISO 25178-2:2015 [32] and others. Important parameters for surface evaluation in research include ordinate value, evaluation height, recess depth, and profile

element width. Since the nozzle needle is part of the injector nozzle, a topographical analysis must be performed to evaluate it [23]. Representative features of the object's condition should be selected for technical state assessment.

RESULTS

Roughness measurements

This section presents the results of surface roughness measurements of injector nozzles. Surface roughness measurements were performed. The surface view was mapped using the 3-point method. The roughness of the nozzle body of the used AL20 9 × 0.25 × 159° II 7 was measured. Higher roughness but better anisotropy was obtained.

There is left-hand skew, with valley volume peaks due to machining and wear. The analysis of the mapped 3D roughness surface using a Gaussian center-profile filter of 0.08 mm is shown in Figure 3. A limitation affecting the measured SGS values was the misalignment of the cut nozzles, and cutting the samples for geometric measurements is a destructive process.

The roughness of the AL20 9 × 0.25 × 159° II 7 nozzle in use was relatively low (small Ra). Still, the extreme values Rz indicate a significant spread in the heights of surface peaks and the depths of their valleys. The design value Ra = 0.0 μm, and the measurements showed 0.08 mm. The measured average Ra was $53.5 \pm \sigma = 16.4 \mu\text{m}$ from many averages in the X–Y plane.

Deposit, oxidation, and corrosion affected the result. The surfaces were scanned with an MITUTOYO HYPER WLI device. During the analysis, the average surface roughness was calculated. However, the Rz indicator is “more sensitive,” and depending on the degree of wear on the same surface, its value may change by 200–300%. The Rq parameter effectively reflects the mean-square distance of irregularities from the average surface profile. On the other hand, the value of the Rz index is often influenced by two extreme values among millions of points.

The roughness of the new nozzle hole is very high (Ra = 18 μm, Rz = 17 μm), which results from electroerosion rounding of the inlet edge [23, 27, 29]. The operated scan of the needle surface and needle cross-section measurement of AL20 9 × 0.25 × 159° II 7 are shown in Figure 4.

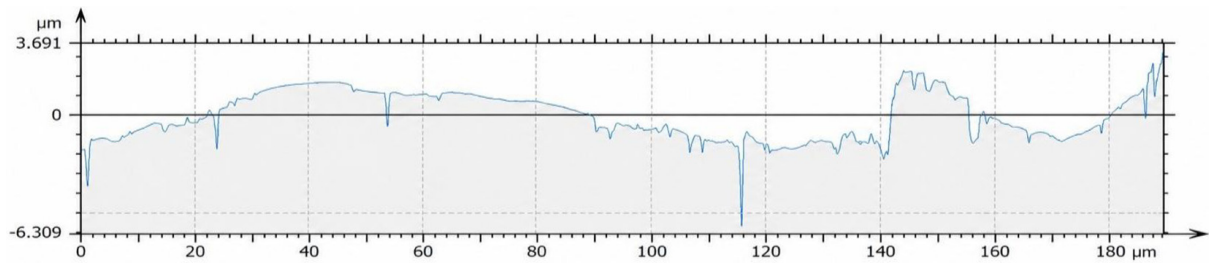


Figure 3. Analysis of the mapped roughness surface using a 3D Gaussian filter and roughness measurement results of the roughness profile

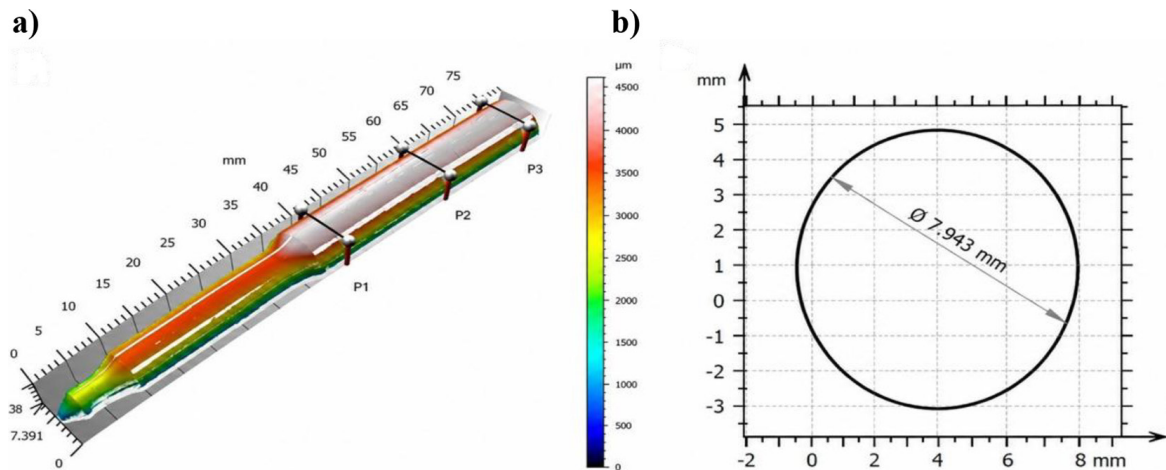


Figure 4. View of the mapped surface of the needle a), and measurement of the diameter in the P2 plane b)

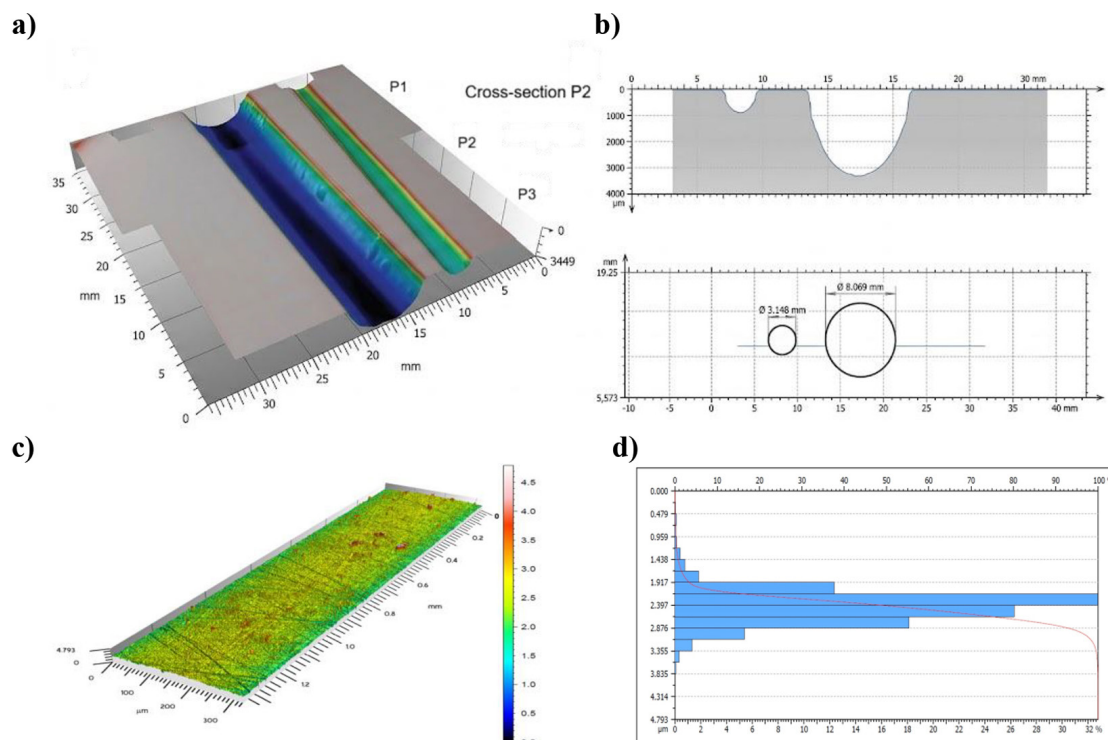


Figure 5. View of the mapped surface of the cut nozzle body a), measurement of the body guide diameter b), view of the body surface roughness without a filter c), and the Abbott-Firestone curve after removing peaks (threshold) and leveling with the average plane (LC) d)

Figure 5a shows a view of the mapped surface of the cut nozzle body, measurement of the body guide diameter (Figure 5b), a view of the roughness of the body surface without a filter (Figure 5c), and the Abbott-Firestone curve after removing peaks (threshold) and leveling with the mean plane (LC) Figure 5d).

Red spots near the spray channel indicate overexposure, and brown spots indicate higher material density. Other authors have studied small automotive nozzles using X-rays [7, 19].

Measurements of the geometry of injector nozzles using microscopy and a mass stream

The diameters of the spray holes were measured using, among other methods, a VHX-6000 microscope with bottom illumination (Figure 6a). A limitation of these measurements was that the spray channels were not continuous cylinders; they exhibited roundness and cylindricity errors and were covered with dark deposits. Other authors have not demonstrated this [8, 24]. Measurement nanotechnology was applied using a DSX 500 type opto-digital contactless microscope (Figure 6b). Born of leading-edge opto-digital technology, the Olympus DSX500 offers, e.g., digital microscope for complete inspection and accurate analysis. The results of the measurements of the orifice shown in (Figure 6b) are presented in Table 3.

The hole diameters were successfully measured non-destructively using the Keyence VR-6000 and VR-6200 measurement system (Figure 7). Unfortunately, this method did not allow for the measurement of deep and small holes, nor were better results achieved at Toyota in Japan.

Table 3. Results of the measurements of the geometry of the spray hole

No.	Distance [μm]
1	250.169
2	239.819
3	261.556
4	333.055
Count	4
Average	271.150
Max.	333.055
Min.	231.819
Range	93.236
σ	37
3 σ	110

Given the limitations of microscopic measurements, flow measurements of Shell Calibration Fluid B or air were used to determine the geometry. By treating the atomizing channels as measuring nozzles, the average cross-sectional area of the orifices can be calculated from the mass flow rate of the medium using the following equation:

$$q_m = \mu_r \varepsilon A_r i_r \sqrt{2 \Delta p \rho_{p,t}} \quad (3)$$

where: $A_r = \frac{\pi d_r^2}{4}$ – cross-sectional area of the nozzle orifice, i_n – number of injector nozzle holes, μ_r – flow number, Δp – pressure difference between the injector nozzle chamber (well) and the combustion chamber, ε – expansion number, $\rho_{p,t}$ – density of the flowing fuel at pressure p and temperature t , determined for conditions immediately upstream of the orifice.

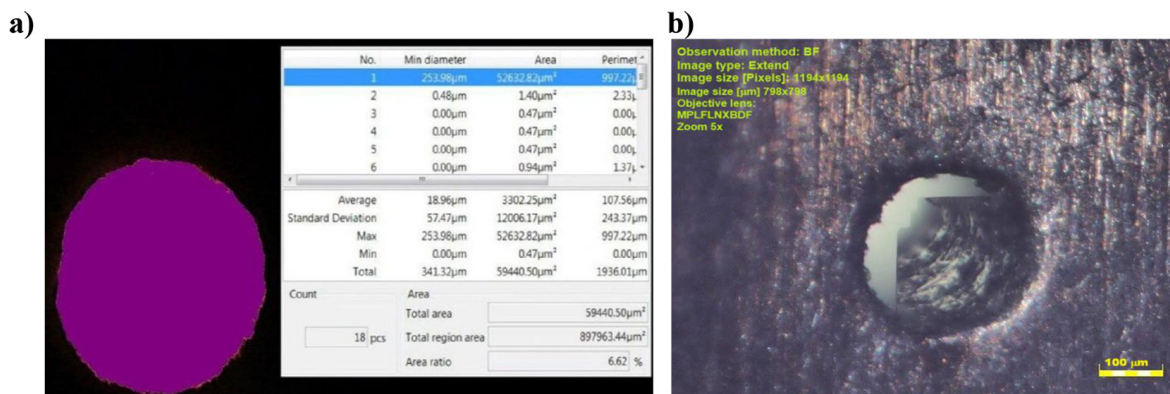


Figure 6. Measurements of the geometry of injector nozzle orifices using a VHX-6000 microscope a), and a DSX 500 contactless optical-digital microscope b)

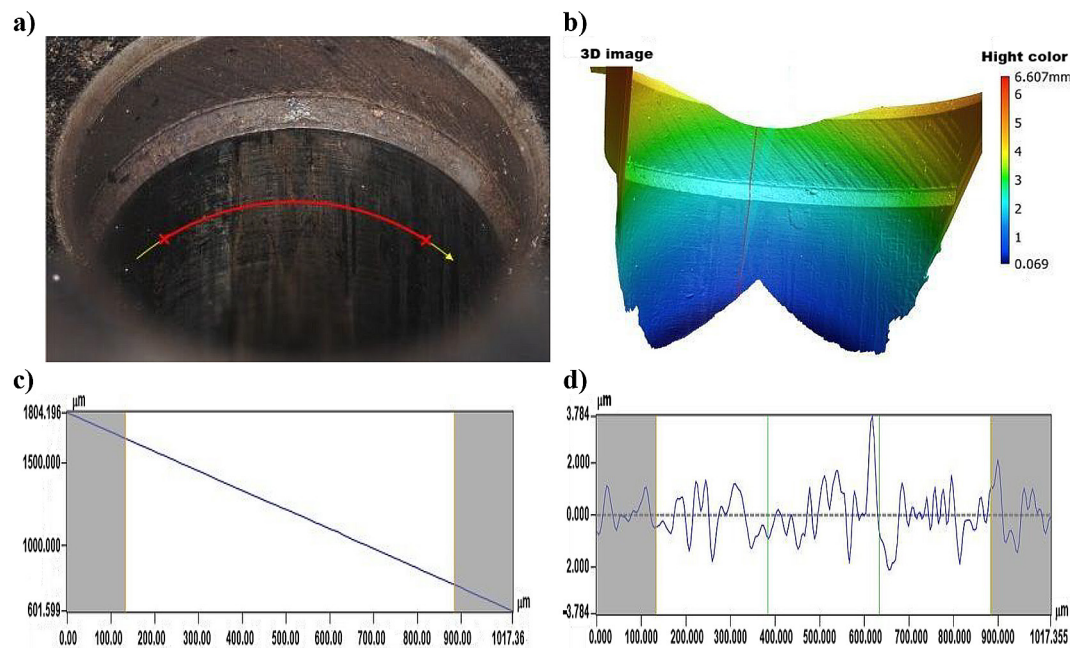


Figure 7. Measurement of the arc of the nozzle body hole (a), 3D image (b), total profile (c), and roughness/primary/waviness profile (d)

Computed tomography scans

Figure 8 shows a scan of the engine injector nozzle along the longitudinal axis, showing the choke space (Figure 8a) and spray holes (Figure 8b), as well as a 3D scan created using a stationary laser scanner in conjunction with a computer (Figure 8c) of the L16/24 engine. The 3D laser scanning technology has a natural advantage in measurement, particularly for contact measurements and the detection of complex components that cannot be measured otherwise. However, measuring small spray holes has proven unsatisfactory. Laser and X-ray scan results revealed the most significant

defects, particularly at the edges and joints of the components.

There is a tight fit between the guide part of the body and the nozzle needle, so that it is impossible to distinguish between them in Figure 8. A Marameter 844K Intramess Mahr self-centering digital bore gauge with an expandable tip and floating holder. Inductive digital comparators were used to measure the inner diameter gauge of the nozzle body's guide part [13]. Using a tomograph, the angle between the body seat and needle was approximately 60°. The diameter of the guide part was approximately 6 mm. The angle of the seat in the nozzle body is challenging to measure without cutting it.

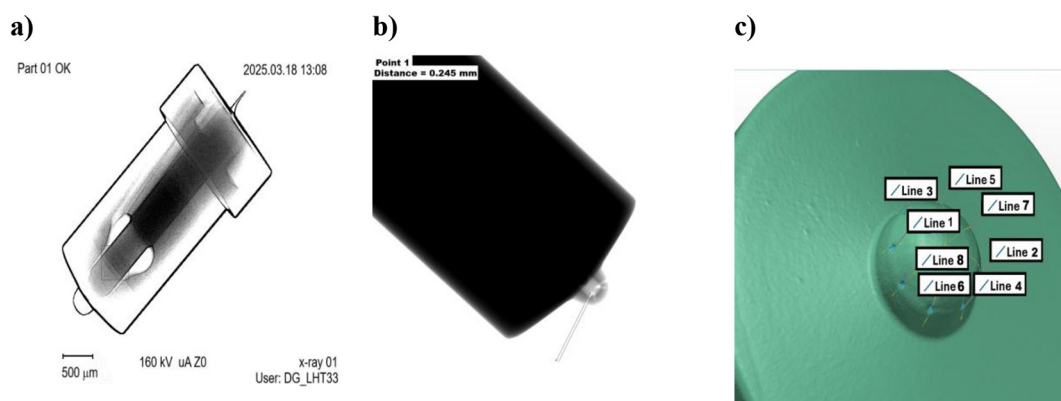


Figure 8. Tomogram of the injector nozzle along the longitudinal axis a), spray holes b), and 3D scan of the L16/24 engine nozzle c)

The spray holes turned out to be conical. The surface covered with deposits in the well and spray channels is highly porous, which affects fuel-flow losses. Therefore, some injector nozzles were found to be initially disabled or to have short durability in flow measurement [13].

Figure 9a shows a tomographic scan of the nozzle body of the 50 ME-B9 main engine injector nozzles. Figure 10a shows tomogram images and attempts to measure interesting features of the technical state of the entire injector nozzle and the well. There were constrictions in the center of some holes (Figure 10b) acting as a measuring orifice. Significant differences in image quality were obtained depending on, among other things, different sampling steps [20]. An attempt was made to use an alternative method involving a special silicone to create internal nozzle molds (Figure 10c). After the molds were obtained, they were photographed under a microscope and measured. This method allows for the mapping of dimensions in areas that are not visually accessible and is also non-destructive. As can be seen in the figure, the injection channel castings broke off when removed from the nozzle body, which posed a problem.

The collection of object dimensions in the form of a library enabled the development of geometric models of individual elements, but the edges are blurred in the X-ray images. Figure 9a and 10b confirm that the design of the injection nozzle in large marine two-stroke engines differs significantly in size and in the asymmetry and eccentric arrangement of holes [6].

Due to its simple design (Figure 2a), testing the delivery valve body geometry posed no problems. However, the delivery valve head has a geometrically complex shape and numerous design details; in this case, evaluation was performed using X-ray tomography (Figure 11a).

The geometric model reconstruction tests for the fuel high-pressure pipe fitting are shown in Figure 11b.

Geometry reconstruction involves converting measurement data (point cloud) into a three-dimensional computer model [1, 13, 29]. Shape errors of injector subsystem components, including cylindricity, were measured.

Results of geometry mapping on a coordinate measuring machine

Figure 12a shows the outline of the cam (a) and the roundness assessment of 0.0515 mm of the journal with 2932 measurement points (Figure 12b) of the camshaft of the L16/24 engine. The cam profile of the camshaft needs to be mapped to model the fuel injection process [1, 22]. This is because its geometry determines the change in the position of the injection pump piston. The cam profile data was provided as a table with roundness errors. Based on geometric measurements, macro- and microscopic image analysis, and 3D scanning, a set of points was obtained from which real objects were mapped [1, 23]. Figure 12c shows a segment of the camshaft with complex geometry and its geometric model (Figure 12d) of the L16/24 engine.

The cam profile of the camshaft needs to be mapped to model the fuel injection process [7, 15]. This is because its geometry determines the change in the position of the injection pump piston. The cam profile data was provided as a table with roundness errors.

Reverse engineering is a fundamental process in modern industry, involving the reconstruction of a digital 3D model of a physical object the original design documentation of which is unavailable or requires verification [31]. This study focused

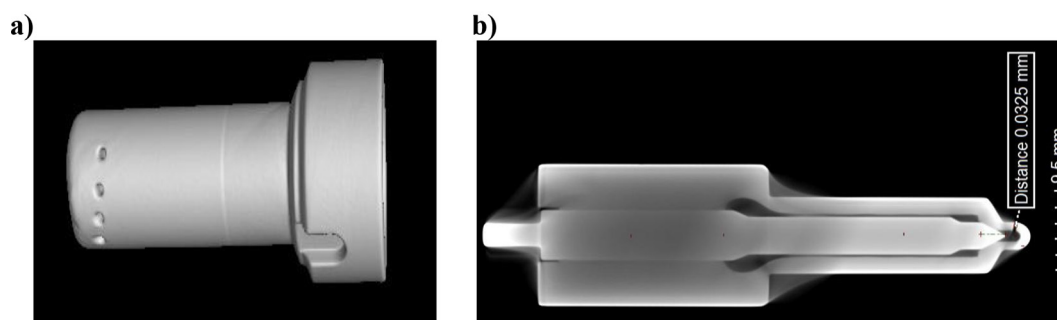


Figure 9. Images of the injector nozzle of the 50 ME-B9 marine main engine scanned in a tomograph, showing a side solid model a), a tomogram along the longitudinal axis of the common rail injector nozzle channel b)

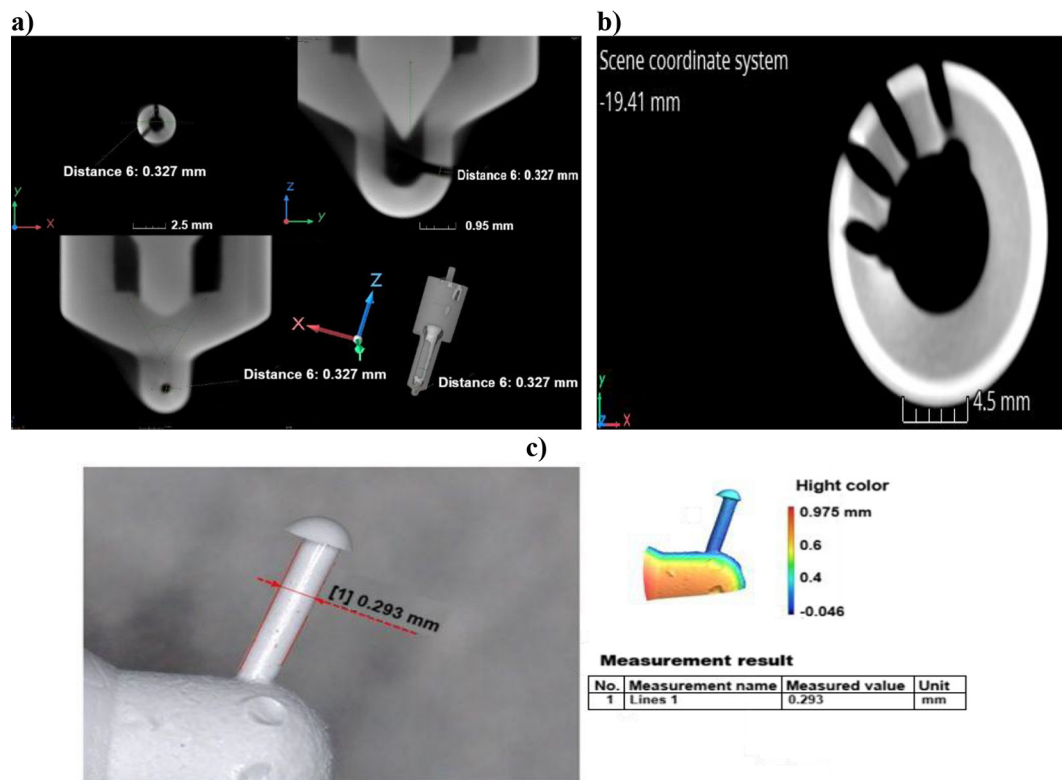


Figure 10. Tomogram images and measurement attempts of interesting technical features of the entire injector nozzle and the nozzle seat a), spray holes of the injector nozzle of the 50 ME-B9 engine b), and measurement of the silicone mold of the spray channel c)

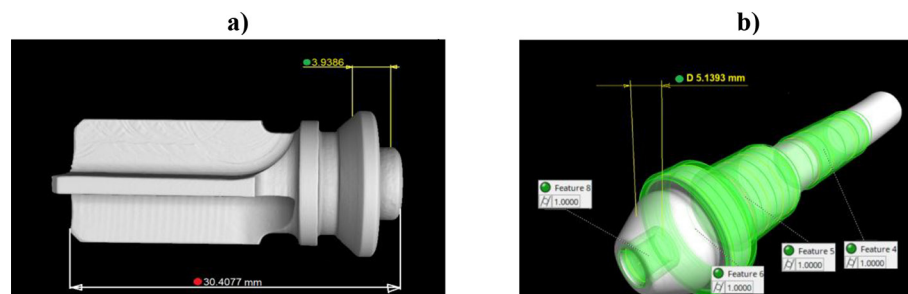


Figure 11. Mapping of the complex geometry of the AL20 engine delivery valve head with $\varnothing = 15$ mm 2D a), and attempt to recreate the geometric model b)

on coordinate measuring systems capable of generating the rapidly digital point clouds required for surface reconstruction and computer-aided design (CAD) modeling. The machine results demonstrated that this method is sufficiently accurate [12] for measuring the geometry of larger components of marine ICEs. The physical object was transferred to a computer-generated virtual reality environment, and once the material (Figure 13) was identified, the reconstructed component could be 3D-printed.

Due to the high pressures (over 200 MPa) and micrometer-level tolerances, it is important

to consider the key characteristics of the injection system components:

- The diameters of the precision pairs of the piston and cylinder, as well as the injection pump's discharge valve, the injector needle, and the orifices of the injector nozzle body, for measuring clearances in the precision pairs.
- The stroke of the injector needle determines the maximum opening of the injector.
- The diameter and shape of the nozzle orifices – quality control of manufacturing and wear (whether the orifices are enlarged, have shape defects, or are covered with deposits).

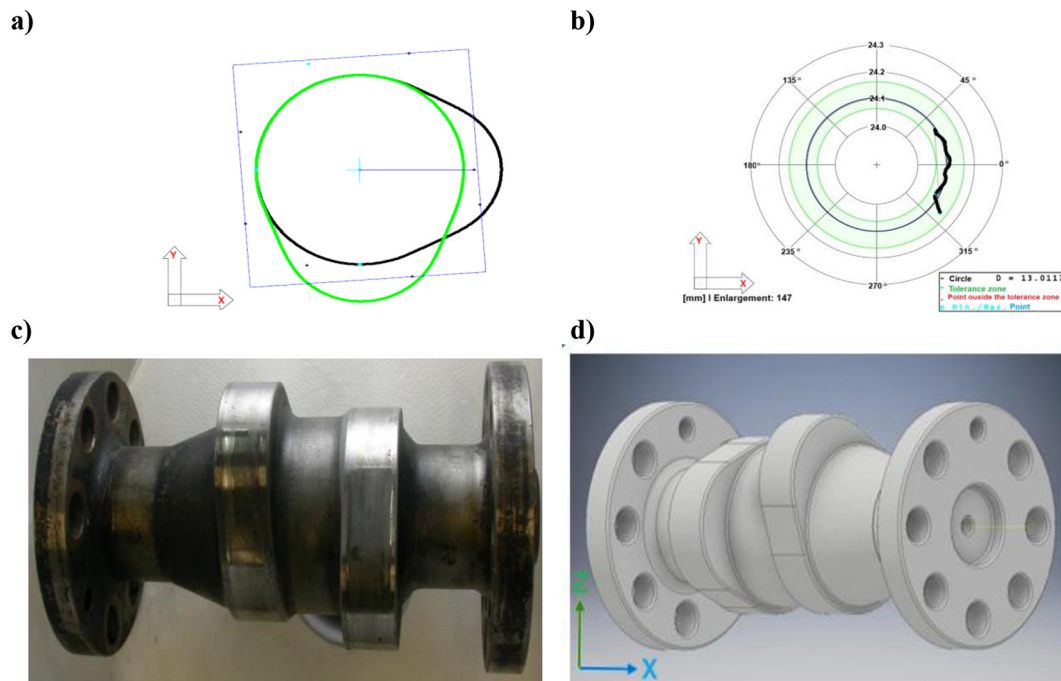


Figure 12. The cam edges of the camshaft a), assessment geometry structure of the roundness of the camshaft journal b), a segment of the camshaft with complex geometry c), and its geometric model d), of the L16/24 engine

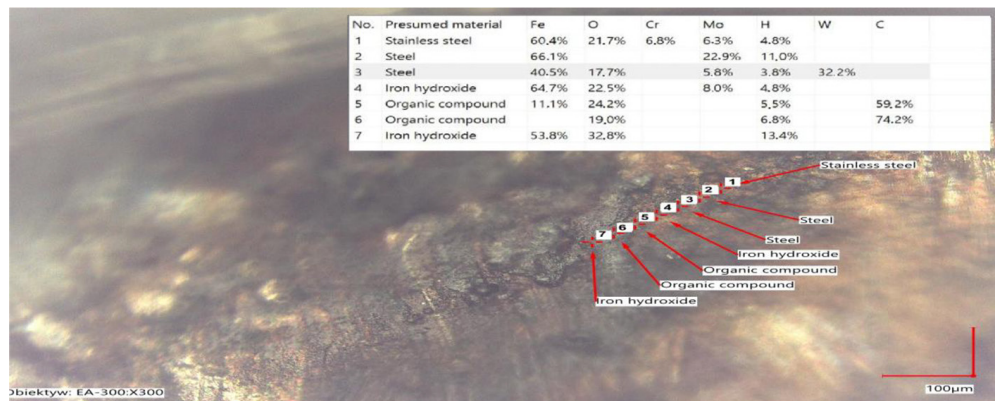


Figure 13. Identification of the material of the tested component and the present deposit using a VHX-X1 series microscope

- The angles of the sealing cone in the body seat and the nozzle needle.
- The flow time of 5 kg of Shell Calibration Fluid B under a constant pressure of 10 ± 0.05 MPa and at a temperature of 35 ± 2 °C was adopted as the measure of the characteristics of nozzle orifices. The built flow test rig consisted of an electronic scale and a stopwatch.
- Maximum friction force between the guiding parts of the friction pairs, up to complete insertion, by applying hydrostatic force or on a tensile testing machine using patented devices and methods [15, 29].

- Seal tightness: measurement of the angles and sealing surfaces of the nozzle.

Measurements of the geometry of marine engine injection systems have significant scientific and implementation significance, focusing on optimizing combustion processes, improving reliability, and diagnosing technical conditions.

The technical state of the injection subsystem depends on the geometry of its components:

$$S_i = f(G_c, G_{ip}, G_{dv}, G_{hp}, G_{iv}, G_{in}) \quad (4)$$

where: G_c – camshaft geometry, G_{ip} – injection pump geometry, G_{dv} – delivery valve

geometry, G_{hp} – fuel injection pipe high-pressure geometry, G_{iv} – injector valve geometry, G_{in} – injector nozzle geometry.

For example, for a camshaft, it can be written that its geometry primarily includes:

$$G_c = (G_{bp} \cup G_{ep} \cup G_{sw} \cup G_{fc}) \quad (5)$$

where: G_{bp} – bearing journal geometry, G_{ep} – end journal geometry, G_{sw} – gear geometry, G_{fc} – fuel cam geometry.

Fuel cam geometry, in turn, is the sum of the highlighted technical state features and not considered:

$$G_{fc} = b_c \cup R_{pc} = (\alpha) \cup E \cup h_c \cup R_{pc} \cup R_v \cup R_z \cup R_c \cup R_t \cup R_a \cup R_q \cup \dots R_{ku} \cup G_{sw} \cup F_{fmax} \cup \dots \quad (6)$$

where: b_c – cam width, $R_{pc} = (\alpha)$ – cam arc radius for angle α , h_c – cam lift, E – longitudinal elastic modulus of cam material, $R_p \dots R_{ku}$ – as in Figure 3, F_{fmax} – maximum friction force.

The final values for many features were taken as the average, and the maximum needle stroke (h_{max}) was taken as the smallest value across all measurements. For the measurement of the needle cone apex angle α_p , the arithmetic mean of the measurements was taken as the final value. The results of measurements of many design features for the tested injector nozzles indicated that they do not fall within the tolerances for ability (Figure 14a).

Based on the results of measurements of the diameters of the nozzle body parts guiding the needles D_k and the diameters of the needle-guiding

parts d_i , the clearances were determined: minimum L_{min} and maximum L_{max} . The minimum clearance L_{min} is the difference between the minimum value of D_k and the maximum value of d_i in a given measurement plane:

$$L_{min} = D_{kmin} - d_{imax} \quad (7)$$

The maximum clearance L_{max} is the difference between the maximum value of D_k and the minimum value of d_i in a given measurement plane:

$$L_{max} = D_{kmax} - d_{imin} \quad (8)$$

The state features of the tested injector nozzles were measured. Most were found to be inoperable outside the manufacturer-specified tolerance ranges (Figure 14a). Based on the data in Figure 14b, the repeatability of the results was calculated using the coefficient of variation as the ratio of the standard deviation σ to the mean value q_{ma} and expressed as a percentage:

$$V_v = \frac{\sigma}{q_{ma}} 100\% \quad (9)$$

The coefficient of variation V_v was 27%, indicating a very high degree of variation in the mass stream rate results for individual measurements for various nozzles, and 1.9% for repeated measurements of a single nozzle. In contrast, for measuring the friction force of a single nozzle across 36 planes, it was 0.0038%, indicating good measurement repeatability.

The greatest problem was the mass flow rate of the fuel, which depends on the geometry of the injection channels (Figure 14a). The probability

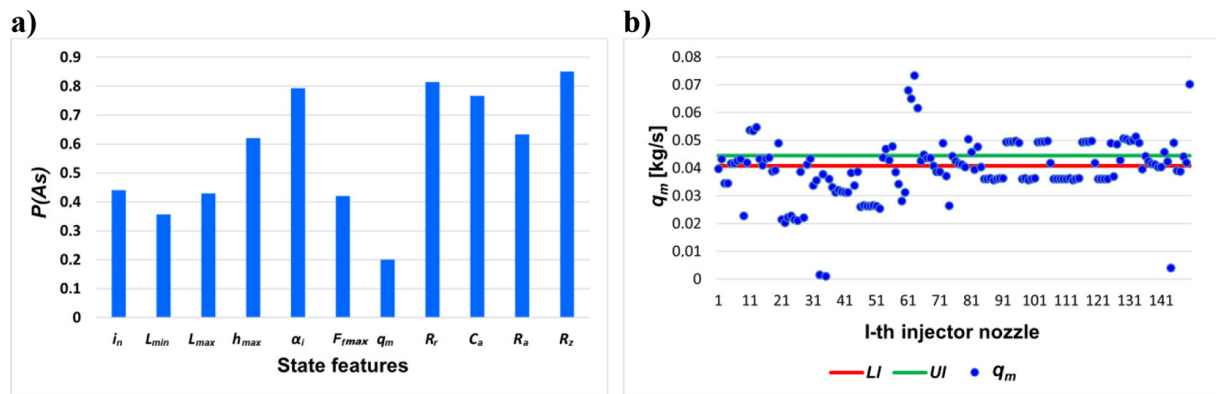


Figure 14. Probability of meeting the ability criteria based on the considered features of the technical state of injector nozzles a), and mass flow values in the flow method relative to the lower limit L_l and upper limit value U_l b): i_n – number of unobstructed spray orifices, F_{fmax} – maximum friction force, R_r – runout of the nozzle guide hole surface, C_a – coaxiality of the seat and the nozzle guide part, $P(AS)$ – probability of an ability state

of meeting the ability criteria based on mass flow values in the flow method was 0.2. Figure 14a and the formulas for technical condition justify the choice of measurement methods and instruments.

During the analysis of the measurement results, correlations were sought between diagnostic parameters, friction force, and other quantities and the technical state features using linear regression functions $f(x) = ax + b$ and polynomial functions, most commonly quadratic:

$$f(x) = ax^2 + bx + c \quad (10)$$

Multiple regression was applied for nonlinear models and second- or higher-degree polynomial models. Multiple regression allowed answering the question: which variables best describe the relationships between diagnostic symptoms and technical state features.

Using multiple regression, we determined which technical state features have a significant influence on the amplitude values of the envelope components of the injector needle displacement spectra (Table 4). The table shows that the greatest influence is exerted by the flow characteristics of the injector (fuel mass stream q_m), followed by the fuel rack setting N and the camshaft rotational speed n , i.e., the test conditions. Therefore, during injector quality control, the fuel setting and rotational speed must be precisely determined to define the test conditions.

The analyses performed in Statistica showed that the best diagnostic feature is the amplitude of the first component of the nozzle needle displacement spectrum, H_{h1} :

$$H_{h1} = f(P_w, F_f, i_n, d, L_a, h_{max}, \alpha_i, n, p_z, t_p, q_m) \quad (11)$$

where: F_f – friction force, i_n – a number of spray holes, $L_a = (L_{min} + L_{max})/2$ – the average diameter clearance between the mating surfaces, P_w – injector opening pressure, p_z – injection pump fuel feed pressure, t_p – fuel temperature at the injection pump inlet.

After applying the stepwise regression model, only the variables q_m , P_w , d , i_n , n , and N . Since N and q_m are highly correlated, and q_m is more strongly correlated with H_{h1} (Table 4), the predictor q_m was included in the model instead of N . In N is a setpoint control, and q_m is the actual fuel flow rate.

The diagnostic symptom used is most closely related to the fuel mass flow rate q_m . State features and control variables that were insignificant or correlated with each other were discarded. Diagnostic parameters are functions of many independent variables, so that a multiple regression model can be presented, for example, for the vibration displacement symptom H_{h1} in the empirical form:

$$H_{h1} = 0.2740 - 0.0023 P_w - 0.0182 i_n - 0.8281 d_r + 0.1856 h_{max} + 0.0004 q_m + 0.0001 n \pm 0.0105 \quad (12)$$

The model fits well, with a coefficient of determination $R^2 = 0.880$, and all the regression coefficients were statistically significant. The correlation between H_{h1} and q_m , which is 0.785, indicates a strong relationship. The correlation matrix indicated that the most significant global technical state feature is the fuel mass stream, which depends on the spray hole geometry.

Unfortunately, manufacturers do not disclose design documentation or data regarding dimensional tolerances and fits between the parts being joined. For the dimensions subject to general tolerances, dimensional tolerance classes in accordance with IT 6–IT 9 have been adopted, which is a common (industry-standard) practice among design offices. The number of features included in formula (12) may be expanded, and their significance will be determined statistically.

DISCUSSION

Based on the state of knowledge and technology analyzed, it can be concluded that no one has ever conducted comprehensive geometric

Table 4. Correlation matrix of the variables H_{h1} , q_m , and N

Variable	Correlations. The labeled correlation coefficients are significant with < 0.05 , $N = 108$				
	Mean	Standard deviation	H_{h1}	N	q_m
H_{h1}	0.04581	0.03	1.000000	0.776837	0.784823
N	74.05556	23.84	0.776837	1.000000	0.986309
q_m	88.99407	45.87	0.784823	0.986309	1.000000

measurements of so many components of the injection subsystem. Previous authors have only examined selected features of a single element of the injection subsystem. The authors of this article have expanded many of the highlighted geometric features to include material properties, friction force [15]. Determining the composition of materials and deposits in percentages is an achievement that reveals the secrets of manufacturers.

CT measurements of small, difficult-to-access nozzle channels for non-destructive testing have been partially performed. The geometry of the spray holes in smaller injectors, which are difficult to measure due to their small dimensions, irregular shapes, and the presence of deposits, has been determined. Limitations in the scanning quality of larger components due to high material density have been addressed through flow testing [15], advanced microscopy, and silicone castings.

Preliminary geometric and technical state models of the objects were recorded as a function of their technical state features. Multiple regression models were used to optimally select important technical state features, enabling control of global and representative fuel mass flux during manufacturing and maintenance. This publication presents a fragment of the research, references previous studies [1, 13, 15, 29, 30], and indicates directions for its continuation.

CONCLUSIONS

Using methods and instruments, the geometry of specific components of marine CEs, especially small internal channels with complex shapes, could be measured. Limitations of some instruments and methods were also noted. The study presented measurements of selected features that determine the technical state. Global technical state features were sought to limit inspections during manufacturing and maintenance. Based on the results obtained, inspection procedures were proposed to assess the quality of manufacturing and operation, optimizing measurement cycle times while maintaining rigorous scientific reliability. Information was obtained on the scatter in geometry results due to manufacturing and the wear of injection subsystem components. The determination of friction force using a patented method as one of the measurable key characteristics of the technical condition of friction pairs constitutes the author's contribution. The authors'

original scientific contribution consisted of a method and a device for measuring the friction force of precision pairs, as well as a method for estimating the limit values of unknown diagnostic parameters and technical state features.

Collecting the dimensions of the tested objects in a library allowed the development of geometric and mathematical models of individual components and the injection subsystem. The injector component's geometry is a function of the measured state features and represents its structural dimensions and shapes.

The solid model makes it possible to develop a signal-technical state relationship and a construction and technology, and to produce a prototype via 3D printing that is difficult to purchase and to bring on board the ship. The authors also addressed reverse engineering to elaborate on geometry and develop technologies for inaccessible engine components, which are scientifically and cognitively interesting and of great applied importance. Using a computer-aided design vector editor, a drawing of the model, divided into design elements, can be created. Limitations were encountered in X-ray tomography of larger components, so small, low-density objects were measured for the time being, and larger ones were measured later. X-ray tomography, silicone casts, and machine learning: the application of established metrological techniques to new research objects. The scientific research presented here is interdisciplinary, combining Metrology 4.0 with reliability, diagnostics, tribology, reverse engineering, manufacturing and maintenance quality, and the modeling of internal combustion engine operating processes. The Internet of Things and artificial intelligence should help facilitate.

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