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CAD TOOLS, REVERSE ENGINEERING, 3D MEASURING AND ARTIFICIAL NEURAL NETWORKS IN AXIAL PISTON PUMPS STUDY

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Abstract: *The correct definition of technical parameters in the construction of volumetric pumps, especially those with axial pistons, must take into account both their mode of operation, characteristic load curves, and their operating duration. Since hydraulic pumps in general, and axial piston pumps in particular, are equipment capable of utilizing the energy transmitted by the fluid at high powers and moments of operation, great attention is paid to them from the design phase to maintenance. This paper aims to address essential principles in the CAD modeling of an axial piston pump, a study on the inspection of the piston block using a specific reverse engineering measurement technique, which involves 3D scanning of these components and their measurement using specialized software (GOM Inspect), as well as the comparison, through overlay, of CAD models created using CATIA software with scanned models, highlighting the advantages of reverse engineering techniques compared to traditional CAD design. By using coordinate measuring machines, the free-form, internal, and external surfaces of the piston block were measured and inspected to generate coordinates of measured three-dimensional points on the surfaces, with the aim of defining the maximum distances between the real profile and the adjacent circle of the axis channels (deviations from circularity), through parameter specifications such as eccentricity, concentricity, and radial runout. Additionally, a neural network model is proposed for predicting the theoretical fluid flow rate of axial piston pumps based on their technical parameters, such as pump speed, number of pistons, effective piston diameter, or stroke, which aims to optimize the synchronization process between the drive shaft rotation and the piston block rotation and ensure efficient power transfer to the overall hydraulic system.*

Keywords: *Hydraulic pump, axial piston, CATIA, reverse engineering, GOM Scan, GOM Inspect, 3D measurement, artificial neural network (ANN)*

1. Introduction

Pumps are considered primary elements in the structure of hydraulic systems, which have the role of transforming mechanical energy into hydraulic energy and are designed to generate a power flow necessary to overcome the pressures developed against their own load [1,2,3]. Among them, hydraulic pumps with axial pistons, transform mechanical energy into hydraulic energy using pistons that move axially-alternatively in a pistons block, during the rotation of the central shaft, being among the most widespread in industrial and mobile hydraulic drives [4]. Due to the small moment of inertia and the axial balancing, they can operate at high speeds, frequently at *1500÷2000 rpm* and, in special cases, at *4000÷20000 rpm*, ensuring both the efficient transmission of the hydraulic fluid from the tank, as well as pumping it into hydrostatic systems at nominal working pressures and flows. They circulate flows between *Q=3÷800 l/min* at high and very high pressures p=200÷700 bar. These machines can reach powers up to *3500 kW* [5,6,7]. Axial piston pumps consist of a specially designed piston block within which the pistons move axially where, during operation, the central shaft of the pump is set into movement by an electric motor, which causes the piston to move. This process consists of two distinct and complementary stages: suction, when the piston moves in the axial direction, thus creating a suction space into the pump cylinder, and discharge, when the piston returns to its original position, reducing the volume of the cylinder.

This causes the pressure inside the cylinder to increase, which causes the fluid aspirated in the previous stage to be pushed into the hydraulic system. Thus, a constant flow of fluid is obtained at the pressure required to supply and control various hydraulic applications [3,8,9]. According to the location of the piston block in relation to the driving disk, three main categories of axial piston pumps are distinguished: with inclined block, with inclined disk, with rotating swashplate [1,7]. Multiple studies of axial piston pumps have been considered component analysis to understand and highlight a series of wear mechanisms under rapid maintenance conditions in order to reduce hydrostatic drive flow shutdown times involving such pumps [10,11,12]. This can be done both by 3D measurements of the surfaces of the pump components, especially of the pistons and their bores, whose non-uniformity can lead to not ensuring optimal loading and lubrication conditions [13,14], but also by optimizing the shape of the piston couple surface/cylinder, of technical operating parameters [15] through genetic algorithms [16] or neural networks [17,18], or graphical modeling or reverse engineering techniques [19,20,21].
Reverse engineering has gained momentum as an investigative method and starts from a real model or an existing construction of a functional technical component, identifiable by measurement, and retrieves appearance, shape and structure data, data used later to build digital 3D models [22]. Such a working technique, which starts from existing physical characteristics, but for which there is no specific technical documentation, is extremely useful in the reconditioning processes of various components within axial piston pumps.
Thus, if the constructive form of these components can be obtained much more easily by actually measuring them, by scanning and making 3D models of the components and is doubled by an analysis with neural networks, as universal approximators that work best if the systems that models have a high error tolerance, then some of the advantages of the reverse engineering technique over traditional CAD design can be highlighted. Among them could be exemplified: speed in processing the results, reduced time in transposing the models in digital form, precise determination of deviations by comparison with CAD model etc.
The paper presents a three-dimensional measurement technique specific to reverse engineering, which involves the 3D scanning of the piston block of an axial piston pump, followed by the dimensional measurement of the functional components with the help of a specific software (*GOM Inspect*) and comparison, by overlap, with the CAD model made with *CATIA* software. At the same time, an analysis based on an artificial neural network (*ANN*) of modeling and optimization was developed to determine the specific process variables corresponding to the theoretical fluid flow of axial piston pumps.

2. The scanning process

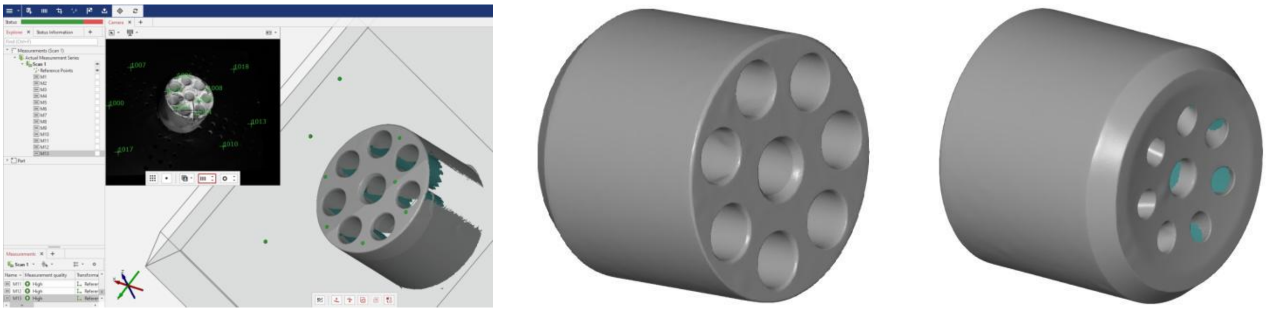
The scanning of the piston block from the axial piston pump structure was performed using the *Atos Core* [23] equipment, which relies on advanced and innovative technology to accurately and fully automate the inspection and measurement of the parts. The processing of the images obtained from the scanning process was performed with the help of the *GOM Scan* program, a specialized software solution designed to satisfy the requirements in the fields of reverse engineering and rapid protyping. Calibration procedures, automatic configuration of scan parameters such as resolution and exposure times and performing polygonalization were performed. The *GOM Scan* program provides data from the scanned surface in a three-dimensional representation, the measurement process being performed with or without the use of reference markers, which are adhesive elements that are applied both to the scanned object and to the table of the equipment before starting the actual process scanning. The software identifies and captures visible reference points in camera images.
These points are later recognized and used to transform all subsequent scans. In each subsequent scan, it is necessary to capture at least three known reference points to ensure the correctness of the transformations in the three-dimensional views. Thus, before starting the scanning procedure, reference markers are applied to the piston block, Figure 1.

Fig. 1. Applying reference markers to the piston block

In order to ensure a high level of accuracy in the scanning process, it is essential to use an anti-reflective spray that is applied to the part. After the reference markers have been carefully applied and after the surface of the part has been covered with the anti-reflective spray, the actual process scanning of the piston block is initiated, Figure 2.

Fig. 2. Applying the anti-reflective spray and starting the scanning process of the piston block

The piston block scanning process included a total number of 54 scans, of which 17 scans were performed for the top view, 7 scans for the side view, and 30 scans for the bottom view. This detailed approach to scanning from multiple angles and perspectives contributes to obtaining a comprehensive and accurate image of the analyzed object.
After the piston block scanning process is completed, the polygonalization step follows. This involves correlating and merging all scans performed on the object to obtain a complete and detailed numerical model. The polygonization process is initiated by accessing the *GOM Scan* menu and selecting the appropriate options: *Acquisition -> Measurement series -> Polygonize and Recalculate*.
Thus, the necessary calculations are performed to create the network of points that will represent the surface of the scanned part. To ensure the quality of the model and to remove any imperfections or unwanted edges on the surface of the scanned part, the *Select/Deselect Through Surface* command is used. This function allows the operator to precisely identify and remove unwanted details, thus ensuring that the final model obtained is as accurate as possible and precisely represents the scanned part.
Figure 3 shows the final result of the piston block scan made with the Atos Core equipment.



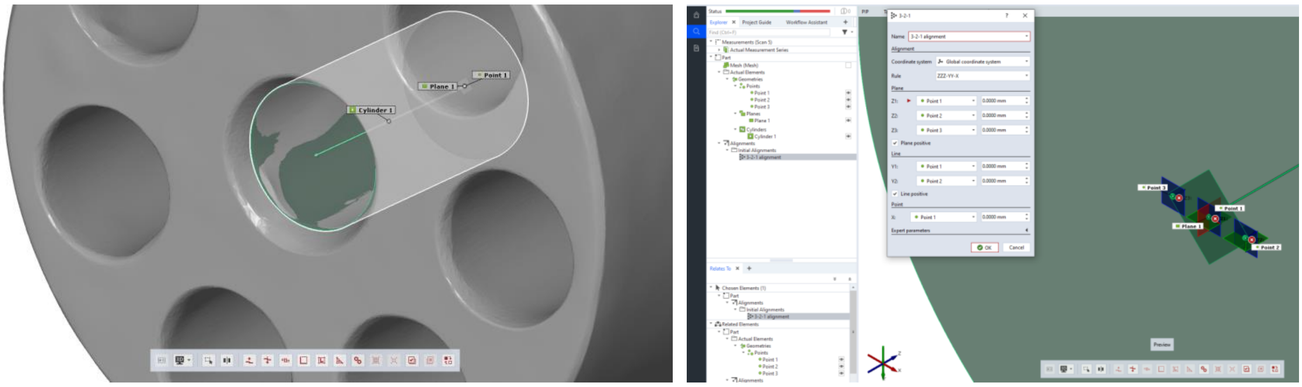
a. b.

Fig. 3. Sequences during the piston block scanning process (a) and scanned model of the piston block (b)

The scanned part will be saved as a file with **.stl* extension, which later allows it to be opened in a variety of design software such as *CATIA*, *AutoCAD*, *Autodesk Inventor*, *SolidWorks* etc. This file format (**.stl*) is a widely accepted standard in the CAD industry and enables the compatibility and efficient transfer of 3D models between different platforms and design applications.

3. The inspection process

The inspection process of the piston block is performed with the help of the *GOM Inspect* program, in order to determine the dimensional characteristics of the part and to create a model of it in a specialized software, in order to compare it with the CAD model. In a first stage, in order to determine the dimensions of the piston block, the construction of a reference system for the part is initiated. This process begins by creating a cylinder in the area inside it using the *Fitting Cylinder* function. The cylinder is built to approximate the shape and dimensions of that area. In the next step, a point is constructed, using the *Point from Line* function, with the direction defined by the axis of the cylinder. This point is an essential element in establishing the reference system. At the same time, the plane perpendicular to the axis of the cylinder is created using the *Point-Normal Plane* command. This plane has as reference point the previously created point, point *1*, and the direction of the normal will be given by the axis of the cylinder, Figure 4a.



a. b.

Fig. 4. Generating the reference elements in order to establish the coordinate system of the part (a) and *3-2-1 Alignment* function in order to establish the coordinate system of the part (b)

In the final step of the process, an alignment operation is performed in order to establish the reference system, using the *3-2-1 Alignment* function, which is usually used as an initial system alignment. With the help of the *3-2-1 Alignment* command, the nominal reference system position is established. In this alignment process, six 3D points are used to define the reference system.
Thus, in addition to the initial point (*Point 1*), two additional points are created on plane *1*, this being done using the *Point* command. Thus, having all the elements built, the alignment process

that defines the reference system is performed, Figure 4b. To obtain the dimensions of the piston block, essential for building later the 3D model, the contour of the part is created using the *Single Section* function. Thus, to determine the cross sections, a reference plane is chosen that is parallel to the axis of the cylinder (*Z* plane), located at a specific distance of *17 mm*, respectively *-25 mm*, in relation to the initial reference plane, Figure 5.

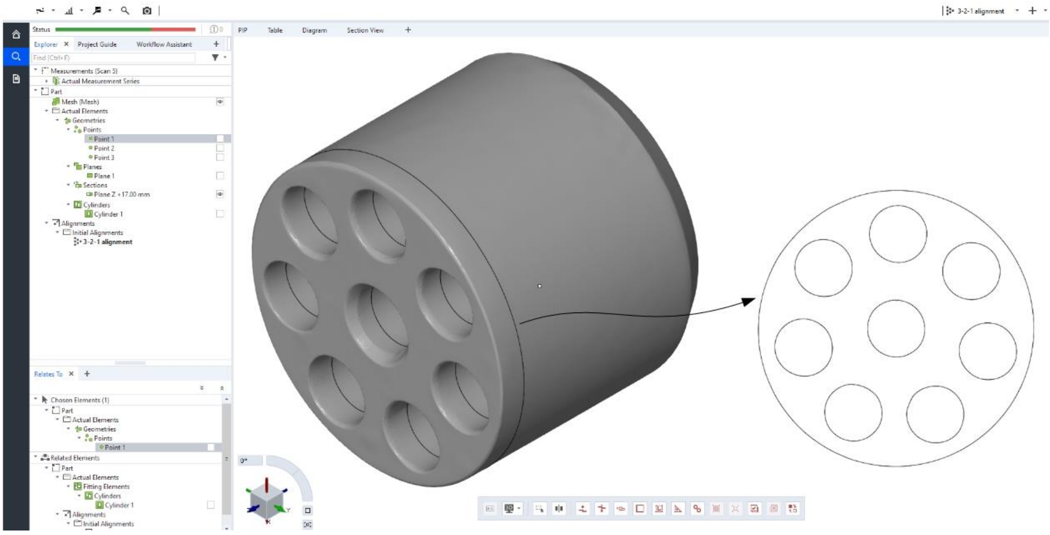


Fig. 5. The transversal cross-section of the piston block

Thus, using these sections, the dimensions of the piston block can be identified, which are necessary to create the 3D model in a dedicated software program. The dimensions of the cross sections are shown in Figure 6. These were determined by constructing circles on the surface of the contours, using the *Fitting Circle* command.

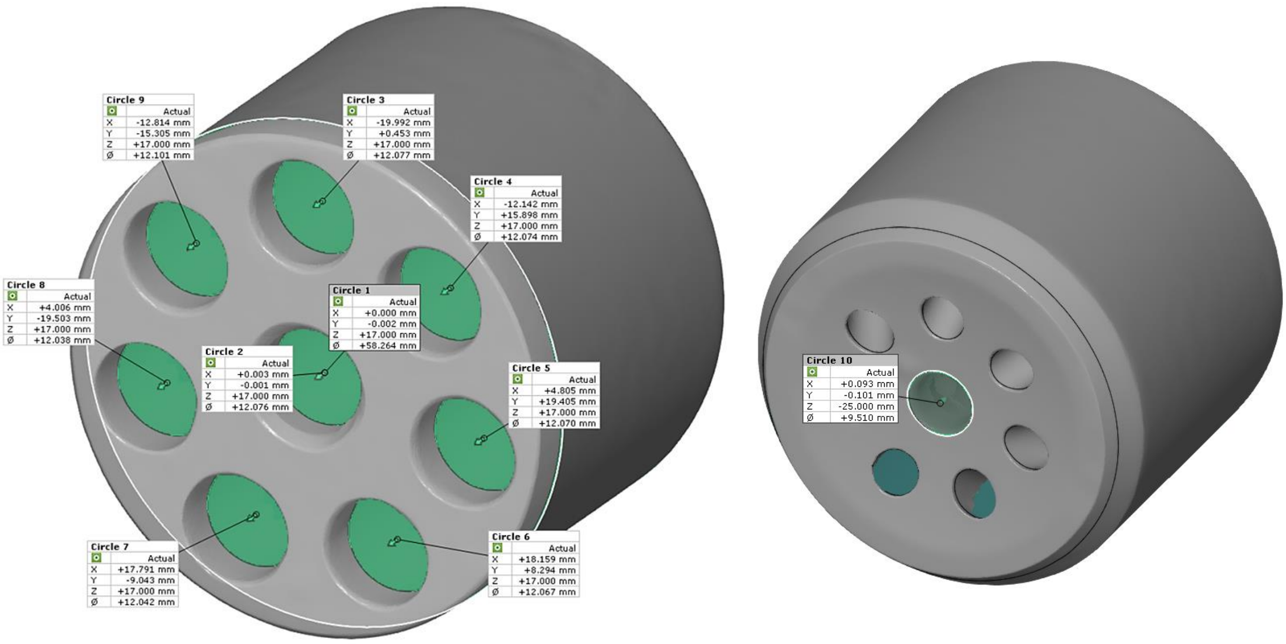


Fig. 6. The cross-section dimensions of the piston block

4. Graphical modeling of the piston block and comparison between models

The graphical modeling of the piston block was performed using the *CATIA V5R21* program in the *Part Design* module. *CATIA* is a computer-aided design software product developed by *Dassault Systèmes* [24]. This program is widely used in the engineering and design industry, allowing users to create complex 3D models and perform advanced analysis on them. Through *CATIA*, engineers and designers can perform detailed modeling of components and assemblies and apply various design functionalities such as simulations, tests and analyzes to verify their performance and quality. At the same time, it represents an essential tool in product development and in their design in a virtual environment before physical production. Therefore, the three-dimensional model of the piston block and the axial piston pump are shown in Figure 7. In its construction, 2D and 3D drawing commands were used, as well as editing commands (*Line*, *Point*, *Circle*, *Quick Trim*, *Pad*, *Shaft*, *Pocket*, *EdgeFillet* etc.).

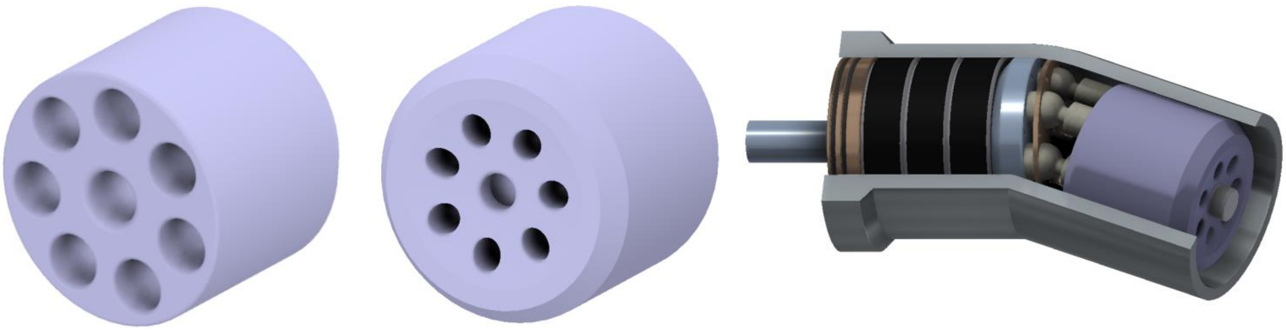
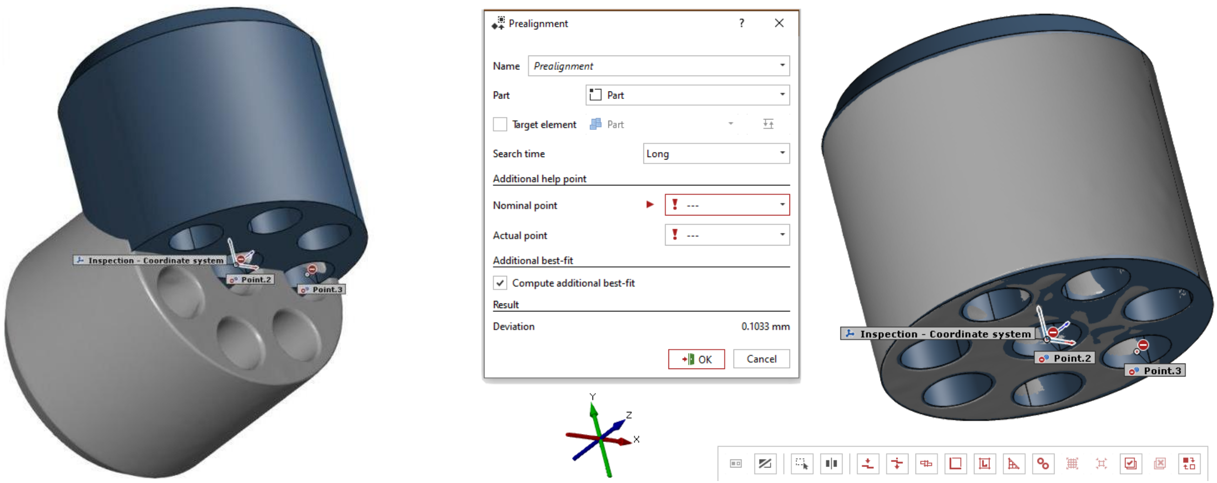


Fig. 7. 3D model of the piston block and the axial piston pump

The comparison between the two models of the piston block (CAD and scanned) was realized in the *GOM Inspect* software. The scanned model in **.stl* format and the CAD model in **.stp* format are imported into the GOM Inspect software. In the inspection process, an essential step is to align the actual model of the part, obtained by scanning, with the nominal model obtained by CAD modeling, since the two models are oriented differently from the coordinate system prescribed in the *GOM Inspect* program. There are several alignment methods available, but the most convenient and default method is prealignment. This prealignment process automatically performs a correlation of the two models, independent of the position in which the scan of the physical model was taken. By using these options of the prealignment function, a proper alignment can be ensured between the actual model and the nominal one, thus facilitating the process of inspecting and analyzing the part.



a. b.

Fig. 8. Orientation of the piston block models (a) and the overlap process (b)

Thus, Figure 8a shows the two models imported into the *GOM Inspect* program. In order to overlap the model scanned with the *Atos Core* equipment with the model made in the *CATIA* program, the *Prealignment* command, option *Long* is used, Figure 8.b. This step is essential to properly overlay the two models in the same reference system, thus facilitating the analysis and the inspection process. After the alignment between nominal and actual data has been achieved, the inspection process can be initiated, thus allowing the determination of dimensional deviations between the two sets of data. This process is done using the *Surface Comparison on CAD* command.
The result is presented in the form of a map of deviations, where they are visually represented by means of colors. In this context, the blue color indicates a negative deviation, the green color signifies a zero deviation, while the red color represents a positive deviation. In areas where dimensional deviations could not be calculated, they are highlighted on the deviation map with a gray color. After the map has been generated, the program presents a legend explaining the meaning of the values corresponding to each individual color. This legend is useful to better understand and interpret the information presented on the map, making the analysis process more accessible and comprehensible, Figure 9.

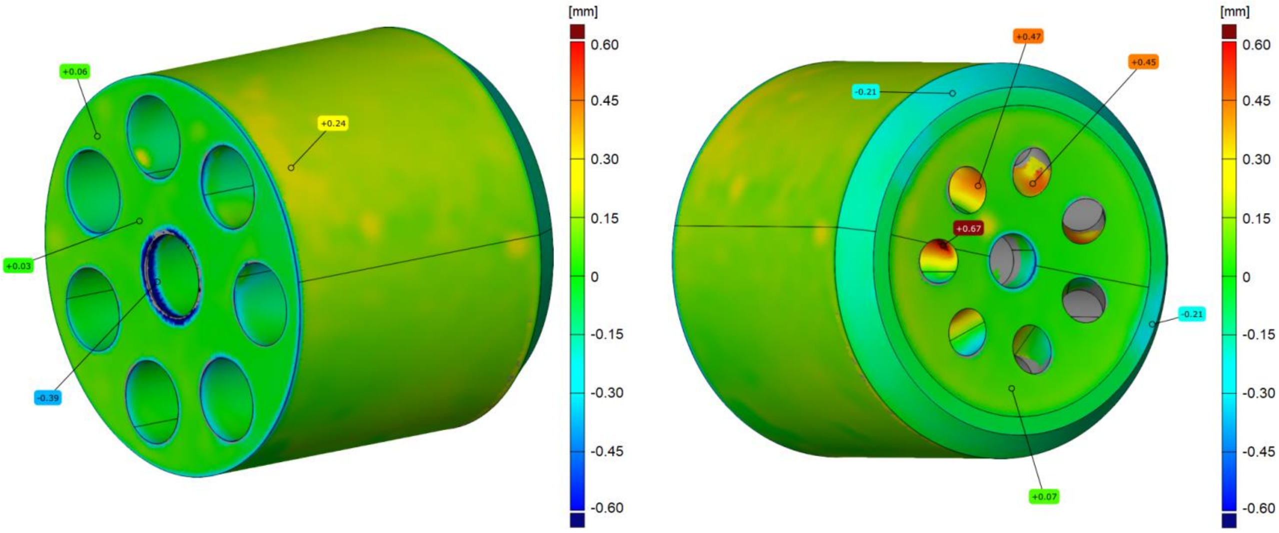


Fig. 9. The deviations map of the block piston

5. The precision of the geometric shape of the piston cylinders

Following the operation of axial piston pumps, a technical cycle of wear occurs due to the translational movement of the pistons in the block cylinders, the deviations from the precision of the geometric shape of the pistons cylinders, the most frequently encountered being the deviation from circularity and the deviation from cylindricity. The deviation from circularity or non-circularity is defined as the maximum distance between the real profile and the adjacent circle, Figure 10a, and the deviation from cylindricity is defined as the maximum distance between the real surface and the adjacent cylinder, considered within the limits of the reference length, Figure 10b. This deviation consists of the deviation from circularity, considered in the cross section of the part and the deviation of the longitudinal (axial) profile. The diameter and circularity errors were determined with the *Tesa Micro-Hite 3D* coordinate measuring machine [25], Figure 10c. The deviations from circularity in the piston cylinder sections were determined by measuring the diameters of the section in different directions. For each of the piston cylinders, marked with numbers from 1 to 7, the values of the diameters measured at several points, in an interval of 1÷5 mm below the frontal plane of the piston block, were determined.

a. b. c.

Fig. 10. Deviation from circularity (a) and cylindricity (b). Tesa Micro-Hite measuring machine (c) [25]

Table 1 shows the average values recorded for the piston cylinder diameters measured with the help of the *GOM Inspect* program, see Figure 6, respectively those recorded by measuring with the *Tesa Micro-Hite 3D* coordinate measuring machine.

Table 1: Values of piston cylinder diameters and tolerances

Cylinder No.	Cylinder diameter [mm] *GOM Inspect*	Tolerance [mm] *GOM Inspect*	Cylinder diameter [mm] *Tesa Micro-Hite 3D*	Tolerance [mm] *Tesa Micro-Hite 3D*
1	12.077	0.077	12.026	0.026
2	12.074	0.074	12.030	0.030
3	12.070	0.070	12.018	0.018
4	12.067	0.067	12.012	0.012
5	12.042	0.042	12.002	0.002
6	12.038	0.038	11.993	-0,007
7	12.101	0.101	12.044	0.044

Figure 11 shows the graphical representation of the tolerances obtained from *GOM Inspect* and *Tesa Micro-Hite 3D*.

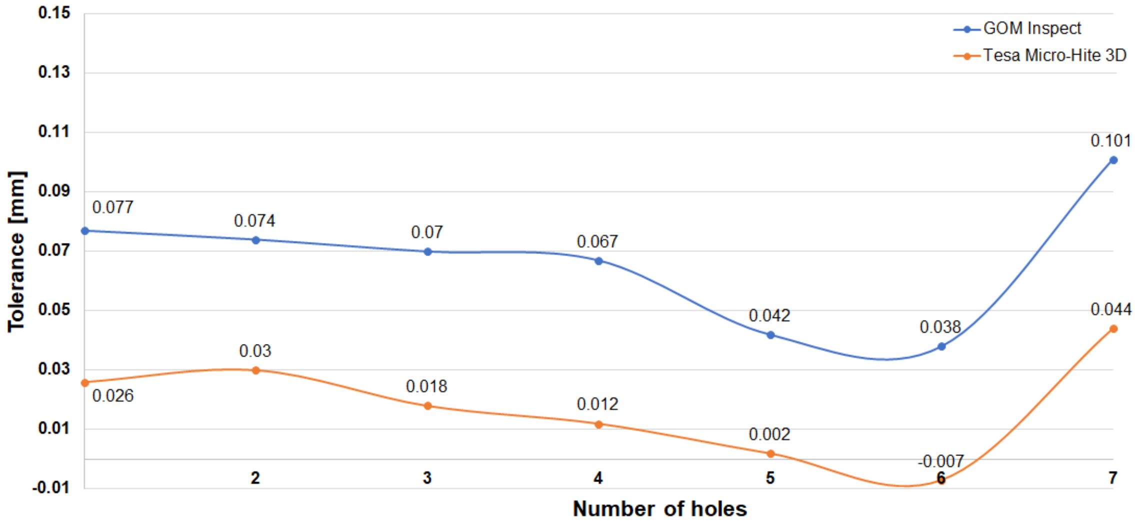


Fig. 11. Graphical representation of the tolerances obtained from *GOM Inspect* and *Tesa Micro-Hite 3D*

6. Artificial neural network (ANN) and piston stroke prediction in axial piston pump

In order to define the theoretical flow rate of the axial piston pump, the basic relationship is used:

$$Q = V \cdot n \left[\mathrm{m}^3/\mathrm{s} \right], \tag{1}$$

where:
- V is the oil volume discharged at one rotation;
- n - pump speed, in rpm.

The oil volume discharged at one rotation of the piston block is:

$$V = \frac{\pi \cdot d^2}{4} \cdot h \cdot z \; \left[\mathrm{mm}^3 \right], \tag{2}$$

where:
- d is the effective diameter of a piston, in mm;
- z - the number of pistons;
- h - piston stroke, in mm.

For n speed, the flow rate of the axial piston pump is given by the expression:

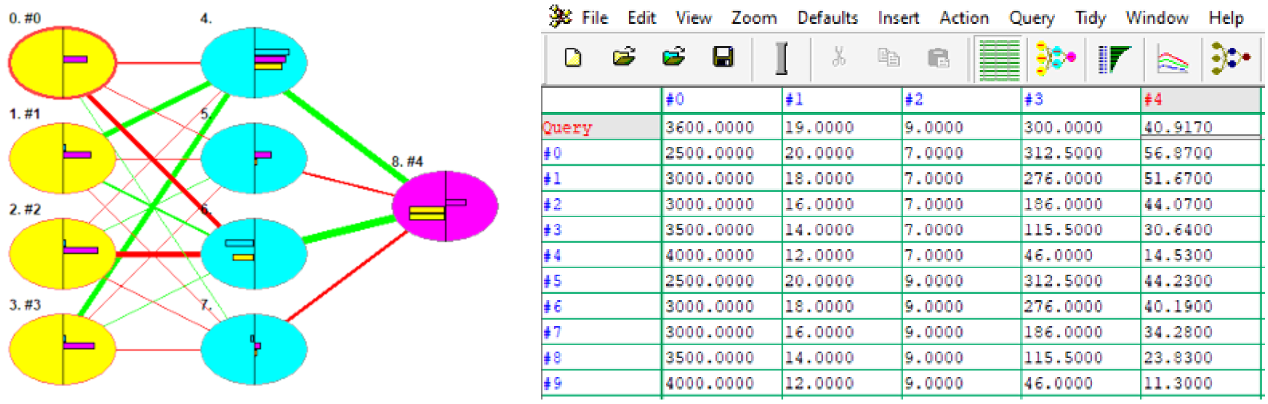
$$Q = 10^{-6} \cdot \frac{\pi \cdot d^2}{4} \cdot h \cdot z \cdot n \left[\mathrm{l/min} \right]. \tag{3}$$

To highlight the importance order of the parameters that influence the functionality of an axial piston pump, a piston stroke prediction method based on an artificial neural network (ANN) model is used. It starts from known values of flow (Q) and speed (n) of some types of Rotary Power pumps [26]. To train the neural network, the fact that the number of pistons is generally odd is taken into account and two such situations are considered - with 7 and 9 pistons, Table 2.

Table 2: Technical parameters of axial piston pumps [26] in ANN training

No.	n [rpm]	d [mm]	z	Q [l/min]
1	2500	20	7/9	312.50
2	3000	18	7/9	276.00
3	3000	16	7/9	186.00
4	3500	14	7/9	115.50
5	4000	12	7/9	46.00

A standard neural model consists of an input layer with 4 neurons corresponding to the input variables, a hidden layer containing 4 hidden neurons and an output layer containing one neuron corresponding to the piston stroke (h). For the multi-layer neural networks used as input parameters were: speed (n), piston diameter (d), number of pistons (z) and fluid flow rate (Q). In this way, 9 possible combinations are obtained. When training the networks, 8 of the combinations were used, the ninth one being used to check the training result, the stroke of the pistons, Figure 12a. After querying the networks, 16107 cycles, piston stroke values were obtained for various combinations, Figure 12b.



	#0	#1	#2	#3	#4
Query	3600.0000	19.0000	9.0000	300.0000	40.9170
#0	2500.0000	20.0000	7.0000	312.5000	56.8700
#1	3000.0000	18.0000	7.0000	276.0000	51.6700
#2	3000.0000	16.0000	7.0000	186.0000	44.0700
#3	3500.0000	14.0000	7.0000	115.5000	30.6400
#4	4000.0000	12.0000	7.0000	46.0000	14.5300
#5	2500.0000	20.0000	9.0000	312.5000	44.2300
#6	3000.0000	18.0000	9.0000	276.0000	40.1900
#7	3000.0000	16.0000	9.0000	186.0000	34.2800
#8	3500.0000	14.0000	9.0000	115.5000	23.8300
#9	4000.0000	12.0000	9.0000	46.0000	11.3000

a. b.

Fig. 12. Neural model for piston stroke prediction (a); neural network training data (b)

Conclusions

The main defining characteristic of axial piston pumps is their ability to deliver a continuous fluid flow under pressure, making them essential components in the field of hydraulics, being recognized for their exceptional level of efficiency and their ability to deliver both pressure, as well as constant flow, essential features for a variety of industrial and mobile applications. The paper highlights how modern rapid analysis tools can give extremely valuable indications for a specific reaction to non-conformities in the functionality of such pumps. So:

- an automatic scanning and analysis system was used, with the help of which a quick and precise inspection of the piston cylinders was realized, reducing the effort and time required for manual measurement by traditional methods;
- the CAD model could be created both based on the dimensions in the data sheet, but also based on the scanned model. The accuracy of the models (CAD and scanned), by comparison, was proven by the upper and lower limit values of ±0.6 mm. Even if there are small deviations, they are due to the imperfections appearing in the piston block due to multiple operating cycles, as well as the measurement and scanning difficulties caused by the depth of the piston cylinders;
- powerful 3D measuring instruments were used to control dimensional deviations from circularity and cylindricity in the piston block, highlighting the superior accuracy of the coordinate measuring machine, but also the net superior working speed of the scanning system, which had the role to quickly create a 3D model, consisting of a ”cloud of points” obtained after scanning the inner surfaces of the piston cylinders, with the possibility of exporting them in various formats for digital design and analysis applications;
- following the analysis of the training results of the neural network, in defining the average value of the pistons stroke (h), the importance of the parameters, in descending order, are: fluid flow rate (Q), diameter of the pistons (d), speed (n), number of pistons (z). It can be concluded that the ANN approach is an appropriate tool for such an application, being able to lead to the design of some algorithms that assume the possibility of increasing the value of the fluid flow, but also of the diameter of the pistons, for a functionality with a higher technical yield.

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