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Salah H. R. Ali[1], H. H. Mohamed[2], M. K. Bedewy[3]

[1]National Institute of Standards (NIS), POBox 135, Giza (12211), Egypt
[2]Faculty of Engineering, Helwan University, Mataria, Cairo, Egypt
[3]Faculty of Engineering, Cairo University, Giza (12613), Egypt
e-mail: [1]SalahAli20@yahoo.com

μ-SCALE CMM: A PROPOSED DIAGNOSTIC TOOL BASED ON EVOLVED DEVIATIONS IN GEOMETRICAL MEASUREMENTS

μ-scale measurements of dimensional and geometrical features of components require an advanced precise and accurate device such as the CMM machine. Evolved changes in the dimensional and geometrical measurements as referred to benchmark values can be employed as a reliable diagnostic tool in monitoring the functional deterioration of mechanical parts that involve working surfaces during their operation. It is evident that excessive wear in a cylinder bore of an internal combustion engine can dramatically affect the quality of performance, the sealing function, the scheme of lubrication, and eventually the service life span of the piston rings and in turn of the engine as a whole.

In this work, precise and accurate measurements of evolved deviations in the diameter, roundness, straightness, and concentricity in a cylinder bore of an air cooled Automotive Diesel Engine using a CMM machine have been carried out and analyzed. The results have been presented, discussed, and interpreted in order to demonstrate making use of them in monitoring the status of the engine during operation. Locations of severe wear occurrence in the cylinder bore are then detected and investigated. The measurements within relevant uncertainties would reflect the quality of engine performance, the suitability of the applied scheduled maintenance plan, and the adverse operating conditions which may have been probably encountered during service life. Thus, in the light of the findings, recommendations can be provided to the engine designer to improve his design regarding changes of material selection and/or surface treatments. Furthermore, an innovative constructional modification may be suggested to homogenize the wear occurrence in the cylinder bore during operation. For instance, a device can be added to the construction in order to cause continuous slow rotation of the cylinder about its geometrical axis while the engine is running, without having to dismantle the components. This may extend the operating life span of the cylinder and in turn reduce the maintenance expenses. In addition, power loss due to friction and wear in the engine may be favorably affected.

Keywords: Dimensional metrology, surface geometry, uncertainty, diesel engine, friction and wear

1. INTRODUCTION

Accurate dimensional and geometrical measurements using precision devices are crucial during the manufacturing processes of parts to insure their compliance with the design requirements. In addition, these measurements may also be employed with reference to their benchmark values to monitor the extent and severity of functional deterioration of the parts, especially those working with their surfaces during service. This helps the maintenance engineer take proper decisions regarding his forthcoming maintenance plan and/or repair actions. Thus, the durability and reliability of the parts and the assembly would be favorably affected.

The air -cooled Diesel engine, for instance, is commonly used in heavy duty transport fleets applications due to its high performance, efficiency, and low fuel consumption. The surface contact problems between cylinders and pistons through their rings are vital to the engine performance within the adverse operating conditions of high pressure, temperature rise, and high relative velocity of the contacting surfaces [1]-[2]. Fine finish and surface treatment together with proper dimensional and geometrical tolerances standards implementation are required in order to ensure a good seal between the cylinder wall and piston rings, good load-carrying capacity, good lubrication conditions, less friction, suitable wear resistance, low translated vibration levels, high engine efficiency, and longer service life span [3]-[4]. The main function of the piston rings assembly is to provide good dynamic seal between the combustion chamber and crankcase during compression and power strokes. Reasonable sealing minimizes power loss due to charge escape from the combustion chamber within a suitable ring expansion gap and limited friction force. For long sealing service life, friction and wear between piston rings and the cylinder wall have to be properly controlled [5]. They are controlled by lubrication of the interface with dry lubrication of cylinder bore material composition besides an oil film thick enough to separate the asperities of piston rings and cylinder surface [2]-[5]. The friction loss varies according to piston velocity between top dead center (TDC) and bottom dead center (BDC), where the oil film thickness depends on the instantaneous relative velocity of the piston ring, which varies from zero at TDC and BDC to a maximum in the midstroke section. This means that wear conditions will vary along the piston ring traveling distance, from mild to severe [6].

Normally the cylinder bore is not perfectly cylindrical along its entire length. Practically, the bore distortion causes loss of conformity between piston rings and cylinder wall which in turn produces some trouble to oil film distribution. Variation in the oil film thickness exposes piston rings and cylinder to the whole spectrum of lubrication regimes, from mixed and probably elastohydrodynamic to full film hydrodynamic lubrication [4]-[5]. Consequently, different wear mechanisms will develop geometrical departures in transverse sections along the cylinder bore [6]. TDC location on the bore suffers heavily from oil starvation more than that at the BDC and its vicinity. Although the piston at both locations is kinematically characterized by marginal inversion velocity situations where it reaches zero before starting to get inverted, the most severe wear is expected to appear at the TDC due to the oil shortage while at the BDC the oil is available either from the source or due to gravity. However, the BDC may also experience high wear rate due to the existence of hard grit and wear debris accumulated by the gravity at this location and the neighboring area. In the midstroke location and the nearby zone, where the piston velocity reaches its maximum value, mild wear only is expected because the oil film becomes dynamically thick enough to separate the mating solid surfaces and prevent metal-to-metal contact [7].

Although there is a lot of new advanced inspection equipment such as CMM machines, their use is so far only monopolized to the manufacturing fields [8]-[9], rare published research work yet exists in the use of such advanced CMM metrology utilities in the field of engine health monitoring through geometrical departure measurements and analysis.

Characterization of engine cylinder bore geometry and dimensions is a twofold problem. The first is related to the applied techniques and quality standards adopted during manufacturing inspection process. This concerns the prescribed surface design parameters such as dimensional and geometrical tolerances, and surface roughness. The second is related to processing such data with the purpose of monitoring the changes that happened to the surface geometry and dimensions during the engine service life span. This would help in two aspects: the first is related to maintenance decisions, while the second is related to design modifications. Research work has been done on surfaces with Gaussian distribution roughness, but the cylinder wall fine finished surface with specified geometrical features and properties participates simultaneously together to control the environment that critically affects the engine functional performance and life [10]-[11]. Although the specified surface parameters represent advanced features, their definition is generally unrelated to any physical or mathematical properties of the surface topography [12]. The plotted accumulation of surface asperity heights according to the Gaussian distribution appears as straight line scales. For transitional surface topography, such a scale appears as two intersecting straight lines. The slopes of the lines are proportional to the standard deviations of the two distributions, while the point of intersection represents the depth of transition from one finish to another. Difficulties encountered during the application of this technique have been recently solved with developed advanced calculations software [8].

On the other hand, the numerical description of the changes in the operating surface geometry during the service life span necessitates detecting and follow-up the surface geometrical deviations. However, some changes occur in such a way that a band of surface fine wavelength may disappear. Hence, Fourier Transformation Analysis is needed in this case to determine the surface power spectrum response of special software to characterize the changes in surface straightness and roundness relevant to operation environment changes [7]. Statistical analysis of expanded uncertainty calculations (type UA) is also needed for CMM measurements [13].

The purpose of this work is to demonstrate accurate precise surface dimensional and geometrical measurements to monitor and follow-up the extent of severity of wear changes in a worn-out cylinder of an Automotive Diesel Engine as related to the resulting geometrical distortions in both transverse directions (out-of-roundness and derived concentricity), and longitudinal directions (out-of-straightness). Thus, design improvements and/or correction actions to the scheduled maintenance plan could be suggested in the light of the analysis of the obtained measurements within the relevant uncertainties. Innovative design modification and inspired ideas may also be pointed at for the sake of extending the engine service life span and minimizing the running operational and maintenance expenses.

2. CYLINDER FORCES AND SURFACE MEASUREMENTS

2.1. Dynamic Friction Forces

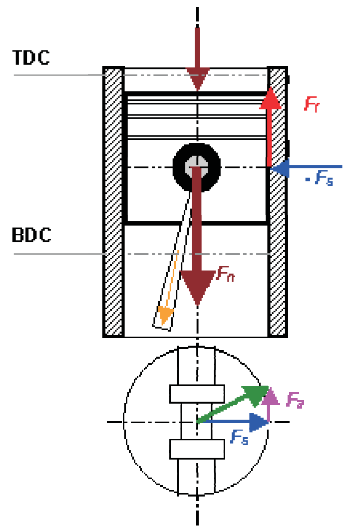

Fig. 1. Forces acting on the cylinder bore.

Combustion gas pressure represents the essential axial force acting on the piston crown area to move it downwards against reciprocating mass inertia. F_n is the instantaneous sum of the normal acting forces on the piston pin, Fig. 1. Reciprocating piston motion on angular movable connecting rod generates a variable piston side force F_s. An axial transmitted force F_a of the crankshaft due to clutch engagement force and timing gear force components affect the cylinder wall. The resultant of piston forces F_s and F_a attacks the wall at an angle with F_s. The angle value varies as a function of the force amplitude to generate a resultant force causing rotation around the cylinder axis. Dynamic friction force F_f has been produced due to relative motion of piston rings with respect to the cylinder wall under the effect of the resultant force in a spiral-like motion. This causes the cylinder bore to wear at rates corresponding to the resultant force amplitude and direction to generate eventually a cylinder out-of-roundness (OOR) and out-of-straightness (OOS).

2.2. Surface Geometry Measurements

Dimensional and geometrical characteristics of the cylinder bore surface have been measured using a computerized Coordinate Measuring Machine (CMM) equipped with a contact scanning probe and a Least Square (LSQ) computing algorithm. The CMM used throughout this work was Carl Zeiss bridge model available at the Engineering and Surface Metrology Lab, Precision Division, Egyptian National Institute of Standards (NIS). The CMM measurement performance was verified according to ISO-10360 [14]. It is capable of producing accurate results with reasonable repeatability and reproducibility for the surface geometrical departure features. Before making measurements with the CMM in the cylinder, the CMM was calibrated using a master probe to evaluate the standard sphere and using standard sphere to evaluate the used probe. The output standard deviation (SD) and CMM test element specification are presented in Table 1.

Table 1. Output data of CMM probes and sphere.

CMM element	Measured radius, mm	S_D, mm
Master probe	4.0000	0.0001
Reference sphere	14.9942	0.0001
Used probe	4.0002	0.0001

The maximum permissible values of error of the used CMM machine can be judged using the following equations:

$$MPE_E = \pm\{0.9\mu m + (L/350)\}\mu m \quad (1)$$

$$MPE_P = \pm 1.00\mu m \quad (2)$$

$$MPE_{Tij} = \pm 1.90\mu m \quad (3)$$

MPE_E is the maximum permissible equipment error where L is the measured length in mm, MPE_P is the maximum permissible probing error, and MPE_{Tij} is the maximum permissible tangential scanning probing error.

An experimental investigation has been conducted on an air-cooled Diesel engine cylinder made of high quality grey cast iron (GG 25) having initially a design diameter of 110 mm and the configuration shown in Fig.2a. The chemical analysis and mechanical properties of the cylinder material are presented in Table 2, where HB is the Brinell hardness and t is the tensile strength. The piston stroke is 140 mm.

Table 2. Cylinder material specifications.

Chemical analysis, wt. %							Mechanical properties	
C	Si	Mn	P	S_{Max}	Cr	Ni	HB	σ_t, MPa
3.10	2.10	0.65	0.30	0.10	0.20	0.32	220	Min. 220

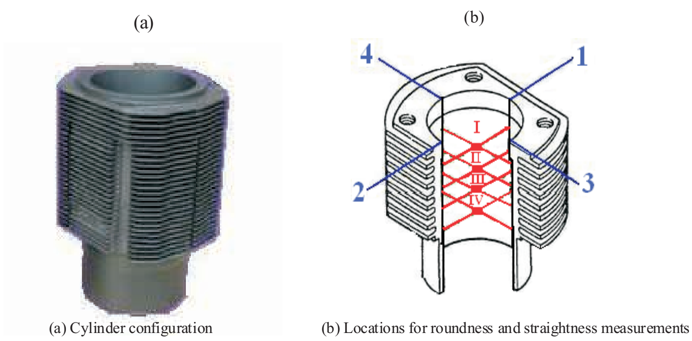

Fig. 2. Engine cylinder configuration and locations of measurements.

A straight Stylus tungsten carbide shaft probe with a 4 mm radius ruby tip attached to PRISMO CMM machine was used to quantify the surface geometric and dimension departure characteristics of the cylinder bore. The CMM traveling speed was 40 mm/s and the probe scanning speed was 10 mm/s during measurements. The straightness measurements were carried out along four longitudinal eqally spaced locations, 90° apart around the circumference, at 1, 2, 3, and 4 as indicated in Fig. 2b. Cylinder bore roundness quantification was conducted at sections I, II, III and IV near the TDC, midway, and BDC planes as shown in Fig. 2b. The surface geometrical and dimensional features were represented by mean average values of five repeated test measurements.

3. UNCERTAINTY ASSESSMENT OF MEASUREMENTS

Table 3. Measurements of both roundness and straightness together with the uncertainty assessment.

Tests / Points	Test 1	Test 2	Test 3	Test 4	Test 5	M_{AV}	S_D	U_C	U_A
1. Roundness, µm									
@ circle I	91.0	90.9	90.9	90.9	91.0	90.94	0.0548	0.0245	0.0480
@ circle II	32.1	31.8	32.1	31.9	31.8	31.94	0.1152	0.0678	0.1329
@ circle III	23.0	23.5	24.2	24.0	24.3	23.80	0.5431	0.2429	0.4761
@ circle IV	18.2	18.3	18.3	18.5	18.9	18.44	0.2793	0.1249	0.2448
2. Straightness, µm									
@ line 1	71.0	71.0	70.3	70.5	70.1	70.58	0.4087	0.1828	0.3583
@ line 2	54.4	54.1	54.3	54.5	54.5	54.36	0.1673	0.0748	0.1467
@ line 3	13.6	13.8	13.7	13.6	13.7	13.68	0.0837	0.0347	0.0733
@ line 4	34.6	34.7	34.8	34.8	34.9	34.76	0.1140	0.0510	0.1000

The mean average values and uncertainty of roundness and straightness measurements for the engine cylinder bore are presented in Table 3, where M_{AV} is the mean value of five repeated test measurements, S_D is the standard deviation, and U_C is the combined standard uncertainty due to measurement repeatability (U_C=S_D/√), where n where is the number of repeated tests for each target measurement [13]. It is worth mentioning that type B source of uncertainty is not accounted for by U_A values because of its relative insignificance to the OOR and OOS. The expanded uncertainty is U_A=K.U_C [13], where K is the standardized variable (coverage factor) which equals to 1.96 corresponding to 95% probability or confidence level [15].

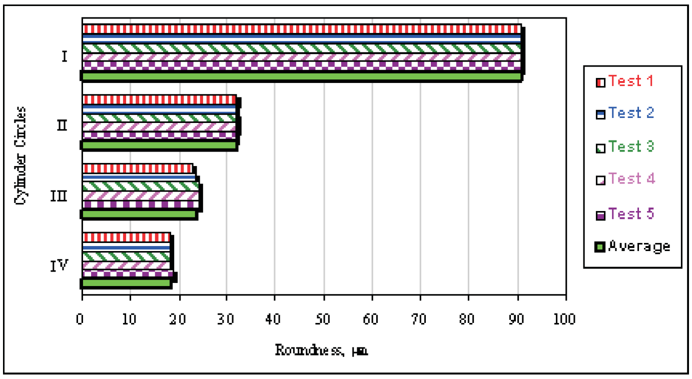

Fig. 3. Bore roundness measurements at four transverse sections along piston stroke.

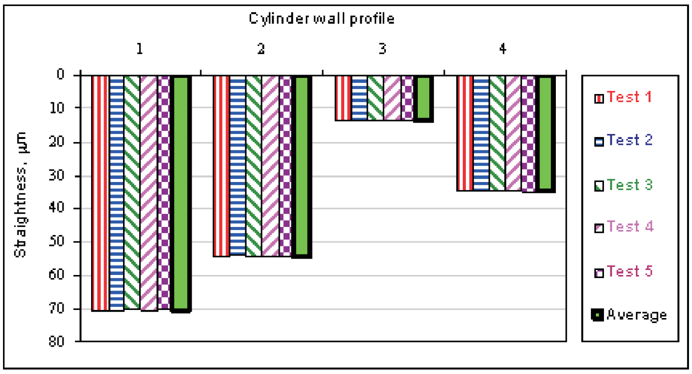

Fig. 4. Bore straightness measurements at four longitudinal equispaced locations.

The roundness and straightness results of five repeated laboratory tests conducted on each one of the adopted four transverse sections I, II, III, and IV, and the four longitudinal profiles 1, 2, 3, and 4, have been processed and presented in Fig. 3 and

Fig. 4, respectively. The results are also tabulated in Table 2 and the calculated values of the relevant uncertainty are plotted in Fig. 5.

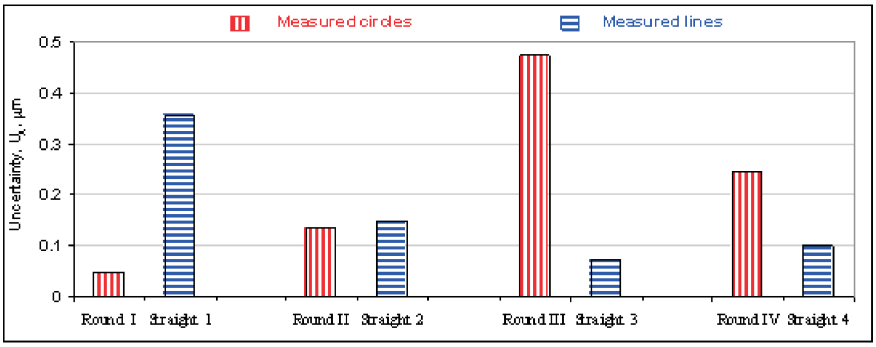

Fig. 5. Uncertainty values of five repeatable tests of OOR and OOS.

4. RESULTS AND DISCUSSION

Average runout measurements of worn cylinder bore; roundness, straightness, and concentricity, have been conducted using the accurate stylus surface scanning technique on a programmable CMM machine. The concentricity is represented by the relative roundness runout at the selected transverse sections I, II, III, and IV with respect to profile I taken as a datum as shown in Fig.2b. RMS averaged values of five similar arrays of measurements have been considered. The results have been presented, discussed, and interpreted.

4.1. Out-Of-Roundness Measurement Results

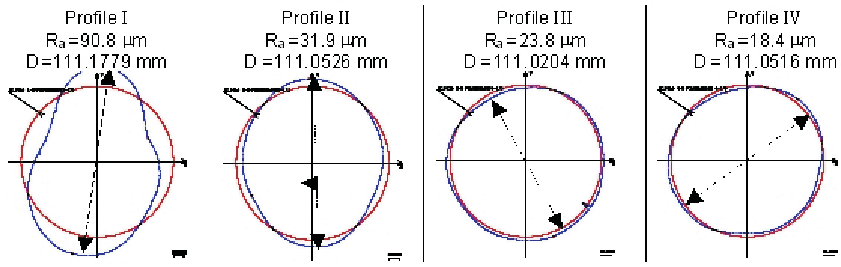

Fig. 6. Roundness sample measurement records of engine cylinder bore (— maximum amplitudes).

Average out-of-roundness results (Ra values) have been processed for each measured circle on the bore surface and presented in Figure 6 with reference to the nominal diameter which is numerically computed and found equal to 111 mm. The roundness is represented at each transverse section by the domain between the two virtual enveloping circles tangent to the distorted shape processed using LSQ fitting technique built in the machine as indicated in Figure 6. Analysis of the roundness patterns of the cylinder bore, illustrated in Fig 6, indicates the following points:

- The CMM machine software establishes a reference geometric feature of ideal regular form, deduced numerically from one or more realistic irregular scanned shapes. The established reference datum can be used in the assessment process of the runout values of the geometric features of the object under investigation.
- Circle I nearby the TDC, as expected due to lubricant starvation, depicted the highest average distorted dimension of D_I=111.1779 mm and the largest average out-of-roundness (R_a=90.8 μm).Whereas, the smallest distorted dimension was depicted at section III (D_{III}=111.0204 mm) in the vicinity of the mid-stroke point of the piston crown ring with average OOR value R_a=23.8 μm., while the smallest out-of-roundness value was found nearby the BDC at circle IV (R_a=18.4 μm).
- Roundness of circle I has two maximum amplitudes (arrow tips in Fig. 6) at points corresponding to the location of resultant surface reaction $\sqrt{F_s^2 + F_a^2}$ of piston side force F_s and crankshaft axial force F_a. The side force amplitude and direction vary according to the nature of piston traveling displacement especially at compression and power strokes.
- Amplitudes of circle III have the smallest wear variation rate with relatively small out-of-roundness which may be due to good lubrication conditions and light side forces at that location, whilst roundness nearby the BDC (circle IV) has different directions of peak amplitude going with the indicated direction of cylinder distorted shape. This may be attributed to the stud clamping force situation (magnitude and direction) when the piston passes by this location. At both BDC and TDC marginal inversion locations, the loads on the piston generate a stringent translated piston dynamics.

4.2. Concentricity Measurements

Experimentally measured values of the relative roundness on the bore at different transverse locations (concentricity) have been found as 39.1, 44.4, and 61.2 m between round profiles I and II, I and III, and I and IV, respectively with the axial center line of round profile I as reference datum. This would reflect the distortion resulted from the extremely severe wear mechanism to which the engine cylinder bore was being exposed during service.

4.3. Out-Of-Straightness Measurement Results

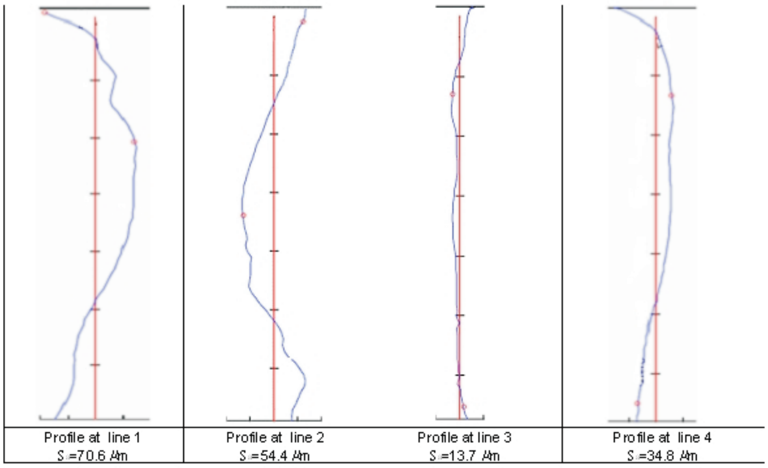

Fig. 7. Longitudinal sample profiles of cylinder straightness (Sa is the averaged straightness of the profile).

Figure 7 shows a sample record of four averaged longitudinal profiles at equispaced locations 1, 2, 3, and 4 along the cylinder inner wall as indicated in Fig. 2 above. The maximum out-of-straightness value (S_a) processed from the measurements along each longitudinal profile represents the deviation domain around the relevant reference line obtained by applying the LSQ fitting technique. Straightness profile sample records shown in Fig. 7 disclose the following points:

- Non-uniform wear rates are exposed along all averaged longitudinal profiles. It is clear that every point on the cylinder bore is subjected to different concurrent dynamic and environmental conditions of pressure, friction, lubrication scheme, sliding velocity, contact temperature, and contact force (orientation and magnitude). Thus, frequent evaluation of bore surface geometrical status is needed whenever possible to help monitoring the functional degradation and diagnosing the surface failure symptoms in anticipation, so that reasonable decisions can be taken regarding surface treatment implementation and/or constructional design improvement inspiration.
- Maximum wear rates have been found to consistently lie within the TDC of the first pressure ring contact area for all averaged profile measurements of 70.6, 54.4, 13.7 and 34.8 m. This may be explained by the bad tribological conditions at the TDC location as aforementioned. The largest value of straightness departure (70.6 μm) which lies on profile 1 was formed during power strokes as a direct response

to large side force reaction at high combustion temperatures. These findings are in agreement of a study carried out by Schneider et al [3].

- Wear valleys of bore straightness have large values for profile at points 1 and 2 of power and compression stroke ends (nearby BDC) due to side force reaction of concentrated piston inertia, while profiles of points 4 and 3 have shown the smallest amplitude valleys, respectively.
- An extended valley of straightness has the first profile of power stroke till 70 mm long; it may be produced by piston-skirt stringent side pressure and combustion gas high temperature beside piston rotation around its pins under the effect of the friction force moment. Strong piston skirt dynamics accelerates the wear of the crankshaft axial movement control washers.

5. CONCLUSIONS

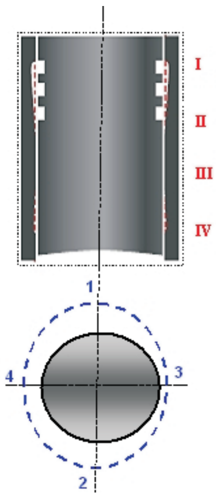

Fig. 8. Bore geometrical and dimensional deviations.

- Precision geometrical and -scale dimensional measurements of straightness, roundness, bore diameter and concentricity of the internal surface of a worn-out engine cylinder have been executed using the CMM machine. If compared to its original design GT&D tolerance limits, these measurements are supposed to represent a diagnostic tool for the wear development and aggression monitoring. Scenarios of the probable adverse operating conditions during service may also be inspired. The dimensional measurements of the bore diameter at different transverse locations along the traveling stroke have assured previous findings using other different complicated measuring techniques. In turn this may provide feedback to both the engine designer for modifications and the maintenance engineer for his forthcoming preventive and corrective maintenance plans.

- The maximum uncertainty values as shown in Table 3 and Fig. 5 have been found smaller than the CMM machine maximum permissible errors. This confirms that the CMM measurements are reliably accurate and precise.
- The wear at the TDC and BDC transverse sections has been found to be much larger than the wear which occurred at the middle of the stroke and in the vicinity of the BDC. This phenomenon is attributed to the continuous existence of a lubricating oil film dynamically preserved at that location.
- CMM machine precision measurements may also provide an insight in the engine dynamics that may contribute to the excessive wear occurrence in the engine cylinder. The geometrical deviation due to inhomogeneous wear has caused a distortion in the bore where ($S_{a1} > S_{a2} > S_{a4} > S_{a3}$), as depicted in Fig. 8. This may inspire the engine designer to introduce an innovative modification to the engine by developing a controllable cylinder rotating device about its axis probably without having to dismantle the engine parts, so that the wear can be homogenized. Thus, the power loss due to friction and wear in the cylinder can be minimized and the engine operating life span may be rather prolonged. In addition, the maintenance expenses may be also reduced.

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