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EVALUATION OF GAUGES APPLIED TO PERFORMANCE AND INTERLABORATORY COMPARISON OF AACMM

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Abstract. *This work presents an analysis of the errors obtained with three different gauges during performance evaluation of Articulated Arm Coordinate Measuring Machines (AACMM). The experiments were accomplished in a Romer AACMM, model Arm 100, with expanded uncertainty (95%) of 0.06 mm, taking in account the Standards requisitions. The gauges used were a Ring gauge, a Step gauge and a Virtual Spheres Plate (VSP). These gauges were measured in different positions and orientations in AACMM work volume to determine the bias and repeatability. Ring gauges with diameters 35 mm and 40 mm were used, positioned in three locations in respect to the AACMM: near, medium and far from machine basis. A Step gauge 600 mm long was used and positioned in four different locations in work volume, X-axis (radial), Y-axis (near), Y-axis (far) and XY direction (diagonal), measuring 10 lengths in each one. A "L" shaped VSP gauge with seven virtual spheres was used and placed in three different locations at AACMM work volume, near, medium and far from the machine basis. All measurements were performed five times and the bias and the repeatability were determined. A factorial design of experiments was applied and the Analysis of Variance (ANOVA) was carried with the error values and the statistically significant variables were determined. As intended for interlaboratory comparison of AACMMs, it was found that the VSP with the factorial design is an interesting option since analysis is improved by the use of statistical techniques.*

Keywords: *interlaboratory comparison, AACMM performance, error analysis*

1. INTRODUCTION

The application of Articulated Arm Coordinate Measuring Machines (AACMM) is increasing in industry thanks to its flexibility and ease of use in shop floor and quality control laboratories. These measuring machines can be moved to carry out field measurements as it is done for large parts like hydraulic or wind turbine runners. Their construction involves tubular composite segments connected by rotary joints that compose an arm-like structure. An operator handles AACMM movements manually in order to reach the contact points on part surface (Piratelli-Filho and Lesnau, 2010; González-Madruga *et al.*, 2014).

There is an increasing search for methods of performance tests and interlaboratory comparison of these machines, driven by Metrology institutes and research laboratories around the world. In general, most of the existing methods are based on ASME B89.4.22 (2004), VDI 2617-9 (2009) and ISO 10360-2 (2009) Standards. The ASME B89.4.22 Standard proposes a performance test of AACMMs using sphere and ball bar gauges in three different tests: effective diameter test, Single-Point Articulation test (SPAT) and volumetric test. The VDI Standard recommends two tests and equivalent error parameters by measuring a calibration sphere and a length gauge in 7 positions in work volume. ISO 10360-2 is applied to inspect Cartesian CMMs and specify a probing error test using the machine spherical probe and calibrated reference sphere (repeatability verification) and a Step gauge measured in three positions (near, middle and far) to determine the errors (combination of SPAT and effective diameter test of ASME B89). In common, the verification of the single point test and the length error evaluation are important steps to verify AACMMs performance (QMT, 2013; Mutilba *et al.*, 2013).

Santolaria *et al.* (2014) observed that the lack of Standards about verification and calibration procedures of AACMMs initially motivated the manufacturers to develop their own evaluation procedures and different criteria has been used to determine measurement errors in these machines. Methods for performance evaluation and interlaboratory comparison of AACMMs were developed such as proposed by Santolaria *et al.* (2008), Santolaria *et al.* (2009), Piratelli-Filho *et al.* (2010), Piratelli-Filho *et al.* (2012), Mutilba *et al.* (2013) and Santolaria *et al.* (2014).

Mutilba *et al.* (2013) evaluated the performance of a Romer Absolute Arm in agreement with the ASME B89.4.22 Standard, using a precision ceramic reference ball with 30 mm in diameter for effective diameter test and Single-Point

Articulation test (SPAT). The SPAT test was carried out with hard probes and a trihedral seat having three hardened spheres placed in a flat bottom or “cup”. A carbon-fibre reinforced polymer (CFRP) ball bar with 2400 mm in length was applied to the volumetric performance test.

González-Madruga *et al.* (2014) evaluated a Sigma Romer AACMM using a hard probe with a stylus 45 mm long and a 4 mm diameter ruby sphere. The authors investigated different measurement parameters (operator, contact force and type of feature) by means of contact force sensor on the AACMM probe and geometric gauges. They concluded that the probe bending force was the most relevant force parameter. Santolaria *et al.* (2014) proposed an alternative procedure for calibration of a Faro Platinum AACMM, considering a non-linear system of equations and applying the Denavit-Hartenberg (D-H) method to every chain in the mechanism.

Piratelli-Filho *et al.* (2012) developed and applied a Virtual Spheres Plate (VSP) gauge to performance test and interlaboratorial comparison of AACMMs. This gauge has pyramidal inserts with four conic holes at each to determine the points and fit virtual spheres. The length of center-to-center of spheres were determined and used to evaluate the machine.

Efforts are under way to develop and disseminate a method for interlaboratory comparison of AACMMs, as there is no agreement about the most suitable. The requisition of traceability drives the research to the gauge selection in order to determine the errors and the uncertainty to make comparisons. Improvement can be attained by applying statistical methods to analyse data. The method must evaluate the human, technical and methodological components of the machine, including the hardware, the software, the probe and the strategy followed to capture the points. This work presents an analysis of the errors obtained with three different gauges during performance evaluation of Articulated Arm Coordinate Measuring Machines (AACMM), Ring gauge, step gauge and VSP gauge.

2. EXPERIMENTAL

2.1 - Methodology for performance evaluation

A Romer ARM 100 Articulated Arm Coordinate Measuring Machine (AACMM) was used to carry out the experiments. This machine has six degrees of freedom and an arm reach of 2.5 m in diameter. The software GPad was applied to drive the measurements with the machine. A rigid probe was fixed at the arm end having a 5 mm diameter ruby-made spherical stylus. The AACMM had an expanded uncertainty (95%) of 0.060 mm, declared in calibration certificate. The measurements took place with the machine fixed over a cast iron standard basis by its magnetic supports.

Three different gauges were selected to evaluate the AACMM performance: i) two Ring gauges with diameters 35 mm and 40 mm, with expanded uncertainty of 0.0010 mm; ii) one Step gauge with 600 mm length, with blocks spaced by 10 mm one from another and having expanded uncertainty of 0.5 + L/1000 µm (L is the length in mm); iii) one Virtual Spheres Plate (VSP) in “L” format with seven virtual spheres, having an expanded uncertainty of 0.017 mm. The gauges were cleaned and placed over a cast iron standard basis with the room temperature controlled in 20 ± 1 ºC. The relative air humidity was monitored at 50 ± 10 % during the experiments. Figure 1 presents these gauges.

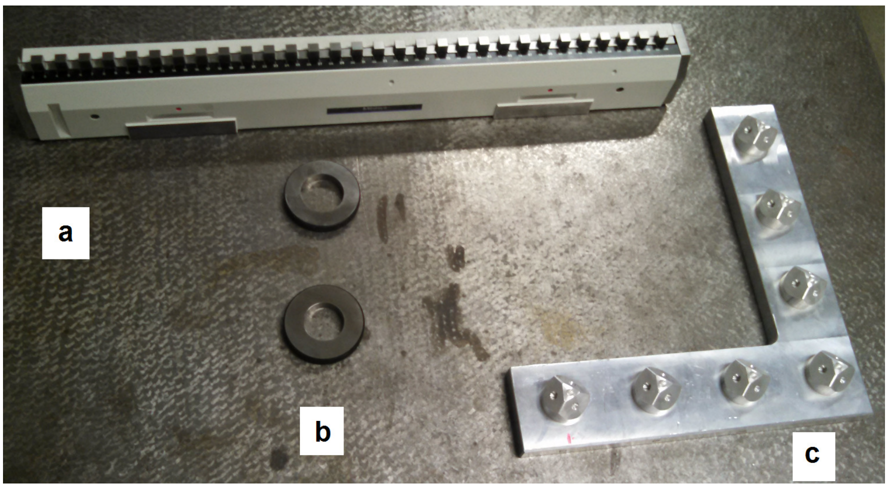

Figure 1. a) Step gauge; b) Ring gauges; c) “L” shaped Virtual Spheres Plate (VSP).

The measurement strategies were established according to the gauge used and are described below.

a) Ring gauge: the standard cast iron basis was marked to determine three positions in respect to the arm center, near (1), middle (2) and far (3). These measuring positions were fixed according to the maximum arm reach and it has the intent of verify the errors in different measuring distances from the AACMM basis. The position (1) verify the errors when the arm is near the center, the position (2) verify in the middle range and position (3) the placement near the maximum reach of the machine probe. In each position, the Ring gauge diameter was measured trough determining 9 points in the internal Ring surface, projected on superior plane surface by using GPad option *MEASURE CIRCLE PROJECTED IN PLANE*. The internal diameter was measured five times to the 35 mm and 40 mm nominal diameters of the Ring gauges, touching different regions of the circle.

b) Step gauge: four measurement positions were established to verify the performance in different location of the probe and configuration of the arm articulations: position (1) was defined as the direction of the y-axis, near to the arm center; position (2) was considered as the direction of y-axis, but far from the arm basis; position (3) was in the direction of x-axis, taking the radial direction of the AACMM work volume; position (4) was the diagonal direction formed by positions (1) and (3), xy direction. The measurement was carried out in each position by determining a plane of the first gauge block surface by using the GPad option *MEASURE PLANE*, determining 15 points with the AACMM. There was determined one point at each gauge block and the distances plane-point were determined to each of the 30 points taken, using the GPad calculator. Five replicates of each distance were determined.

c) "L" shaped VSP: the same strategy used in standard Rings was applied, selecting three positions to measure the VSP, near (1), medium (2) and far (3) to the arm basis. At each position, the points of the virtual spheres were determined and the values of the diameter and centre of the virtual spheres were calculated by GPad *MEASURE SPHERE*. The GPad calculator was used to determine the distance from the first sphere (reference) to the others, obtaining six distances center-to-center of the spheres. Five replicates were determined of each measurement.

2.2 – Measurement and analysis

The experimental work was planned to follow according to the Factorial Design of experiments, to detect the effect of the two variables and its interaction. This Factorial Design requires the implementation of all combination of the variables in its levels or values. A common variable was the POSITION in work volume, having 3 levels (Ring gauge and VSP gauge) or 4 levels (Step gauge). The second variable was related to the measured length, but for Ring gauge was adopted as DIAMETER in two levels, for Step gauge was adopted as plane-plane LENGTH in 30 levels and for the VSP gauge was adopted as center-to-center of spheres LENGTH in 6 levels. The interaction effect is considered as the effect over the error when the two variables are modified simultaneously. The runs of the design were executed in random order and the Figure (2) shows the factorial design with coded variables A (Diameter or Length) and B (Position) and interaction AB.

Table 1. Factorial Design applied to: (a) Ring gauge; (b) Step gauge; (c) VSP gauge. The lines represent the runs and are a combination of the variables length/diameter (A) and position (B), in respective levels (1 to 4).

(a)

A	B
35	1
35	2
35	3
40	1
40	2
40	3

(b)

A	B	A	B	A	B	A	B
20	1	20	2	20	3	20	4
40	1	40	2	40	3	40	4
60	1	60	2	60	3	60	4
80	1	80	2	80	3	80	4
100	1	100	2	100	3	100	4
120	1	120	2	120	3	120	4
140	1	140	2	140	3	140	4
160	1	160	2	160	3	160	4
180	1	180	2	180	3	180	4
200	1	200	2	200	3	200	4
220	1	220	2	220	3	220	4
240	1	240	2	240	3	240	4
260	1	260	2	260	3	260	4
280	1	280	2	280	3	280	4
300	1	300	2	300	3	300	4
320	1	320	2	320	3	320	4
340	1	340	2	340	3	340	4
360	1	360	2	360	3	360	4
380	1	380	2	380	3	380	4
400	1	400	2	400	3	400	4
420	1	420	2	420	3	420	4
440	1	440	2	440	3	440	4
460	1	460	2	460	3	460	4
480	1	480	2	480	3	480	4
500	1	500	2	500	3	500	4
520	1	520	2	520	3	520	4
540	1	540	2	540	3	540	4
560	1	560	2	560	3	560	4
580	1	580	2	580	3	580	4
600	1	600	2	600	3	600	4

(c)

A	B
1	1
2	1
3	1
4	1
5	1
6	1
1	2
2	2
3	2
4	2
5	2
6	2
1	3
2	3
3	3
4	3
5	3
6	3

The software MatLab was used to perform calculations of errors, based on calibrated diameters and distances of the gauges. An algorithm was developed to carry out an Analysis of Variance (ANOVA) with the errors results. The estimates of the variance (mean squares, MS) were determined to the variables and interaction by the respective sum of the squares (SS) and degrees of freedom (DF). Thus, the most significant variables were detected by applying the statistical F test, comparing the variables and interaction variance estimates (MS) to the residual mean square. The residual analysis was performed to check if the assumptions of independence and identically distributed residuals with Normal distribution with mean 0 and standard deviation σ - NIID(0, σ). Detailed explanation of this procedure can be found in literature (Box *et al.*, 1978; Montgomery, 1991).

3. RESULTS AND DISCUSSION

The systematic mean errors (bias) associated to the measurement with the ring gauges (diameters 35 mm and 40 mm) are presented in Figure 2. It was observed changes in bias according to the position in respect to the AACMM basis, in particular for positions (2) and (3), medium and far from the machine basis. For position (1), there is a small change in bias when increasing the diameter, from 0.011 mm to 0.009 mm. For position (2), the bias change increased from 0.030 mm to -0.012 mm, as shown by curve 'Série 2' in this Figure. For position (3), the same was observed but with variation of 0.270 mm to -0.260 mm. This behavior may be explained by the increasing difficulty in measurement when approaching the arm reach limits. The standard deviation was also determined and it was observed values greater than the mean, as presented, and then it was not possible to conclude about the differences in mean errors and bias in this range of standard values that are close each other.

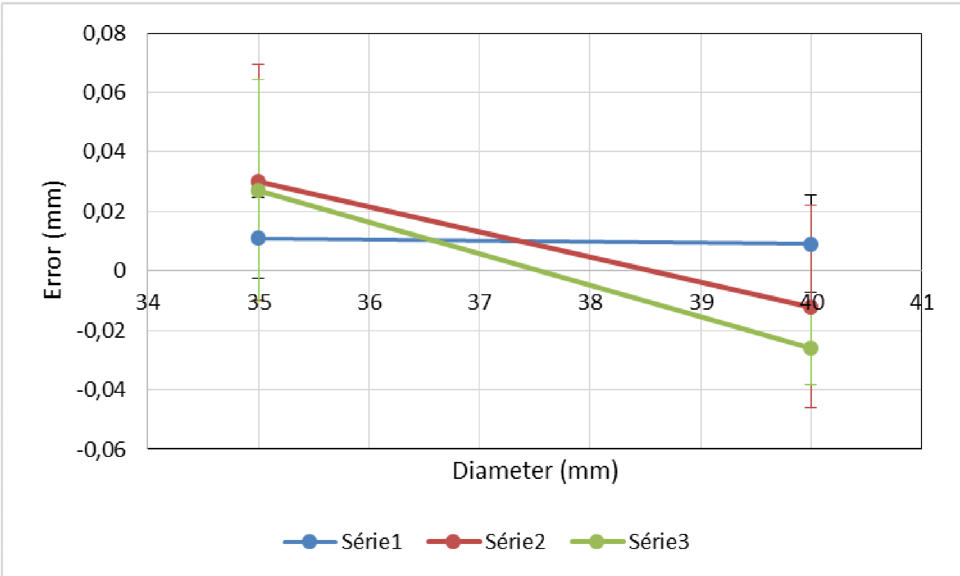

Figure 2 – Ring gauge diameter x position x mean error.

The analysis of variance (ANOVA) is presented in Table 2. The F test showed that only variable Diameter was statistically significant, at 99% probability, e.g., the diameter promotes significant modifications in mean error values. A mathematical model (y=b0+b1.x1, x1=Diameter) was fitted by multiple regression and the coefficients were determined as b0= 0.2480 and b1= -0.0064. The residuals were determined by difference between observed and estimated (model) and the assumption of Normal Distribution was verified by the probability plot of residuals, presented in Figure 3. According to this figure, the assumption was accepted and the ANOVA validated.

Table 2 - ANOVA results with Ring gauge errors.

Source	SS	DF	MS	F Value	Pr > F
Diameter	0.00778	1	0.00778	9.89	0.0044
Position	0.00060	2	0.00030	0.38	0.6880
Diameter x Position	0.00363	2	0.00182	2.31	0.1212
Residual	0.01888	24	0.00079		
Total	0.03089	29			

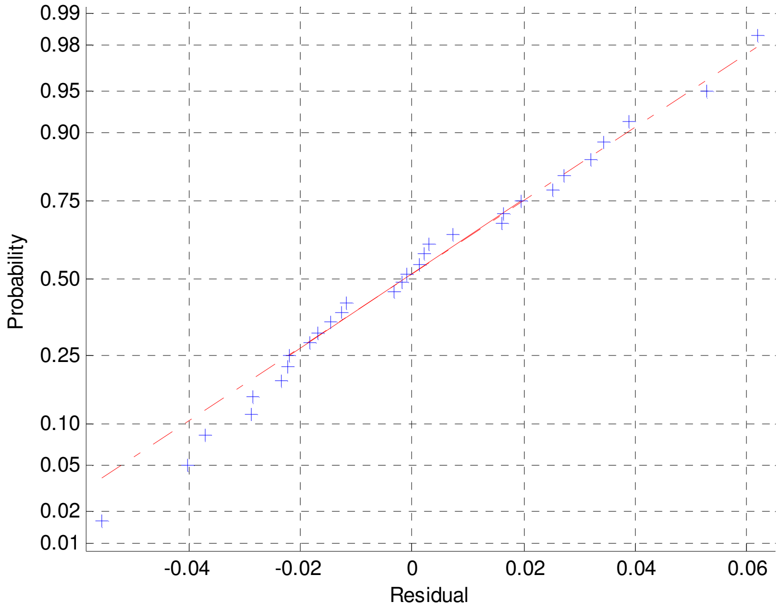

Figure 3. Residual analysis for Ring gauge model.

The mean errors (bias) obtained with the Step gauge are presented in Figure 4, together with the bar errors determined by one standard deviation. It was observed that as length increase, the mean errors decrease, all positions giving the similar appearance. For position denoted by 'Série 2' (Y far from the center), the mean errors were all negative and greater than (in modulus) in other positions, Y-near ('Série 1'), X-radial ('Série 3') and XY ('Série 3'), changing from -0.280 mm to -0.570 mm. The ANOVA results are presented in Table 3. The F test showed that variables Length and Position and the interaction Length x Position were all statistically significant at 99% probability. A regression model was fitted to data (y=b0+b1.x1+b2.x2+b12.x1.x2, with x1=Length and x2=Position) and the regression coefficients were determined as b0= -0.1575, b1= -0.0004, b2= 0.0026 and b12= -0.0000. The residual analysis is showed in Figure 5 and the assumption of Normal distribution of the residuals was not rejected.

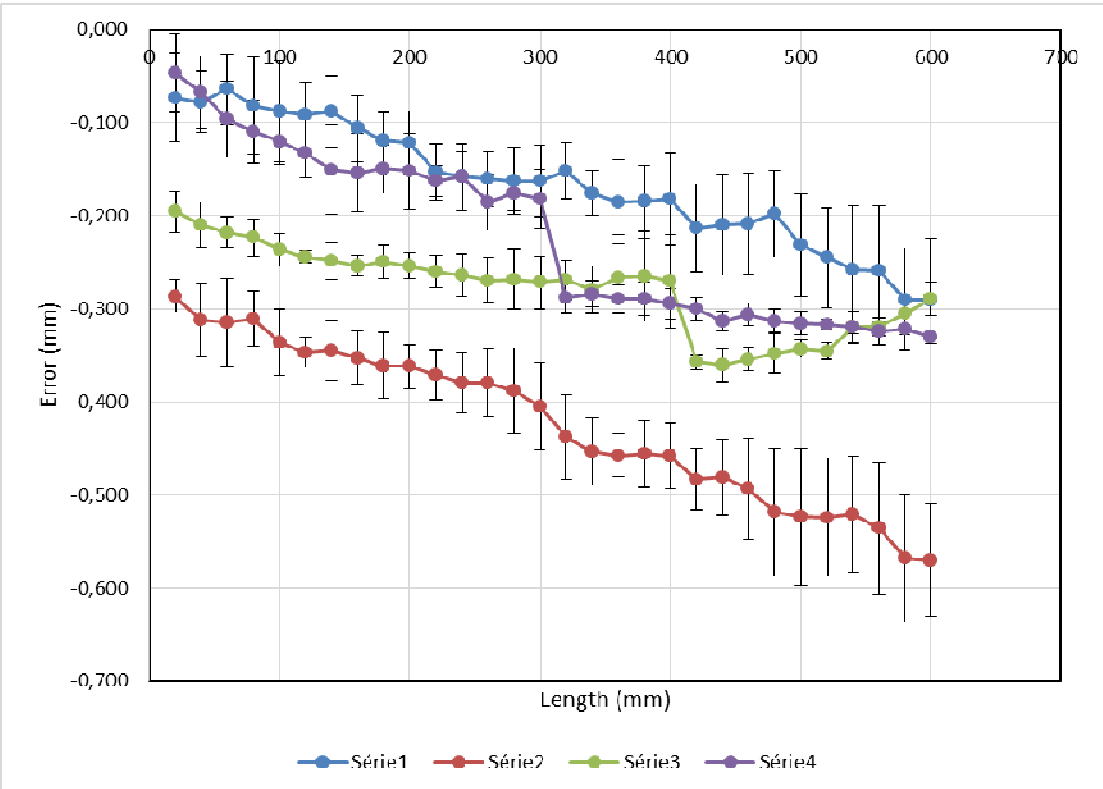

Figure 4. Step gauge position x lengths x mean errors.

Table 3 - ANOVA results with Step gauge errors.

Source	SS	DF	MS	F Value	Pr > F
Length	2.81595	29	0.09710	72.91	<.0001
Position	5.55230	3	1.85077	1389.64	<.0001
Length x Position	0.38852	87	0.00447	3.35	<.0001
Residual	0.63928	480	0.00133		
Total	9.39606	599			

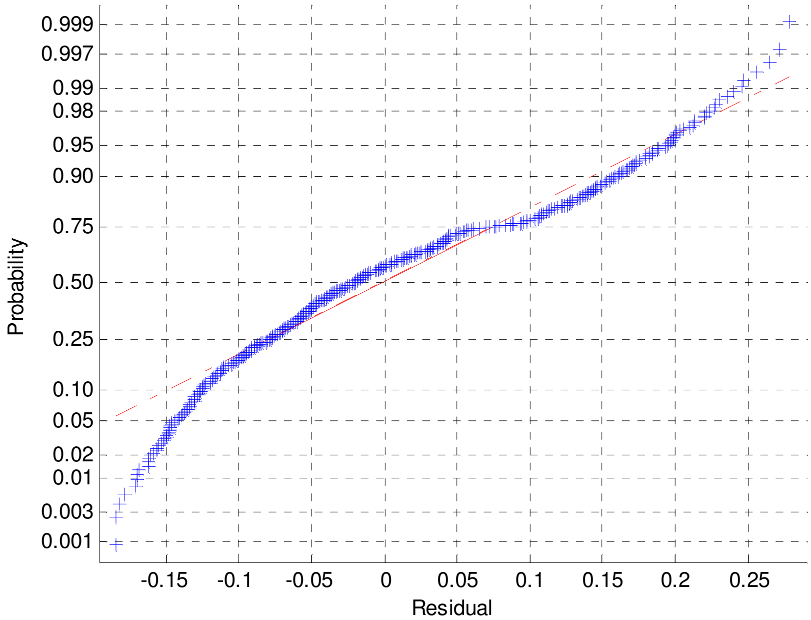

Figure 5. Residual analysis for Step gauge model.

The mean errors determined with the ‘L’ shaped Virtual Spheres Plate (VSP) are presented in Figure 6, with the error bar determined by one standard deviation. It was showed that as length increase, the bias (mean errors) decrease, all positions giving the similar appearance. For position denoted by ‘Série 2’ (midlle), the mean errors were all negative and showed small variation with length center-to-center of spheres changing, of about -0.050 mm. The standard deviations denoted by error bars found a maximum of 0.05 mm to position 1 (near the machine basis) and length 78.000 mm. This value is of the same order of the machine uncertainty. The ANOVA results are presented in Table 3 and the F test showed that variables Lengthspheres and Position and the interaction Lengthspheres x Position were all statistically significant at 99% probability. A regression model was fitted to data (y=b0+b1.x1+b2.x2+b12.x1.x2, with x1=Lengthspheres and x2=Position) and the regression coefficients were determined as b0= 0.0186, b1= -0.0189, b2= -0.0195 and b12= -0.0017. The residual analysis is showed in Figure 7 and the assumption of Normal distribution of the residuals cannot be rejected.

The bias found with the “L” shaped VSP were greater than the Step gauge ones, at a given length. A possible reason is the additional movements needed to take points over the conical holes and the calculations involved in determination of the distance center-to-center of spheres, associated to the algorithm involved in calculations.

The variability presented in error bars (one standard deviation) of the VSP evaluation was at the same order of that presented by Step gauge results, at the same length. Comparing the positions adopted, near the machine basis gives a standard deviation of 0.042 mm, the position far produced 0.035 mm and the medium was 0.022 mm.

The ANOVA results presented the residual mean squares in ANOVA tables and these values are associated to the unknown variability sources. These values may be used to estimate the standard deviation that was 0.028 mm, 0.036 mm and 0.049 mm for the Ring, Step and VSP gauges, respectively.

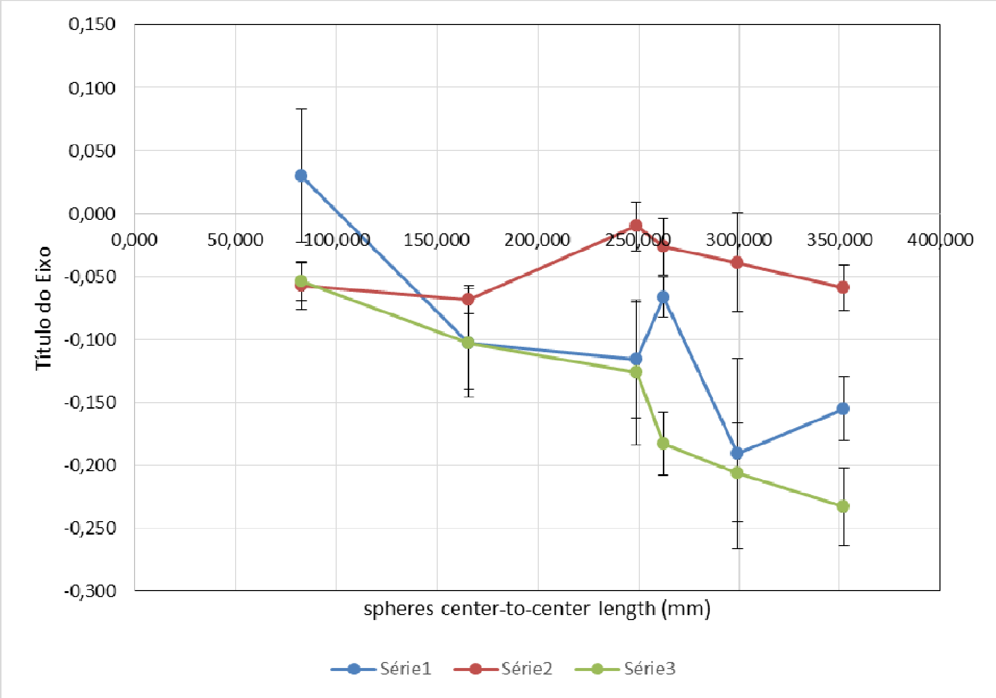

Figure 6. VSP gauge Position x distance x mean errors.

Table 4 - ANOVA results with "L" shaped VSP errors.

Source	SS	DF	MS	F Value	Pr > F
Lengthspheres	0.15204	5	0.03041	22.09	<.0001
Position	0.17363	2	0.08681	63.08	<.0001
Lengthspheres x Position	0.12425	10	0.01243	9.03	<.0001
Residual	0.09910	72	0.00243		
Total	0.54901	89			

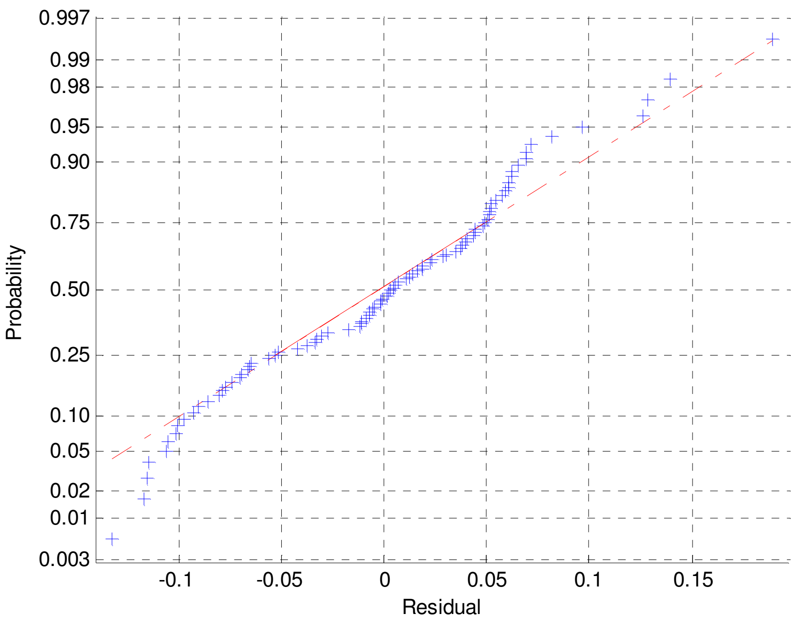

Figure 7. Residual analysis for VSP gauge model.

4 - CONCLUSIONS

This work presented a comparison of Ring gauge, Step gauge and VSP gauges applied to performance evaluation of an Articulated Arm CMM (AACMM). There were used statistical methods of factorial design to carry out the experiments and the analysis of variance (ANOVA) to compare the results.

The graphical analysis showed that the bias increased as the gauge was positioned far from the machine center and with increase of gauge length. The differences obtained can be associated to the algorithm of the machine software required to process data from gauge measurement and a bias of -0.570 mm was observed with the VSP gauge at position far from the center and with a 600 mm distance center-to-center of spheres. The repeatability was determined by the standard deviation and it was observed a value of 0.070 mm to the Step and VSP gauges. The search for this value required careful attention to the graphics and can be improved by statistical methods.

The factorial design systematized the experimentation as it was possible to combine all variables involved at different levels. The ANOVA showed the variables and their contribution to variability, at a given probability, and the residual mean squares (MS) can be used to determine a variability or repeatability parameter to the investigated parameter. For the small dimensions of the Ring gauges, the main source of variability came from the ring diameter, and for the Step and VSP gauges the main source came from position in work volume, as presented by the mean squares values (MS) at the ANOVA tables.

Future works can be developed to investigate more variables like operator, software algorithm, strategy in measurement and others, using complex geometry gauges and factorial design with ANOVA technique.

5. ACKNOWLEDGMENTS

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