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Study of Virtual Features in the Performance of Coordinate Measuring Arms

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Abstract

Coordinate Measuring Arms (AACMMs or CMAs) made up their own type of dimensional measurement machines due to their unique characteristics: structural redundancy, portability and manual control. Therefore, specific evaluation methodologies have been developed in order to guarantee their measurement reliability and traceability. Despite the fact that some AACMM evaluation parameters and test have been defined, current methodologies are based on CMM previous experience and they have to be adapted to AACMM characteristics. Virtual features, made of kinematic seats, have been proved as a singular and useful feature for AACMM measurement as well as a suitable method for a fast and low cost evaluation. In order to simplify these features and processes the required input for evaluation has been reduced to 3 points or kinematic seats, which define a virtual circle. This work studies the suitability of these virtual features at the same time that reduces the evaluation time and gauge cost.

Keywords: AACMM; CMA; Coordinate Measuring Arms; metrologycal qualification; virtual circles

1. Introduction

AACMMs development has make possible fast measurements, especially of complex parts, outside the laboratory environment. Because of their flexibility and manual control, AACMMs easily adapt to the part geometry without careful collision and path studies. Furthermore, their portability allows them to be located at any place that provides

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with a fixed point for AACMM mounting. In contrast with their great potential, a few studies and standards, which deal with AACMM reliability and traceability, are available.

Current evaluation methodologies imply many measurements and time consumption as a large amount of data is required [1, 2]. ASME standard [1] evaluation performance requires three test with three gauges. In the "Effective diameter performance test" a calibration sphere is measured and its diameter checked, a kinematic hole is used for point repeatability in the "single point articulation performance test" and a ball bar is measured within the workspace for the "volumetric performance test". Similarly, VDI standard [2] provide with two tests: "probing test" and "volumetric performance test". In the first one the diameter and center error of a calibration sphere is evaluated and in the second one a ball bar is used to measure distance within the workspace.

Ball bars are the most common type of evaluation gauge for AACMM [1-4]. Santolaria et al. [3] presented a complete calibration method by means of measuring the distance error and a point repeatability of a ball bar. They also defined several gauge positions that allow them to validate all subsequent measurement within the AACMM workspace. Furutani et al. [5] compared several ball bar configurations and determined a two ball bar as the most suitable gauge for AACMM calibration. In addition, Kovac et al. [6] suggested a linear gauge for AACMM calibration although it appears to be too heavy and complex when compared to AACMM portability and flexibility. As mentioned, kinematic seats are also used as a gauge for point repeatability evaluation in ASME standard. This kind of feature fits into AACMM manual control and kinematic structure since their geometry can accommodate the probe sphere and measure the same point repeatedly. In addition, kinematic seat measurement avoids negative effects of manual control as point repeatability, reproducibility, probe orientation, measurement force which affect to evaluation results [7, 8]. Thus, some author incorporated this feature into surveys. Gao et al [9, 10] proposed a calibration process based on the repeatability of several points, determined by a gauge with kinematic seats.

From a new point of view, Piratelli et al. [11, 12] introduce the virtual sphere concept as a substitute for AACMM evaluation with ball bars. Four kinematics seats determine four spatial points that define a virtual sphere. When two virtual spheres are located at the end of a bar, it works similarly to the ball bar and evaluation methodologies can be adapted to this kind of gauge. They compared a virtual sphere bar with a ball bar following ASME standard and they also succeed in reducing the minimum number of gauge position to 9 positions. In a previous work [13], it was proposed a simplified method and gauge, virtual circles, which uses less input data, and their results are comparable to the ASME or VDI test outputs. In this paper, a further research of virtual circles, as a mean for AACMM evaluation, is carried out. Virtual circles are compared to virtual spheres in order to be validated. In addition several virtual circles are tested. At last, this proposed methodology, equivalent to standards tests, saves time and the cost of expensive gauges and calibration spheres.

2. Methodology

Using calibrated spheres to calibrate metrological equipment is highly widespread, in spite of the cost associated with the manufacturing of precision spheres. Whereas this type of gauges has been proved suitable for CMM calibration and evaluation, AACMM manual control causes a significant lack of repeatability and reproducibility on the evaluation process.

An alternative to avoid this problem consist in using gauges with virtual spheres defined by kinematic seats. This kind of elements fits perfectly the way AACMMs work, where passive probes are frequently used. During the measurement of the gauge, the operator put the probing sphere into the seat obtaining a contact that is stable and repeatable through the space. Piratelli et al. [11] introduced the concept of virtual sphere gauge as a way to a fast and reliable evaluation of AACMMs. A further analysis of virtual features is introduced by decreasing the necessary input data from a virtual sphere to a virtual circle.

2.1. Test methodology

In order to study this type of features a gauge with two virtual spheres was built, Fig. 1. The gauge has an inverted-T shape with a total length of 1000 mm. It was machined from a hard aluminum alloy with a subsequent anodized treatment that increased its superficial hardness. Each virtual sphere is defined by four kinematic seats in each bar end. Each kinematic seat (conic hole) has been drilled deep enough to fit the probe sphere. They are similar to the kinematic seats that the ASME standard [1] proposes and uses in 'Single-point articulation performance' test. Each set of four seats defines four points that are used to virtually construct a sphere. These spheres simulate perfect calibration spheres. If a larger number of kinematic seats were used to define the virtual sphere, a really careful manufacturing would be required to fit all points with the virtual sphere geometry. In addition, several virtual circles have been also constructed using only three points of each virtual sphere.

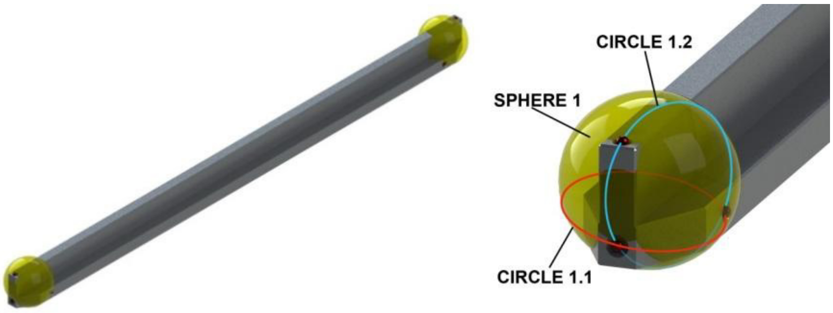


Fig. 1. Virtual spheres and its virtual circles located at the ends of the gauge.

A Romer Sigma arm with the characteristics that are shown in the Table 1 has been used. The "Sphere test" measures the diameter deviation of a calibrated sphere. The "Cone test" obtains the repeatability of the AACMM measuring a point in the workspace, kinematic seat. Finally, the "Length accuracy" value means the capacity of the AACMM to measure distances.

Table 1. AACMM technical specifications.

Technical specification	Romer Sigma	
Measuring Range [mm]	1800	
Sphere repeatability, Sphere test [mm]	0.010	
Point repeatability, Cone test[mm]	0.018	
Length Accuracy [mm]	0.025	

The ASME standard [1] defines 20 positions considering their orientation, evaluated octant and length of the gauge. The VDI recommendation [2] includes a lower number, of 7 positions, for its volumetric performance test. They are also defined from their orientation and sector of the workspace that will be evaluate. These two standards allow the definition of other different positions as long as they cover the workspace totally. Piratelli et al. [9] reduces the 20 positions defined by the ASME standard to 9 positions with similar evaluation results. A number of 12 positions were defined for this work, considering the quadrant that will be evaluated and the gauge position, Table 2.

2.2. Test setup

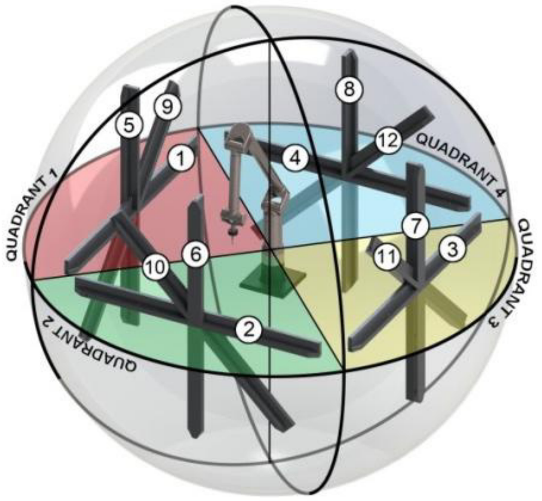
In order to materialize the defined positions, the AACMM was attached to a worktable and the gauge was placed on a tripod provided by the manufacturer of the AACMM. Evaluation of each quadrant is achieved by rotating the arm 90° around its fixed position on the worktable. A multi-position device, which can be coupled with the tripod, was built to place the gauge in different orientations: horizontal, vertical and inclined. It enables the orientation of the gauge with different angles at a height that is appropriate for measuring.

Measurement data used in the calculation has been obtained with PC-DMIS® as measurement software. From each group of four points that defines a virtual sphere the following data are obtained: sphere diameter (80 mm approximately) and the center coordinates. Distance between the virtual spheres (921 mm) is also obtained as distance between sphere centers. Two pairs of virtual circles are constructed from the combination of three of the four kinematic seats with the purpose of comparing virtual spheres and virtual circles. Same data are obtained in this virtual circle case: diameter (74 mm y 76 mm respectively) and center coordinates. Virtual circles are constructed with points measured with different probing vectors. The used terminology is defined as follows. The two spheres are named after the end of the gauge where are manufactured: sphere 1 and sphere 2. The virtual circles have two numbers in their denomination. The first one is the same as the number of their homologous sphere (1 or 2), and the second one distinguishes between the two virtual circles (1 or 2) of each sphere, as shown in Fig 1.

Each feature was measured 15 times. Measurement data was subsequently processed to eliminate wrong points and outliers by applying Chauvenet's criteria only once in the set of data require it. Choosing a sample of 15 points per position enables us to study at least 10 measurements once the data has been processed. This means that each entity was measured, at least, 120 times. The test was carried out in an environment with its temperature controlled within 20±1 ºC.

Table 2. Test positions.

Position	Gauge orientation	Quadrant
1	Horizontal	1
2	Horizontal	2
3	Horizontal	3
4	Horizontal	4
5	Vertical	1
6	Vertical	2
7	Vertical	3
8	Vertical	4
9	45º	1
10	45º	2
11	45º	3
12	45º	4



2.3. Test results and discussion

Three different sets of data were obtained from the test: center error, diameter error and distance error, from virtual circles and spheres. Mean values of these parameters are taken as reference values for further analysis and comparison between features. Center error is the difference between each of the obtained centers in one position and the reference center of that position. Similarly, diameter error is calculated as the difference between each measured diameter in one position and reference diameter of that position, and distance error is the difference between each distance and its mean value. Fig. 2 shows center and diameter errors for spheres 1 and 2. The maximum center errors for the spheres are 0.0820 and 0.1581 mm respectively. The maximum diameter error is -0.0505 mm for sphere 1 and -0.0862 mm for sphere 2. Both maximum errors for sphere 1 are located in the position number 10, meanwhile maximum errors for sphere 2 are located in the position number 7. The largest range for the center error is 0.0667 and 0.1388 mm. It is 0.0902 and 0.1524 mm for the diameter error of sphere 1 and sphere 2. The highest errors and dispersions are located in positions number 5, 6, 7 and 8 of the sphere 2 as the figures shows.

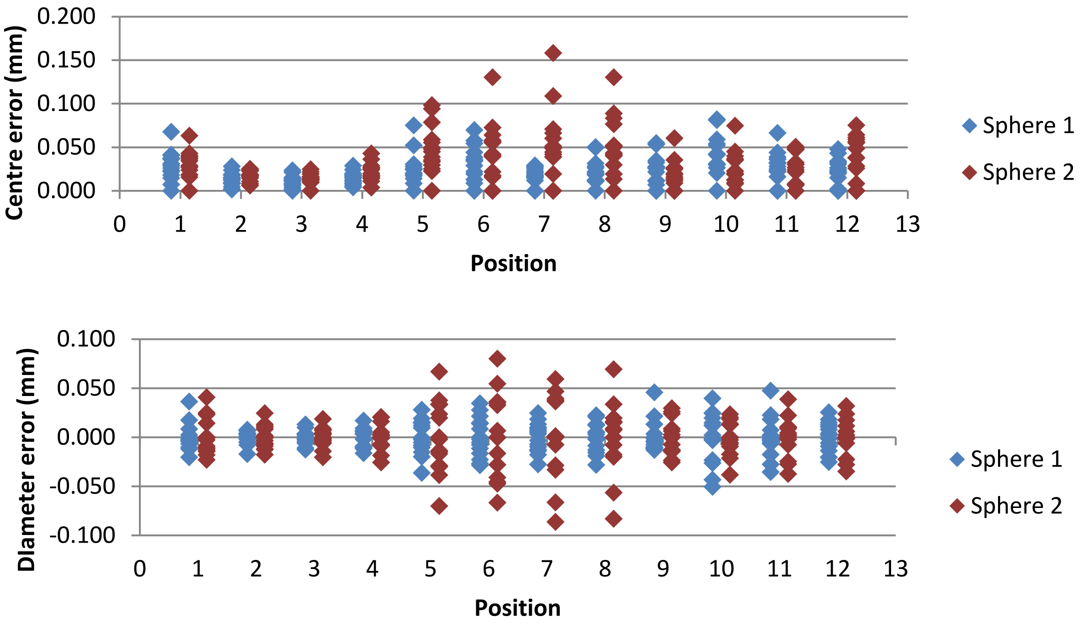


Fig. 2. *Up)* Centre error and, *Down)* Diameter error for sphere 1 and sphere 2.

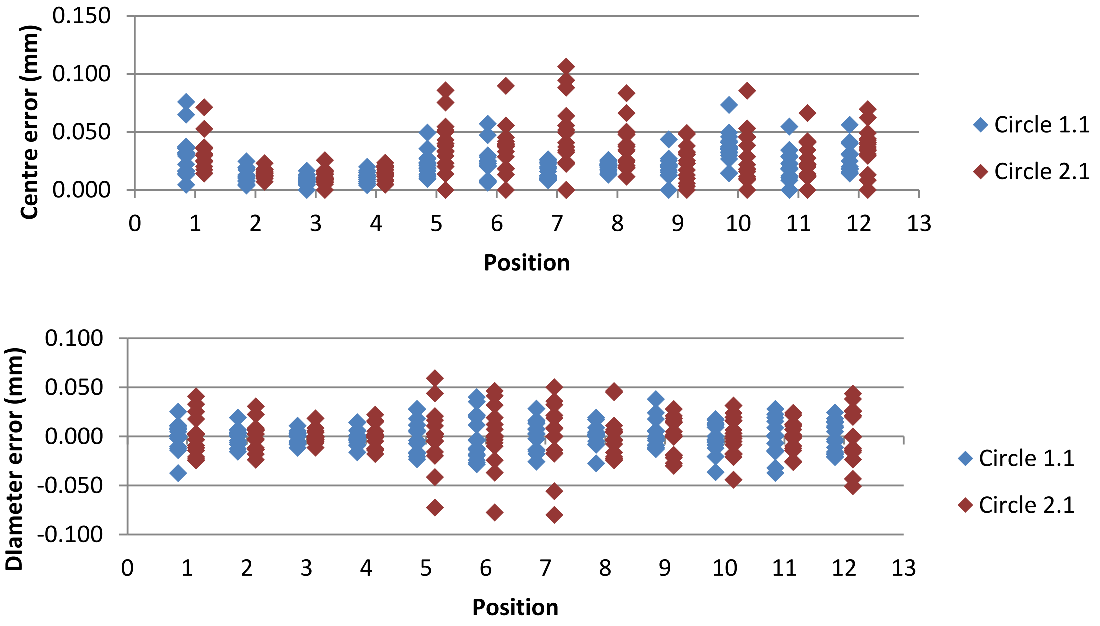


Fig. 3. *Up)* Centre error and, *Down)* Diameter error for virtual circle 1.1 and virtual circle 2.1.

Fig. 3 shows center and diameter errors for virtual circles 1.1 and 2.1. The maximum center errors are 0.0758 mm for the Virtual circle 1.1 in the position number 1 and 0.1062 mm for the virtual circle 2.1 in the position number 7.

The highest ranges of this parameter are 0.0713 for the virtual circle 1.1 and 0.0837 mm for the virtual circle 2.1. The maximum diameter errors are 0.0410 mm for virtual circle 1.1 in the position 6 and -0.0799 mm for virtual circle 2.1 in the position 5. The highest ranges are 0.0763 and 0.1465 mm for these features. It can be seen that the positions 5, 6, 7 y 8 for the virtual circle 2.1 also have the highest errors and dispersions. Maximum center errors of 0.0635 and 0.1862 are obtained when studying virtual circle 1.2 and 2.2. The maximum diameter errors are -0.0906 and -0.1065 mm for these features. The highest ranges for this error are 0.1465 and 0.2011 respectively.

Distance errors for spheres and virtual circles are shown in Fig 4. Distance between virtual circles 1.1 and 2.1 is called distance 1, and distance between virtual circles 1.2 and 2.2 is called distance 2.

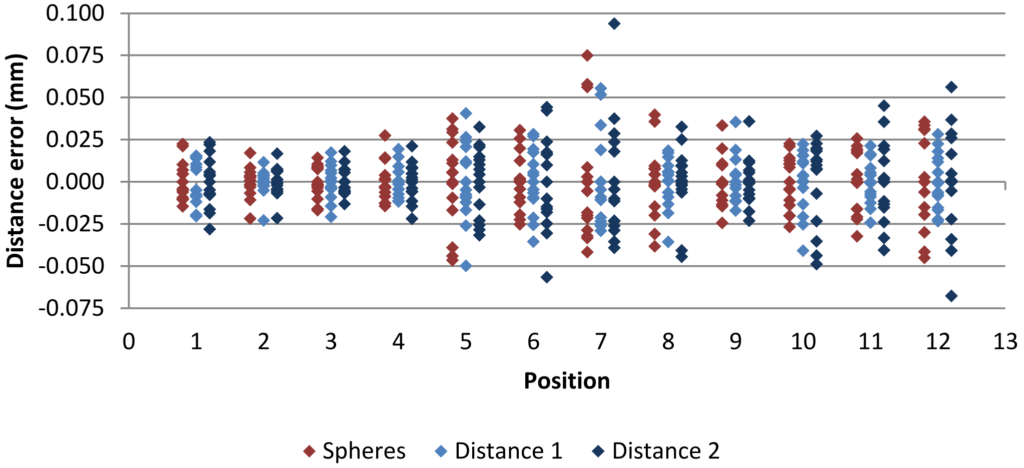


Fig. 4. Error for distance between spheres (1 to 2), and between virtual circles (1.1 to 2.1), and (1.2 to 2.2).

A comparison of maximum values can be seen in the Table 3. Maximum distance error is 0.0939 mm and corresponds with distance 2. Maximum error is 0.0555 mm for distance 1, and 0.0750 mm for distance between spheres. The three values are located in the position number 7. The highest ranges are 0.0905 mm for the distance 1 in the position number 5, 0.1330 mm for distance 2 in the position number 7 and 0.1167 mm for the distance between spheres in the position number 7 as well. The values for spheres are situated between the values for the distance 1 and the values for the distance 2.

Table 3. Comparison of maximum errors and ranges of errors.

Distance error	Maximum (mm)	Range (mm)
Spheres	0.0750	0.1167
Distance 1	0.0555	0.0905
Distance 2	0.0939	0.1330

2.4. Evaluation in repeteability terms

Mean errors and the standard deviation per position are calculated for each measurement, Fig. 5 y Fig. 6. From results, it can be seen that a tendency is shared among mean values for spheres and virtual circles. Mean error for spheres is higher than the values for virtual circles. In some positions (10, 11, 12 and 13) the virtual circle 2.2 is which has the highest values. A tendency in standard deviation also exists. Although values for the two virtual circles are not necessarily close to the values of their homologous sphere, there is always a value of standard deviation for the virtual circles that approximates the value for the sphere.

In global terms, the global standard deviation is 0.0160 mm for the sphere 1, which can be compared with 0.0129 and 0.0126 mm for the virtual circles 1.1 and 1.2 respectively. The sphere 2 has a global deviation of 0.0253 mm, which is comparable with 0.0227 and 0.0259 mm for its homologous virtual circles. It can be seen that values for virtual spheres and virtual circles are close.

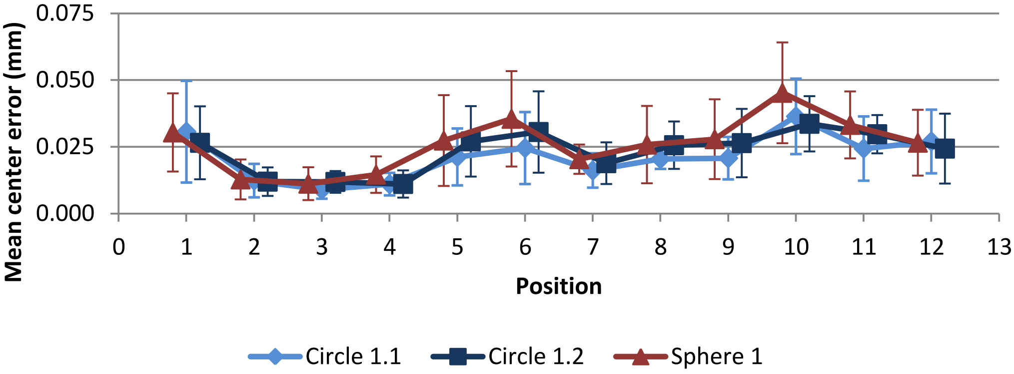


Fig. 5. Mean and standard deviation of center error for sphere 1, virtual circle 1.1, virtual circle 1.2.

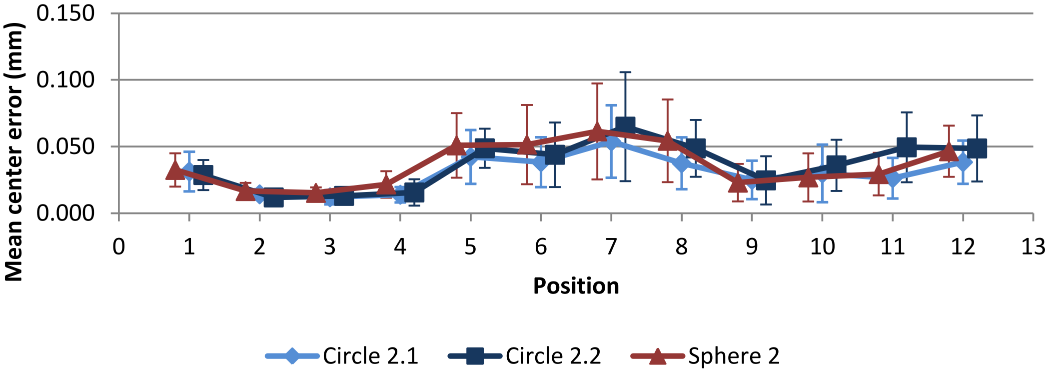


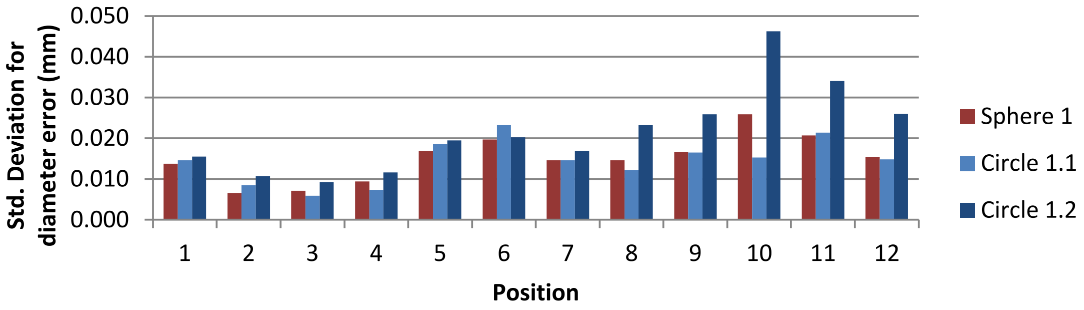
Fig. 6. Mean and Standard Deviation of center error for sphere 2, virtual circle 2.1 and virtual circle 2.2.

Global standard deviation for the diameter error is 0.0155 mm for sphere 1. It can be compared with values of 0.0148 and 0.0231 mm that correspond with virtual circles 1.1 and 1.2 respectively. Sphere 2 has a total standard deviation of 0.0263 mm, which can be compared with values of 0.0227 and 0.0338 mm for virtual circles 2.1 and 2.2. It can be seen that there are significant differences between values for virtual circles 1.2 and 2.2 and the ones for their homologous spheres. Nevertheless, at least one value from virtual circles fits the value of the sphere. Therefore, it can be determined that virtual circles can be used instead of virtual spheres.

In some positions, measurement results for virtual circles 1.2 and 2.2 are particularly dispersed. Virtual circle 1.2 has its worst values in positions number 10 and 11, and virtual circle 2.2 has them in positions number 6 and 7. They are positions where operator has to measure the end 2 of the gauge in an uncomfortable way. Table 4 summarizes the comparison of global standard deviation for center errors and diameter errors.

Table 4. Global standard deviations of center and diameter errors.

Feature	Center error (mm)	Diameter error (mm)
Virtual Sphere 1	0.0160	0.0155
Virtual circle 1.1	0.0129	0.0148
Virtual circle 1.2	0.0126	0.0231
Virtual Sphere 2	0.0253	0.0263
Virtual circle 2.1	0.0227	0.0227
Virtual circle 2.2	0.0259	0.0338



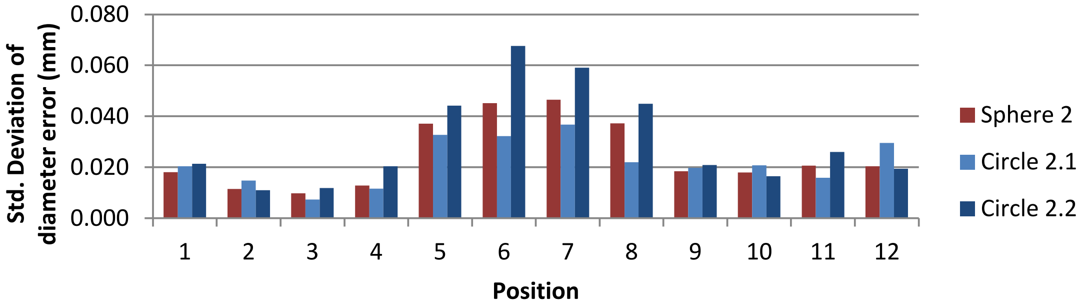


Fig. 7. Standard deviation of diameter error from features on *Up)* End 1 and *Down)* End 2 of the gauge.

2.5. Evaluation in length accuracy terms

The standard deviation of the distance error between virtual circles and spheres was obtained, Fig. 8.

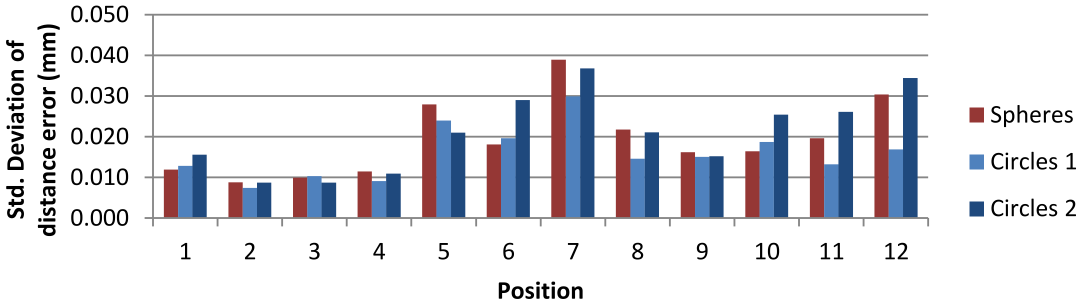


Fig. 8. Standard Deviation of distance between virtual circles and spheres.

Global standard deviation, Table 5, is 0.0201 mm for distance between spheres, 0.0163 and 0.0220 mm, distance 1 and 2 respectively. They are all close values that do not exceed the Length Accuracy term of 0.025 mm that is provided by the manufacturer. While this is also true for most of the position standard deviations, in the positions number 5, 6, 7 and 12 the value is exceeded in some elements.

Table 5. Comparison of global standard deviations of distance errors.

Element	Global standard Deviation (mm)
Virtual Spheres	0.0201
Distance 1	0.0163
Distance 2	0.0220

3. Conclusion

A gauge with virtual circles and spheres for AACMM performance evaluation has been presented. According to this new gauge and to international standards an evaluation methodology has been developed. Both the virtual circles and the virtual spheres offer similar variability values in according with the specifications provided by the manufacturer. Therefore, this gauge, and within its measuring methodology, have been proved suitable for a proper AACMM evaluation by measuring virtual circles and spheres. Moreover, the use of the virtual circles entities is recommended since it enables measuring a less number of points, and running a shorter test; not only when consider multi ball-bar gauge (solid spheres), but even when consider virtual spheres. In any case, the use of this "virtual gauge" reduces the cost of manufacturing and the complexity of the AACMM evaluation to a great extent.

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