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Metrological characterization of interior circular features using digital optical machines: Calculation models and application scope

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ABSTRACT

The objective of this work is to analyze and compare common methods used for indirect metrological characterization of circular geometrical features: least square circle, minimum zone circle, maximum inscribed circle and minimum circumscribing circle, based on images obtained using digital optical machines. The self-developed calculation algorithms used were implemented with Matlab® software considering the following study variables: the amplitude of the angular sector of the circular feature, its nominal radius and the magnification used by the optical machine. Under different measuring conditions the radius and roundness error of an angular sector of a piece of LEGO and of a ring gauge were determined. That is, the proposed algorithms allow the characterization of both full circumferences as angular sectors. We were able to determine the degree of precision of each method and its scope of application by comparing the results obtained with different adjustments to values certified by an accredited laboratory.

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1. Introduction

The use of digital optical measuring systems has been widely distributed in the industrial domain, reaching around 20% of the world market [1]. These systems present very interesting advantages with regards to three-coordinate measuring machines (CMMs) using mechanical probing methods [2–5], the main advantages being the speed of data acquisition, measuring function automation and, above all, the absence of contact [1].

The use of mechanical probing is usually impracticable for carrying out dimensional measurements in micro- and nanomanufacturing and therefore the use of optical instruments is commonplace. A special case is constituted by circular features, for example: small holes, rounded notches, fillet radii, etc. [6]. It is possible to classify those circular features according to angular sector available in full circumferences and partial arcs ($\alpha \leq 360^\circ$). To characterize these circular features, the circumference that best adjust the angular sector considered and its roundness error are calculated. In all of these cases, the centre coordinates, radius value and roundness error can be determined indirectly based on the coordinates of three or more edge pixels. A direct measurement method, wherein the measured value is obtained by reading an instrument, does not allow us to fully characterize the circular feature, e.g. a Horizontal Coordinate Measuring Machine provides us only and directly the diameter value. These geometric parameters can be determined by means of four well known calculation methods: Least Squares Circle (LSC), Minimum Zone Circle (MZC), Maximum Inscribed Circle (MIC) and Minimum Circumscribing Circle (MCC) [7–12]. The reviewed metrological literature shows a range of studies in which these methods are applied in order to evaluate circular features based on points obtained with three-coordinate measuring machines (CMMs) [2–7]. However, in the field of digital optical measuring machines considered in this paper, no relevant work approaching this problem has been found.

Studies carried out on mechanical probing three-coordinate measuring machines indicate that the most significant variable for this type of indirect measuring is the angular separation (α) between extreme probing points (Fig. 1) [2], such that by increasing α the calculated diameter (d_c) converges towards a nominal value for the measurand (d_0); however, in many cases the physical characteristics of the measurands oblige us to take measurements based on reduced angular values, thus resulting in large result deviations and enormous variability (Fig. 2). This is a very similar situation to that produced with digital optical machines.

From an analytical point of view, an optical device can be considered as a three-coordinate measuring device from which the Z axis has been removed. In principal, such a circumstance could appear to simplify the problem; however, despite only measuring in two dimensions, the digital optical equipment includes additional sources of uncertainty which require special study. These sources include not only the aforementioned angular separation of the extreme measurement points (α), but also the density of the

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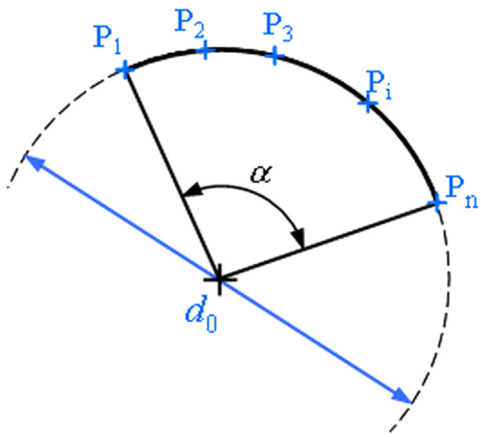

Fig. 1. Probing points on an angular sector α.

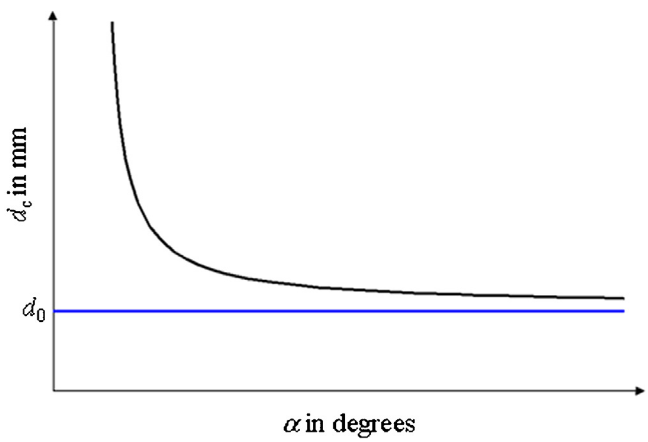

Fig. 2. Example of a diameter calculated as a factor of α [6].

pixels captured along the circular profile, the equipment's resolution, magnification, optical aberrations, etc.

The *Simplex* method [13] is used in this paper to mathematically solve the MZC, MIC and MCC methods. The algorithms described have been adapted to the metrological conditions of digital optical machines, based on the (x_i, y_i) coordinates of the pixels detected on the edge of the circular profile (Fig. 3).

The solution to the LSC method uses a linear parameterization model (LLS) proposed by the *National Physical Laboratory* (NPL) [14], developed using their own algorithm. This method has been proven to be effective and reliable when solving for complete circles and also for circle arcs; it does not present implementation difficulties or problems and has a calculation time under "standard" conditions of around 1 s [15].

In this paper we will analyze the algorithms discussed above to characterize arcs by varying the angular separation (α) between the extreme points [$0°$–$360°$]. To materialize these arcs, we have used images of angular sectors belonging to a piece of Lego and a ring gauge.

2. State of the art

In the last decade, feature identification techniques have caught the attention of researchers seeking to develop new algorithms capable of solving geometric characterization problems, especially for circular features due to their presence in a great number of mechanical parts. At the same time, the use of Computer-Aided Inspection methods (CAI) has become widespread in recent years [16,17] due to their versatility and efficiency. Consequently, multiple studies have focused on the analysis of errors in circular features and the development of algorithms for their characterization. These studies serve as a basis for the analysis described in this paper.

With regards to the determination of form errors, only the MZC (Fig. 4(a)) conforms to ANSI and ISO standards [18,19]. However, this model is formulated as an optimization problem with nonlinear (non-differentiable) restrictions, which is difficult to resolve in practice. The MCC (Fig. 4(b)) is reserved for cases associated with the material's maximum condition, such as a shaft, whereas

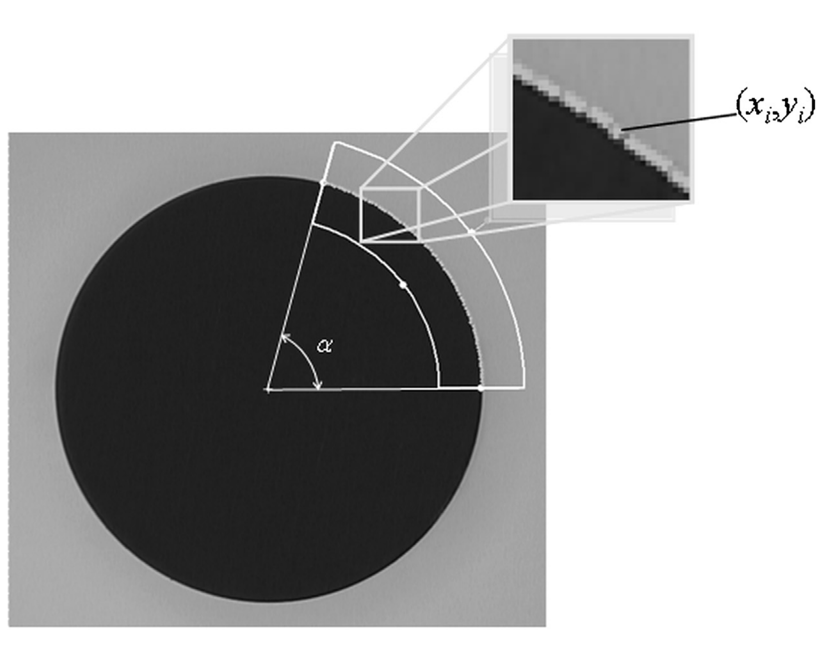

Fig. 3. Image of a plug gauge taken by a CCD camera.

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