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Calibration of freeform standard

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Abstract
A new freeform reference standard has been developed and manufactured in cooperation of CMI (Czech Metrology Institute) and CTU in Prague (Czech Technical University) for testing freeform measurement capability of coordinate measuring machines. Geometrical-mathematical approach to design the standard has been applied and a surface of hyperbolic paraboloid (basic feature of the standard) has been chosen as a challenging surface for freeform measurement. The surface of hyperbolic paraboloid can be considered not only as a freeform surface but also as a set of 3D straight lines. Specially, the mathematical model used to design the standard has been developed in such a way that the surface of hyperbolic paraboloid contains two sets of straight lines. Two different calibration strategies have been prepared and realised by tactile measurement on coordinate measuring machine SIP CMM 5. According to the first calibration strategy corresponding to the freeform measurement commonly used, surface points have been measured and form error of the material standard with respect to the CAD (Computer Aided Design) model has been evaluated. According to the second calibration strategy, points along four selected 3D lines (two from both sets) have been measured. Here, the points have been measured in the normal direction to the surface of hyperbolic paraboloid to respect the fact that the lines are located on the freeform surface. Additionally, the deviations of the measured points from the theoretical line located on the surface of hyperbolic paraboloid have been evaluated and compared with the form error of the whole free-from shape obtained by measurement according to the first calibration strategy.

Keywords: freeform measurement, freeform standard, freeform standard calibration, free-from surface, 3D line, normal vector

1. Introduction

Design and manufacturing of components with functional freeform surfaces in precision engineering lay great demands on metrological procedures applied and reliable evaluation of measured results. To establish the traceability of measurements on coordinate measuring machines (CMMs), calibrated standards with sufficient precision, stability, reasonable cost and sufficiently small calibration uncertainty are used. Calibration standards of regular shapes (spheres, cylinders, step gauge blocks, ball plates, hole bars, hexapods, etc.) are well developed [1], while the traceability and quality control in freeform manufacturing are issues due to lack of traceable verification standards [2]. The initial design of freeform standards based on using geometric elements arranged in a suitable way [3] resulted in the Modular Freeform Gauge [4, 5, 6] where a freeform measurement was simulated with the measurement of surfaces on regular objects, combined in a manner that represents the shape of interest as closely as possible. Another approach was used in NPL freeform standard [1, 7] where several basic geometries were blended to form a single surface. Mathematical description of freeform surface was firstly used in the case of PTB Double-sine standard [5, 6]. CMI participated in interlaboratory comparison of both NPL freeform standard [1] and PTB Double-sine standard [6]. Still, the design of freeform calibration artefacts represents a very challenging problem.

This paper describes calibration of a new traceable freeform standard Hyperbolic paraboloid which has been developed and manufactured by CMI in cooperation with CTU in Prague during the EMRP project Traceable in-process measurement [8].

The paper is organized as follows. Design of freeform standard is described in section 2. Section 3 is focused on calibration procedure and section 4 concludes the obtained results.

2. Design based on geometrical-mathematical approach

In computational geometry a surface of hyperbolic paraboloid is defined by four corners as a bilinear surface with normalized domain of parametrization. If the corners are placed above axis aligned square in the plane (x, y) with the centre at origin of coordinate system, it is possible to express the surface of hyperbolic paraboloid explicitly in the following form

$$z(x,y) = p + k(x-m)(y-n),$$

where (m, n, p) are Cartesian coordinates of vertex of hyperbolic paraboloid an k is a shape coefficient. It is obvious that for constant values of one variable $x = a$ or $y = b$, parametric straight lines (linear sections) are obtained. Thus, the surface of hyperbolic parabolic can be considered not only as a freeform surface but also as a set of straight lines in x- or y-direction with mutually perpendicular projections in (x, y) plane (fig. 1). Due to this excellent geometrical property, a surface of hyperbolic paraboloid has been chosen as a basic feature of the standard. In particular, the surface of hyperbolic paraboloid used in freeform standard is given by

$$z(x,y) = 24 + \tfrac{1}{64}(x-8)(y-8).$$

The standard (120 mm × 120 mm × 67 mm) consists of step-squared base intended for clamping the standard on CMM. The centre of the upper squared base lies at origin of coordinate system. Four precise reference spheres are glued into the spherical holes on the standard. The surface of hyperbolic paraboloid is trimmed by cylinder of revolution with axis identical with z-axis of coordinate system. The common boundary between the upper squared base and the cylinder is filled with radius 4 mm, i.e. the transition surface is created by a part of torus (fig. 1 right). The standard has been manufactured by 3-axis milling on CNC milling machine US20 by high speed cutting from steel EN X10CrNi18-9.

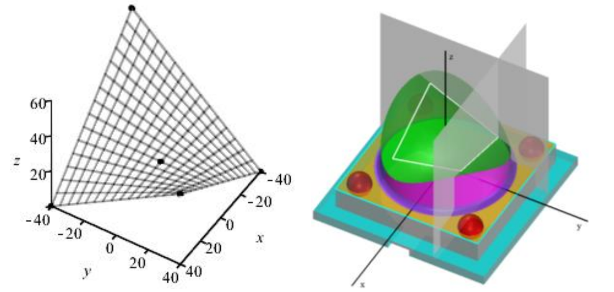

Figure 1. Hyperbolic paraboloid given by four definition points (left) and CAD model of the standard with linear sections (right).

3. Calibration of the standard

The manufactured standard has been calibrated using tactile probe on SIP CMM 5 (fig. 2 left). The traceability of the standard (described by the following chain: Czech State standard, laser interferometer, ball plate, SIP CMM 5, free form standard) has been kept. The first step of the calibration was determination of coordinate system. Here, three of the four spheres were used for alignment of the standard and its coordinate system determination. During measurement, the repeatability of the coordinate system determination was influenced mainly by sphericity of the spheres and the repeatability and measurement accuracy of SIP CMM 5 (maximum permissible error (0.8 + 1.3L) µm). Based on SIP CMM 5 specification, calibration of the machine by means of laserrail and performance of number of tests acc. to [9], the measurement uncertainty 1.6 µm was estimated for all measured data.

Geometrical properties of a surface of hyperbolic paraboloid allow to measure this surface as a freeform surface and evaluate form error of the whole shape. Additionally, it is possible to verify profile tolerance very easy because of linear sections parallel with coordinate planes (fig. 1 right). Therefore, two different calibration strategies have been prepared and realised.

According to the first metrology strategy, 5 000 surface points located in predefined grid has been measured. Next, best fit transformation with respect to the CAD model of the freeform surface has been applied and, finally, the deviation (normal distance) of each point from the reference CAD model of the surface has been evaluated. In fig. 2 (right) the colour map of all deviations is drawn. Based on the first calibration strategy, the deviations in the range [-15.7, 037.9] µm have been obtained.

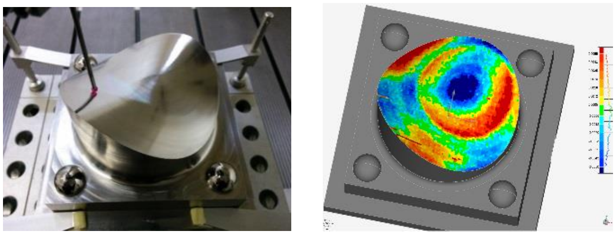

Figure 2. Calibration of the standard on CMM SIP 5 machine (left) and colour map of deviations at 5 000 surface points (right).

According to the second calibration strategy, 202 points uniformly placed along four selected 3D lines (fig. 1 right) have been measured in normal direction to the freeform surface. After that, best fit transformation with respect to the CAD model of the freeform surface has been applied as in the previous case. The deviations of points measured along 3D lines have been evaluated by two different ways. Firstly, the normal distance of each point from the surface of hyperbolic paraboloid has been evaluated and the range of deviations [-0.8, 1.2] µm has been found (fig. 3 left). Secondly, the normal distance of each measured point from the theoretical line located on freeform surface has been evaluated and the range of deviations [7.9, 42.8] µm (wider than in the previous case) has been found (fig. 3 right). Due to the limitations of the reference CAD model consideration in the CMM measuring software (there is no possibility to consider a line to be a reference CAD model), evaluation of deviations was performed using an external software.

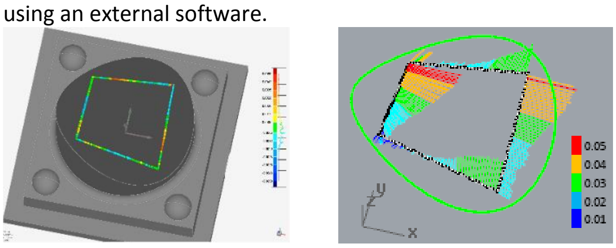

Figure 3. Colour map of deviations at points along linear sections with respect to the surface (left) and deviations at points along linear sections with respect to the theoretical 3D lines (right).

4. Conclusion

Two strategies of calibration of a newly developed and manufactured freeform standard Hyperbolic paraboloid are described in this paper. These strategies differ in measured data processing and form error evaluation. Therefore, the resulting deviations obtained by both strategies are different, too. The wider range of deviations obtained by the second strategy is the consequence of spatially smaller reference figure. While the reference figure in the first strategy is CAD model of the whole freeform surface, the reference figure in the second strategy is represented only by CAD model of theoretical line located on this freeform surface.

Acknowledgments

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