Good practice guide for verification of area-scanning on-board metrology systems on machine tools

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1 Introduction

This deliverable belongs to the WP5 Demonstration and integration focused on end-user needs, Task 5.4 Provision of good practice guidelines. The aim of this deliverable is to prepare a good practice guide for the verification of area-scanning on-board metrology system using a freeform material standard FF-MS Hyperbolic paraboloid.

The guide covers the process of FF-MS Hyperbolic paraboloid and its CAD model calibration. The guide describes a method for estimation of freeform measurement uncertainty of tested machine tool, too.

1.1 Good measurement practice

There are six guiding principles to good measurement practice that have been defined by NPL. These following principles should be a part of user's quality system.

1. **The right measurements**: Measurements should only be made to satisfy agreed and well-specified requirements.
2. **The right tools**: Measurements should be made using equipment and methods that have been demonstrated to be fit for purpose.
3. **The right people**: Measurement staff should be competent, properly qualified and well informed.
4. **Regular review**: There should be both internal and independent assessment of the technical performance of all measurement facilities and procedures.
5. **Demonstrable consistency**: Measurements made in one location should be consistent with those made elsewhere.
6. **The right procedures**: Well-defined procedures consistent with national or international standards should be in place for all measurements.

The user can make a significant difference to concrete measurement capabilities by following these principles in the case of basic length measurement as well as in the case of freeform measurement.

2 FF-MS Hyperbolic paraboloid

Design and manufacturing of components with functional freeform surfaces in precision engineering lay great demands on metrological procedures applied and reliable evaluation of measured data and interpretation of obtained 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, 2], while the traceability and quality control in freeform manufacturing are issues due to lack of traceable verification standards [3].

The initial design of freeform standards based on using geometric elements arranged in a suitable way [4] resulted in the Modular Freeform Gauge [5, 6, 7] 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 [2, 8] 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 [6, 7]. Still, the design of freeform calibration artefacts represents a very challenging problem.

As the quality and relevance of reference standard in CAD-based metrology is significantly influenced by shape correspondence of the standard and its CAD representation, a new traceable FF-MS Hyperbolic paraboloid has been developed, manufactured and calibrated within this JRP [9, 10]. Geometrical-mathematical approach based on purposeful application of B-spline representation and effective usage of their properties has been used. Thus, it is possible to develop CAD model of the standard identical with its mathematical description. Moreover, the CAD model in B-spline representation can be easily modified according to the values measured on physical standard.

2.1 B-spline representation

An analytic representation of uniform clamped B-spline surface of degree p in the u-direction and degree q in the v-direction is a bivariate vector piecewise polynomial function given by

$$\mathbf{S}(u,v) = \sum_{i=0}^{m} \sum_{j=0}^{n} \mathbf{P}_{i,j} N_{i,p}(u) N_{j,q}(v), \tag{1}$$

where $\left(\mathbf{P}_{i,j}\right)$ are control points, $\left(N_{i,p}(u)\right)$ and $\left(N_{j,q}(v)\right)$ are univariate B-spline basis functions given by

$$\begin{gathered} N_{k,0}(t) = \begin{cases} 0 & \text{if } t \in [t_k, t_{k+1}) \\ 1 & \text{otherwise} \end{cases} \\ N_{k,l}(t) = \frac{t - t_k}{t_{k+l} - t_k} N_{k,l-1}(t) + \frac{t_{k+l+1} - t}{t_{k+l+1} - t_{k+1}} N_{k+1,l-1}(t), \\ k = i,j;\, t = u,v;\, l = p,q, \end{gathered} \tag{2}$$

defined on the knot vectors

$$\begin{gathered} U = \left(\underbrace{0, \cdots, 0}_{p+1}, u_{p+1}, \cdots, u_{r-p-1}, \underbrace{1, \cdots, 1}_{p+1} \right), \\ V = \left(\underbrace{0, \cdots, 0}_{q+1}, v_{q+1}, \cdots, v_{s-q-1}, \underbrace{1, \cdots, 1}_{q+1} \right), \end{gathered} \tag{3}$$

where $r = m + p + 1$ and $s = n + q + 1$.

If $m, n = 1$, the resulting surface is bilinear B-spline surface ($p = q = 1$)

$$\begin{gathered} \mathbf{S}(u,v) = (1-u)(1-v)\mathbf{P}_{0,0} + (1-u)v\mathbf{P}_{0,1} + u(1-v)\mathbf{P}_{1,0} + uv\mathbf{P}_{1,1}, \\ (u,v) \in [0,1]^2, \end{gathered} \tag{4}$$

created by one surface patch. This surface is known as hyperbolic paraboloid (double-ruled or saddle surface). Hyperbolic paraboloid has very useful geometrical property independent on position of the four control points in three-dimensional space – both sets of parametric curves are straight lines. It can be proven by substituting constant value $u \in [0,1]$ or $v \in [0,1]$ in (4). In Figure 1 left, an example of such a surface is drawn together with two inner parametric straight lines in both directions. Note that this surface is created by one patch.

Moreover, it is possible to create a piecewise bilinear surface represented by (1) of the same shape as is the surface given by (4) but defined by higher number of control points located at intersections of parametric straight lines of the original hyperbolic paraboloid (4). This surface is created by more than one patch. Individual patches of such a surface are C^0 continuously connected. An example of piecewise bilinear surface is drawn in Figure 1 right. Here, the surface is given by 13×13 control points, i.e. consists of 144 patches. The shapes of both surfaces depicted in Figure 1 are precisely the same even though their vector equations are different.

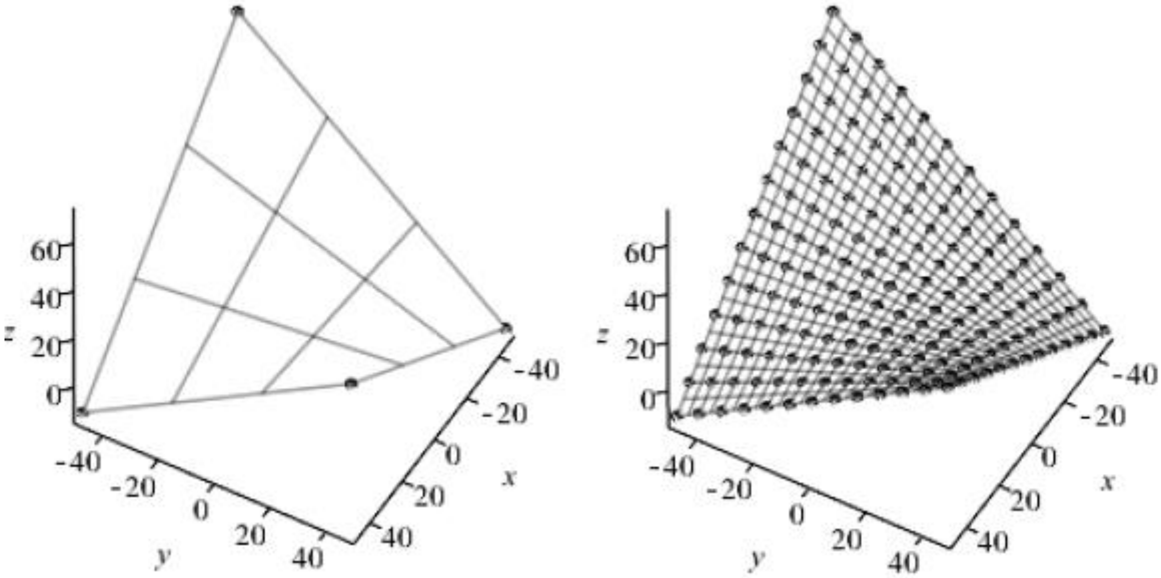


Figure 1: Bilinear B-spline surface of the same shape given by 4 (left) and 169 (right) control points (all dimensions in mm)

In particularly, the following coordinates of four control points, see Figure 1 left, have been used in the development of FF-MS Hyperbolic paraboloid

$$\begin{gathered} \mathrm{P}_{0,0} = (-48, -48, 73), \mathrm{P}_{0,1} = (-48, 48, -11), \\ \mathrm{P}_{1,0} = (48, -48, -11), \mathrm{P}_{1,1} = (48, 48, 49). \end{gathered} \tag{5}$$

Thus, the freeform surface of the standard has the following mathematical model

$$\mathbf{S}(u, v) = (96u - 48, 96v - 48, 144uv - 84u - 84v + 73). \tag{6}$$

A piecewise bilinear B-spline surface consisting of more than one patch enables local modifications of the shape by changing position of control points. The higher number of control points, the finer local modifications of the shape can be applied. This remarkable property of bilinear B-spline surface represents the main idea applied in the process of freeform standard as well as its calibrated CAD model development [11].

2.2 Calibration of FF-MS and calibration of CAD model of FF-MS

The FF-MS Hyperbolic paraboloid (120 mm × 120 mm × 67 mm) consists of step-squared base intended for clamping the standard on measurement machine. 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. The CAD model of the standard is depicted in Figure 2 left. The standard has been manufactured by 3-axis milling on CNC milling machine US20 by high speed cutting from steel EN X10CrNi18-9. The manufactured standard is shown in Figure 2 right.

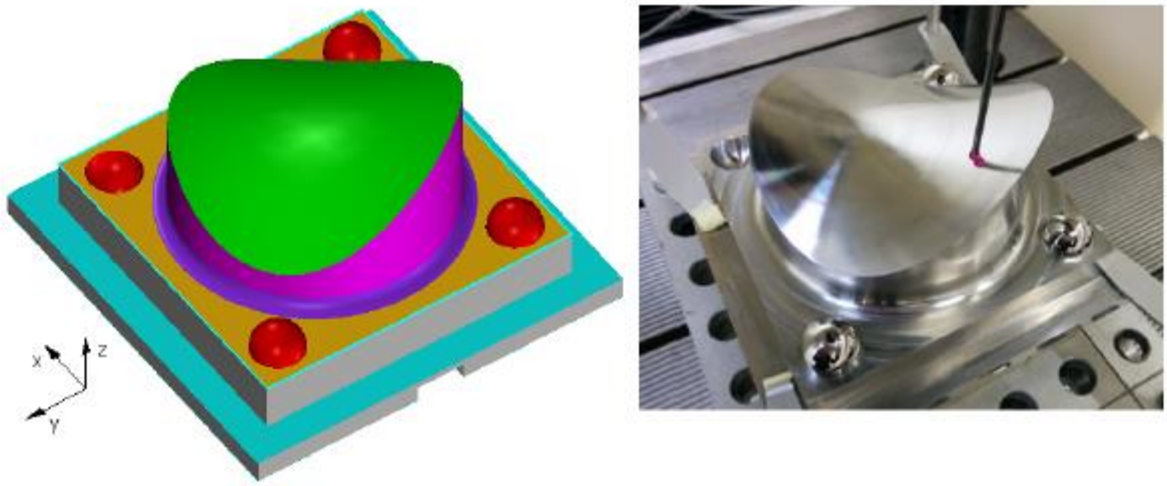


Figure 2: CAD model of FF-MS Hyperbolic paraboloid (left) and manufactured standard (right)

During the whole process of calibration, the standard is repeatedly measured without any changes of position in clamping device. The constant temperature (20 ± 0.2)°C in the environment has to be kept. The measured data is immediately processed and new input data for the measurement is continuously generated.

The first step of the calibration is to determine the coordinate system. Here, three of the four spheres are used for alignment of the standard and its coordinate system determination. During measurement, the repeatability of the coordinate system determination is influenced mainly by sphericity of the spheres and the repeatability and measurement accuracy of measuring device.

After coordinate system of the standard determination, the CAD model of the standard is calibrated in the following steps.

2.2.1 Calibrated CAD model of the first stage

1. **Mathematical and theoretical CAD model** – as the surface of hyperbolic paraboloid has precise B-spline parametrisation, it is necessary to use CAD system based on NURBS (non-uniform rational B-spline) representation to create CAD model of the standard. In such a case, the CAD model and mathematical model of the surface are identical, i.e. no approximation (e.g. stl triangulation) is used. Mathematical model as well as theoretical CAD model of the standard are given by (6).

2. **Theoretical piecewise bilinear surface** – a set of $25 \times 25 = 625$ control points $(\mathbf{P}^{625})$ represented by function values of surface (6) uniformly distributed with respect to the domain of parametrisation are generated

$$(\mathbf{P}^{625}): \left(\mathbf{S}\left(\frac{i}{24}, \frac{j}{24}\right) = \left(x_{\mathbf{P}_{i,j}}, y_{\mathbf{P}_{i,j}}, z_{\mathbf{P}_{i,j}}\right)\right)_{i.j=0}^{24}, \tag{7}$$

   see the green mesh of control points in Figure 3 left.

3. **Input data for the primary measurement** – a subset $(\mathbf{P}^{301})$ of 301 control points belonging to the area of physical standard is selected from the set $(\mathbf{P}^{625})$ as input data for the primary measurement. This subset is highlighted in red in Figure 3 right. The condition of selection is given by

$$(\mathbf{P}^{301}): \left(\sqrt{x_{\mathbf{P}_{i,j}}^2 + y_{\mathbf{P}_{i,j}}^2} \le 40\right)_{i.j=0}^{24}. \tag{8}$$

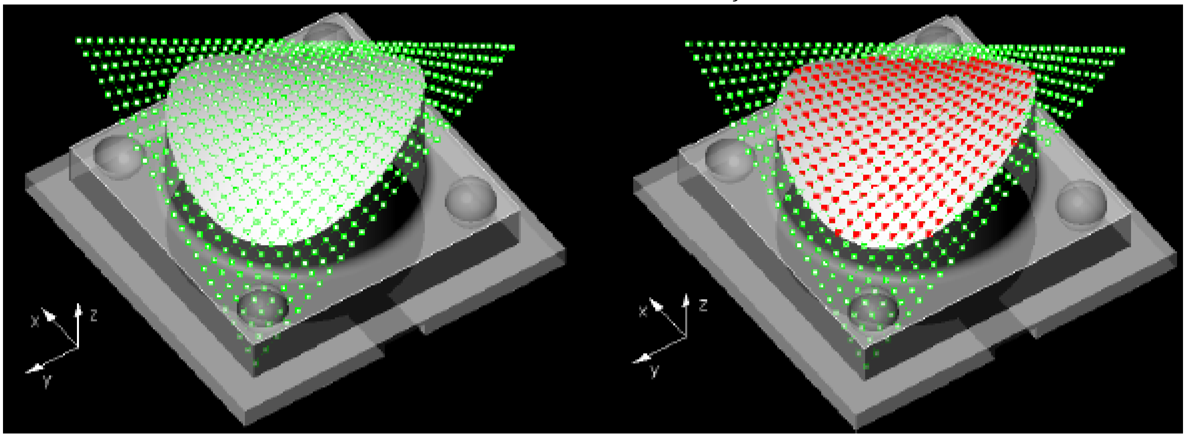


Figure 3: Piecewise bilinear surface given by 625 control points (left) and subset of points belonging to the area of physical standard (right)

4. **Primary measurement** – tactile CAD based measurement of the standard is performed. The input data is represented by the subset $(\mathbf{P}^{301})$ with theoretical CAD model $\mathbf{S}(u, v)$ as the reference surface. Thus, the measured data $(\mathbf{M}^{301})$ is obtained.

5. **Modification of the theoretical CAD model** – the set of control points $(\mathbf{P}^{625})$ is modified by replacement of the subset $(\mathbf{P}^{301})$ on subset $(\mathbf{M}^{301})$. Thus, the modified set of control points $(\mathbf{R}^{625})$ is obtained.

6. **Calibrated CAD model of the first stage** – bilinear B-spline surface passes through all control points (all control points are located on bilinear B-spline surface), B-spline surface of higher degrees approximates the control points. Therefore, it is recommended to use B-spline surface $(p = q = 3)$ in this step, to be able to measurement uncertainty in the calibrated CAD model of the standard.

   Calibrated CAD model of the first stage is mathematically represented by piecewise bicubic B-spline surface $\mathbf{C}(u, v)$ with analytical representation given by

$$\mathbf{C}(u, v) = \sum_{i=0}^{24} \sum_{j=0}^{24} \boldsymbol{R}_{i,j} N_{i,3}(u) N_{j,3}(v), \tag{9}$$

   where the control points are represented by the modified mesh $(\mathbf{R}^{625})$ and B-spline basis functions of third degree ($p = q = 3$) are defined on the following knot vectors

$$U, V = \left(0,0,0,0, \frac{1}{24}, \frac{2}{24}, \cdots, \frac{23}{24}, 1,1,1,1\right). \tag{10}$$

   If the calibrated CAD model of the first stage is considered to be the final calibrated CAD model, it is recommended to trim the surface $\mathbf{C}(u, v)$ by cylinder of revolution with axis identical with z-axis and radius equal to 37 mm to eliminate uncertainty of calibrated CAD model along the circular boundary of physical standard. Thus, the following condition is necessary to add

$$\sqrt{[x(u, v)]^2 + [y(u, v)]^2} \le 37. \tag{11}$$

2.2.2 Calibrated CAD model of the second stage

1. **Input data for the secondary measurement –** the set of $97\times 97 = 9409$ control points ($\mathbf{B}^{9409}$) uniformly distributed (with respect to the domain of parametrisation) on the bicubic B-spline surface $\mathbf{C}(u,v)$ given by (9) is generated (see green mesh in Figure 4 left)

$$(\mathbf{B}^{9409}):\left(\mathbf{C}\left(\frac{i}{96},\frac{j}{96}\right)=\left(x_{\mathbf{B}_{i,j}},y_{\mathbf{B}_{i,j}},z_{\mathbf{B}_{i,j}}\right)\right)_{i.j=0}^{96}. \tag{12}$$

After that, a subset ($\mathbf{B}^{5002}$) belonging to the area of the physical standard is selected as input data for the secondary measurement (see red points in Figure 4 right)

$$(\mathbf{B}^{5002}):\left(\sqrt{x_{\mathbf{B}_{i,j}}^2+y_{\mathbf{B}_{i,j}}^2}\le 40\right)_{i.j=0}^{96}. \tag{13}$$

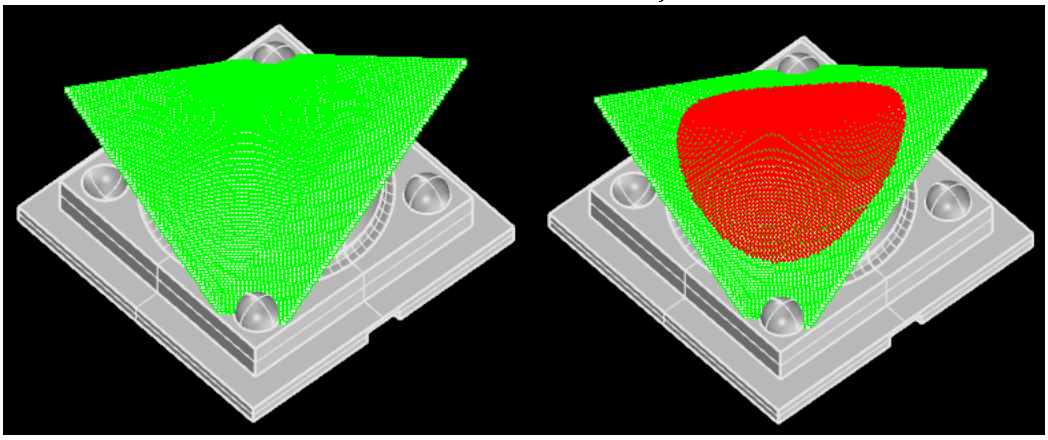


Figure 4: Piecewise bicubic surface given by 9409 control points (left) and subset of points belonging to the area of physical standard (right)

2. **Secondary measurement** – tactile CAD based measurement of the standard is performed. The input data is represented by the subset ($\mathbf{B}^{5002}$) with bicubic B-spline surface $\mathbf{C}(u,v)$ as the reference surface. Thus, the measured data ($\mathbf{M}^{5002}$) is obtained.

3. **Modification of the calibrated CAD model of the first stage** – the set of control points ($\mathbf{B}^{9409}$) is modified by replacement of the subset ($\mathbf{B}^{5002}$) on subset ($\mathbf{M}^{5002}$). Thus, the modified set of control points ($\mathbf{R}^{9409}$) is obtained.

4. **Calibrated CAD model of the second stage –** calibrated CAD model of the second stage is represented by piecewise bilinear B-spline surface $\mathbf{K}(u,v)$ with analytical representation given by

$$\mathbf{K}(u,v)=\sum_{i=0}^{96}\sum_{j=0}^{96}\boldsymbol{R}_{i,j}N_{i,1}(u)N_{j,1}(v), \tag{14}$$

where the control points are represented by the modified mesh ($\mathbf{R}^{9409}$) and B-spline basis functions of the first degree ($p=q=1$) are defined on the following knot vectors

$$U,V=\left(0,0,\frac{1}{96},\frac{2}{96},\cdots,\frac{95}{96},1,1\right). \tag{15}$$

As the distance of control points from B-spline surfaces of higher degrees is significantly less than the measurement uncertainty of the most precise nowadays used measurement devices, bilinear B-spline surface is considered to be a suitable representation of the calibrated CAD model of FF-MS in this step.

The final calibrated CAD model of the second stage is represented by the surface $\mathbf{K}(u, v)$ trimmed by cylinder of revolution with axis identical with z-axis and radius equal to 37 mm to eliminate uncertainty of calibrated CAD model along the circular boundary of physical standard (see yellow 3 mm zone in Figure 5)

$$\sqrt{[x(u,v)]^2 + [y(u,v)]^2} \leq 37. \tag{16}$$

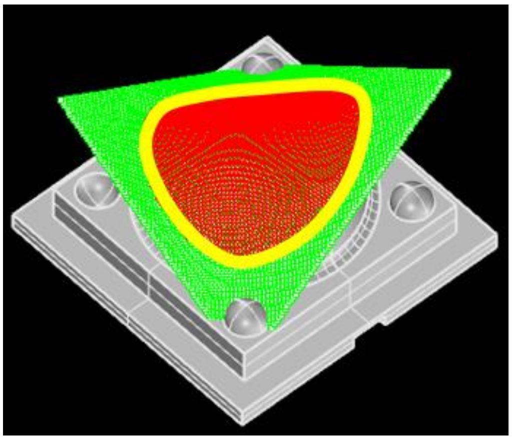


Figure 5: Trimmed 3 mm zone along boundary of physical standard

3 Measurement strategies

From the metrological point of view, the surface of hyperbolic paraboloid can be considered a freeform surface or a set of straight lines or parabolas or hyperbolas located on freeform surface. It follows that there are different types of features to be measured such as surface point located on freeform surface, points along 3D straight lines, points along 3D parabolas and points along 3D hyperbolas. Consequently, the recommended metrology strategy depends on the measured feature.

Note that 3D geometrical feature means the corresponding figure located on freeform surface. It follows that the underlying geometry has to be taken into consideration, i.e. the direction of normal vector is calculated with respect to the freeform surface. The tactile probe has to move in the direction of normal vector to the freeform surface. The direction of normal vectors is different at each measured point.

1. **Measurement of freeform surface** – when measuring the freeform surface, individual surface points are measured by tactile probe and their normal distance from the reference CAD model is evaluated. Usually, the points are distributed in uniform (x, y) grid, see example in Figure 6 left. In the case of scanning probe using, the scanning paths can be arranged, for example in the direction of x- or y-axis, as is shown in Figure 6 right.
2. **Measurement of points along 3D lines on freeform surface** - 3D lines are obtained as intersections of the surface of hyperbolic paraboloid by planes parallel with coordinate x- or y-axis, see example in Figure 7.
3. **Measurement of points along 3D parabolas on freeform surface** – 3D parabolas are obtained as intersections of the surface of hyperbolic paraboloid by planes parallel with axis of the first and third quadrants or parallel with axis of the second and fourth quadrants, see example in Figure 8.

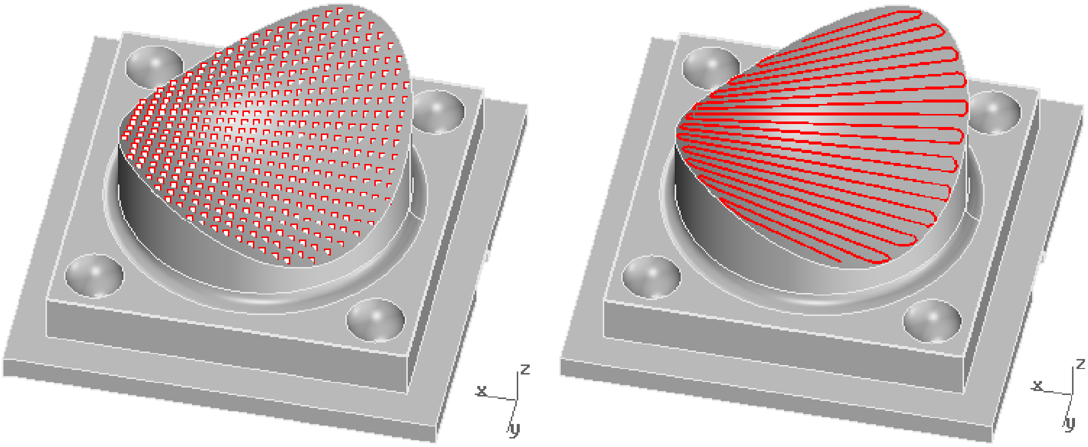


Figure 6: Metrology strategies for freeform measurement by tactile probe (left) and by tactile scanning probe (right)

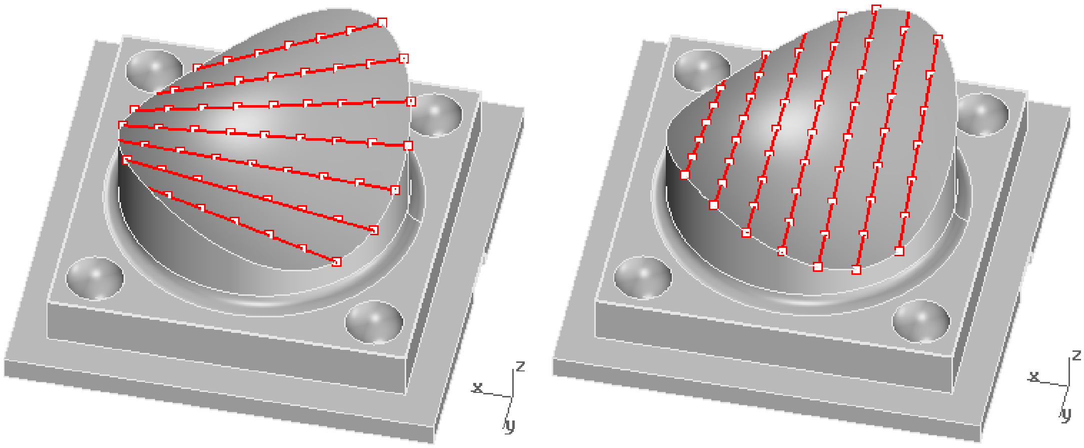


Figure 7: Metrology strategies for measurement points along 3D straight lines parallel with x-axis (left) and parallel with y-axis (right)

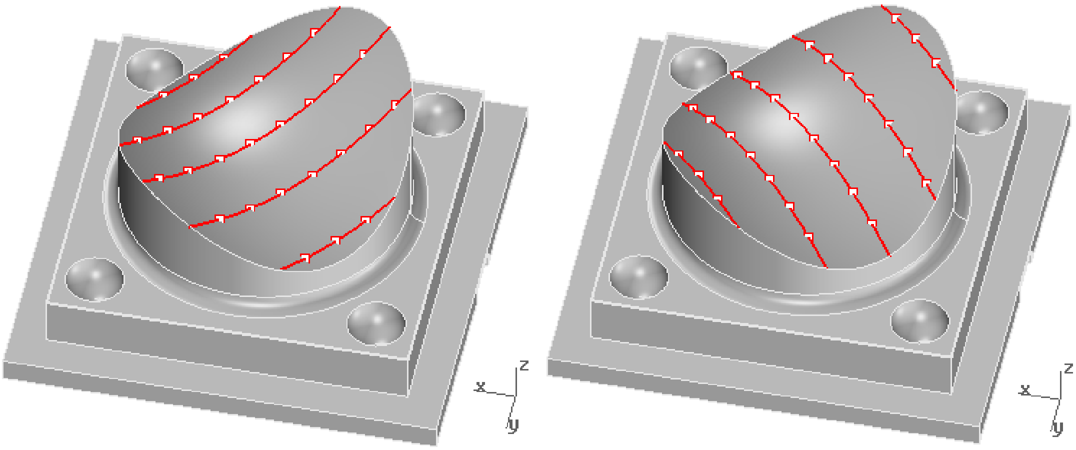


Figure 8: Metrology strategies for measurement points along 3D parabolas parallel with axis of the first and third quadrants (left) and parallel with axis of the second and fourth quadrants (right)

4. **Measurement of points along 3D hyperbolas on freeform surface** – 3D hyperbolas are obtained as intersections of the surface of hyperbolic paraboloid by planes parallel with (x,y) planes, see example in Figure 9.

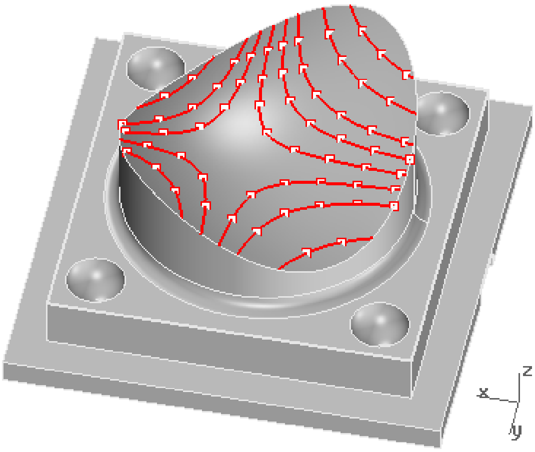


Figure 9: Metrology strategies for measurement points along 3D hyperbolas parallel with (x,y) plane

4 Freeform measurement uncertainty

Traceable measurement of components with functional freeform surfaces in precision engineering represents a challenging problem regarding a freeform measurement uncertainty estimation. A practical solution to establish the traceability of freeform measurements for a specific application (the measurement of turbine blades) based on using a Modular Freeform Gauge when a given freeform surface is modelled by combination of calibrated artefacts with simple geometry is described in [1]. The method based on performance of uncertainty assessment by means of various measurement conditions (different positions, orientations, number and distribution of measured points and scanning speed) is developed in [2]. Important specificities of freeform measurement and its traceability are summarized in [3]. An evaluation of key factors affecting task specific measurement uncertainty using statistical analysis tools, physical measurements and virtual coordinate measuring machine (CMM) is presented in [4].

In this good practice guide, two alternative approaches to estimate the freeform measurement uncertainty of machine tool are described. The first approach is based on tactile CAD based measurement of FF-MS Hyperbolic paraboloid with respect to the reference calibrated CAD model developed according to the procedure described in section 2. The shape correspondence of the physical standard and its calibrated CAD model is as precise as possible. Therefore, the deviations of measured points from their theoretical values do not represent inaccuracy of manufacturing process but to a large degree measurement uncertainty of measuring device. Description of practical experiments demonstrating this approach are given in sections 4.1.1 and 4.1.2.

The second approach uses E_n numbers performance statistic [5, 6] commonly applied in evaluation of interlaboratory comparison. Calibrated FF-MS Hyperbolic paraboloid is measured by both – reference laboratory (represented by calibrated CMM with known well-estimated measurement uncertainty) and tested laboratory (represented by the tested machine tool with unknown measurement uncertainty). The theoretical CAD model serves as the reference CAD model. For a well-estimated reference expanded measurement uncertainty and suitably chosen critical value of E_n number (less or equal to one) as the known variables, the expanded measurement uncertainty of the tested machine tool can be considered the unknown variable. Thus, it is possible to estimate its value in the process of E_n numbers performance statistic application. Description of practical experiment demonstrating freeform measurement uncertainty by means of application of E_n number is given in section 4.2.1.

4.1 Measurement of FF-MS Hyperbolic paraboloid with respect to the calibrated CAD model

In this section, the measurement of FF-MS Hyperbolic paraboloid with respect to the calibrated CAD model is demonstrated on two practical experiments. In the first experiment, approximately 5 000 surface points distributed in uniform (x, y) grid on the freeform surface of the standard has been measured by reference CMM, see section 4.1.1. The second experiment covers the measurement by means of active scanning probe on Zeiss Prismo CMM, see section 4.1.2. This experiment has been used to confirm the results of the first experiment.

4.1.1 Tactile measurement of surface points

The measurement of surface points of FF-MS Hyperbolic paraboloid has been realised on SIP CMM 5 machine, see specification in Figure 10. The main information about the measurement conditions and colour map of deviations is given in Figure 11.

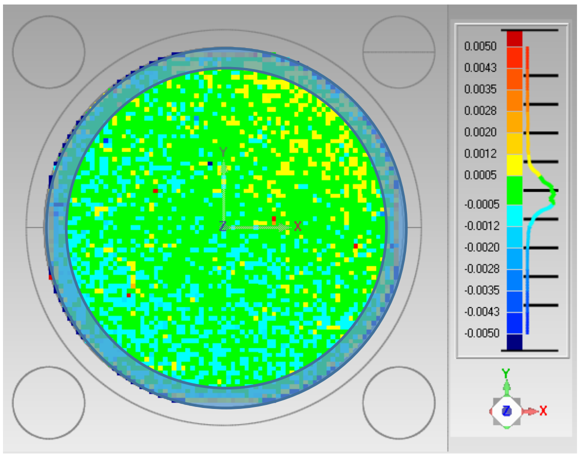
Specification of SIP CMM 5	
Measurement system	Tactile probe
Maximum permissible error	(0.5 + 0.8L) µm
Measurement uncertainty	1.6 µm
Maximal measurement dimensions	Length 720 mm Width 720 mm Height: 550 mm

Figure 10: SIP CMM 5 – specification of measuring machine

In the colour map in Figure 11, the 3 mm zone (see Section 2.2.2) along the boundary of freeform surface of the standard is depicted. Points located in this zone have not been taken into consideration when evaluating the measured data. Thus, a set of 3992 surface points has been obtained. Normal deviation of each point from this set from its theoretical position located on the calibrated CAD model has been evaluated, see blue data in the graph in Figure 12. The theoretical reference value which is not influenced by measurement uncertainty is represented by zero deviation in this graph, i.e. by the green characteristic.

The freeform measurement uncertainty ± 0.9 µm of the measurement machine has been determined as form error belonging to two-sigma limit (i.e. 95 % of measured data). The zone corresponding to this value is bounded by red characteristics in the graph.

Note that the measurement uncertainty of ± 1.6 µm declared by SIP CMM 5 producer is not exceeded in 99.6 % of measured data.



Measurement on SIP CMM 5	
Output data format	TXT points on freeform surface
Evaluation SW	Geomegic
Comparison method	Bestfit alignment with respect to the calibrated CAD model
Form error, i.e. estimated freeform measurement uncertainty (two-sigma limit)	[-0.9, 0.9] μm

Figure 11: SIP CMM 5 – measurement of surface points in (x, y) grid

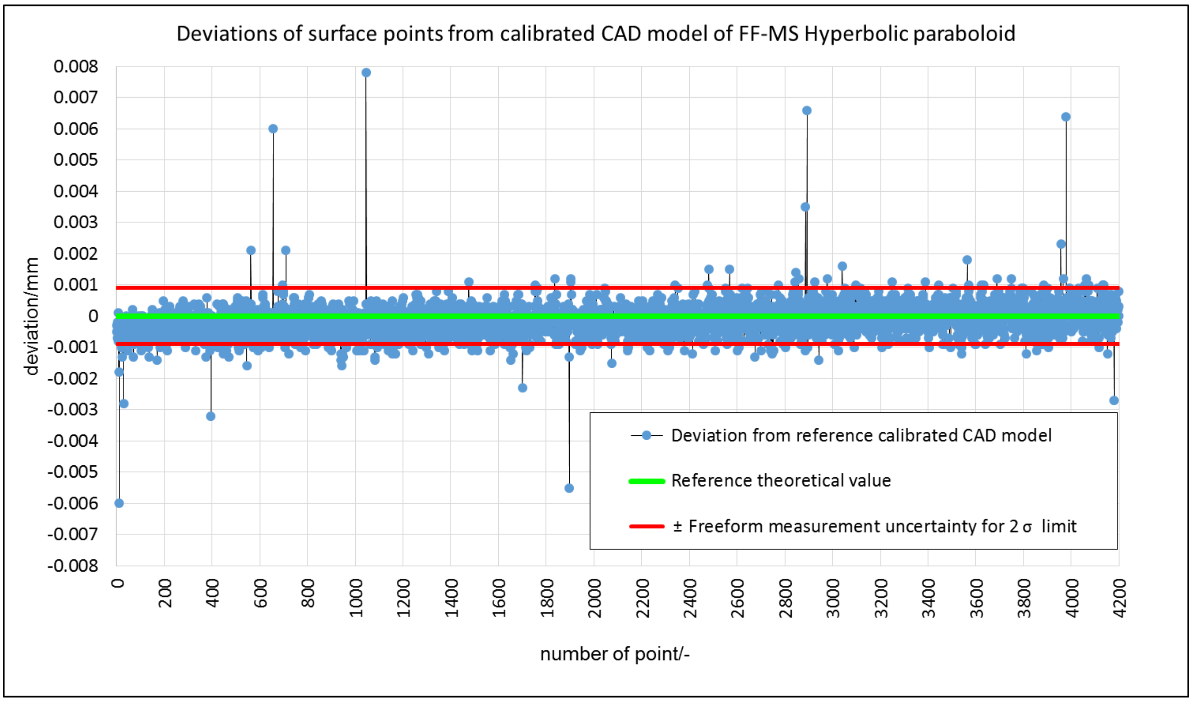
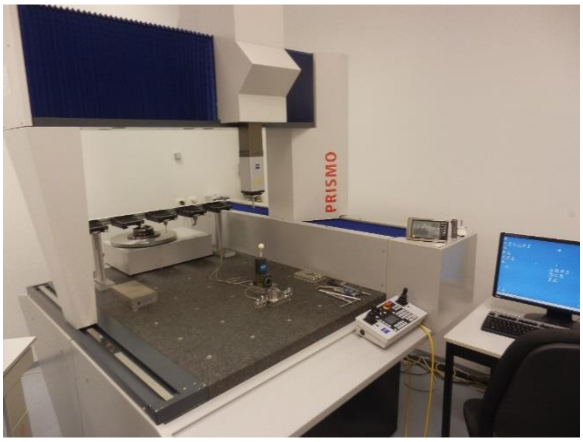


Figure 12: SIP CMM 5 – Deviations of surface points from calibrated CAD model of FF-MS Hyperbolic paraboloid

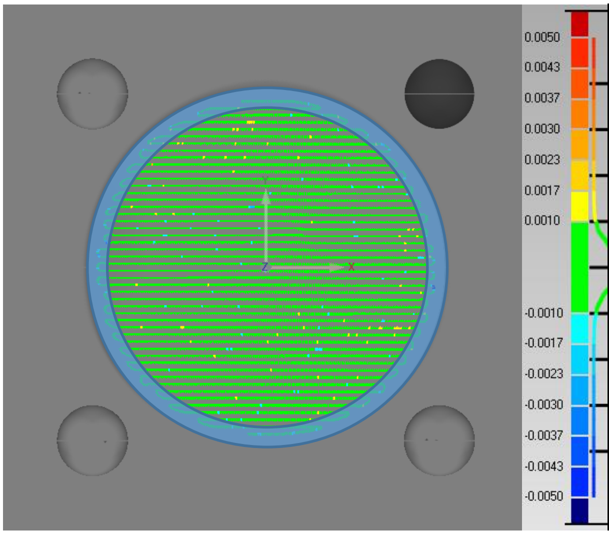
4.1.2 Area scanning by active scanning probe

The area scanning of FF-MS Hyperbolic paraboloid by active scanning probe has been realised on Zeiss Prismo CMM with active scanning probe VAST, see specification in Figure 13. The main information about the measurement conditions and colour map of deviations is given in Figure 14.



Specification of Zeiss Prismo	
Measurement system	Active scanning probe VAST
Maximum permissible error	(1.0 + L/330) µm
Measurement uncertainty	1 µm
Maximal measurement dimensions	Length 1200 mm Width 850 mm Height: 700 mm

Figure 13: Zeiss Prismo – specification of measuring machine



Measurement on Zeiss Prismo	
Output data format	TXT points obtained by area scanning
Evaluation SW	Geomegic
Comparison method	Bestfit alignment with respect to the calibrated CAD model
Form error, i.e. estimated freeform measurement uncertainty (two-sigma limit)	[-0.87, 0.87] µm

Figure 14: Zeiss Prismo – area scanning measurement

The principal direction of scanning paths in Figure 14 is parallel with x-axis. Approximately 6 000 points have been measured along the scanning paths. In final evaluation, the points located in the 3 mm zone along the boundary of the freeform surface of the standard have not been taken into consideration, again. Thus, a set of 5 384 has been obtained. Normal deviation of each point from this set from its theoretical position located on the calibrated CAD model has been evaluated, see blue data in the graph in Figure 15. The theoretical reference value which is not influenced by measurement uncertainty is represented by zero deviation in this graph, i.e. by the green characteristic.

The freeform measurement uncertainty ± 0.87 µm of the CMM has been estimated as form error belonging to two-sigma limit (i.e. 95 % of measured data). The zone corresponding to this value is bounded by red characteristics in the graph.

Note that the measurement uncertainty of ± 1 µm declared by Zeiss Prismo producer is not exceeded in 97.5 % of measured data.

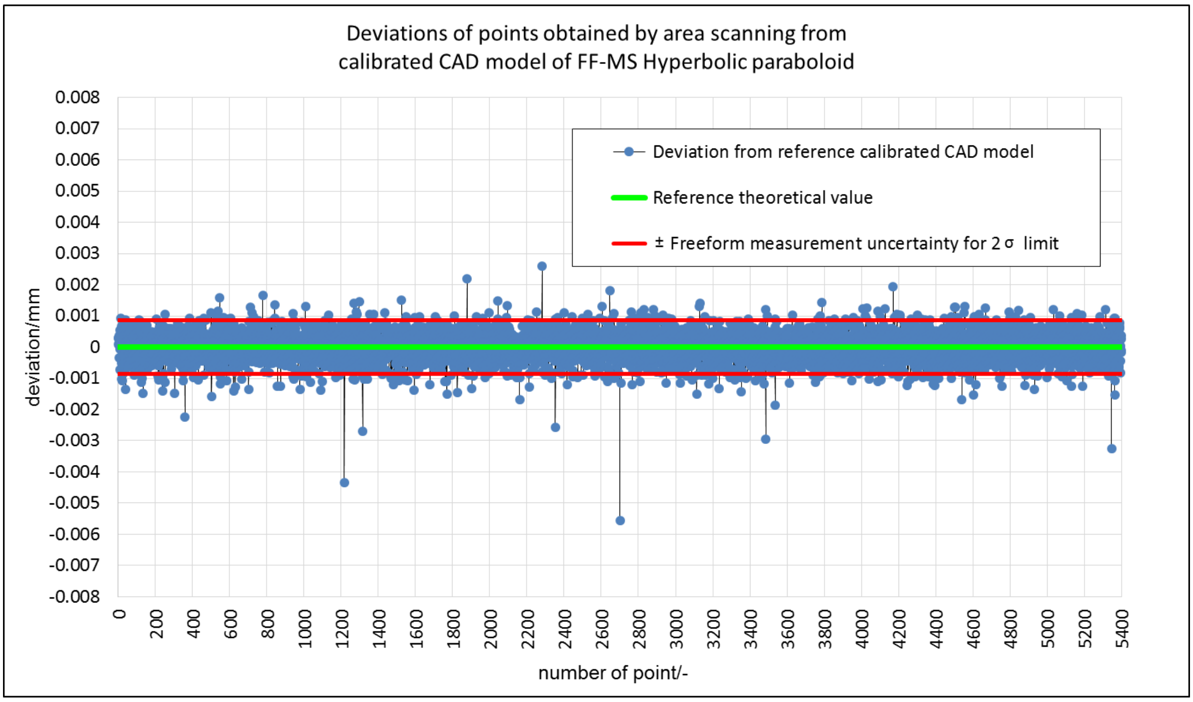


Figure 15: Zeiss Prixmo – Deviations of points obtained by area scanning from calibrated CAD model of FF-MS Hyperbolic paraboloid

4.2 Estimation of freeform measurement uncertainty based on E_n numbers application

In this section, the method of freeform measurement uncertainty estimation which is based on E_n number performance statistic application is described, see section 4.2.1. The practical experiment covering the measurement of FF-MS Hyperbolic paraboloid realised on machine tool Deckel Maho DMU 50 with Renishaw probe OMP 400 and freeform measurement uncertainty of this machine tool estimation is given in section 4.2.2.

4.2.1 E_n numbers performance statistic

The method of freeform measurement uncertainty estimation based on modification of E_n number performance statistic commonly used to indicate performance of interlaboratory comparison consists in the following ideas. According to [13, 14] the value of E_n is calculated by

$$E_n = \frac{|X_R - X_L|}{\sqrt{U_R^2 + U_L^2}} \tag{17}$$

and satisfactory performance is indicated if $E_n \leq 1$. X_R is the assigned value determined in a reference laboratory, X_L is the value measured in a tested laboratory, U_R is the expanded uncertainty of X_R and U_L is the expanded uncertainty of X_L.

In the method described here, the critical value of E_n is supposed to be known variable (suitably chosen value less or equal to one). Consequently, the expanded measurement uncertainty of the tested laboratory can be considered the unknown variable obtained by solving (17) with respect to U_L

$$U_L = \pm\sqrt{\frac{(X_R - X_L)^2}{E_n^2} - U_R^2}\,. \tag{18}$$

From the practical point of view, only positive sign in (18) can be considered. Moreover, in the framework of real numbers, the following condition

$$\frac{(X_R - X_L)^2}{E_n^2} \geq U_R^2$$

has to be valid to avoid square root of negative number.
In the procedure of freeform measurement uncertainty estimation, n points located on freeform surface are measured by both reference CMM and tested machine tool with respect to the reference CAD model of the standard first. Then, the measured data is processed and normal deviation of each measured point from its reference value is calculated. Thus, two sets of deviations

$$\left(X_R^i\right)_{i=1}^n \text{ and } \left(X_L^i\right)_{i=1}^n \tag{19}$$

are obtained. Next, measurement uncertainties u_L^i of individual deviations X_L^i for chosen value E_n are calculated by

$$u_L^i = \sqrt{\frac{\left(X_R^i - X_L^i\right)^2}{E_n^2} - U_R^2}, \qquad \frac{\left(X_R^i - X_L^i\right)^2}{E_n^2} \geq U_R^2, i = 1, \cdots n. \tag{20}$$

Finally, the resulting freeform measurement uncertainty of the tested machine tool is determined as maximal value

$$U_L = \max\left(u_L^i\right)_{i=1}^n \tag{21}$$

belonging to the two sigma limits (95%) of deviations $\left(X_L^i\right)_{i=1}^n$.

4.2.1 Experimental measurement

To demonstrate the described approach, an experimental measurements of FF-MS Hyperbolic paraboloid on SIP CMM 5 machine (reference laboratory, $U_L = 0.0013\mu\text{m}$), see specification in Figure 10, and on machine tool Deckel Maho DMU 50 with Renishaw probe OMP 400 (tested laboratory, see specification in Figure 17 have been performed. In this case, points along four selected 3D lines, two 3D parabolas and two 3D hyperbolas are measured by tactile probe, see Figure 17, where these features are highlighted in red, black and blue in the given order.

Specification of Deckel Maho DMU 50	
Measurement system	Renishaw probe OMP 400
Maximum permissible error	(4.7 + L/75) µm
Maximal measurement dimensions	Length 710 mm Diameter 500 mm

Figure 16: Deckel Maho DMU 50– specification of measuring machine

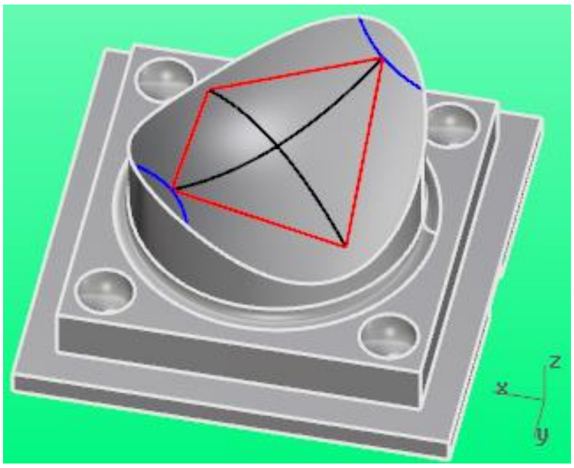


Figure 17: Geometrical features located on freeform surface
3D lines (red), 3D parabolas (black) and 3D hyperbolas (blue)

About 350 surface points along above mentioned curves have been measured and two sets of deviations given by (19) have been obtained. The colour maps of these deviations are depicted in Figure 18. Behaviour of individual differences of deviations $X_R^i - X_L^i$ is shown in Figure 19 Then, two critical values $E_n = 1$ and $E_n = 0.8$ have been chosen and uncertainties u_L^i of individual deviations X_L^i according to (20) have been calculated for $U_R = 0.0013$ mm. Finally, the unknown uncertainty U_L of the tested machine tool have been determined by (21) so that the satisfactory performance is indicated for $E_n \leq 1$ (representing the limit situation) and for $E_n \leq 0.8$ (representing the situation with 20 % safety zone) in two sigma limit, i.e. for 95 % of all measured points. The values of estimated freeform uncertainty of the tested machine tool are given in Table 1, the behaviour of E_n number is shown in Figure 20.

Table 1 Estimated freeform measurement uncertainty of tested machine tool for
$U_R = 0.0013$ mm and two sigma limit

$\boldsymbol{E_n}$ **number**	$E_n \leq 1$	$E_n \leq 0.8$
$\boldsymbol{U_L}$	$U_L = 0.0015$ mm	$U_L = 0.0021$ mm

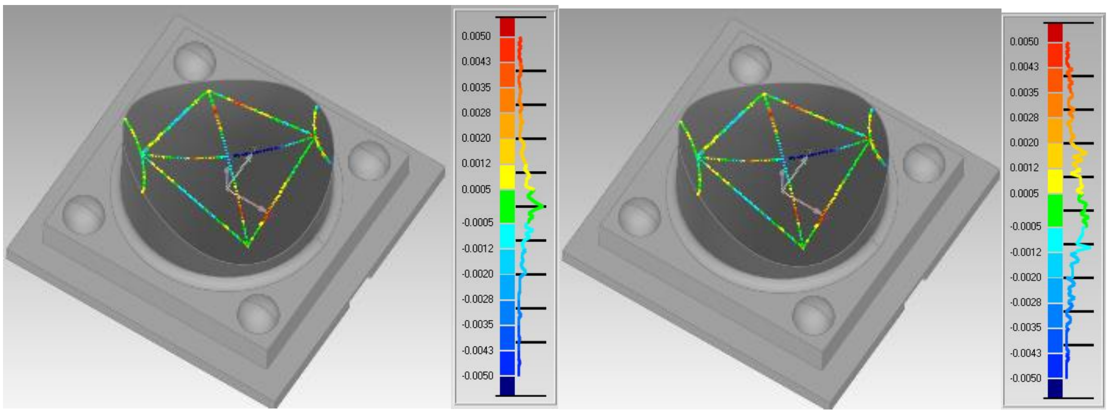


Figure 18: Colour maps of deviations X_R^i measured by reference CMM (left) and deviations X_L^i measured by tested machine tool (right)

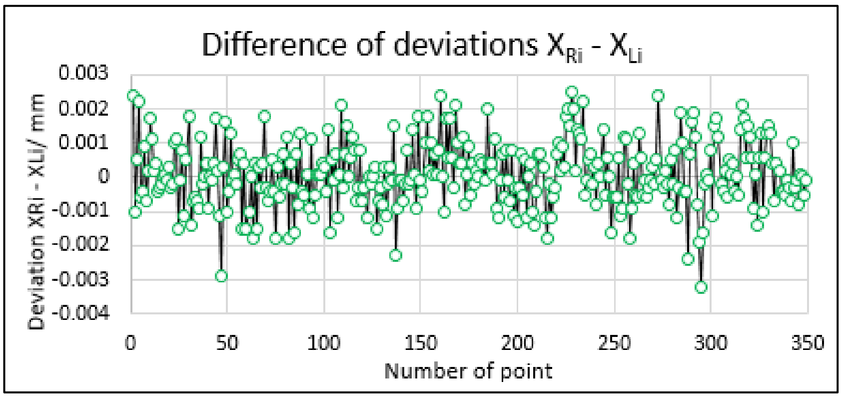


Figure 19: Graph of differences of deviations $X_R^i - X_L^i$

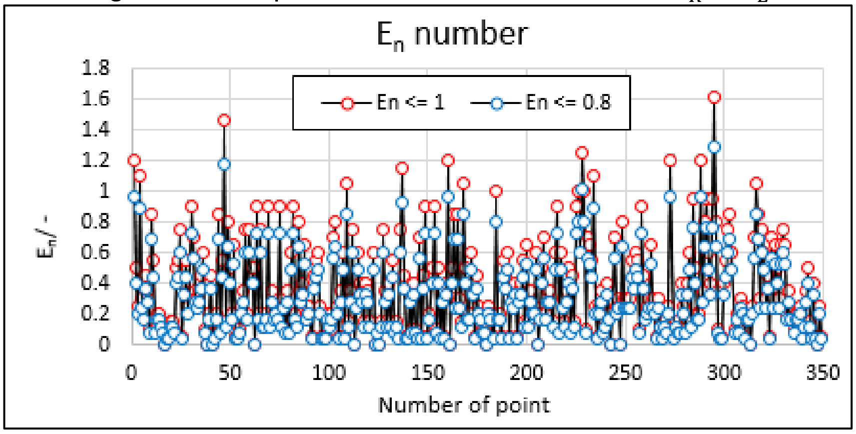


Figure 20: Graph of E_n numbers

3 Conclusion

The good practice guide described in this deliverable serves for verification of area-scanning on-board metrology system using a freeform material standard FF-MS Hyperbolic paraboloid developed and manufactured within JRP.
Firstly, the general guiding principles to good measurement practice defined by NPL are given. After that, the mathematical description and CAD model of the developed FF-MS Hyperbolic paraboloid are described. Then, the calibration procedure of both physical standard and the corresponding CAD model is explained. Next, the main possible measurement strategies of FF-MS Hyperbolic paraboloid application are discussed. Finally, two approaches to estimate the freeform measurement uncertainty of the machine tool are presented. The guide is completed by description of practical experiments performed by both CMM and machine tool.

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