A New Approach for the Effectiveness of Coaxiality Tolerance Verification

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Abstract

One of the most complex tasks that are carried out by Coordinate Measuring Machines (CMM) is the verification of coaxial deviation of cylindrical features. The paper addresses the difficulties met in the evaluation of coaxiality tolerances. A set of criteria, based on current GD&T standards and industrial engineering practice, are introduced in order to safeguard the effectiveness of the coaxiality tolerance verification by CMMs. The proposed criteria, along with the novel CMM measurement strategies for the practical verification of coaxial deviation that are presented, can be easily implemented in CAD/ CMM environments. The functionality of the approach is illustrated through an application example.

***Keywords** : GD&T, Tolerance verification, CAD, Coaxiality, Concentricity, CMM*

1 Introduction

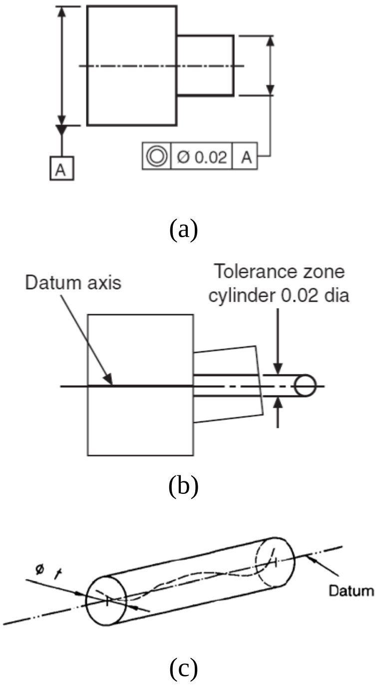
The control of inevitable deviations from nominal geometric and dimensional requirements during the manufacture of mechanical components and assemblies is currently pursued through the series of Geometric Dimensioning and Tolerancing (GD&T) standards. Coordinate measuring machines (CMM) constitute the most flexible and powerful tools for GD&T verification and are widely used in the manufacturing industry. One of the most complex tasks that are carried out by means of the CMMs is the measurement of coaxial deviations of cylindrical features and/or features of size in general. Coaxiality requirement can be specified in the engineering drawings in several different ways, in accordance with current national and/or international GD&T standards, *(positional, runout, profile, concentricity, coaxiality tolerances).* However, concentricity/ coaxiality tolerances are usually applied in cases where the *dynamical balance* of the controlled feature about the datum axis is considered critical. Taking into consideration that the great majority of mechanical components and assemblies comprise of internal and external cylindrical/ rotational features, the efficient accomplishment of this measurement task is of particular importance in industrial dimensional metrology, product – process design and quality management. Concentricity/ coaxiality tolerance verification, especially as defined in ASME GD&T standards, [1], [2], is considered a costly and time consuming procedure, far more complex than runout or true position tolerance verification. Designation of concentricity and coaxiality tolerances has been addressed, on the other hand, by a limited number of research papers under various aspects including tolerance analysis and synthesis, datum establishment, inspection procedures, measurement instrumentation, [3 – 8]. Industrial metrology problems on their interpretation and verification with CMMs have been only recently, however, drawn attention, [9], [10]. This paper extends the research on this area by introducing a set of criteria and two novel CMM measurement strategies for the verification of concentricity and coaxiality tolerances as per

ISO and ASME GD&T standards. The proposed methodology deals with the problem in a systematic, time and cost efficient way, compatible with the current industrial insight. The approach, to the extent of the authors' knowledge, is the first of the kind for this type of engineering problems that can be directly implemented within a CAD/CAT (Computer Aided Tolerancing)/CMM environments. The rest of the paper is organised as follows: in the second section of the paper the interpretations of coaxiality tolerancing in current GD&T standards are compared and the practical difficulties met in their evaluation are briefly discussed. A set of criteria, based on industrial engineering practice, are then established in order to safeguard the effectiveness of the coaxiality tolerance verification by CMMs. The introduced criteria can be easily integrated in tolerance assignment software for respective realistic tolerancing in the design phase. Two novel CMM measurement strategies for the verification of coaxial deviation of features of size are further presented. The functionality of the developed approach is illustrated through an application example.

2 Evaluation of coaxiality tolerance

2.1 *Coaxiality and Concentricity in current GD&T Standards*

The most commonly used GD&T standards are the ones that are established by the International Organization for Standardization (ISO) and the American National Standard Institute (ANSI). Although these two have emerged as the primary standards in the field of dimensioning, there are also several others that are in use worldwide, such as the GD&T standards that come from large manufacturing corporations, e.g. [11]. Due to the increasing pressure to migrate toward a common GD&T standardisation as the world evolves toward a global marketplace, important steps have been made for GD&T standards of ISO and ANSI to maintain same key concepts and to appear similar. Nevertheless, they still have quite a few subtle but significant differences that concern the definition, application and interpretation of several GD&T issues, such as coaxiality and concentricity tolerances. The ISO GPS (Geometrical Product Specifications) series of standards divide dimensioning and tolerancing into topic subsets with a separate ISO standard covering each dimensioning topic, e.g. [12], [13]. In contrast, the ANSI standard collected all relevant issues in the ASME Y14.5M, [2], a popular standard commonly used in industry. The coaxiality and concentricity definitions as per ASME Y14.5M are thoroughly discussed hereafter. Two circles are said to be concentric when their centers are coincident. Moreover, coaxiality is the relationship of one axis to another, thus two cylinders are said to be coaxial when their axes are coincident. The deviation from the true centre or axis of the datum is controlled by the magnitude of the concentricity and coaxiality tolerance zone respectively. Coaxiality and concentricity tolerances in ISO standards can apply on Regardless of Feature Size (RFS), Maximum Material Condition (MMC) or Least Material Condition (LMC) basis and must have at least one datum that also applies at RFS, MMC or LMC. The method of indicating concentricity/coaxiality tolerance on engineering drawings in accordance with ISO 1101, [12], is presented in Figure 1(a). The product requirement is to contain the axis of the right-hand cylinder within a 0.02mm cylindrical tolerance zone which is coaxial with the axis of the datum cylinder, **A**, Figure 1(b). In that context, coaxiality tolerance zone as per ISO 1101 is interpreted as a cylinder of diameter ***t*** the median line of which is the datum axis **A** and will just enclose *the extracted (actual) median line* of the toleranced cylinder, Figure 1(c).



(a)

(b)

(c)

Figure 1 : Coaxiality tolerance according to ISO 1101.

The *"extracted median line"* of a cylinder is defined in ISO 14660-2 [14] as the locus of centres of cross-sections, where the centres of cross-sections are centres of associated circles; and the cross-sections are perpendicular to the axis of the associated cylinder obtained from the extracted surface (i.e. the radius could be different from the nominal radius).

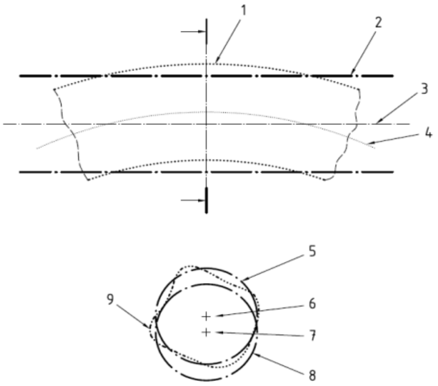


Figure 2 : Extracted median line of a cylinder according to ISO 14660-2 [14].

Moreover, for the above default definition *(unless otherwise specified)* of the extracted median line of a cylinder, the following conditions apply [14]:

- the associated circles are the total least squares circles (Figure 2):

- the associated cylinder is the total least squares cylinder (Figure 2).

In Figure 2, number 1 denotes the Extracted surface, number 2 the Associated cylinder, 3 the Associated cylinder axis, 4 the Extracted median line, 5 the Associated circle, 6 the Associated circle center, 7 the Associated cylinder axis, 8 the Associated cylinder and 9 the Extracted line. On the other hand, according to the ASME Y14.5M standard, [2], concentricity/coaxiality is "that condition where the median points of all diametrically opposed elements of a surface of revolution (or the median points of correspondingly located elements of two or more radially disposed features) are congruent with a datum axis (or center point)". The acceptable method of placing a concentricity control on a drawing is the same as in the ISO 1101 standard, Figure 1(a). This control creates a cylindrical (or spherical) tolerance zone whose axis coincides with the axis of the datum feature(s). Nevertheless, in that case, it is not the extracted (actual) median line of the toleranced cylinder but the median points of each of the opposed elements of the toleranced feature that must lie within the tolerance zone, as it is shown Figure 3.

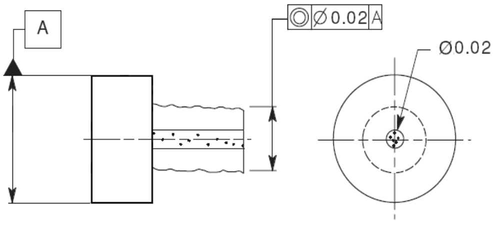


Figure 3 : Coaxiality tolerance according to ASME Y14.5M.

Hence, concentricity applies to correspondingly located points of two or more radially disposed features, such as the flats on a regular hexagon, or opposing lobes on features such as an ellipse. Concentricity tolerance can only apply on an RFS basis and it must have at least one datum that also applies only at RFS. Since concentricity in the

ASME standard controls all median points of all diametrically opposed points on the surface of the toleranced feature, the aggregate of all median points, sometimes described as a “cloud of median points,” must lie within a cylindrical tolerance zone whose axis is coincident with the axis of the datum feature. Hence, ASME concentricity tolerance is independent of both size and form deviations. While the ASME Y14.5M standard does not give specific instructions on how to derive the median points, the ASME Y14.5.1 standard, [1], that concerns the mathematical definition of geometrical tolerancing, does. In the latter it is stated that a concentricity tolerance “specifies that the centroid of corresponding point elements on the surfaces of the actual features must lie in (the) tolerance zone” and that the centroids (median points) are “obtained by intersecting a pattern of *symmetry rays* with the actual feature.” The symmetry rays are projected from and perpendicular to the datum axis and are also projected 180° apart. The intersection of these two symmetry rays with the feature surface defines two points, for example A and B. The median point, C, between A and B must lie within the cylindrical tolerance zone. At each cross section, there are several sets of opposed symmetry rays. Therefore, at each cross section a cloud of median points that all must lie within the tolerance zone should be derived. Thus, if point A moves farther away from the datum axis, then point B must also move farther away for the centroid to remain in the tolerance zone. Along with the above context, it is clear the concentricity/coaxiality as per ASME Y14.5M controls the toleranced feature to be centered on the datum and it also controls the form of its surface, *but only at diametrically opposed points*. The controlled feature could not be D-shaped, but it could be elliptical or it could have a flat on one side, as long as it had a corresponding flat on the opposite side.

2.2 *Comparison of ISO and ASME coaxial controls*

According to the ISO 1101 standard, concentricity /coaxiality tolerance can be considered as a particular case of location tolerancing, in which the toleranced feature and the datum feature are mainly circles or cylinders respectively. The tolerance limits the deviation of the position of the centre or axis of the toleranced feature from its “true position”, i.e. the centre or axis of the datum feature, and the tolerance value is the diameter of the tolerance zone. In that context, true position tolerances can alternatively be used for the expression of the same design intend as coaxiality tolerances for coaxial cylinders. The ASME Y14.5M standard explicitly states that “the selection of the proper coaxial features control depends on the functional requirements of the design” and, as well as, that “the amount of permissible variation from coaxiality may be expressed by a position tolerance, a runout tolerance or a profile tolerance”. However, concentricity requirement is substantially different than position, profile or runout tolerances, [2]. In general, a position control is recommended when parts are mated in a static assembly and runout should be specified for high-speed rotating assemblies. According to the ASME standard, concentricity should only be applied where the major design requirement is that a part is dynamically balanced about the datum axis. Often where balance is required, the out of circularity or lobbing effect and other possible form errors may be permissible. Hence, any basically symmetrical form of revolution, *(e.g. hexagons, cones)* or consistently symmetrical variation of such shape, could satisfy a concentricity tolerance where a runout requirement may not. Nevertheless, due to its definition, the concentricity control requires a rather sophisticated and expensive inspection process; it is therefore appropriate only in applications where precise balance is strongly required. The terms concentricity and coaxiality as described in the ISO standard are *not interchangeable* with the same terms described in the ASME standard. However, a frequent mistake in industrial metrological practice is that a concentricity tolerance as per ASME is arbitrarily converted to a concentricity tolerance as described in the ISO standard.

2.3 *Problems in measuring coaxiality by CMM*

CMM measurement strategy, number and distribution of contact points, performance of the probing system, measurement speed and acceleration, thermal and environmental stability are, among others, the most common factors that influence the uncertainty of CMM measurement results of all the types of GD&T tolerances. However, industrial metrological practice points out two additional important issues that may strongly affect the reliability of CMM concentricity and coaxiality deviation measurements, in particular:

- The length of the datum feature.
- The intermediate distance between the controlled feature and the datum feature.

In order to safeguard the effectiveness of the CMM coaxiality inspection the above issues should be taken into account during the early stages of a product life cycle and especially during the tolerance designation phase of a mechanical assembly, in either use of ISO or ASME GD&T standards. Focusing on ASME concentricity tolerance, its inspection is a rather complicated task. Generally, a CMM with advanced metrological software tools or a dedicated inspection machine with a precision spindle should be used for that purpose. As mentioned in Section 2.1, for an entire feature to conform to its concentricity tolerance, all median points shall conform, for every possible ray pattern, for every possible origin point on the datum axis within the feature. Although it's impossible to verify infinitely many median points, a sufficient sample (perhaps dozens or hundreds) should be constructed and computationally evaluated [15]. Undoubtedly this is a tedious, costly and time consuming procedure. Most CMM measurement software packages evaluate concentricity and coaxiality deviations using a calculation based on the controlled feature's derived centre point or axis, hence they do not evaluate concentricity as per the ASME definition. For instance, PC-DMIS, a well-established CMM measurement software developed by Wilcox Associates Inc., uses the start point and end point of the toleranced feature to calculate coaxiality deviation. The perpendicular distance of each of these points from the datum feature's axis is calculated. These two distances define the maximum and minimum values and the coaxiality is twice the maximum value [16]. Even though the calculation algorithms that control the measurement procedures of commercially available CMM metrology software are not accessible by the user [9], the fact that during the measurement procedure the user is not prompted to probe the measured feature in opposed point pairs eliminates the possibility for the results to be in accordance with the ASME concentricity definition.

3 Effective CMM coaxiality tolerance verification

3.1 *Set of criteria - Decision rules*

A datum feature is chosen on the basis of its geometric relationship to the toleranced feature and the particular characteristics of the design intent. The direction of the datum's axis vector is extremely important for the calculation of concentricity and coaxiality deviation as defined in both the ISO and ASME standards. Only a datum cylinder *with sufficient length* that is accessible for probing near both its ends can provide a repeatable datum axis vector and therefore safeguard the repeatability of coaxiality CMM measurements. Additionally, for the ISO 1101 standard, the axis of the toleranced feature has to be derived as well from a limited number of contact points and its vector has also a strong effect on coaxiality tolerance calculations. The accuracy specification of the measurement equipment that is used has a direct impact on a vector's calculated 3D direction, thus it should be considered in conjunction with the geometrical characteristics of the datum and the controlled feature. The above issues are systematically addressed in the paper in order to safeguard the effectiveness of CMM coaxiality tolerance verification. For that purpose a set of criteria in the form of geometrical constraints, that can also be used as decision rules for tolerance designation in the design phase, is formulated.

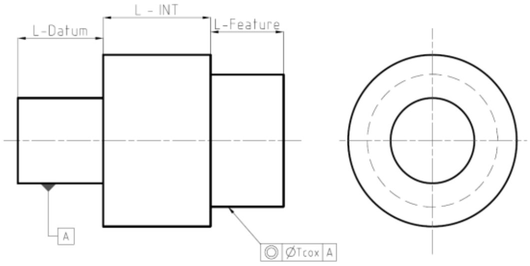


Figure 4 : Introduced symbols for the decision rules.

The mathematical expressions of the decision rules are given below, eq. (1) – (6). The symbols that are used are illustrated in the typical component of Figure 4. Let $\mathbf{T_{COX}}$ be the designated coaxiality tolerance, $\mathbf{L_D}$ the length of the datum feature, $\mathbf{L_F}$ the length of the toleranced feature and $\mathbf{L_{INT}}$ the intermediate distance between them. The actual distance of their centroids is defined as the effective length, $\mathbf{L_{EF}}$, and is approximated by equation (6). The coefficients **k** and **p** are calculated as the integral part of the expressions in the right side of the equations (3) and (4) respectively.

$$L_D \geq \frac{L_{EF}}{k} \qquad (1)$$

$$L_{EF} \leq p\,(L_D + L_F) \qquad (2)$$

$$k = \frac{T_{cox}}{MPE_E} \qquad (3)$$

$$p = \frac{T_{cox}}{5\,MPE_E} \qquad (4)$$

$$T_{cox} \geq 5\,MPE_E \qquad (5)$$

$$L_{EF} = \frac{L_D + L_F}{2} + L_{INT} \qquad (6)$$

In the above expressions, $\mathbf{MPE_E}$ *(Maximum Permissible Error)* is a commonly used parameter that describes the volumetric accuracy performance of a CMM as per ISO 10360-2 [17]. In equation (7) MPE_E is calculated in microns (μm), A and B are integer constants that are specified by the equipment manufacturer and L_{EF} is put in millimetres. In the ISO 10360 series of standards the effects of CMM geometric errors of single point probing are evaluated when measuring block gauges or step gauges in several directions in the working volume of the machine.

$$MPE_E = A + \frac{L_{EF}}{B} \qquad (7)$$

Non conformance with the presented decision rules during the inspection phase of a mechanical component can be used as a technically sound guideline for the selection of the appropriate measurement equipment that can effectively validate its concentricity and/ or coaxiality tolerance requirements.

3.2 *CMM measurement approach for ISO 1101 coaxiality verification*

A frequently met industrial problem is when the tolerance designation and the geometrical configuration of a mechanical component cannot be modified and the available inspection equipment does not conform to the above criteria (1) – (7). In such a case the effectiveness of the coaxiality tolerance verification can still be safeguarded if the standard CMM measurement strategy is modified. The developed approach is illustrated in Figure 5 and encompasses the following steps:

i. A series of circular cross sections, typically four to eight, are taken on the full length, L_F, of the toleranced feature and their centers are established.

ii. The set of points created in Step *i.* are used by the CMM measurement software for the construction of the 3D axis of the *toleranced feature.*

iii. A series of circular cross sections, typically four to eight, are taken on the full length, L_D, of the datum feature and their centers are established.

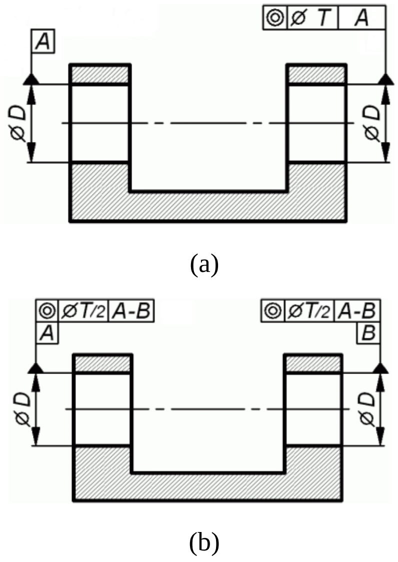
iv. The set of points created in Step *iii.* are used by the CMM measurement software for the construction of the 3D axis of the *datum feature*.

v. The full set of points created in both Steps *i.* and *iii.* are used by the CMM measurement software for the construction of a 3D axis.

vi. The coaxiality deviations of the toleranced feature and the datum feature's axes from the axis constructed in Step *v.* are evaluated with the standard measurement procedure of the CMM software.

vii. The component is in tolerance only if the coaxiality deviations of *both the toleranced and the datum feature* are within half the originally designated T_{COX} cylindrical tolerance zone (T/2, Figure 5(b)) established from the common 3D axis that was constructed in Step *v.*

The 3D axes of the toleranced feature *(step ii)*, of the datum feature *(step iv)* and the common axis *(step v)* are the total least square axial features in 3D space that are constructed by mathematical fitting on the relevant set of points. Hence, the available points are best fitted so that the average squared error is minimized in the least squares method and the maximal error is minimized in the minmax method. The proposed CMM measurement approach allows for an alternative kind of specific control of feature-to-feature coaxiality. It is strongly based on the concept of compound datum feature that appears in ISO 1101 and ISO 5459 [18] and allows for a common axis construction that can be used as a single datum. Moreover, the proposed approach offers high repeatability of CMM coaxiality measurement results which cannot be achieved by the standard CMM strategy for components/ equipment that do not meet the criteria of Section 3.1. A common requirement in coordinate measurement technology is to fit an associated feature to a data set consisting of coordinate measurements of a real feature. This fitting is carried out by dedicated software algorithms. The reliability of information about real features that is determined from associated features is strongly influenced by the quality of the software for computing these features. Therefore it is considered critical for the trustworthiness of the above approach that the accuracy of fitting algorithms used by the CMM software is tested and adhere to relevant ISO 10360-6 requirements [19].



(a)

(b)

Figure 5 : Coaxiality requirement based on single (a) and on compound (b) datum.

The establishment of a common 3D axis from both the datum and the measured feature and its further use as the *"new datum"* is clearly not in absolute conformance with the coaxiality requirement originally denoted on the engineering drawings of the component. Apparently, according to the GD&T standards the coaxiality tolerance of a cylinder, the datum being another cylinder, is a *different tolerance* than coaxiality in their common zone. In metrological inspection, tolerances must be verified in accordance with their standardized definition or as near as possible depending on the capabilities of the available metrological tools. In that context, the approach of the above steps (i – vii) can only be considered as an alternative under the following conditions:

a. On both the datum and the measured features certain accuracy and geometrical characteristics *(e.g. tolerances of form, limits of size, surface roughness, nominal diameter, symmetrical location on the part)* are identical and/ or of the same range.

b. All members of the engineering team involved in product development *(design, manufacturing, inspection, assembly, ...)* concurrently approve the modified coaxiality CMM verification method *(Figure 5(b))*, being aware that it does not directly correspond to the design intend as denoted on the original blueprints *(Figure 5(a))*.

Such an agreement can be further combined/ reinforced with a modified quality management plan, e.g. coaxiality verification by the standard CMM strategy on a typical sample size of the components using third party, "high accuracy" equipment that satisfies the criteria of Section 3.1.

The described CMM strategy does not intend to substitute or replace the standard "datum – toleranced feature" coaxiality tolerance verification. However, for a certain range of applications and under the conditions (a) and (b), it aims to offer a viable, time and cost-effective option, compatible with the current industrial metrological insight.

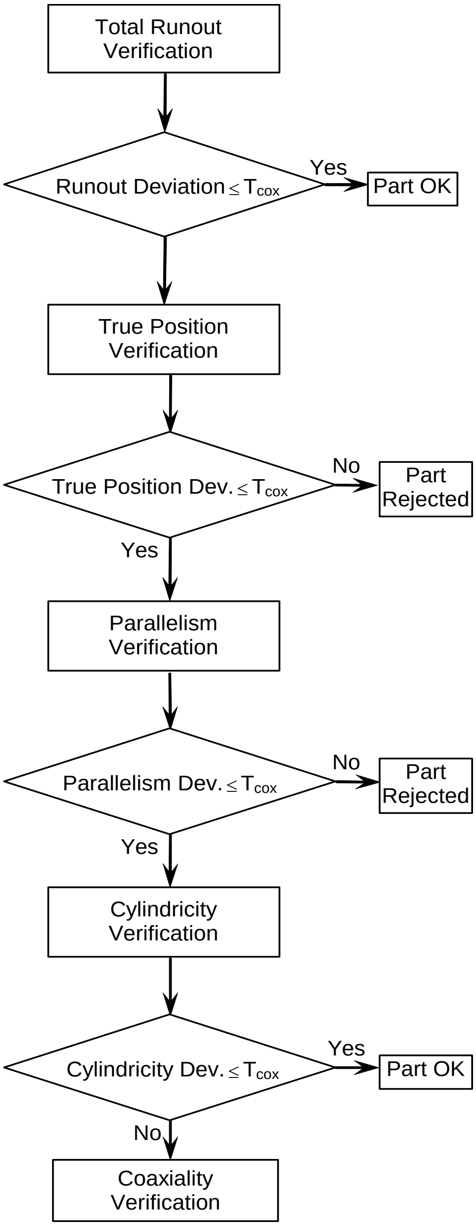


Figure 6 : Overview of the proposed CMM approach for ASME Y14.5M coaxiality verification.

3.3 *CMM measurement approach for ASME Y14.5M coaxiality verification*

As discussed in section 2.3 the ASME definition of concentricity and coaxiality is difficult for manufacturers to measure in a fast and inexpensive manner. The paper examines the feasibility of a novel CMM measurement approach that combines the evaluation of location, orientation and form geometric tolerances in order to verify the coaxiality requirement in a faster and more cost effective way. Geometrical tolerances such as runout, true position, parallelism and cylindricity can be straightforwardly evaluated with a CMM by physically probing the surfaces of the examined component without any sophisticated analysis of its cross sections. In that context, the procedure presented in Figure 6 can provide an alternative strategy for coaxiality tolerance verification as per ASME Y14.5M. Runout, true position and parallelism deviations are evaluated using the same datum feature that is designated in the coaxiality tolerance control frame of the toleranced feature. Along with its' cylindricity deviation, they are all readily available by the standard measurement procedures of the CMM software as long as the surfaces of the toleranced and the datum feature are physically probed. Thus, the elaborate and time consuming formal verification of the ASME coaxiality specification can only be performed for those few mechanical parts that failed the CMM evaluation approach illustrated in Figure 6.

4 Application example and discussion

The effectiveness of the proposed approach for this kind of engineering problems is illustrated in a typical industrial case study. A rotary shaft with overall length of 540mm has an ISO 1101 coaxiality tolerance specification of T_{COX}=0.08mm that concerns the two cylindrical features on its left and right ends, Figure 7. In the engineering drawings the designated datum for coaxiality is the cylinder in the right end of the component and the toleranced feature is the cylinder in its left end. Their lengths are 72mm (L_D) and 80mm (L_F) respectively. Measurements were performed by means of a direct computer controlled CMM (*Mistral*, Brown & Sharpe-DEA) with ISO 10360-2 max. permissible error, [17], 3.5(μm)+L(mm)/250 and PC-DMIS v.4.2 measurement software, Figure 8. The decision rules and the CMM measurement approaches presented in Section 3 are integrated as a set of macros developed for that purpose in PC-DMIS using the BASIC Scripting Language, which is a standard part of the software. An industrial dimensional metrology standard Renishaw PH10M indexable head with TP200 touch trigger contact probe and a 10mm length ruby-ball tip with diameter of 2mm were used. The number and distribution of sampling points conformed to the recommendations of BS7172:1989, [20], i.e. 7 points for circles and 15 points for cylinders (5 points in three cross sections).

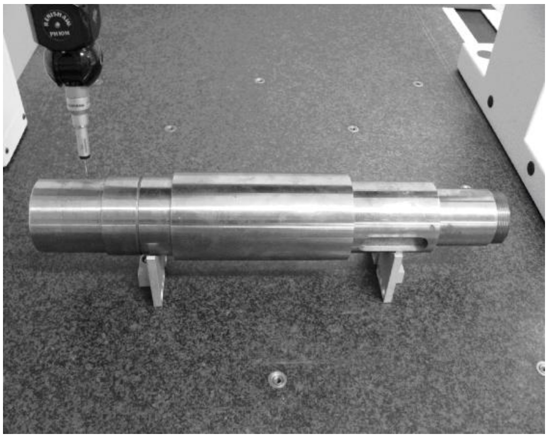


Figure 7 : CMM measurements in the application example component.

The numerical result produced for coaxiality deviation by the standard CMM measurement procedure was 0.096mm, which means that the feature is out of tolerance and that the part has either to be reworked or rejected. However, according to the coaxiality tolerance verification methodology presented in Section 3.2 the coaxiality deviation of the toleranced feature was 0.008mm and that of the datum feature was 0.013mm. These measured values are considerably lower than half the designated coaxiality tolerance ($T_{COX}/2$), thus the component is accepted.

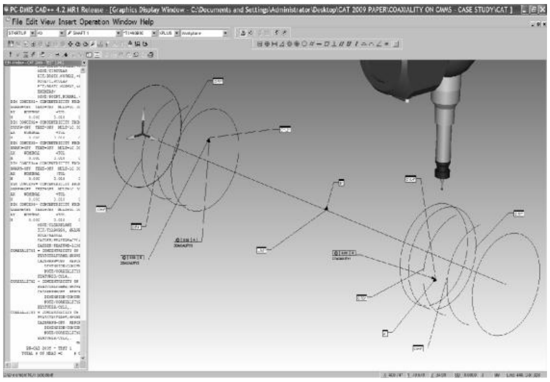


Figure 8 : Coaxiality evaluation through CMM measurement software for the case study.

Using the designated datum feature the total runout deviation of the toleranced feature was also measured and found to be 0.074mm. In case that the coaxiality tolerance was specified as per ASME Y14.5M in its engineering drawings, following the approach presented in Section 3.3, the component would also have been accepted. The fact that the application example component actually fulfils the design requirements that are implied by the coaxiality tolerance allocation was experimentally verified and well approved by fitting the specific component in an existing assembly. The interchangeability and the conformance with functional requirements of a component that without the application of the proposed approach should have been rejected, demonstrate its effectiveness.

5 Conclusions

GD&T concepts of concentricity and coaxiality are often required by design engineers for balance of rotating parts and precision mating parts. The paper aims to reduce the interpretation problems that occur when coaxiality and concentricity callouts defined by different GD&T standards are encountered. A set of geometrical constraints that link the geometrical configuration of the measured component with the designated coaxiality tolerance and the accuracy specifications of the CMM are presented. Non conformance with these decision rules can influence tolerance designation during the design stage or the selection of the appropriate measurement equipment during the inspection phase. Moreover, in case of violation of the decision rules and in order to safeguard the effectiveness of the ISO coaxiality tolerance verification, a novel CMM measurement strategy that is consistent with the industrial dimensional metrology good practice rules is introduced. As far as the ASME definition of concentricity and coaxiality is concerned it is difficult for manufacturers to measure them quickly and inexpensively. The paper demonstrates the feasibility of an alternative CMM measurement strategy that combines the evaluation of location, orientation and form geometric tolerances in order to verify the ASME coaxiality requirement in a faster and more cost effective way. The use and the effectiveness of the presented approaches have been demonstrated through an actual industrial case study. Future work is oriented towards the analytical evaluation of the differences on coaxiality verification between the presented approach and other coaxiality control methods and practices *(e.g. run-out, straightness in common zone of the axis, toleranced feature and datum inversion)* as are defined in current GD&T standards, based on theoretical/ mathematical definition and vectorial tolerancing.

References

[1] ASME Y14.5.1M-1994, 1995, Mathematical Definition of Dimensioning and Tolerancing Principles, The American Society of Mechanical Engineers, New York.

[2] ASME Y14.5M–2009, 2009, Dimensioning and Tolerancing, The American Society of Mechanical Engineers, New York

[3] Waters C. and Roy U., 1996, Automated Inspection of Coaxiality Requirements, Proceedings of XXIVth NAMRC Conference, Ann Arbor, Michigan, USA, May 21-23, MS96 -147 1-6.

[4] Qianghua Ch., Dejiao L., Jian W., Juqun Y. and Chunyong Y., 2005, Straightness/ Coaxiality Measurement System with Transverse Zeeman Dual-frequency Laser, Measurement Science & Technology, Vol. 16 (10), 2030–2037.

[5] Tomilin S.A., 2007, Monitoring the deviation of coaxiality of nominally cylindrical surfaces of a component, Measurement Techniques, Vol. 50, No. 12, 1261-1265.

[6] Giordano M., Samper S. and Petit J. P., 2007, Tolerance Analysis and Synthesis by Means of Deviation Domains, Axi-Symmetric Cases, Models for Computer Aided Tolerancing in Design and Manufacturing, J.K. Davidson (ed.), 85-94, Springer, The Netherlands.

[7] Zhang K., 2007, Research on Coaxiality Errors Evaluation Based on Ant Colony Optimization Algorithm, Lecture Notes in Computer Science (LNCS) vol. 4688, K. Li et al. (Eds.), LSMS 2007, 267 – 276, Springer Verlag, Berlin – Heidelberg.

[8] Germain F. Denimal D. and Giordano M., 2008, A Method for Three Dimensional Tolerance Analysis and Synthesis Applied to Complex and Precise Assemblies, in International Federation for Information Processing (IFIP), Volume 260, Micro-Assembly Technologies and Applications, Ratchev, S., Koelemeijer, S. (Eds), 55-65, Springer, Boston.

[9] Bubnowicz S. and Łukianowicz C., 2008, Practical problems in measuring coaxiality by coordinate measuring machine, Proceedings of VIIIth International Scientific Conference on Coordinate Measuring Technique, Bielsko-Biala – Ustron, Poland, March 31 – April 2, 223-230.

[10] Jakubiec W., 2009, Analytical estimation of uncertainty of coordinate measurements of geometric deviations: models based on distance between point and straight line, Advances in Manufacturing Science and Technology, Vol. 33, No. 2, 45 – 53.

[11] Volvo Corporate Standard SDT 112-0003E, 2006, Geometrical tolerances indication and definitions, Volvo Car Corporation. Available online at:

http://www.tech.volvo.com/std/docs/112-0003 (accessed 02/03/2011).

[12] ISO-1101, 2004, Geometrical Product Specifications (GPS) - Geometrical tolerancing - Tolerances of form, orientation, location and run-out, The International Organization for Standardization, Geneva.

[13] ISO 5458, 1998, Geometrical product specifications (GPS) – geometrical tolerancing – positional tolerancing, International Organization for Standardization, Geneva.

[14] ISO 14660-2, 1999, Geometrical Product Specifications (GPS) — Geometrical features — Part 2: Extracted median line of a cylinder and a cone, extracted median surface, local size of an extracted feature, The International Organization for Standardization, Geneva.

[15] Drake P.J., 1999, Dimensioning and Tolerancing Handbook, McGraw – Hill, New York.

[16] Wilcox Associates Inc., 2004, Mathematical Definition of Dimensions for PC-DMIS measurement software – Version 2.0, Available online:

http://www.wilcoxassoc.com/downloads/dl_instructionalfiles.php (accessed 2/03/2011).

[17] ISO 10360-2, 2001, Geometrical Product Specifications (GPS) – Acceptance and reverification tests for coordinate measuring machines (CMM) – Part 2: CMMs used for measuring size, The International Organization for Standardization, Geneva.

[18] ISO 5459, 2011, Geometrical Product Specifications (GPS) – Geometrical tolerancing - Datums and datum systems, The International Organization for Standardization, Geneva.

[19] ISO 10360-6, 2001, Geometrical Product Specifications (GPS) – Acceptance and reverification tests for coordinate measuring machines (CMM) – Part 6: Estimation of errors in computing Gaussian associated features, The International Organization for Standardization, Geneva.

[20] Flack D., 2001, CMM Measurement Strategies, NPL Measurement Good Practice Guide No. 41, NPL - Crown, Teddington.