14th CIRP Conference on Computer Aided Tolerancing (CAT)

Requirements for Datum Systems in Computer Aided Tolerancing and the Verification Process

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Abstract

The recent attempt in Geometrical Product Specification to change from dimensional to geometrical tolerancing leads to a stronger focus on datum systems. Two aspects on the requirements for these and their effects on each other will therefore be discussed in this paper. A new approach to develop a functional datum system in the early stages of the methodical design process that is derived from the functional interaction of the indeterminate workpiece geometry within the outlined assembly group will be explained. It will also show current research results to overcome the gaps in ISO 5459 about extraction and association requirements for the verification process.

**Keywords:** Geometrical Product Specification, Datum Systems, Computer Aided Tolerancing, Verification, Coordinate Measuring Machines

1. Introduction

Dealing with the function, the manufacturing and the verification of a workpiece, the System of the Geometrical Product Specification (GPS) [1] provides a universal language for the nonverbal communication in the mechanical engineering process. GPS provides the rules for an unambiguous description and verification.

The recent attempt in GPS to change from dimensional to geometrical tolerancing leads to a stronger focus on datum systems, being also a complex part within the GPS system. The current state of scientific knowledge on this subject still shows gaps in how to derive a datum system in a function-oriented design process as well as what are standard definitions for extraction and association for the verification process. Therefore, design and measurement engineers at Technische Universität Chemnitz work together to derive requirements for datum systems based on the functional (nominal) and the verification (real) aspects understanding the importance of the datum system for the quality of the workpiece.

2. Current state of scientific knowledge

2.1. Computer Aided Tolerancing for the methodical design process

In the function-oriented design process, a datum system is the basis for the connection of the geometrical features within one workpiece and within the assembly group to fulfill the functional aspect and define the orientation and location of the tolerance zones. The uncertainty of the manufacturing process to produce the real workpiece and the uncertainty of the verification process to control its properties depends on this basis datum system.

The engineering design process is similarly defined in several publications. One process defined by Pahl and Beitz [2] introduces four main phases, i.e. clarification and planning of the task, conceptual design, embodiment design and...
detailed design. The nominal geometry of the product is the result of the last detailed designing process using standards and including standard parts. After that, in many cases drawings are derived for the manufacturing. At this point, most engineers start with the tolerancing process. In many cases assembly and manufacturing processes are the basis for the tolerance specification. Armillotti [3] e.g. introduces a method of computer-aided specification of geometric tolerances, analysing the contact relation between parts and the assembly operations. A study in several midsize companies in Germany [4] also shows that today the focus for the geometrical tolerancing is on the manufacturing aspect.

Clearly understood is the need for the definition of functional requirements in an early development stage by other researchers [5,6]. In the closed loop tolerance engineering process introduced by Schleich [7], it is described that the functional requirements are derived by e.g. the Quality Function Deployment method, followed by the translation into geometrical requirements by different other tools like e.g. function-means trees. Ballu and Dantan generate a geometric specification from the functional requirements in relation to the assembly group by assembly graphs for the assembling steps of an assembly group and a virtual gauging process [8]. With the integrated tolerancing process (ITP) Dantan et al. also show a functional decomposition of the workpiece function [9]. Software tools for the following design process (e.g. PTC®’s CreoTM Parametric) provide support for modeling and also tolerancing. Special tools like the Sigmetrix® GD&T Advisor Software based on CETOL 6σ Technology offer even further help with the GPS requirements.

With the focus on the development of a datum system, based on the functional requirements, the knowledge of the interaction of real surfaces has to be considered. Therefore it is necessary to understand how this knowledge is gained and where the gaps for the functional description are.

2.2. Verification for datum systems according to ISO 5459 in the GPS system

The current state of scientific knowledge on datums and datum systems in GPS is summarized in the ISO 5459 [10] standard. The relationship of two geometrical features of a workpiece is established by the location and/or orientation of a tolerance zone according to an ideal feature derived from one or more geometrical features of the real surface as a datum [11].

The datum system ties two or three datums together and can be understood as a coordinate system for the workpiece [12]. Three perpendicular planes lock six degrees of freedom for the workpiece in Fig. 1.

To establish an associated feature as a datum a partition, an extraction of the real surface, filtration and the association of an ideal geometrical feature, for example a plane or cylinder is necessary. These operations for specification and verification in GPS [13,14] are explained by the examples in Fig. 2.

In ISO 5459 it is not defined how to partition or extract a surface for the calculation of a datum. Extraction strategies are defined in ISO 14406 [15], but there is no general rule implemented on how to derive the number and location of the measuring points to extract the significant information of a surface. Filtration, in contrast, is according to ISO 5459 necessary, but also not defined. It is only advised to retain the highest points and remove the voids.

Association features connect the nominal geometry with the real surface by simulating a contact between the real surface and an ideal. The default associated feature stated in ISO 5459 is ideal and outside of the material. If this does not lead to a unique result, an association feature which balances the associated feature by minimizing the maximum distance (MinMax) shall be used. Other mathematical solution for the calculation of an ideal feature contacting the surface from the material free is e.g. a constraint L2 criterion for planes introduced by Shakarji [16]. L1 and other criteria are possible as well [17,18].

Based on this state of knowledge an alternative methodical design process has been developed. A research project aimed at the definition of extraction and association within the verification process and the results in the next chapter will present the still unsolved problems on this subject.

3. New functional datum system in the specification process

3.1. An alternative approach dealing with datum systems in early phases of the engineering and design process

The method, summarized in Fig. 3, starts at the stage of the geometrical definition before the model exists. Ballu et al. showed with the GASAP (geometry as soon as possible) approach a very similar methodology [19].
The method should also be applied in the design process after the functional requirements are defined as shown in [9] and physical principles are selected. Calculations based on these physical principles provide the first approximate dimensions of the future product and first standard parts can be chosen as a first step.

With the help of CAD systems, a function-face-skeleton can be built in the assembly mode in the second step. These faces are deduced out of connections between moving elements the given geometries and calculated results.

In the third step the hierarchy of the surfaces has to be derived to create an assembly group datum system that fulfills the functional requirements. Aspects, such as action of force, motion sequences or other product interactions influence this functional structure. Ballu did this in [19] with GAIA-tool developed by EADS CCR [20].

Within the modularization to subassemblies and parts in step four, the single surfaces, which are the future contacts, will be split in surface (chapter 3.2) pairs to receive one surface for each future module (part or subassembly). This is also visible in the fourth step of Fig. 3. At this point, the new datum systems for these parts are derived from the existing assembly datum system. The dimensional tolerances for the datum system are divided by influences like flux of force, size or the rank of the surface in the defined datum system.

In the next step more sub-functional surfaces are added to the geometrical definition of parts and subassemblies. Their tolerances depend on the existing system and the tolerances of the standard parts selected. At this point tolerance simulation methods can be applied to analyze statistically and generate information for an appropriate manufacturing method. Finally the design of the parts can follow this method and the tolerances can be adjusted to the function as seen in the fifth picture of Fig. 3.

3.2. Surface pairs as an origin for part datum systems

Figure 4 shows cylindrical surface pairs for gliding with the two faces and their axis. Due to the clearance fit, the inner cylinder with the smaller diameter can shift in different extreme positions.

Form deviations, like cone (below in Fig. 4) or barrel shape are superimposed (upper line in Fig. 4). Even with the deviation it is still possible that the function is ensured, depending on the force which acts on the piston but the consequences for wear and malfunction are not predictable.

The orientation of the datum feature that represents the inner or outer cylinder will be strongly influenced by the real geometry as presented in the next chapter. Form deviations can be tolerated by tolerance zones but cannot limit the variation along the cylinder outline. Further tolerancing methods should be developed to describe the interaction more detailed.

The same problem exists with planes and can be explained with the following virtual example. The primary function of a combustion engines cylinder head is to seal the combustion chamber against high pressure. The better the sealing is the higher becomes the compression. Fig. 5 shows the pairing of the cylinder head made of an aluminum alloy and the cylinder made of steel. The red marked faces are the sealing surfaces.

The sealing surface is defined with flatness as the primary datum. The secondary datum is the cylinder face, which is responsible for the position of the head. Both are shown in Fig. 5. Nevertheless, the datum axis and planes are not perfect pairs of straight lines and plane faces. It is assumed that the cylinders plane surface is the ideal datum feature. Fig. 6 shows possible realistic geometries paired with the ideal cylinder face. The question is how each of these cases influences the function. The bolting of the head for the first convex geometry should take care of the heads deformation to the plane geometry. It is possible to calculate how much of the pulling force of the bolting is needed for the elastic
deformation and how much is needed to seal the combustion chamber for a local plastic deformation of the aluminum alloy.

Therefore, a specimen with combined deviations was created to trace the impact on the different approaches. Fig. 8 presents the specimen and the CAD model with the planes and cylinders labeled as well as the deviations applied. Based on this specimen extraction, filtration and association strategies have been studied.

This paper will only cover results for a convex plane with superimposed waviness and roughness. In the research project also other surfaces were analyzed and evaluated with an uncertainty concept [24], not explained in this paper.

4. Closing the gaps in ISO 5459 for the verification process

This chapter presents results of a joint research project (3D-BBS) of the Technische Universität Chemnitz, the Physikalisch Technische Bundesanstalt (PTB) und the Carl Zeiss IMT GmbH finished in 2014 on the verification strategies for datums and datum systems with tactile Coordinate Measuring Machines [22,23,18].

Finding a workpiece with predefined and known form, roughness and orientation deviations is almost impossible.

4.1. Extraction strategies for plane datum features

The holistic extraction of the convex plane B (Fig. 9) of the specimen is the basis for the comparison of different strategies to analyze the influence of the number of measuring points without missing the important points for the calculation of the associated feature compared to the time necessary for the extraction. The selection of the strategies follows the classification by Petro [24].

Extraction strategy I represents the current standard in the industry. Single points, usually a small amount, are distributed equally on the surface. For strategy II an orthogonal grid has been used which is also equally distributed over the surface.

Polylines are the basis for the third strategy to gather surface points also widely and equally distributed over the surface. With the focus on the highest points an iteration process by extracting further polylines within a region of interest was applied. The results of the strategy III (second iteration) performed on plane B are presented in Fig. 10.
In comparison to the holistic extraction, we calculated the deviation of the flatness. In Fig. 11, these deviations for the different strategies are summarized and compared with the time necessary to extract. The time depends on defined dynamics and characteristic properties of the machine used. It proves the expected results, that an additional iteration step decreases the deviation. Convex surfaces are especially sensitive and more iteration steps can help to prove the convex form.

It is a well-known fact that the previous knowledge of the production process leads generally to an extraction strategy with less measuring points than applying a grid or polylines.

4.2. Filtering

The studies on filtration in the context of datums and datum systems within the 3D-BBS research project indicate that it is not clear why the ISO standard includes this operation. Common linear profile filtering methods (Gauß, Spline) manipulate the surface in a way that the highest points of the surface change. Orientation and location of the associated feature will therefore also change compared to the unfiltered surface. This leads to an orientation shift in a datum system.

With a focus on the highest points for associated features from the material free side, other filtering methods like morphological filters according to ISO 16610-40 [25] have also been discussed, but the necessity of applying is not comprehensible. A further point of criticism is that the application of a filter requires a minimum number of points. Due to the usually small number of measuring points extracted this is useless.

Outlier filtering on the other side is necessary if the associated feature contacts the surface from outside the material. In industrial applications the outliers are deleted either manually or by statistical methods [26]. Reliable outlier reduction should be implemented in the software to be used for datums as introduced by Probst [27]. As a conclusion, filtration should not be included in the verification process except for the elimination of outliers.

4.3. Association

The application of different association features as a datum [18], results in the shift of the orientation and location of the origin of the datum system (Fig. 12).

The MinMax association is more stable when gathering more points within the iteration steps of the third strategy as the range in Fig. 13 shows.

As one main result of the 3D-BBS research project it becomes clear, that the definition of the associated feature is not possible without the consideration of other aspects like the functional purpose of the workpiece. As an overall conclusion of the 3D-BBS project it becomes clear that further research is necessary to establish a unique and application-oriented verification method for datum systems.

5. Conclusion

5.1. Resulting

The functional aspect of datum systems and the derivation of requirements have been the focus in this paper. It has shown that today the functional interaction of datum features are not fully considered for the derivation of the associated features.
The functional requirements of surface pairs, such as press fit, transition fit, clearance fit, screw connection or sealing have to be considered for the selection of the associated feature (Fig. 14). Primary, secondary and tertiary datums may therefore require different associated features.

The function of the combustion engine example might lead to a combination of all in Fig. 14 presented associated features. This cannot be derived without further research.

5.2. Summary

The datum system is the basis for the description of the deviations of geometrical features within the workpiece and should also be the basis for the connection of workpieces within the assembly group. The paper introduced an alternative methodology for the early tolerancing process that follows this approach for the development of a function-oriented datum system. The second part of the paper introduced results from a research project on the extraction and calculation of datum features to overcome the gaps in the ISO GPS-System on this topic. The methodology for the tolerancing and the verification process are connected at the level of surface pairs which generate the function at the workpiece level. The conclusion is that the functional requirements of surface pairs like press fit, transition fit, clearance fit, screw connection or sealing should be the basis for the algorithms of the associated features within the verification process.

5.3. Outlook

The function-oriented tolerancing method has to be developed further to provide rules for e.g. the identification of primary, secondary or tertiary datums. Research is also necessary to find algorithm and geometrical description that represent the functional interaction of surface pairs. It has to analyze if existing approaches can be used. Manufacturing datum systems and datum systems considering the assembly of workpieces in the assembly group have to be harmonized with the functional datum system to provide an unbroken chain also in the verification process.

Acknowledgements

The research project 3D-BBS was supported by the Federal Ministry for Economic Affairs and Energy (BMWi) on the basis of a resolution passed by the German Bundestag. We thank our project partners at Carl Zeiss IMT and PTB for contributing to the presented research results.

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