Gear Standards and ISO GPS

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In today's globalized manufacturing, all industrial products having dimensional constraints must undergo conformity specifications assessments on a regular basis. Consequently, (standardization) associated with GD&T (geometrical dimensioning and tolerancing) should be un-ambiguous and based on common, accepted rules. Of course gears — and their mechanical assemblies — are special items, widely present in industrial applications where energy conversion and power transmission are involved.

The ISO (International Standards Organization) GPS (geometrical product specifications) standard is a new approach to providing the basic tools and developing a common language supported by mathematical formalisms for acceptance in:

- Design geometrical definitions
- Specification limits for (tolerancing) classification
- Inspection methods
- Conformity assessment rules for acceptance

Upon general consensus between experts, the following basic, GPS-related documents should be considered in the future development and revision of gear standards:

- ISO/TR 14638
- ISO/TS 17450–1
- ISO/TS 17450–2
- ISO/14253–1
- ISO/TS 14253–2

The need for a GPS standard became apparent near the end of 1992, about the same time that the newest-generation tools were becoming available in the field of industrial products design. The development chain was going to be increasingly based on "virtual development" — right up to the physical realization of the single parts constituting the final product.

In this chain are involved:

- Basic design idea
- CAD implementation of drawings
- CAM programming for machine tools, robots, etc.
- CNC machining

At this stage, *everything* is "virtual" (i.e., numbers, codes) until the "physical" part is realized. There is then need of an interface able to compare the "real part" with the "virtual data," — thus capturing feedback for eventual modifications, corrections and final acceptance.

This "interface" is the aforementioned, modern measuring tool-set, possessing a certain degree of "intelligence"; e.g., computerized, electronic metrology devices (GMMs, CMMs, etc.).

Soon upon (the new devices') implementation came the realization that the traditional design specification methods (ISO1101, et al.) were no longer sufficient, and now operative only for the old-metrology tools like dial comparators, gauges, etc.

And so 1968 presented major problems for (manufacturers) like myself and others who were involved in the design and manufacturing of those new measuring tools (CMMs, GMMs); i.e., where the dimensional characteristics of measured parts are derived by reversing the mathematics of analytical geometry (from points to mathematical synthesis of geometrical features), and not comparing an artificial feature (artifact, reference frame, etc.) with a real one, as done in traditional metrology.

But despite some uncertainty over new processes of product development, (I found that) the uncertainty will diminish if:

Figure 1 Gears are special items — widely present in industrial applications where energy conversion and power transmission are involved.

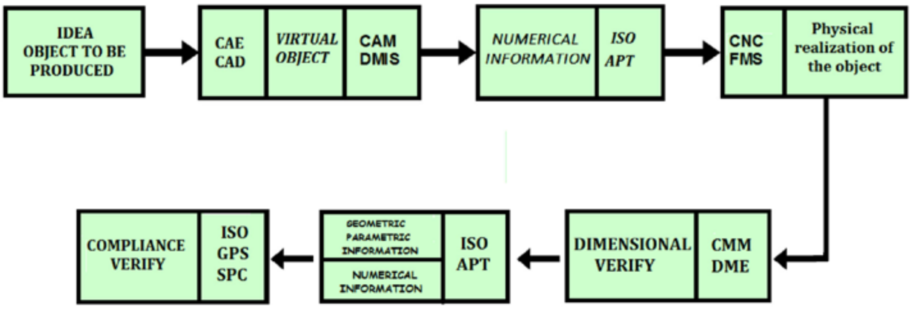

Figure 2 With ISO GPS, the manufacturing process is based increasingly upon "virtual development" — right up to the physical realization of the single parts constituting the final product.

Figure 3a and 3b (GMM 70) **This "interface" is the aforementioned, modern measuring tool-set, possessing a certain degree of "intelligence"; e.g., computerized, electronic metrology devices (GMMs, CMMs, etc.).**

The GD&T (geometric dimensioning and tolerancing) specifications implemented in the CAD drawings have the best "correlation" with the final functionality of the product, or "low correlation uncertainty."

- The GD&T specifications are self-consistent with an intrinsic low "specification uncertainty."
- The adopted verification method is at least "compliant" with the specifications in the drawing, or "compliance uncertainty."
- The conformity assessment for acceptance is based on "traceable" measurements.
- Following are some tecnical reports and technical standards containing conceptions of GPS systems:

ISO/TR 14638. This technical report contains the "master plan" of the hierarchy in which the GPS standards are organized, consisting of the fundamental, global, general and complementary standards containing the basic principles and general tenets.

ISO/TS 17450–1. This technical specification, which is part of global GPS documents, contains the model for geometrical specification used in the design of assemblies and individual parts that will deal with compliant measurement procedures.

These tools are based on the characteristics of features, on the constraints between features, and on operations used for the creation of different geometrical features. The aim is to define the fundamental concepts for the geometrical specification of a part (workpiece), and provide a mathematization of those concepts in order to have common, standardized rules for CAD users, developers of metrology algorithms, and conformity verification methods.

Some observations and perspective are necessary in order to better understand the philosophy of this ISO/TS. With the advent of new design tools like CAD, CAM, CNC and coordinate metrology, there was the need to change a way of thinking. The parts designed in a drawing represent an assembly of ideal geometric features, and the GD&T is related to the geometric parameters that define those features. So in the drawing we have dimensions and tolerances relative to ideal-perfect, geometrical elements.

The machined parts derived from the same drawing are imperfect, with errors relative to size, form, deviation and position. Here we have the problem of how to get a set of parameters for each feature present on the workpiece that might be comparable to the "ideal" ones on the drawing.

Utilizing coordinate metrology, the problem was solved with the introduction of a new "substitute geometrical feature." This is another perfect ideal feature "extracted" from the workpiece by means of the measuring procedure (probing or scanning points on the part). The parameters of this "substitute feature" can be compared with those represented in the drawing, and hence be able to reveal errors of size, deviation and position; but not form errors — they are not contained in the "substitute feature."

This approach is possible only in the case of what I call "metrology in predefined geometry," as the mathematical formalization of the measured part must be known "a priori" and constitutes a "target feature" for the "best-fit" mathematical algorithm that will produce the aforesaid substitute geometrical feature.

From this situation derives one of the most important principles of GPS — the "independency principle" — or ISO/8015 ISO/14659.

For this principle, any tolerance specification reported in a drawing must be independent of all other specifications. So if the substitute feature is introduced, eventual form errors must not influence the size, deviation or position errors. In my experience I have seen this principle violated very frequently in many blueprint specifications; e.g.: size tolerance specifications smaller than the admitted — or practically achievable — form errors. All of the concepts and definitions reported in this document are operative in the practice of the design and tolerancing specifications of gears.

The designer first defines a part of perfect ideal form with shape and dimensions, and with tolerance specifications that best fit the functionality of the final product. Let's call this defined part the "nominal model."

It is evident that the final realization of this part may not fit completely the ideal requirements of funcionality. This will be, in the end, an economic factor pertaining to the realization of the product. This economic factor is the "correlation uncertainty" in the GPS system. It is only the first step in the complete process of conformance assessment for the acceptance of the product in terms of economic finalization, evaluation of risk in case of acceptance or rejection, quality assurance and, not the least, security conformance.

In this document (ISO/TS 17450–1) all the definitions related to geometrical features and their geometrical characteristics are reported. It must be said that the majority of those definitions are pertaining more to specification and verification of pre-defined, geometrical features like line plane, cylinder, etc., and leave it to the tools to compare the real with the ideal geometrical characteristics, thus avoiding the form errors.

But this may not be the case of a gear's characteristics where the form error is relevant and best-fit algorithms for gear surfaces, where "transcendent" mathematical geometries are involved, are at present in an early stage of develpment, and, sometimes, cannot be applied.

The GPS may well need in the near future a contribution from the "gear people" with an international project tasked to the "fusion" of the two cultures. Some terms and definitions of this TS are particularly useful for the future work, like:

- ***Feature.*** Geometric feature: point, line, surface (involute, helix, worm and bevel in our case)
- ***Ideal feature.*** Feature defined by a parametrized equation
- ***Characteristic.*** Single property of one or more features expressed in linear or angular
- ***Specification.*** Expression of permissible limits on a characteristic
- ***Deviation.*** Difference between the value of a characteristic obtained from the non-ideal surface model (skin) and the corresponding nominal value
- ***Extraction.*** Operation used to identify specific points from a non-ideal surface
- ***Filtration.*** Operation used to create the non-ideal feature by reducing the level of information of an extracted non-ideal feature
- ***Association.*** Operation used to fit ideal features to non-ideal features according to a criterion (metrologic operator)
- ***Associated feature.*** Ideal feature established from a non-ideal surface model (skin model), or from a real surface through an association operation

A practical consequence of these definitions is the "conformity assessment" procedure, normally adopted for a machined part, that follows five steps:

1. Partition
2. Extraction
3. Filtration
4. Association
5. Evaluation

We think that there are more definitions that may occur in the future development or revision of gear standards.

ISO/TS 17450–2. This TS is another global GPS document and contains the basic issues for the development of the overall system that is based on the four tenets listed as A,B,C and D.

A. Simply states that GPS specifications on a drawing and functionality of the final product derived from those specifications are correlated at a certain degree (correlation uncertainty).

B. If a product is realized using a product documentation (blueprint) where GPS geometrical characteristics are reported, this product is acceptable if GPS specifications are fulfilled and measures are compliant, at a certain degree, to the same specifications (compliance uncertainty). The GPS specification itself may be "incomplete" (leading to bad functionality or difficult assembling), so an eventual specification uncertainty has to be accounted for regarding acceptance or rejection purposes.

C. Here the document points out that the process of realization of the product is independent from the GPS specification, and the GPS specification does not deal with the choice of the verification operator (measurement method). The lowest specification and measuring uncertainties obtainable dictate the best choice: ISO/TR 14253–2 PUMA method.

D. Here the document states that the implementation of the best selected verification process always leads to imperfections, and the implementation uncertainty has to be accounted for (compliance uncertainty).

(*Author's Note*: *In offering justification for this way of thinking in the GPS environment,a philosophical approach contends that in the community of metrologists recently, two schools of thinking have evolved, similar to what happened at the beginning of the last century for the communities of logicians and mathematicians.* Of *the two schools, one accepted the postulate of "completeness" posed from* ***Hilbert****, the other one, by contrast, belived in the Godel theorem of "incompleteness."*)

Thus on one side we have metrologists that believe that specifications on the blueprint are self-evident, and if those specifications are completely fullfilled there are no problems (principle of completeness). On the other side there are metrologists (GPS) that think this is not the case and specifications are incomplete (principle of incompleteness).

The problem is that for every specification there must be a verification — with a preventive measurement at the final stage of assembly or at the stage of functionality proof.

So it can be stated that a specification is complete only if all the intended functions are perfectly described and controlled with the specified characteristics. Unfortunately, most of the specifications will be incomplete because some funcions are imperfectly described and controlled — and sometimes not at all. The consequence is that there may be a more or less good — or bad — connection, between the function and the relative specification. Correlation uncertainty refers to the case of imperfect control, while specification uncertainty implies absence of control. Consequently, we can say that a measurement with low uncertainty is of little value when correlation or specification uncertainty is large. For metrologists the GPS is a good thing, as finally the responsibility of designers will be strongly accounted for in the production process.

The specfication process is step one, and is the responsibility of the designer.

The verification process follows the specification and is done by implementing the actual specification operator in an actual verification operation.

Some definitions:

Operator-ordered set of operations :

- ***Specification operations***. Operation formulated using only mathematical and/or geometrical expressions and/or algorithms
- ***Specification operator***. Made up of specifications operations
- ***Verification operator.*** Operator made up of verification operations (derived from specification operator)

ISO/14253-1. This standard is now well known by experts, and will soon gain in global importance and acceptance in the industrial environment, as the rules for the conformity assessment become clearly defined.

The role of uncertainty as an economic factor is evident, and the decision rules for who is going to pay are clear. The uncertainty contributions are introduced at different levels of the conformity assessment, going from the final level of the measurement uncertainty up to the level of the correlation uncertainty finalized to the functionality proof, passing through the specification uncertainty.

ISO/TS 14253–2. This technical specification provides a general rule of how to find the best specification and verification operators, known as the "PUMA" method.

Conclusion

In the future development and revision of existing standards dealing with technical specifications for gears, it should be mandatory to consider that any specification tool must be uniquivically associated to a corresponding verification operator.

Unfortunately, it seems that, given a particular specification, there is not much freedom for implementing a verification procedure that must be, at best, compliant witrh this specification, if relevant economic fallouts are to be avoided in a global production environment.

It is also suggested to take in account the following normative tools:

- The "VIM" for basic terminology. (*Editor's Note: This document gives guidance on the concepts and terms used in various approaches to measurement*).
- The GPS principles for specifications and verification items
- The "GUM" for measurement uncertainty evaluation . (*A series of documents establishing general rules for evaluating and expressing uncertainty in measurement that can be followed at various levels of accuracy and in many fields — from the shop floor to fundamental research for measurement uncertainty evaluation*).
- The ISO/14253–1 for conformity acceptance, activities.

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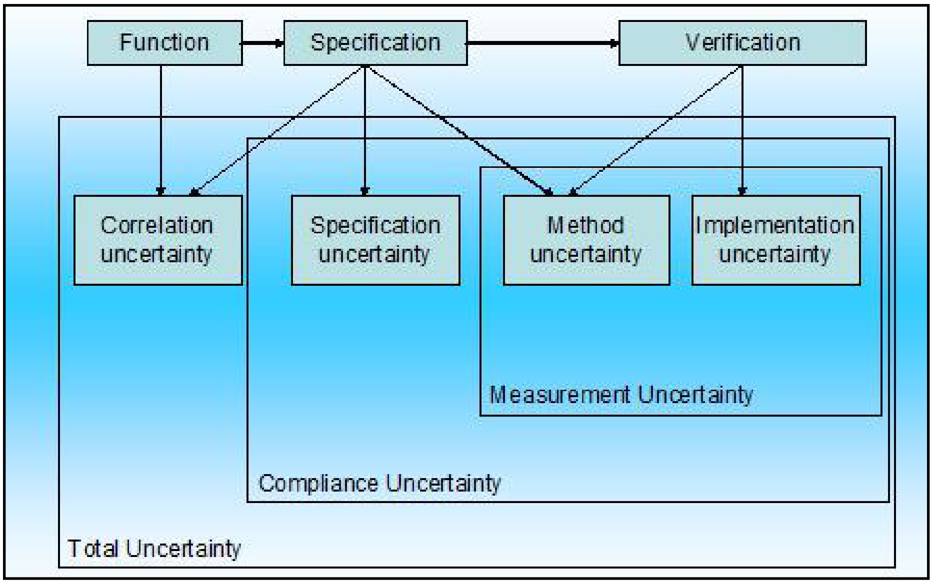

Figure 4 **The verification operator is the basis for the conformity assessment procedure.**

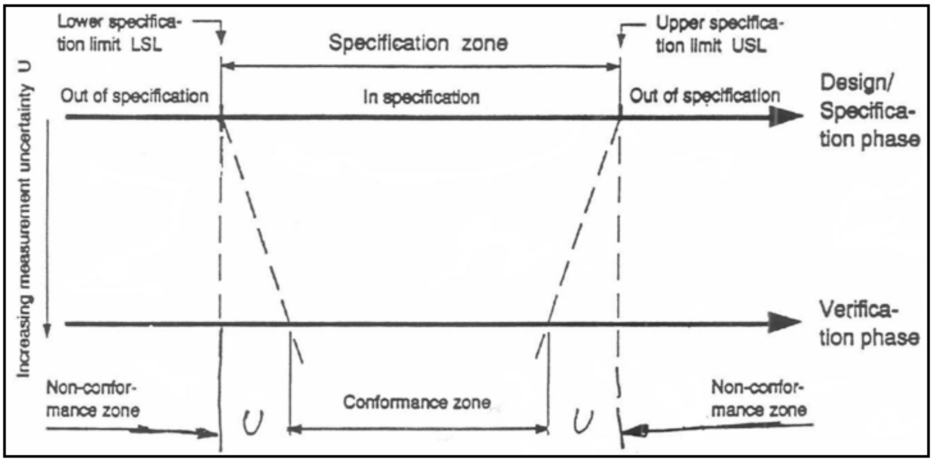

Figure 5 **Uncertainty—cost unknowns—present at different levels throughout conformity assessment—from measurement uncertainty to correlation uncertainty, and finalized at functionality proof level.**

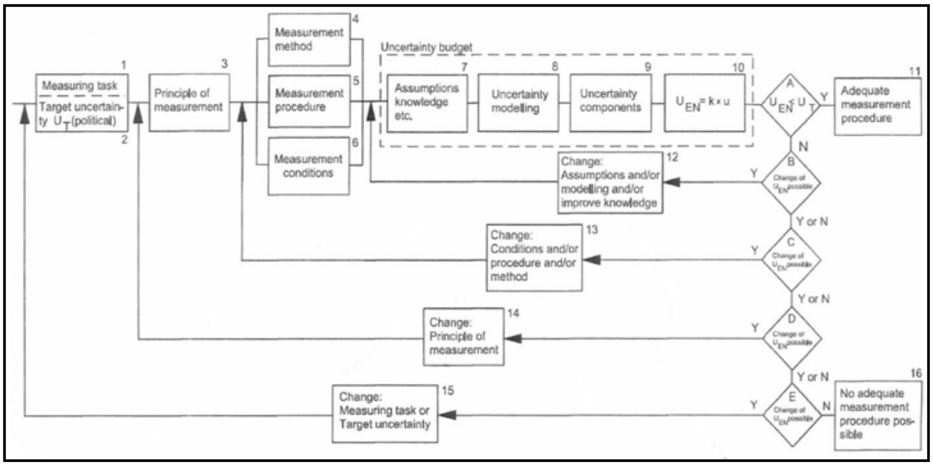

Figure 6 **ISO/TS 14253–2's general rule—the "PUMA" method—shows how to find the best specification and verification operators.**