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Integration of thermal effects into Tolerancing using Skin Model Shapes

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Abstract

The integration of more physical properties into the Skin model is fundamental for extending the tolerancing process to the different phases of the product lifecycle. This paper presents a study of the deformation effects on the Skin model provoked by the thermal and working environment of the workpiece. The proposed methodology departs from the Skin model at room temperature, and generates Skin Model Shapes by performing a Finite Element Analysis (FEA). The simulation tool has been successfully tested in the study of a practical industrial application, a gas turbine blade, which combines many of the nowadays challenges of CAD, FEA and CAT.

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1. Introduction

To date, the efficient consideration of real product geometric variations remains an open problem and new paradigms for geometric product modeling that replace the actual CAD models need to be developed [1]. The nominal model is a geometrical model with perfect boundary surface. However, a real workpiece differs from this ideal model due to the inevitable geometrical deviations caused by manufacturing imprecision and verification uncertainty [2]. These geometric deviations have a great influence on the functional behavior of the final products. Moreover, the quality, cost and competitiveness of the products rely on a proper tolerance specification and management [3]. Consequently, modeling the non-ideal geometry is an important subject for enhancing the tolerancing process.

Among the several research directions towards improving Computer Aided Tolerancing (CAT), the skin model, which also comprises the geometrical deviations, appears as a powerful alternative to the nominal model. The skin model has the potential for a wide range of applications. For instance, the skin model can be used for analyzing and visualizing 3D shape deviations for both measured and simulated parts, for computing the deviations accumulations for assemblies and multi-station manufacturing processes, and for Geometrical Product Specifications (GPS) and virtual metrology applications. Nevertheless, in the foreseeable future the aim is to integrate more physical properties in the simulation of the geometric deviations, hence making the skin model more complete [1]. The efficient representation and simulation of the skin model considering the main physical properties may enable a better modelization of the non-ideal geometries for Computer Aided Tolerancing (CAT) and product development.

This paper aims to integrate the shape changes that occur due to thermal effects into the skin model concept. In many applications the workpieces operate in a different temperature range to that in which they were verified and thus, the final shape differs from the measured one. Moreover, when the temperature increases around 50ºC, the expansion of the workpiece and the tolerances are of the same order of magnitude [4]. Thereby, it is necessary to simulate how the thermal loads affect the skin model evolution from standard temperature for GPS (20ºC) to operational temperature [4]-[5]. As simulation tools advance, with the benefit of increasing performance and reducing production time and cost, the integration of thermal deformations with manufacturing imprecision appears as a fundamental next step not only for

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GPS but also for realistic Finite Element Analysis (FEA) simulation. Indeed, other authors such as Loring S. et al. [6]-[7] highlighted this importance proposing a methodology for combining CAT simulations with thermal or stress simulations under the conditions of use based on the method of influence coefficients (MIC).

The terms standard and operational skin model are proposed in the second section of this work with the purpose of easily distinguishing between the skin model that only accounts for the manufacturing imprecision, and the skin model that also reproduces the shape changes due the functioning of the workpiece after it has been produced. Then, the third section describes the approach followed to integrate the thermo-mechanical deformations with Skin Model Shapes (SMS). Finally, the study of a practical industrial application, a gas turbine blade is presented and the main conclusions of the work are drawn.

2. Standard and Operational Skin Models

The skin model or non-ideal surface model has been defined in ISO 17450-1 as a “model of the physical interface of the workpiece with its environment” [8]. Moreover, the skin model has infinite describability and thus, its concept is purely theoretical. In addition, as the workpiece is made of material, its physical interface may vary as the environmental conditions evolve. Therefore, skin model is dynamic since the model of the physical interface depends on external conditions in which the skin model is considered. In this way, the “standard skin model” concept is proposed to refer to the skin model captured in compliance with ISO standards in the field of GPS [8]-[9]. Conversely, the “operational skin model” concept accounts for the skin model under working environment conditions that may differ from the ones defined by the ISO standard for GPS. Thus, the concept of “operational skin model” is as an extension of “standard skin model” because it adds to the geometrical variations from manufacturing the shape changes that occur under the operational circumstances of the workpiece (e.g. structural loads, thermal expansion, wear, etc.). Note that these operational circumstances are highly interesting for product development. Indeed, the operational skin model can be implemented for process capability evaluation, assembly analysis, tolerance activities and product simulation. For instance, the product simulation comprises activities such as FEA simulation or Computational Fluid Dynamics (CFD). In these simulations the consideration of the operational skin model, which comprises the non-ideal shapes generated from the standard skin model, would enable the generation of more accurate models of the final product as well as increase the predictability of their final performance and functional capabilities. In regard to tolerance activities, the operational skin model is useful to analyze key characteristics and functional tolerances of the part or assemblies. Precisely, it allows to consider the effect of the working environment on the real workpiece so that tolerances may be optimized.

Although skin model is aimed to have infinite describability, finite models have been proposed to represent particular skin models in a computer system [3]. In these Skin Model Shapes (SMS) the geometrical deviations of a real surface with respect to the nominal model are decomposed into systematic and random deviations [1], which are modeled through experimental and mathematical analysis. On the one side, the systematic deviations repeat in every workpiece, and depend mainly on the manufacturing and verification processes, which are assumed to be the same for every part. As suggested by Zhang M., Anwer N. et al. [10], in this research the systematic deviations are reproduced by means of second order shapes. Indeed, second order shapes proved to replicate the anisotropy and principle curvature of complex shapes better than first order or higher order deviations [11]. On the other side, the random deviations are generated by fluctuating sources that may vary in time and space such as environment conditions, and tool wear, inter-alia. In general, as random deviations have an intrinsically aleatory nature, they are more difficult to detect, isolate and correct than systematic errors. For this reason, random deviations are modeled using statistical methods. In this work, the Theory of Random Fields is implemented to generate random deviations of non-ideal shapes following the work of Schleich B. et al.[3], [12]-[13]. Precisely, this approach allows to model the influence on the shape from the nodes close to each other.

Once the systematic and random deviations have been computed and added to the nominal shape model, it is necessary to verify form, orientation and location tolerance specifications [11]. To do so, each tolerance specified in the nominal CAD model has to be checked. As this verification process is carried out in compliance with the ISO standards for GPS [9], the generated SMS corresponds to the standard SMS.

3. Integration of Thermo-mechanical Deformations into the Skin Model

3.1. Finite Element Analysis

The temperature-displacement problem, also known as coupled thermal-stress analysis can be solved either sequentially or simultaneously (coupled) depending on the characteristics of the case to be analyzed. For the particular case of this work, the conditions of the problem require solving the temperature-displacement analysis in a coupled way. The mechanical properties of the material used depend on the temperature and hence there is a strong interaction between temperatures and displacements. The coupled temperature-displacement simulation is a nonlinear problem in which the displacements and temperatures are solved simultaneously. Thereby, the reciprocal action of the displacements on the temperature and vice-versa is taken into account [14].

The temperatures are integrated using a backward-difference scheme and the nonlinear coupled system is solved by means of Newton’s method. The exact implementation of Newton’s method involves a non-symmetric Jacobian matrix. The coupled equations of the corresponding system are represented by:

$$\begin{bmatrix} K_{uu} & K_{u\theta} \\ K_{\theta u} & K_{\theta\theta} \end{bmatrix} \begin{Bmatrix} \Delta u \\ \Delta \theta \end{Bmatrix} = \begin{Bmatrix} R_u \\ R_\theta \end{Bmatrix} \quad (1)$$