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14th CIRP Conference on Computer Aided Tolerancing (CAT)

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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Keywords: Skin model; Thermal effects; Geometrical deviations; FEA simulation; Geometrical Product Specifications (GPS)

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 50°C, 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 (20°C) 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

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:

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

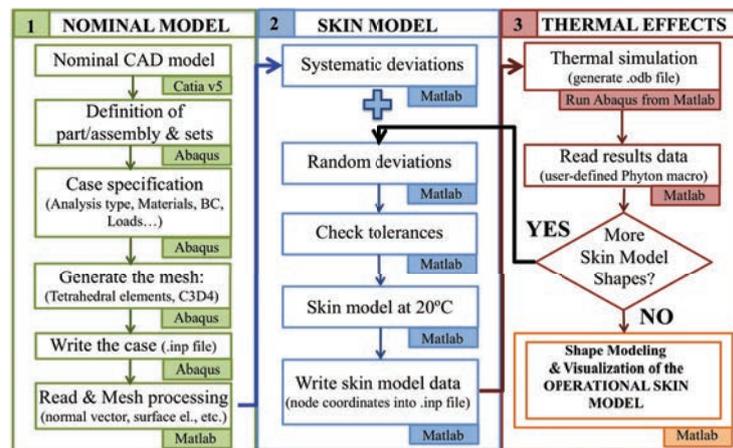


Fig. 1. Process flow to generate the Skin Model Shapes (SMS) considering thermal FEA simulation.

where Δu and $\Delta \theta$ stand for the corrections to the incremental displacement and temperature, K_{ij} represent the submatrices of the fully coupled Jacobian matrix, and R_u and R_θ are the mechanical and thermal residual vectors, respectively. The coupled solution to this system of equations requires using un-symmetric matrix storage and solution scheme. If the solution estimate lies within the radius of convergence of the algorithm, the method provides quadratic convergence. The numerical schemes and modeling implemented are adapted for Abaqus CAE /Standard [15].

3.2. Modeling and Simulation Framework

The framework proposed to model and generate Skin Model Shapes of the operational skin model is shown in Fig. 1. Since the operational skin model comprises the standard skin model, it is first required to generate the standard skin model. The process consists of three main steps that are identified as 1, 2 and 3 in Fig. 1: definition and pre-processing of the nominal CAD model, the generation of standard Skin Model Shapes and the consideration of the thermal effects resulting in Skin Model Shapes.

Nominal model. The nominal CAD model based on ideal shapes is designed and imported to the FEA simulation platform. In the user interface environment of this platform, the different surfaces that form the part or/and the assembly are identified, which mimics the “Partition” operation of GeoSpelling [3]. Afterwards, the material properties are defined, which in case of a thermo-mechanical simulation comprise at least the density, Young modulus, Poisson’s ratio, thermal conductivity, specific heat capacity and coefficient of thermal expansion. In addition, before generating the solid mesh, it is required to define the Boundary Conditions (BCs) and the loads that affect the studied workpiece. Note that the application of BCs consists of defining the constraints that limit the displacement and the temperature of some features. Moreover, user-defined functions, material models or load models can be added. Then, based on the expertise of the engineer, the solid mesh is generated assigning for that

tetrahedral elements. For the coupled thermo-mechanical problem, the C3D4T [15] element type is selected. Furthermore, during the generation of the mesh it is necessary to consider carefully the size of the elements generated. Indeed, the mesh element cannot be very small (i.e. “extremely fine mesh”) because the addition of the standard skin model will distort the mesh. If the distortion is large, convergence problems may appear.

Skin Model. The defined case is used as the input for the platform where the standard skin model shape is generated. The solid mesh is processed so that a mesh of the surface is extracted through a self-developed algorithm. The standard skin model shape is computed considering for that the temperature for GPS (i.e. 20°C) and the surface mesh. Once the SMS is successfully created, the surface mesh is combined with the solid tetrahedral mesh and the input for the FEA solver is created.

Thermal Effects. The FEA software solves the thermo-coupled displacement problem commanded by the platform used to implement the code. As the deviations added by the computation of the standard skin model to the regular mesh are small, in general the convergence of the solution is assured. Once the results have been generated, a customized macro is used to communicate between both platforms and gather the desired data. These FEA results are post-processed and a Skin Model Shape is generated. In case more SMS are desired, the process starts again from the generation of a new Skin Model Shape at room temperature. Once enough SMS are computed, the post-processing of the results is carried out.

3.3. Shape Modeling, Analysis and Visualization

The main objective of the Statistical Shape Modeling (SSM) is to estimate the mean skin model and generate additional SMS using the data gathered from the skin model training sets. To do so, based on statistical analysis, common characteristics of a training set are extracted and a statistical model for the shapes is determined. The landmarks in a training set enables to capture the mean geometrical

characters of the operational shape. Point Distribution Model has been used in this work [11]. Moreover, probability distributions of the verified tolerances of the standard skin model as well as some functional tolerances or key characteristics constrained by the assembly to which belongs the operational skin model can be computed.

In regard to the visualization of the operational skin model, two different visualization techniques have been proposed: based on the magnitude of the calculated nodal displacement and direct plotting of the deformed shape (see Fig. 4). In the former case, the methodology applied is similar to the visualization of the standard skin model based on vertex normal direction [11]. The triangular nominal mesh of the nominal CAD model is used as a reference frame where the distribution of the deviations (i.e. magnitude of the nodal displacements) is plotted. Note that the deformations calculated using the FEA do not occur in the normal direction and hence, the magnitude is used to compare against the deviations provided by the standard skin model.

In case of the direct visualization of the deformed shape, it consists of depicting the triangular surface mesh obtained from the final x , y and z coordinate values of the all the nodes after performing the FEA simulation. However, in order to perceive the shape changes with the human eye, the use of a scale factor may be required.

4. Case Study

The case study of this work consists of simulating and analyzing the standard and operational skin models of a high-pressure unshrouded gas turbine blade. The geometry and the working conditions of the case have been defined considering the actual parameters of typical state of the art turbine blades of aircraft engines. In state of the art jet engines, the turbine inlet temperature can reach 1700°C, the gas flow velocity may exceed 750 m/s in some parts of the turbine and the rotational speed can be faster than 10,000 rpm (blade tips speed over 450 m/s). Therefore, the turbine blades operate under a very aggressive environment in which the temperature is extremely high and the structural loads are very demanding. Altogether, this practical industrial application is an interesting case as it encompasses many of the challenges of CAD, FEA and CAT. Additionally, for the sake of reducing the great complexity of a real case, the geometry and the operational environment of the gas turbine blade have been simplified.

4.1. Definition

The simplified CAD geometry of the unshrouded turbine blade aims to capture the most important features of a real turbine blade while using a reasonable number of surfaces. Each surface is modeled through its own skin model following the approach proposed in previous work [11]. To ease the tolerance checking, all the surfaces of the model are flat surfaces. The x -axis goes in the direction of the gas flow, the y -axis in the tangential direction of the rotation of the turbine and the z -axis in the radial direction of the rotation (up-pointing so as z -axis points in the same direction of the centrifugal load). The turbine blade base has a length of 70

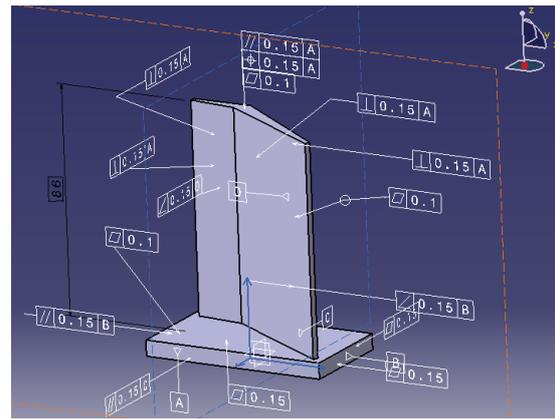


Fig. 2. 3D tolerance specification of the gas turbine blade.

mm (x -axis), a width of 38 mm (y -axis) and a height of 6 mm (z -axis). The blade airfoil has a chord of 70 mm, a height of 80 mm and a constant stagger angle of 25°.

A simplified tolerance specification of the turbine blade is implemented following the multi-scale approach proposed by Petitcuenot M. et al. [16] (see Fig. 2). In this study, the connection specification step has been neglected as no connections of complex surfaces are considered. Furthermore, in the general specification, the main focus is given to the general tolerancing with respect to datum A, which is assumed to be the collection plane. For the sake of simplicity, the base-frame of a typical turbine blade has been suppressed and thus, the definition of the main datum in the general tolerancing is not required. The leading and trailing edge functional tolerancing for the blade airfoil has also been neglected because they have been simplified to a plane feature losing all their original functionality. The top surface tolerance is used for computing the tip clearance (gap between the engine case and the blade tip), which has been set at 2 mm for the engine in static conditions and at room temperature.

The simplified operational environment aims to capture the most important conditions of the actual working regime of gas turbine blades of aircraft engines. The turbine blade studied corresponds to the first stage of an unshrouded high-pressure turbine with an outer diameter (tip diameter) of 0.8 m at 20 °C of temperature. The rotational speed has been set at 10,000 rpm, which is a value within the normal range of operation of state of the art aircraft engines. In regard to the thermal environment, references [17] - [18] are used in order to define the thermal loads that result in the approximate temperature distribution provoked by the hot gas flow around the turbine blade. The hot gas flow pressure forces are not considered, and the only structural load is the centrifugal force. The superalloy Inconel 718 has been chosen as the material of the turbine blade [19]. In order to assure the accuracy of the results, several mesh densities were tried for a single standard SMS and the corresponding thermal deformations were computed. The mesh that had the lowest density and stabilized the thermal deformation results was used as reference to generate the rest of the SMS.

4.2. Results and Analysis

The standard skin model of the turbine blade models the situation in which the gas turbine is static and without structural loads, and the environment temperature is 20°C. In contrast, the operational skin model of the turbine blade represents the situation in which the gas turbine is running (spinning at 10,000 rpm) and the environment temperature is very high. Indeed, the combustion gases are so hot that some points of the turbine blade reach temperatures over 1100 K. The comparison of the deviations of the operational skin model, with that of the standard skin model, reveals that the turbine blade shape deviates significantly from static conditions to working conditions. The shape deformation due to the operational environment is clearly displayed in Fig. 4, where the deviations are exaggerated by a factor of 10. Indeed, the combination of the high temperature environment with the centrifugal load provokes the expansion, bending and twisting of the turbine blade. The maximum displacements are oriented in the radial direction because of the centrifugal load (z-axis). The coupled temperature-displacement problem is nonlinear, and hence, the deformation of the blade is more complex than a simple thermal expansion.

The temperature distribution of the turbine blade is presented in Fig. 3 (left) and it shows that the hottest parts reach around 1100K, which is a value within the operational range of state of the art jet engines turbines. In the stress level, the Von Mises stress distribution of Fig. 3 (right) shows that the turbine is operating in the safe side since the yield stress is 758 MPa at 1033K.

The blade tip clearance is one of the most important functional tolerances of gas turbine engines because of the important role it plays in the turbine efficiency. Indeed, the tip clearance is desired to be as small as possible in order to reduce the inevitable flow leakage that occurs in unshrouded turbine blades. As it is shown in Fig. 6, the blade tip clearance of the operational skin model is around 0.5 mm, which represents approximately a 0.6% of the blade height (80 mm). Indeed, this value is close to the real cases found in state of the art aircraft engines, and provides a good turbine efficiency according to De Maesschalck et al. [20]. The comparison of the probability distribution of the blade tip clearance of the standard SMS (room temperature and engine stopped) with the operational skin model (high temperature environment with the engine running), reflects how much the turbine blade shape evolves from static to working regime.

The approximate difference between the tip clearance of the operational and the standard skin model is 1.45 mm, which means that the blade tip expands significantly during the operational regime. In addition, the comparison of Fig. 5 and Fig. 6 reveals the difference in the probability distribution shape in standard and operational skin models. Precisely, the probability distribution of the blade tip clearance of the standard skin model has a Gaussian shape, which is logical due to the normal distribution used in the random fields. In contrast, in the operational skin model this probability distribution is not symmetrical around the mean value and it is

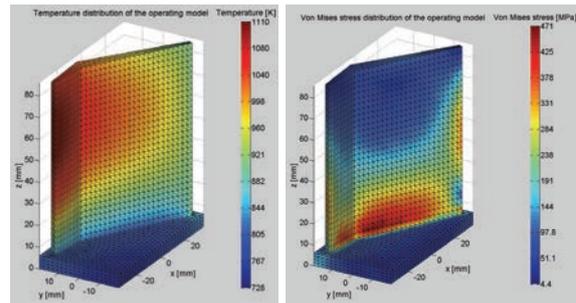


Fig. 3. Temperature (left) and Von Mises stress (right) distributions of the Skin Model Shape #500. Note that the temperature distribution is expressed in degrees Kelvin and the stress in MPa.

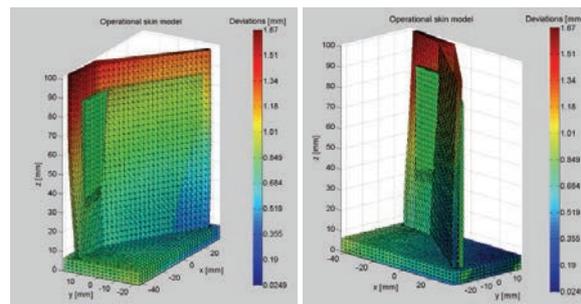


Fig. 4. Visualization of the nominal triangular mesh (green matte) and the operational skin model with a deformation scale factor of 10 (RGB color) of the operational Skin Model Shape #500.

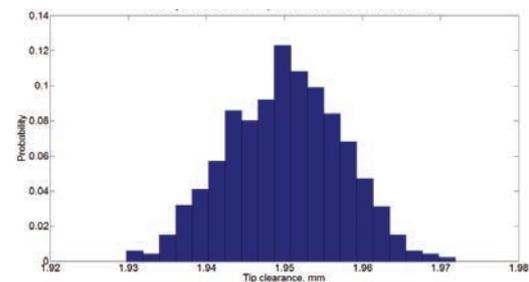


Fig. 5. Probability distribution of the gas turbine blade tip clearance for the standard skin model at 20°C considering 1,000 SMS.

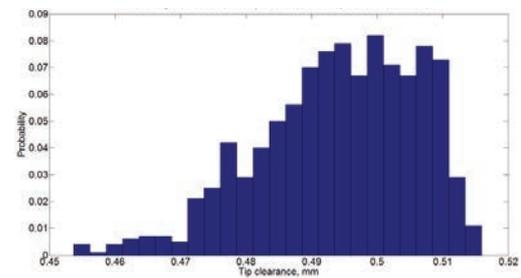


Fig. 6. Probability distribution of the gas turbine tip clearance for the operational skin model considering 1,000 SMS.

more concentrated to the side with higher clearance values. In this way, if the problem were linear, the probability distributions before and after the skin model would have the same shape. Consequently, this result is a consequence of the FEA simulation on the standard skin model as the coupled temperature-displacement problem is nonlinear. Therefore, if the distribution of the standard skin model is Gaussian, by doing the FEA simulation the final result will not necessarily become a normal distribution. Furthermore, in this analysis the training set consists of 1000 SMS which are considered to be sufficient to capture the physics of the case. Finally, the accuracy of the simulations could be enhanced by adding a more detailed blade geometry, an advanced FEA simulation, and the inclusion of high-fidelity CFD calculation, although this features would increase the overall cost and complexity.

5. Conclusions

The case study shows the enormous importance of considering the shape change of a workpiece skin model from its verification to its working state. Indeed, the comparison of the standard and operational skin models reveals how much the turbine blade shape evolves from static to working regime, and hence, the significant variation experienced by its functional tolerances. Even though the turbine blade geometry is simplified, the case study makes evident that the shape deviations occurred in the operational conditions are so important that should not be neglected. The different probability distributions of the maximum displacement and blade tip clearance in the standard and operational skin models has revealed that the FEA simulation on the standard skin model makes the problem become nonlinear. The nonlinearity of the overall problem demonstrates the vital importance of integrating the operational environment into the skin model simulation.

The consideration of non-ideal shapes for the FEA simulation demonstrated the real influence that small deviations due to manufacturing and measurement uncertainty have on the final deformed shape of the product in operation. Indeed, in case only the ideal shape of the CAD model is considered for the FEA simulation, and once the accuracy of the mesh is assured, the expected FEA simulation results may be the same simulating 1 or 1000 SMS. Therefore, the FEA simulation of a training set of skin models provides valuable information for the analysis and optimization of the turbine design. Moreover, the integration of experimental data would increase the accuracy of the simulations.

The possibility of performing FEA simulations departing from non-ideal shapes and based on skin model definition is also developed. Precisely, the operational skin model simulation framework proposed can be extended for other type of operational skin models (e.g. plastic and elastic deformation, etc.) as far as the definition of the FEA simulation case is adapted. Finally, it should be highlighted that this research seeks to pave the way for integrating the non-ideality captured by SMS in complex assemblies that withstand high temperatures and high loads, as it is the case of turbojet engines, which require high-technology in order to assure reliability and high performance.

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