FE-Simulations as a Part of a Tolerance Management System

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ABSTRACT

The high grade of multidisciplinarity in the design process of micro systems requires a extended kind of management of tolerances within the quality assurance. Classical methods of tolerance management being used in engineering design merely work on geometric quantities, like lengths and angles, utilizing simple vector algebra. With micro system technologies further units have to be regarded. This circumstance requests a tolerance description which is independent of dimension on the one hand and tolerance calculation, which leaving the path of simple vector algebra and linear relations between tolerance parameters, on the other hand.

The software called "Tolerance Analysis and Synthesis Tool for Micro Systems" (µ-ToAST) tracks this extended approach for tolerance management and is in continuous development. This paper will show the latest step of development, the integration of FE-Simulations. For a better understanding a MEMS example is shown.

Keywords: numerical methods, FEM, optimization, linear microactuator, tolerance management

1 INTRODUCTION

The term tolerance management unites analysis, i.e. investigation of effects from input tolerances on target tolerance, and synthesis, i.e. the meaningful allocation of input tolerances.

Classical methods of tolerance management being used in engineering design merely work on geometric quantities, like lengths and angles, utilizing simple vector algebra. With micro system technologies further units have to be regarded. These are for example material data, field parameters (electrical, magnetic or thermal), costs and many more [1]. This circumstance requests a tolerance description which is independent of dimension on the one hand and tolerance calculation, which leaving the path of simple vector algebra and linear relations between tolerance parameters, on the other hand [2].

The software called "Tolerance Analysis and Synthesis Tool for Micro Systems" (µ-TOAST) tracks this extended approach for tolerance management and is in continuous development on the Institute for Engineering Design and Microtechnology within the scope of the German Collaborative Research Center (Sonderforschungsbereich 516) "Design and Fabrication of Active Microsystems".

2 µ-TOAST

In the first step µ-TOAST has got the ability to handle tolerances of any origin and to operate on tables with experimental data. Therefore the tool rest upon the Theory of Errors and the Monte Carlo Method, which have no restriction regarding the dimension of the input parameter. Furthermore these methods include the simple consideration of the statistical variation of the tolerances. Figure 1 shows exemplarily how the Monte Carlo Simulation process works. For each step of the Monte Carlo Simulation a set of stochastically selected input parameters is needed. These parameter sets are obtained from the probability distributions and are linked by an objective function with the resulting parameter [3].

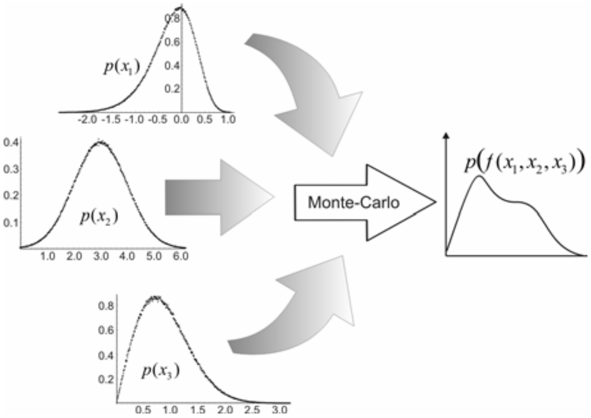

Figure 1: Graphical representation of the Monte Carlo Method [4]

Each parameter can be described as uniform, Gaussian or Weibull distributed. The Weibull Distribution is usefully for lifetime description of products. Additional arbitrary distributions based on experimental data (e. g. material data) can be converted to computer generated random numbers which represent the given probability density.

The ability to define a wide spectrum of objective functions is necessary for the expedient evaluation of the tolerance influence. Therefore μ-TOAST offers the following possibilities:

- Interpolation and approximation of empiric data
- Definition as arbitrary analytic or numeric function
- Solution of geometric constraints
- FE-Simulation
- Technology simulator

The interpolation and approximation of empiric data provide easy use of experimentally gained data [5]. Together with the handling of arbitrary analytic or numeric functions, it represents the core of the tool [6]. Furthermore the tool provides, with assistance of the constraint-solver by UNIGRAPHICS®, the handling of complex geometric constraints based on parametric CAD models [4]. Technology simulators are very important for the design of micro systems with their close connection to manufacturing processes. Therefore an interface to the etching simulator SUZANNA [7] is exemplarily implemented. The main focus in this paper is on tolerance investigations based on FE-Simulations. Therefore TOAST possesses an interface to the commercial FEM software ANSYS®.

2.1 FE-Simulation

FE-Simulations provide support for a wide spectrum of issues. So they are used for structural, electro-magnetic, thermal or fluidic analyses and are an often used tool for the designer of micro systems. A single FE-Model can be very complex and its calculation can take up time from a few minutes to several hours. A complete Monte Carlo Simulation needs more than 10000 single calculated events of different parameter sets. This number of calculations is impracticable for FE-Simulations. You need a simplified description of the solution space.

At this point μ-TOAST supports the user to deduce an interpolated or an approximated description of the FE-Model. It offers to carry out parameter studies within the user defined parameter limits and to check the accuracy of the chosen approximation.

The following examples are for illustrating the potential.

3 EXAMPLES

3.1 Tolerance Analysis

Within the research of “Sonderforschungsbereich 516” a variable reluctance linear microactuator was designed [8]. A schematic representation is shown in figure 2. As described in [8] the relation between driving and normal force is an important parameter for the correct work of the actuator. Only with a ratio $F_x / F_z > \mu_{fric}$ a resulting force in driving direction remains and actuation is possible. Analyses utilizing FE-Simulation of electro magnetic fields have shown the expected interdependence of tooth geometry, air gap height, driving force and vertical force. Depending on production processes tooth geometry and air gap height are varying.

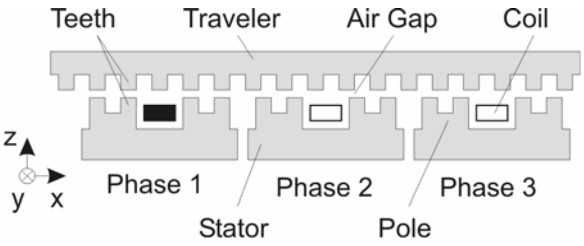

Figure 2: Schematic representation of a three phase variable reluctance motor. Phase 1 is shown magnetized.

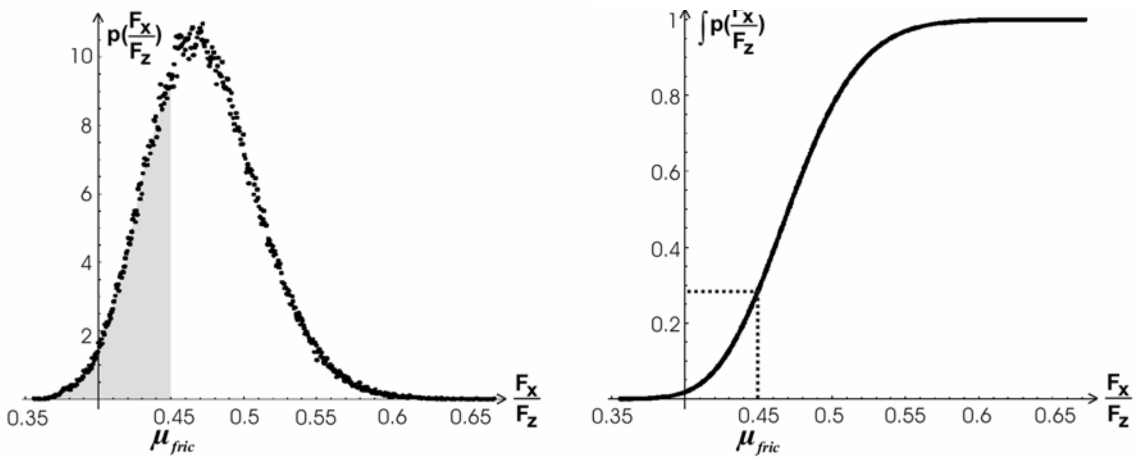

Figure 3: Probability density and its associated distribution function of the force ratio F_x / F_z resulting on a Gaussian distributed air gap height of 0.5 μm with a standard deviation of 0.083 μm.

A statistical tolerance analysis for a varying air gap height has been conducted for a more specific examination. For this example in dependence on production the height is chosen Gaussian distributed with a mean value of 0.5 µm and a standard deviation of 0.083 µm. The resulting probability density and the associated distribution function (integrated probability density) of F_x / F_z after a Monte-Carlo Simulation is shown in Figure 3.

By a critical μ_{fric} of 0.45 (arbitrary chosen for this example) the resulting reject rate would be 26.5% only because of the varying air gap. The distribution is showing an asymmetry which results of the low nonlinear relationship between air gap height and force ratio, shown in figure 4.

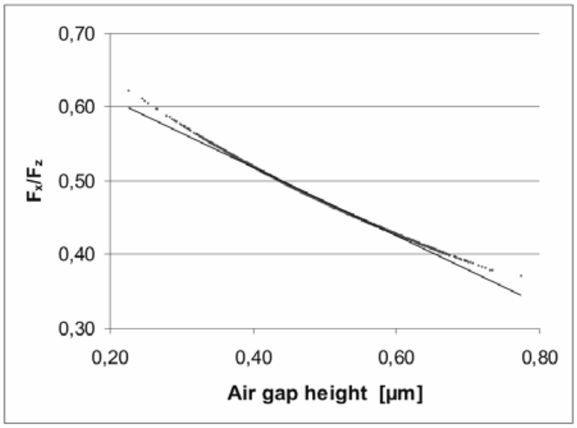

Figure 4: Correlation between force ratio and air gap height. The blue points are the resulting events of the FE-Simulations.

3.2 Tolerance Synthesis

The reject rate is with 26.5% in the tolerance example relatively high. The tolerance synthesis has the aim to figure out, which positioning accuracy is needed to obtain a specific reject rate. In the first step a fit function for the FE-Simulation will be defined. The relation between force ratio and air gap height is low nonlinear and similar to a quadratic polynomial, as shown in figure 4. So a quadratic fit, based on the method of the least square errors, is chosen.

The resulting polynomial is shown in equation (1) with the force ratio *r* and the air gap height *h*:

$$r(h) = 0.782481 - 0.788724 \cdot h + 0.338896 \cdot h^2 \qquad (1)$$

µ-TOAST automatically controls the accuracy of the chosen fit function. Therefore the sample correlation coefficient (e.g. in [9]) according to equation (2) will be calculated:

$$r_{xy}^2 = 1 - \frac{\sum (y_i - \hat{y}_i)^2}{\sum (y_i - \bar{y})^2} \qquad (2)$$

In this case the sample correlation coefficient r_{xy}^2 is equal to 0.99997 and approves the high quality of this approximation. Now the designer can start a tolerance synthesis with an acceptable duration.

The aim of the following tolerance synthesis is to reduce the reject rate from 26.5 % to 10 % by modifying the positioning process. The designer can follow two different strategies to achieve it. The first one is simply to reduce the planned distance between stator and traveller. This has no influence on the quality specification of the positioning process, but a reducing can conflict with minimum requirements for the distance resulting from geometric tolerances of traveller and stator. Another strategy is to reduce the variance of the positioning process and to raise its accuracy. µ-TOAST delivers results for both strategies. They are listed in table 1:

Mean value [µm]	**Deviation** [µm]	μ_{fric} [-]	**Reject rate** [%]
0.5	0.083	0.45	26.5
0.45	0.083	0.45	10.0
0.5	**0.041**	0.45	10.0

Table 1: Results of the tolerance syntheses

You can see in the first row the values of the tolerance analysis with its reject rate of 26.5 %. The result of strategy one is standing in line two. A reducing by 0.05µm to a distance of 0.45µm is adequate. Finally the result of reducing the variance is in line three. The standard deviation has to reduce strongly from 0.083µm to 0.041µm.

Figure 5 shows the resulting probability density and distribution function of the force ratios depend on the calculated Gaussian distributed parameter of this tolerance synthesis. The brighter graph shows the distribution of strategy one and the black one shows the distribution of strategy two. In the right figure you can see clearly the reduced variance of strategy two. Additionally you can see that the areas with force ratio lower than 0.45 have nearly the same size. In the distribution function you can see exactly the intersection of both graphs at a force ratio equal to 0.45 and a proportion of 10%.

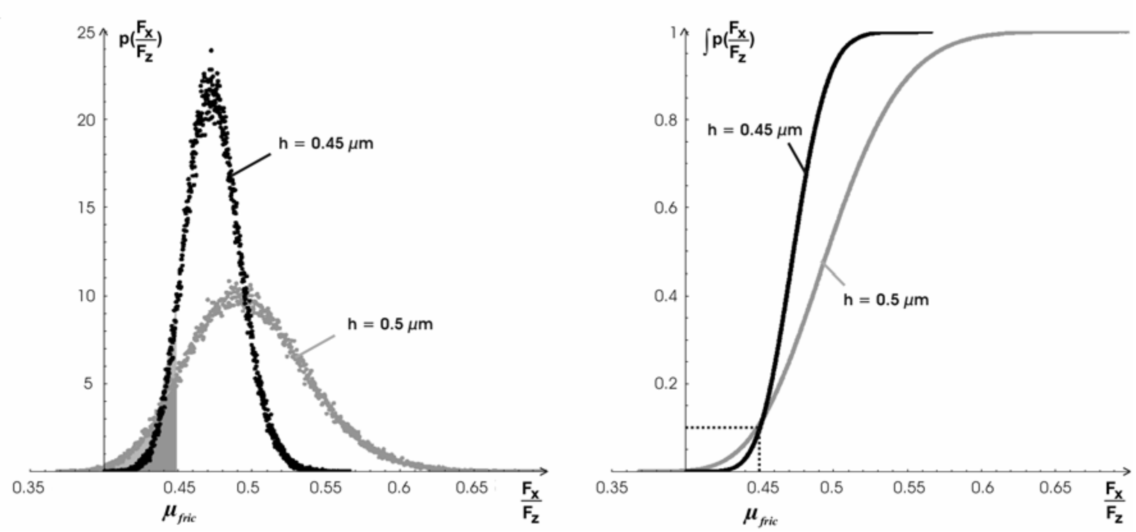

Figure 5: Probability densities and their associated distribution functions of the force ratio F_x / F_z resulting on a Gaussian distributed air gap height h of 0.5 / 0.45 µm with a standard deviation of 0.041 / 0.083 µm.

4 SUMMARY AND PERSPECTIVE

The introduced software µ-ToAST is a powerful tool for tolerance management of complex systems, especially Microsystems. With the now reached development level the tool provides designers the possibility to comfortably gain information about necessary quality requirements based on FE-Simulations.

The future focus of development will be on a better integration of assembling processes. The description of handling and joining of parts as objective functions are a very interesting and promising challenge.

ACKNOWLEDGEMENTS

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