Abstract:

Tolerances, the allowance on dimensional and shape variation of a design, are essential features of the design. As such, they should be present in the virtual prototype world of MCAD. The checking and fine-tuning of tolerances is a painstaking task, which has become easier with advanced dedicated software. The newest trend is to integrate the dedicated expert software systems in the MCAD software. This paper investigates in the solutions offered to designers and engineers to tolerance-model their designs from within the MCAD software.

Keywords: tolerance analysis, CAD software, tolerance stacking

Introduction:

The perfect mechanical part is very difficult, if not impossible, to produce. To cope with this problem, tolerances are added to the dimensions of the part. Tolerances specify a range of accuracy for the size, shape and position of an element or feature of the part. These tolerances include dimensional tolerances and geometrical tolerances, which both influence the size and shape of the product.

The variation of dimensions depending on tolerances has to be studied carefully in a part to ensure its interchange ability in all cases in an assembly. Interchange ability of parts in the assembly depends on size variation due to dimensional tolerances, variations in shape due to geometrical tolerances, and kinematical variations due to small movements between parts due to size variation. Tolerance variations on individual dimensions lead up to a ‘tolerance stack-up’ for combined dimensions, and in essence, for the shape of the complete part. Any tolerance different from the general tolerance is a cost-raising factor and should therefore be studied carefully to be sure that it is functionally necessary to implement the tolerance in the part. Prediction of the fitting probability of production is important to fine-tune the tolerances so that a cost-efficient product is made.

Besides, studies show that most designs undergo several cycles of change before all dimensions and tolerances are finalised. Any change on dimensioning and/or tolerances after production started, has an initial cost of $15000 to $100000 [1]. It is thus cost-efficient to spend time and effort on the tolerance-modelling of the design, next to the geometrical design.

A tedious study of tolerances has been incorporated in software to provide the designing engineer with tools to evaluate more easily the effect of dimensional and shape variations of parts on the behaviour and performance of the part as is, or in assemblies. Nowadays, this software is being integrated in the MCAD software to make it easier and faster to check tolerance stack-ups from within the design software.

We will give an overview of tolerance analysis methods used in MCAD systems, and illustrate with a case study the implementation of tolerance analysis in a high-end performing MCAD system.
Material and Methods

Methods for tolerance analysis
In order to specify the most economic and accurate dimensioning and tolerance scheme on a part, we need an analytical model to predict the influence of tolerances on the final shape and function of the part. Critical clearances or fits or other resultant features of an assembly are generally controlled by the stack-up or sum of several component tolerances. Such a tolerance stack is a calculation used to find an extreme maximum or minimum distance on the part.

The dimensioning scheme itself, although very important in tolerance modelling to lower tolerances, is not considered in this paper. Every dimensioning scheme itself (in the cases) is considered to be acceptable, in other words as is.

A tolerance stack can be calculated using different approaches, as can be seen in Figure 1.

![Tolerance Analysis Approaches](image1.png)

**Figure 1** Tolerance analysis approaches
**Obrázok 1** Metódy tolerančnej analýzy

**Worst-Case Tolerance Analysis**

The worst-case tolerance analysis is the most commonly used type of tolerance stack-up calculation since it can also be done by hand. The individual dimensions are set at their tolerance limits in order to calculate the maximum and minimum values of the considered dimensions.

![Worst-case Stack-up Variation](image2.png)

**Figure 2** Worst-case stack-up variation
**Obrázok 2** Najhorší prípad nahromadenej variácie

The worst-case analysis will only provide information about dimensions that exceed their respective specified tolerance limits. Mathematically, the model assumes that all the tolerance dimensions will equal to one of their limit values, which yields an extreme stack-up condition. This model will predict the maximum expected variation of the measurement. Worst-case tolerance requirements guarantee 100 percent of the parts will assemble and function properly without considering any variation in between parts within the tolerance field. The result is that the worst-case model often leads to very tight individual component tolerances with resulting higher costs in manufacturing and inspection.

The worst-case tolerance analysis is often required for critical mechanical interfaces and spare part replacement interfaces.

**Statistical Variation Analysis**

The statistical variation analysis model takes advantage of the principles of statistics to loosen the part’s tolerances without sacrificing quality. Since the true value of a dimension is just a coincidence somewhere between the limit values of the dimension, we can take into account the distribution of true values in production.
Each component’s variation is modelled as a statistical distribution (Figure 2), and these distributions are summed to predict the distribution of the assembly measurement.

![Figure 3 Statistical stack-up variation](image)

**Figure 3 Statistical stack-up variation**

Obrázok 3 Štatistická nahromadená variácia

This statistical variation analysis predicts a distribution that describes the assembly measurement variation, not the extreme values of that variation. This analysis model provides increased design flexibility since it allows the designer to design for 100 percent (statistical) successful assemblies. The statistical approach is better in line with the definition of tolerances which states that general tolerances on a technical drawing should be selected in accordance with the normal accuracy that the machine shop at the company can obtain. The machine shop accuracy should be measured and observed in time with the use of regular samplings according to the international standard ISO 2768-1: 1989 (E) General tolerances for linear and angular dimensions without individual tolerance indications [2].

**Sampled/simulated analysis**

In these methods of analysis, small random changes are made to dimensions to simulate process variations. Next, the assembly and resulting dimensions are calculated with this simulated set of component dimensions. The number of rejects that are not within the limits of specifications are counted and evaluated as criteria for the dimensioning and tolerance scheme. These methods can make a good prediction of the assembly behaviour with tolerated parts, but does not offer any easy-to-use tool to designers.

**Methods used for the tolerance analysis in MCAD systems**

Since the introduction of (3D)parametric modellers in 1989 with Pro Engineer, dimensional tolerances are an essential part of the model. They control the size and thus the shape of parts and assemblies. A number of techniques for analysing tolerances (dimensional behaviour) is implemented in this kind of MCAD software.

We will explore the methods of tolerance analysis in Creo/Elements (former ProEngineer Wildfire 5.0)

There is a difference when considering single parts in the tolerance analysis, or when considering (complex) assemblies. The interface behaviour of parts can be very tricky in analysing the tolerance stack-up in the assembly. Similar to when modelling a part, where the designer uses perfect (nominal) dimensions, in assembling parts, the designer will model ideal interfacing conditions. These ideal conditions will often fail when dimension bounds are set to tolerance limits – which is the case in the worst-case tolerance analysis.

**Worst-Case Tolerance Analysis**

The worst-case analysis can be done with standard tools within Pro Engineer/Creo (and with the CETOL application).

With standard tools we will set different dimensions in tolerance stacks to limits (upper – lower) and then analyse possible interference/clearance between parts. We can also easily measure stacked lengths etc. An advantage of this method – although there is some manual
work involved – is the unlimited number of parameters which can be set, and the fact that not only linear stacks of tolerances but also 3D stacks can be evaluated.

With this tool we actually have to do all the work manually. Which dimensions to set to their upper/lower/middle tolerance value is the user’s own decision. The checking for actual run out of tolerance is also dependent on the interpretation of the user. He should use tools to measure the distance between interfacing surfaces and analysing tools to check for interference of volumes.

E.g. plate with holes and plate with pens assembled.

After assembly, all tolerances are set to their upper value. When setting a dimensional tolerance to its upper limit, the size of the part will change. All dimensional tolerances are an integral part of the dimension and thus influence the size (and shape). In both parts the dimensions on the drawings are put at their upper values.

As can be seen, there is interference from the pens with the holes, although at nominal value, there would be no problem. We now know that in the worst-case scenario, this assembly will fail. What the chance of success or fail is cannot be discovered.
Statistical Variation Analysis

Statistical variation can only be evaluated for linear (1 D) chains of dimensions. This is done with the integrated CETOL (by Sigmetrix) tool. This tool allows for the statistical and worst-case analysis of linear tolerance stacks, defined by dimensions and geometrical dimensions (position and shape). As such, it is a valuable tool to evaluate dimensional changes.

All tolerances (variation in dimensions) are considered to be Gauss-normal distributed [3] in the analysis tool.

We will analyse the plate with holes: the length of the plate, and the distance for the holes to the sides are important here.

As we can see, the percentage of yield with this dimensioning scheme and tolerances is rather low (70%). This means that there is a big chance the assembly will fail.

We can not only fine-tune with this tool the tolerances but also the process capability can be adjusted to reflect the actual capabilities. This is done by tuning the Cp (capability index). A Cp of 2 is used in case of a 6-sigma production.

Sigma: standard deviation
%Yield: percentage of yield/success
DPMU: defect part per million
When analysing tolerance stacks in assemblies, the interface between parts is also considered. Especially for the behaviour of the assembly of cylinders/holes, there is a possibility to randomise the position of the pen in the hole.

Results and discussion.

Worst-case tolerance analysis. When setting the dimension to the upper/lower/middle tolerance value, we can check for worst-case scenarios. An absolute yes/no to the question to if an assembly will assemble at all possible dimension values of the components can be found at the cost of (a lot of) manual labour. However, the statistical component is lacking in this method, and the setting and interpretation of dimensional/tolerance settings is left completely to the users’ opinion. This will lead up to higher tolerance values and thus more expensive machining.

Statistical tolerance analysis. Statistical analysis of the tolerance stacks show a more realistic picture of the necessary tolerances. The statistical influence of each tolerance is clear, and fine tuning of the particular tolerances can be considered. This leads to considerable cheaper machining, since only those tolerances which have a high influence on the complete stack should be set to a higher – and as such more expensive in machining value.

Conclusion
After geometrical design has been made easy with 3D-feature modelling software, the next step in getting closer to the virtual prototype is the introduction of tolerance modelling tools in MCAD. At least for 1D-tolerance stacks, it seems that the presented tools offer a (simple) solution to the designing engineer for checking the variation of his design. The statistical tools offer the opportunity to fine-tune the design with the data from standard production in the company. Since during the design phase no real (measured) dimensions are available, a controlled guess (through the use of statistics) about real dimensions is a trustworthy and helpful tool to tune the tolerances.

To evaluate the variation of complex assemblies with multiple dimensions and degrees of freedom, the tools will have to be extended and enhanced for 2D and 3D tolerance stacking, too.

**Súhrn**

Tolerancie, ako dovolené odchýlky z pohľadu rozmerov a tvaru, sú dôležitou charakteristikou návrhu a vo virtuálnom prototype MCAD by mali byť začlenené. Kontrola a spresnenie tolerancií je náročnou úlohou, ktoréj zjednodušenie umožnil pokročilý softvér. Najnovším trendom je integrácia príslušných expertných softvérových systémov do softvéru MCAD. Tento príspevok sa zaoberá skúmaním riešení pre projektantov a inžinierov z pohľadu tolerančného modelovania návrhov v prostredí softvéru MCAD.

**Klúčové slová:** tolerančná analýza, softvér CAD, hromadenie tolerancií

**References**


http://www.sigmetrix.com


Further reading:


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