New geometrical product specifications (GPS*) and robust design

Univ.-Prof. Dr.-Ing. Peter Gust and M.Sc. Christoph Schluer

*Mechanical Engineering worldwide, needs the joint output of these standards committees more than ever.

Source ISO/TC 213
Global Problem*

Specification inadequacy is the Achilles heel for many of today’s technologically advanced companies.

Tighter tolerances can often prove phenomenally expensive to apply

*Source ISO/TC 213

An example: **chassis bearing**
State of the Art: New (?) Geometrical Product Specifications

Principle of Duality

- The design engineer is responsible for the specifications
- Production and Quality Management are responsible for validation

Principle of Independency

- Since September 2011 the new standard DIN EN ISO 8015 appeared, the principle of independency is the standard for geometrical tolerancing instead of the Principle of Envelope (Ⓔ)
- ... except if you see the symbol Ⓐ (ISO 14405-1) for the envelope

Structuring all geometrical standards through the

- GPS-Matrix (at the end of each document – to locate the position of the single standard in the whole system )

New Standards from CEN/TC 290

...since 2010 87 new specifications in Europa
IS THE WORLD PERFECT?

No!

Deterministic Approach

Statistical Approach „Robust Design“

It is not the perfect, but the imperfect, who have need of love.

Charles Dickens
Randomly deformed bodies

For the reference case a FE analysis is performed to evaluate the influence of the shape and dimensional tolerances of parts on the stress distribution under load.

<table>
<thead>
<tr>
<th>Order</th>
<th>Shape Non Uniformity</th>
<th>Linear, planar and roundness Non-Uniformity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td></td>
<td>linear, planar and roundness Non-Uniformity</td>
</tr>
<tr>
<td>2.</td>
<td>Waviness</td>
<td>Waves</td>
</tr>
<tr>
<td>3.</td>
<td>Roughness</td>
<td>Grooves</td>
</tr>
<tr>
<td>4.</td>
<td>Roughness</td>
<td>Scratches, Scurfs, ...</td>
</tr>
<tr>
<td>5.</td>
<td>Roughness</td>
<td>Microstructure</td>
</tr>
<tr>
<td>6.</td>
<td>Roughness</td>
<td>Atomic Lattice</td>
</tr>
</tbody>
</table>

Load $F = 10kN$

- Piston guidance
- Contact region incl. friction
- Flat plate, fixed bottom side 000 000

Inhouse Catia Module
Randomly deformed bodies

Contact surface with randomly deformed shape (inside the given tolerance!)

Surface Profile Tolerance (SPT) = 2mm

SPT = 0.2mm
Randomly deformed Bodies

First Result

SPT = 0,1mm

SPT = 0,0mm “Nominal Value”

SPT = 0,2mm
Original Test Object: Bracket-Bolt-Joint

Investigation of the stresses in an assembly with two contact regions and the possibility of experimental validation

Bracket-Bolt-Joint as a standard machine element
Workflow for consideration of non-ideal geometry in the product development process
Generation of the Non-Ideal-Geometry

- The non-ideal model which is required for the simulation, is created in the CAD system.
- Dimensional and geometric tolerances are defined in advance.
- The geometry creation works with parametric point clouds, which form the basis for a surface model.
The generation of the data points in the predetermined tolerance field is carried out according to defined rules. Among other things, the adjacent data points deviate not more than 20% of the permissible tolerance zone from each other → ensuring to get a realistic component surface.
FEM-Model

The non-ideal Components cause complex contact behavior with clearance
- Bracket is fixed on the left side and the rod is loaded with 6300N.
- Friction in the contact regions with $\mu=0.1$ non-linear material S235JR
- The tolerances of the components are the input
- The normal stress distribution in the bolt is the output

$F=6300\text{ N}$
Sensitivity Study

Latin Hypercube Sampling with 120 designs shows the relevant parameters (tolerances) with respect to the normal stress in the bolt under load.

![Graph showing coefficient of importance and linear correlation coefficient for various input parameters.](image-url)
## Parameters of the Bracket

<table>
<thead>
<tr>
<th>Nummer ZB</th>
<th>Bolzen</th>
<th>Gabel</th>
<th>Stange</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Flügel</td>
<td>Bohrung</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lage</td>
<td>Durchm.</td>
</tr>
</tbody>
</table>

1. **min**
   - max & parallel
   - gerade
   - max
   - äußeren max & inneren min
   - max Winkel zu B
   - max

2. **max**
   - angestellt & parallel
   - max Winkel zu B
   - nominal
   - angestellt & parallel
   - halber Winkel zu B
   - max

3. **konisch**
   - äußeren max & inneren min
   - gerade, quer zu $F_{Design}$ versetzt
   - nominal
   - äußeren min & inneren max
   - nominal
   - nominal

4. **ungerade**
   - äußeren min & inneren max
   - gerade
   - min
   - orthogonal
   - max Winkel zu B
   - max

5. **ungerade**
   - max & parallel
   - gerade
   - max
   - angestellt & parallel
   - halber Winkel zu B
   - min

6. **ungerade**
   - äußeren min & inneren max
   - gerade
   - min
   - äußeren min & inneren max
   - nominal
   - nominal

**Begriffsdefinition:**
- **min / max:** Lage der Geometrie im Toleranzfeld
- **konisch:** Bolzenform konisch
- **grade / ungrade:** Ausnutzung der Gradheitstoleranz der Zylinderachsen
- **angestellt:** Rechtwinkligkeitstoleranz maximal ausgenutzt
Comparison of the normal stress distribution for the different geometry variants

<table>
<thead>
<tr>
<th>Variante nach Tabelle 4.1</th>
<th>Spannung im Bolzen in MPa</th>
<th>Abweichung zur Idealvariante in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ideal</td>
<td>248</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>326</td>
<td>31</td>
</tr>
<tr>
<td>2</td>
<td>300</td>
<td>21</td>
</tr>
<tr>
<td>3</td>
<td>315</td>
<td>27</td>
</tr>
<tr>
<td>4</td>
<td>312</td>
<td>26</td>
</tr>
<tr>
<td>5</td>
<td>304</td>
<td>23</td>
</tr>
<tr>
<td>6</td>
<td>292</td>
<td>18</td>
</tr>
</tbody>
</table>

Ideal part

Non-ideal variants
Test Stand for Validation

1. Test specimen
2. Hydraulic power unit
3. Mainframe
4. Cooling fan
5. Measurement Hardware
6. Graphical user interface
Validation Software/Control
Final Results

After a period of initial tests, the ideal assemblys were tested (blue) in comparison to the non-ideal variants 1(red) and 2(green). The vertical lines represent the median of respectively 10 probes.
Actual evaluation of Process Capability

**Process Suitability** $C_p$: Is the process suitable?

$$C_p = \frac{T}{6s} = \frac{OTG - UTG}{6s}$$

with $C_p > 1,33$ the process is suitable!
... the car fits in your garage!

with $C_p < 1,0$ the process is **not** suitable!
... the car does not fit in your garage!

**Process Suitability** $C_{pk}$: Is the process controllable?

$$C_{pk} = \min[Cpo; Cpu]$$

$$C_{pu} = \frac{\bar{x} - UTG}{3s}$$

with $C_{pk} > 1,33$ the process is controllable!
... the car strikes in your garage!

$$C_{po} = \frac{OTG - \bar{x}}{3s}$$

with $C_{pk} < 1,0$ the process is **not** controllable!
... the car does not strike in your garage!
New extended Objectives

We need robust Processes

1. Suitable process,
2. Controllable processes
3. And new: centered Processes

The automotive working committee defined a new Index $C_{pr}^*$:

- It is a value for the robustness and will be calculated through the average quadratic failure
- It can be easily calculated through 4 parameters
- It is suitable for all distribution shapes
- It included $C_p$ und $C_{pk}$.

$$C_{pr}^* = \frac{T}{6 \times \sqrt{\sigma^2 + (m - \mu)^2}}$$

- $T$: Tolerance = difference OTG-UTG
- $m$: Mean Value of the tolerance
- $\mu$: Mean Value
- $\sigma$: Standard deviation

* Quelle Summer School Toleranzanalysen, Uni Erlangen, W.R. Landschoff, VW, 2013
Index for Robustness $C_{pr}$

- $C_{pr}$-Index is on his way to become a future part of the VDA.
- Therefor existing "ok" parts could be defective parts in future.
- But the mounting processes is more "robust" with less defective assemblies.

$$C_{pr} = \frac{T}{6 \cdot \sqrt{\sigma^2 + (m - \mu)^2}}$$
Idea: The consequent usage of Tolerance-Management is capable for a significant cost reduction

And How?

- Usage of the principle of Independency, (Envelope only for functional requirements (Ⓔ ISO 14405-1)
- Usage of Robust Designs (Optimization and Validation) and Tolerance-Management
- Reduction of failure expenses through definition of right references and clear dimensions
- Consistent level of competence through training and installation of internal GPS Coaches
Thanks for your attention, any questions - please?

Contact

Univ.-Prof. Dr.-Ing. Peter Gust

Chair of Engineering Design
University of Wuppertal, Germany
Faculty Mechanical and Safety Engineering
Gaußstrasse 20 - Germany 42119 Wuppertal
Postfach 42097, Tel.: +49 202 439 2046,
Mobile: +49 178 717 0467
eMail: peter.gust@uni-wuppertal.de
http://konstruktion.mbau.uni-wuppertal.de