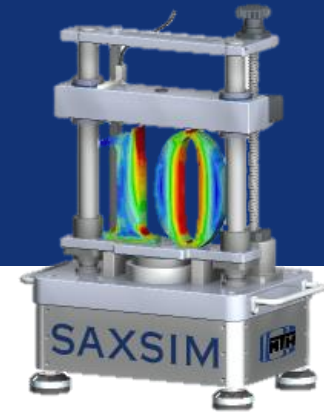




TECHNISCHE UNIVERSITÄT  
CHEMNITZ

10. SAXSIM 2018  
22. März 2018  
Chemnitz



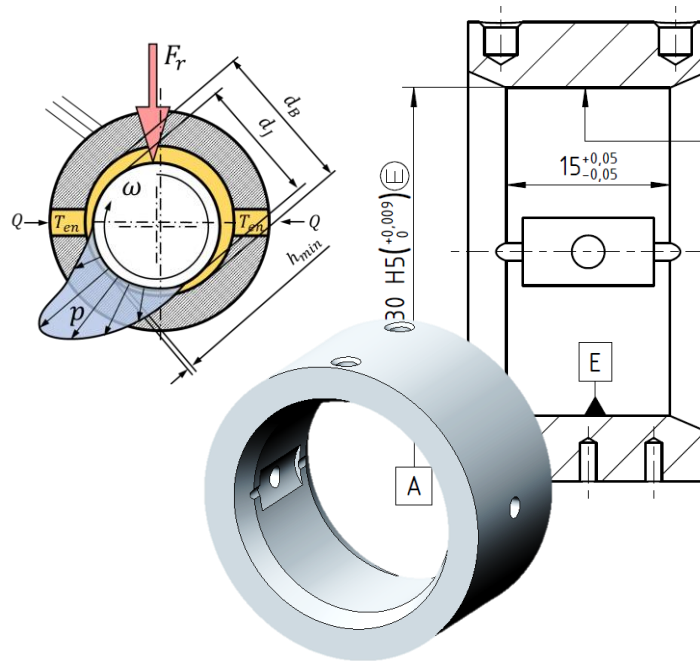
# Simulation des Einflusses von Formabweichungen auf die Betriebseigenschaften hydrodynamischer Gleitlager mit ALP3T und Matlab

Institut für Konstruktions- und Antriebstechnik

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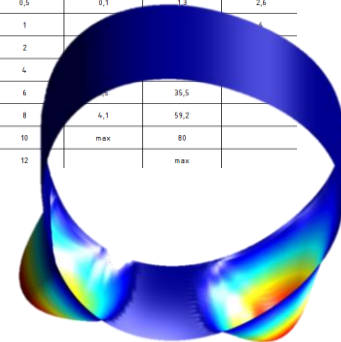
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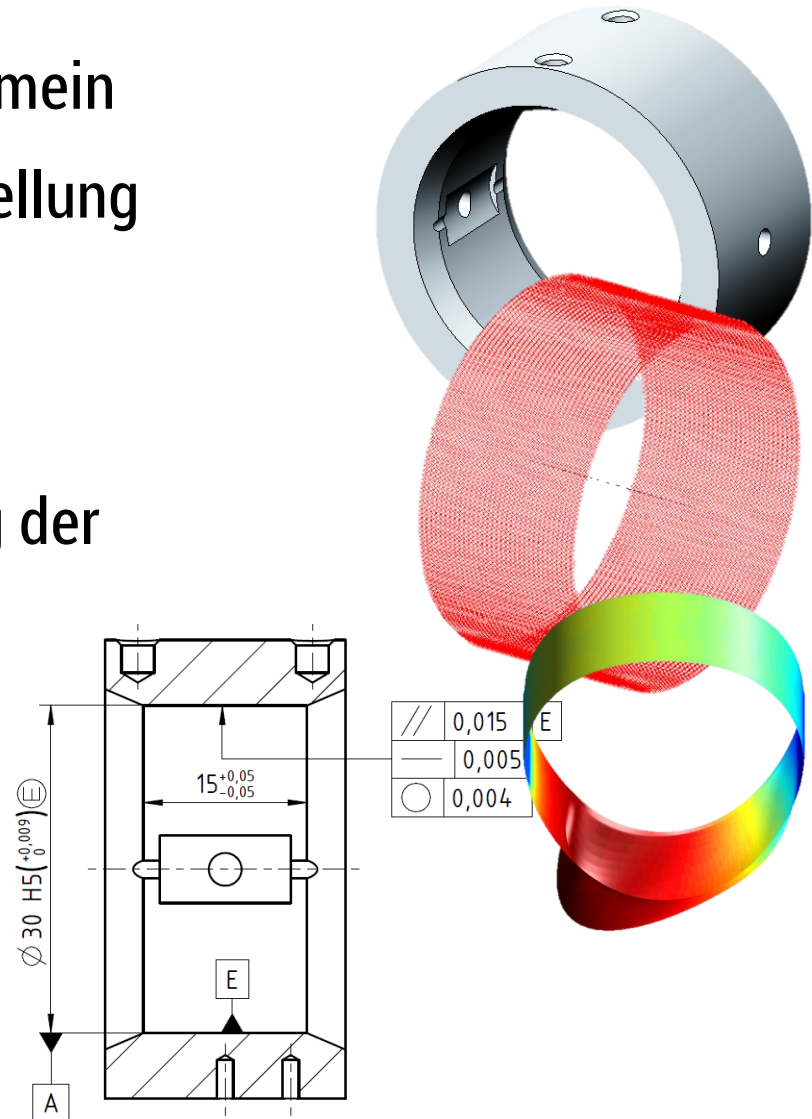


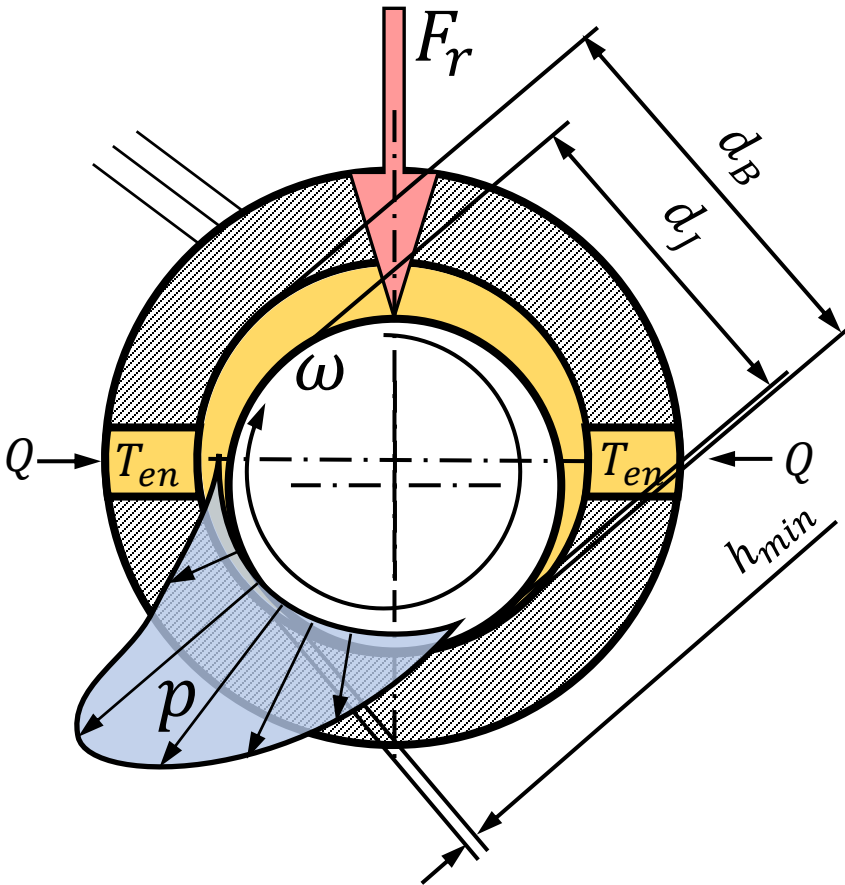
|    |       |   |
|----|-------|---|
| // | 0,015 | E |
| —  | 0,005 |   |
| ○  | 0,004 |   |

| Lagerdurchmesser<br>$\phi$ in mm | spezifische Lagerbelastung für $b/d = 0,5$<br>$\beta$ in MPa | Drehzahl<br>$n$ in 10/min | Rundheitsabweichung<br>$r_t$ in $\mu\text{m}$ | Temperaturdifferenz zum idealen Lager<br>$\Delta T$ in K | Abminderung der min. Schmierfilmsdicke<br>$\Delta h_{\text{min}}$ in % | Abminderung der Steifigkeit in Belastungsrichtung<br>$\Delta c_{\text{St}}$ in % |
|----------------------------------|--------------------------------------------------------------|---------------------------|-----------------------------------------------|----------------------------------------------------------|------------------------------------------------------------------------|----------------------------------------------------------------------------------|
| 30                               | 1,8                                                          | 4000                      | 0,5                                           | 0,1                                                      | 1,3                                                                    | 2,6                                                                              |
|                                  |                                                              |                           | 1                                             |                                                          |                                                                        |                                                                                  |
|                                  |                                                              |                           | 2                                             |                                                          |                                                                        |                                                                                  |
|                                  |                                                              |                           | 4                                             |                                                          |                                                                        |                                                                                  |
|                                  |                                                              |                           | 6                                             |                                                          |                                                                        |                                                                                  |
|                                  |                                                              |                           | 8                                             | 4,1                                                      | 35,5                                                                   |                                                                                  |
|                                  |                                                              |                           | 10                                            | max                                                      | 59,2                                                                   |                                                                                  |
|                                  |                                                              |                           | 12                                            |                                                          | 80                                                                     |                                                                                  |
|                                  |                                                              |                           |                                               |                                                          | max                                                                    |                                                                                  |

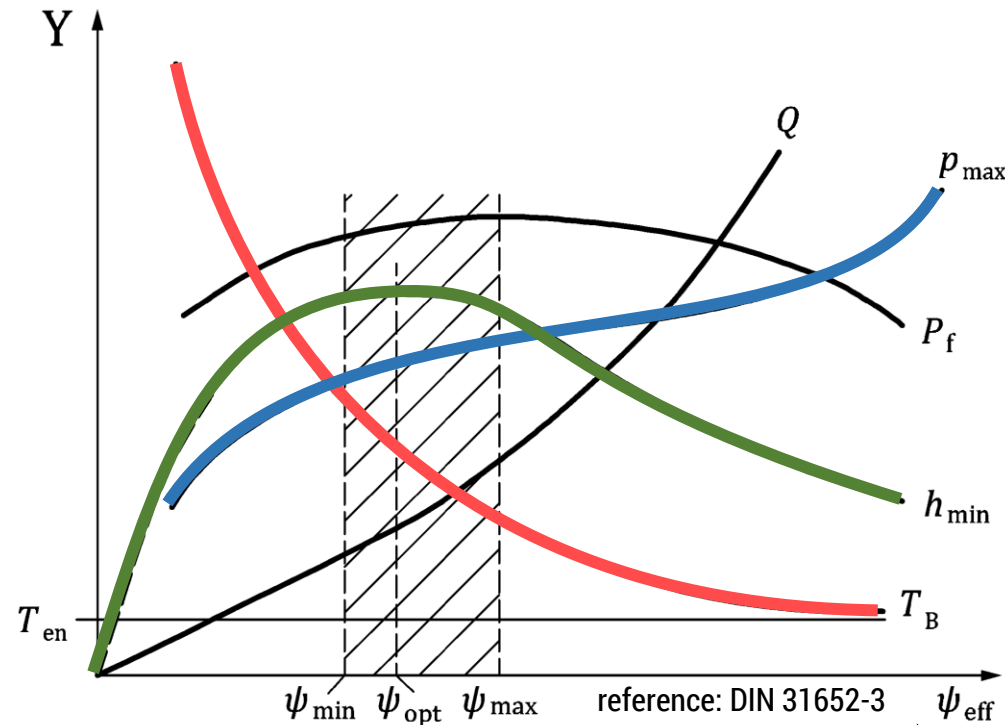


- Einleitung - Gleitlager allgemein
- Ausgangspunkt/Problemstellung
- ALP3T-Modell
- Simulationsergebnisse
- Vorgehensweise Erzeugung der Toleranzauswahlmatrix
- Zusammenfassung
- Ausblick (Systemansatz)





Einfluss des relativen Lagerspiels  $\psi$  (Variation des Durchmessers) auf die Betriebsparameter



$P_f$  – friction power

$p_{max}$  – maximum pressure

$Q$  – lubricant volume flow

$T_B$  – bearing temperature

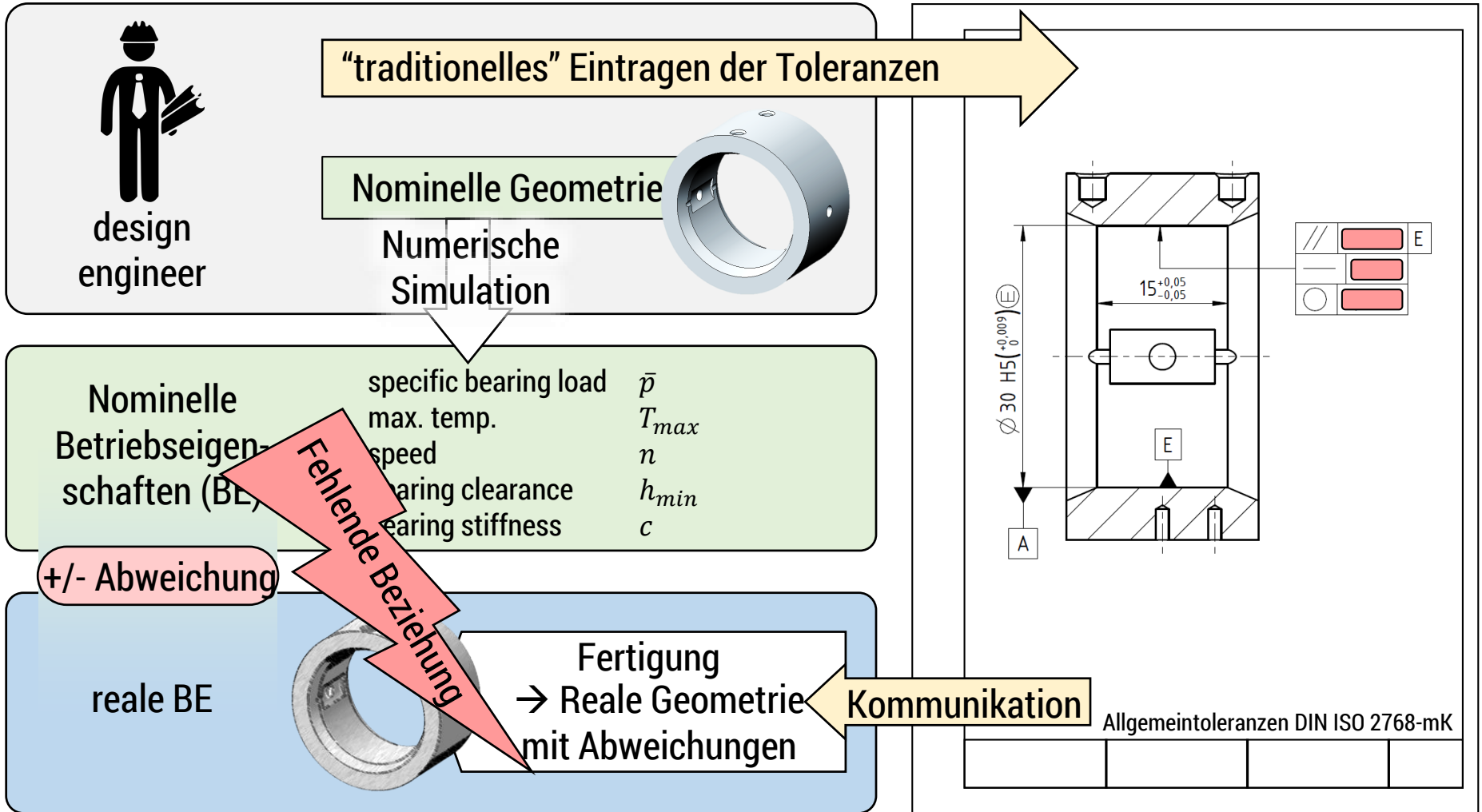
$T_{en}$  – lubricant entry temperature

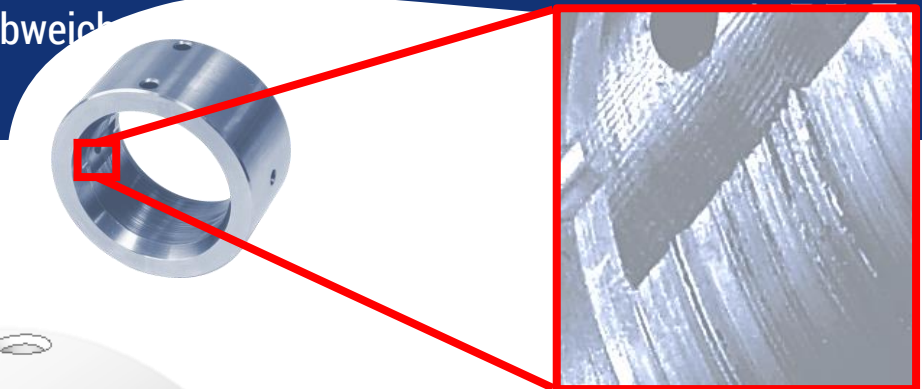
$h_{min}(h_0)$  – minimum lubrication gap

$$\psi = \frac{d_B - d_J}{d_B}$$

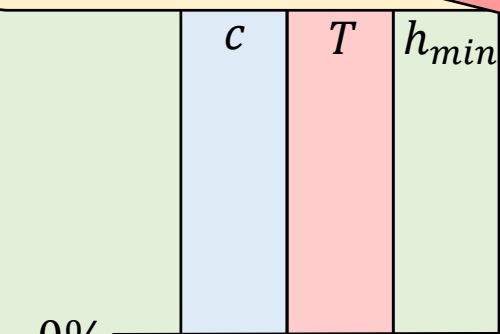
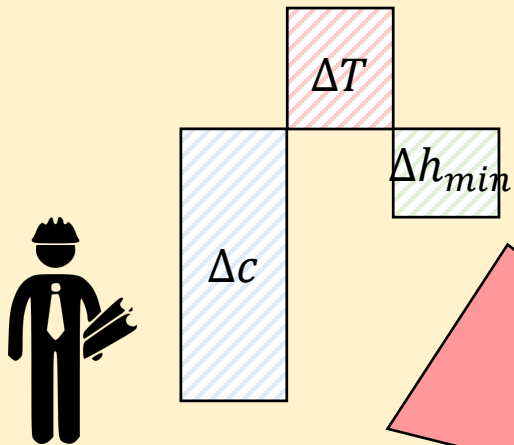
Relatives Lagerspiel

Formabweichungen werden nicht berücksichtigt.





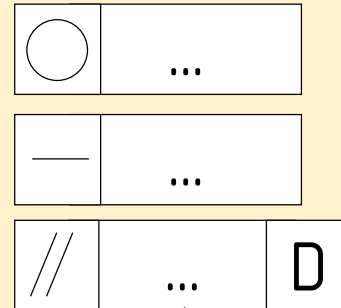
Zulässige Abweichungen der Betriebsparameter  $\Delta$



Nominelle Betriebsparameter

Wie können diese übersetzt werden in ...

... maximal zul. Formabweichungen



Fehlende Beziehung

ISO 12129-2 (DIN 31699)

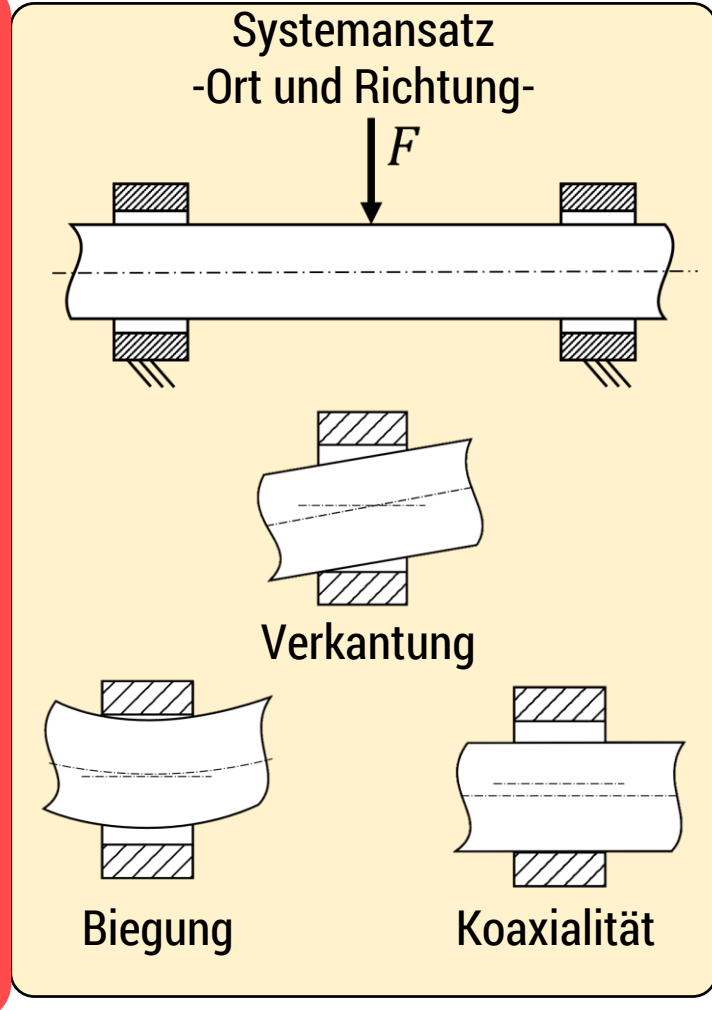
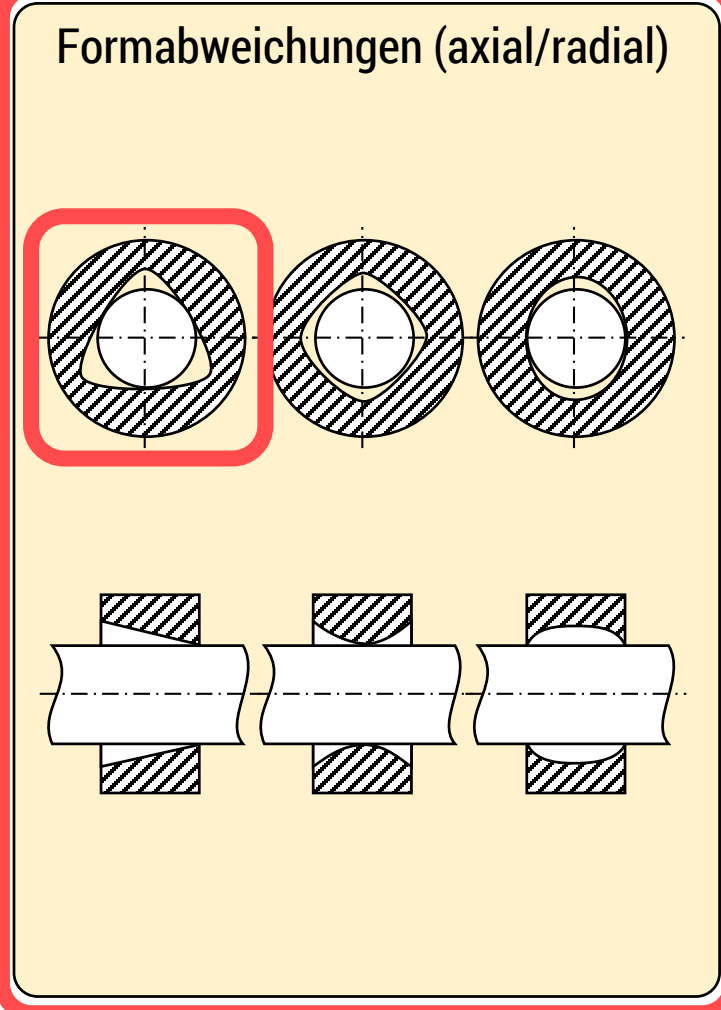
| Feature/parameter on drawing     | Accuracy grade    | Accuracy grade    |                    |                    |               |
|----------------------------------|-------------------|-------------------|--------------------|--------------------|---------------|
|                                  |                   | 5                 | 10                 | 20                 | 30            |
| Thickness                        | $h_0 \mu\text{m}$ | $5 \leq h_0 < 10$ | $10 \leq h_0 < 20$ | $20 \leq h_0 < 30$ | $h_0 \geq 30$ |
| Roundness                        |                   |                   |                    |                    | 0,015         |
| Cylindrical form <sup>1)</sup>   | Straightness      |                   |                    |                    | 0,02          |
|                                  | Parallelism       |                   |                    |                    | 0,04          |
| Runout tolerance                 | $t_4 \text{ mm}$  | 0,006             | 0,008              | 0,012              | 0,018         |
| Flatness tolerance <sup>2)</sup> | $t_5 \text{ mm}$  | 0,006             | 0,008              | 0,012              | 0,018         |
| Concentricity tolerance          | $t_6 \text{ mm}$  | 3)                | 3)                 | 3)                 | 3)            |
| Surface roughness <sup>4)</sup>  | $R_a \mu\text{m}$ | 0,4               | 0,4                | 0,63               | 0,8           |
|                                  | $R_z \mu\text{m}$ | 2,5               | 4                  | 5                  | 6,3           |

Bezieht sich nur auf  $h_{min}$

## Geometrische Abweichungen an zylindrischen Gleitlagern

Dimension  
(Durchmesser)

$\varnothing 30 \text{ H5} \left( \begin{smallmatrix} +0,009 \\ 0 \end{smallmatrix} \right) \text{ E}$



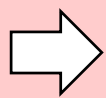
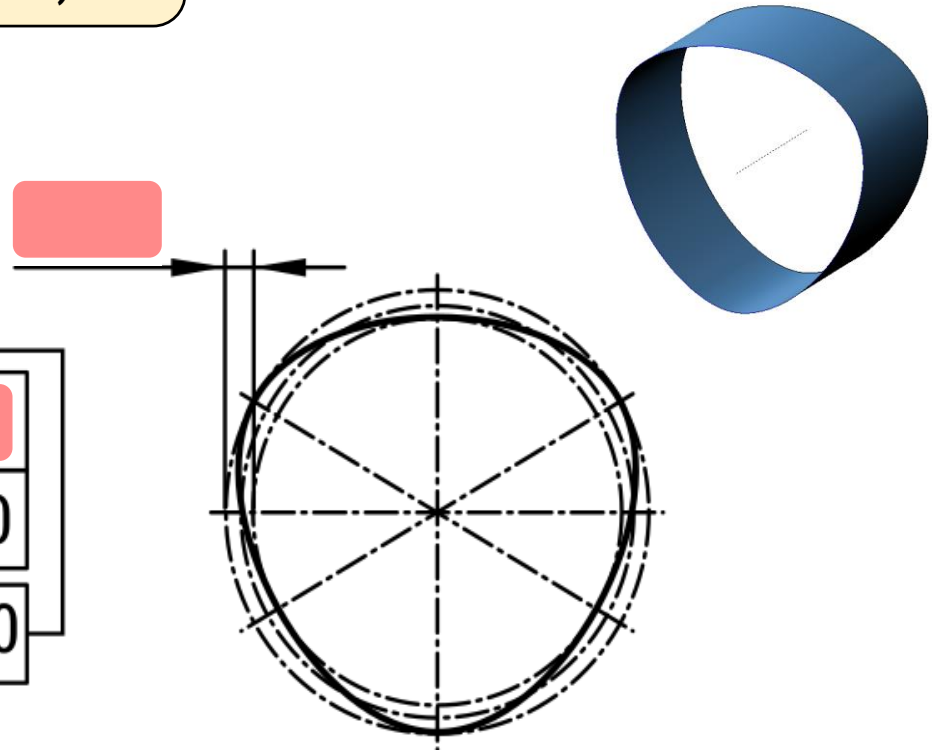
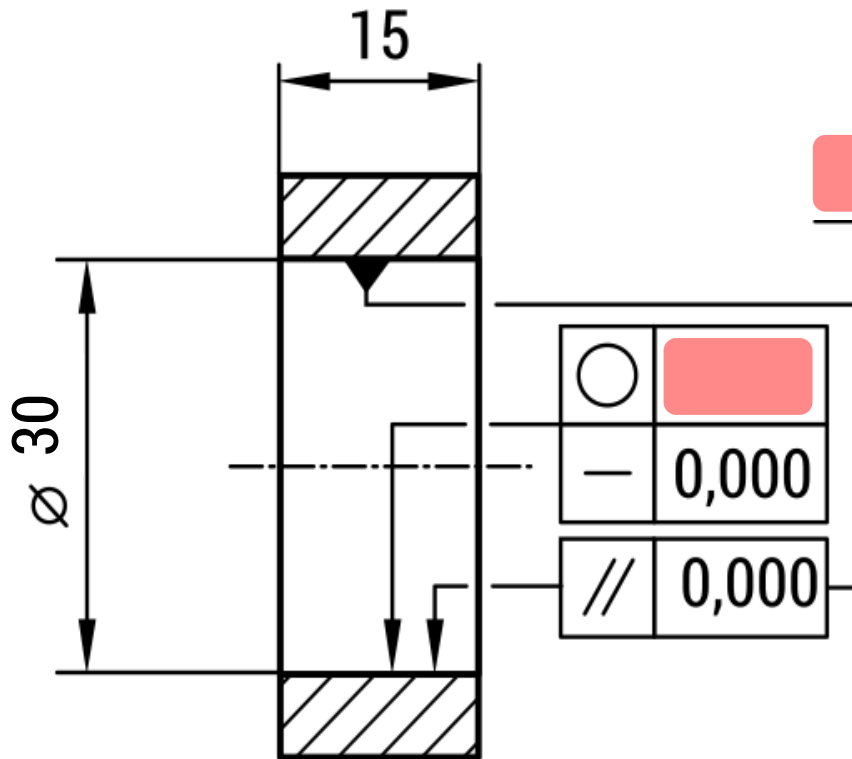
$\psi$

Relatives  
Lagerspiel

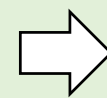
Oberflächengüte, Kantenbruch ...

## AUSGEWÄHLTE FORM DER RUNDHEIT

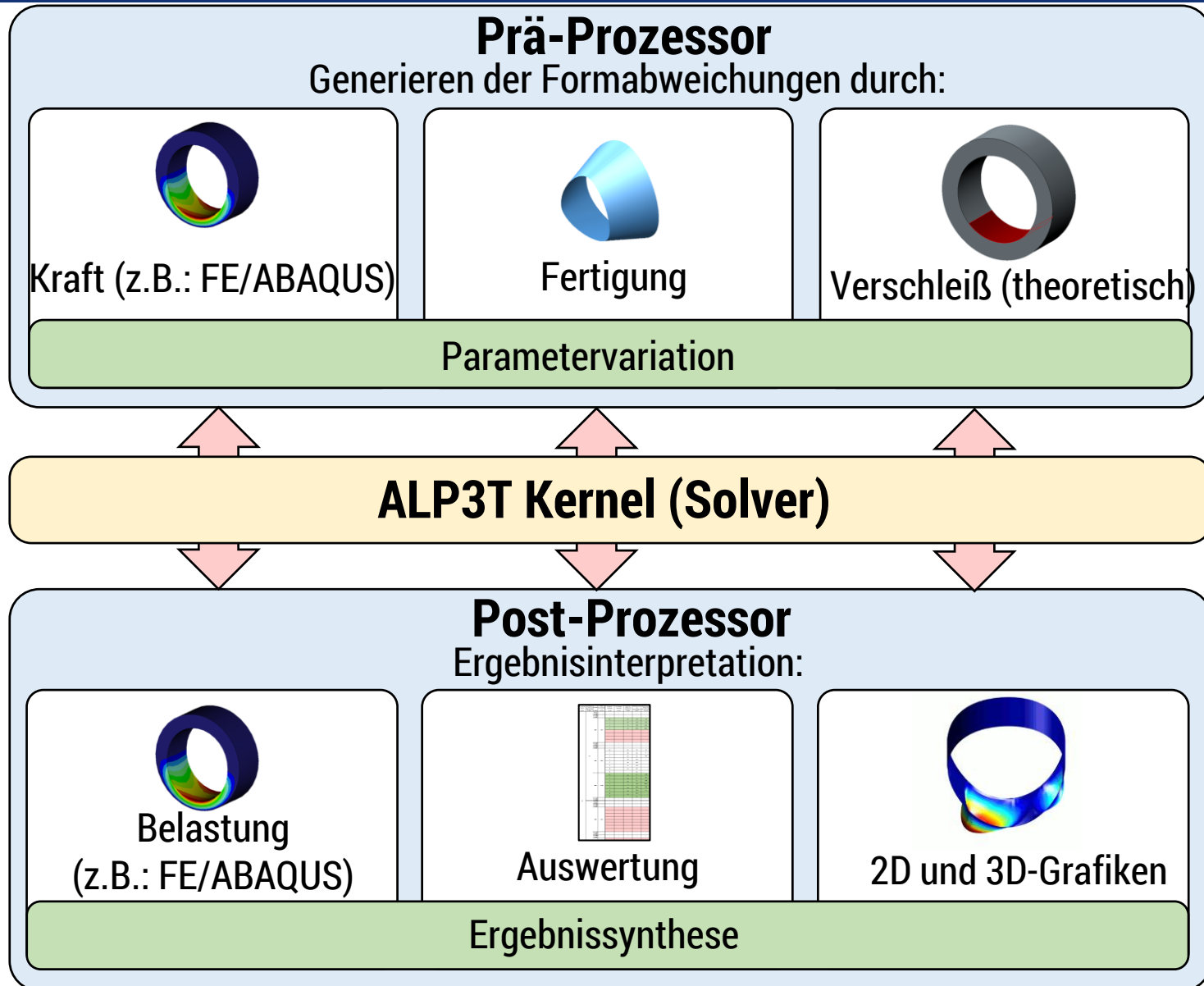
- Gleichdick ist eine der häufigsten Formen der Fertigungsabweichung (Dreibackenfutter)



Geradheit und Parallelität  
werden NULL gesetzt



Variation der Rundheit





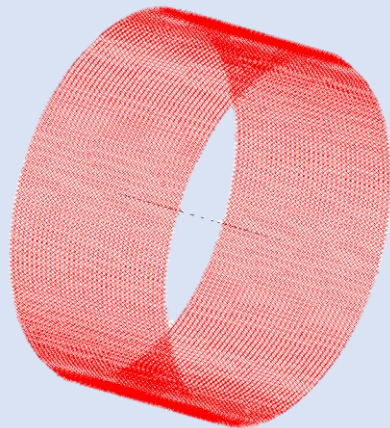
## H3-Polygon nach DIN 32711-1:

$$x(\alpha) = [Dm/2 - e * \cos(3 * \alpha)] * \cos(\alpha) - 3 * e * \sin(3 * \alpha) * \sin(\alpha)$$

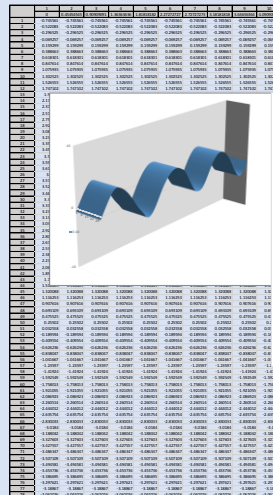
$$y(\alpha) = [Dm/2 - e * \cos(3 * \alpha)] * \sin(\alpha) - 3 * e * \sin(3 * \alpha) * \cos(\alpha)$$

mit  $0 < \alpha < 360^\circ$

### Prä-Prozessor



Netzauflösung:  
256 x 34 = 8704 Punkte



Verschiebungsfeld  
für das Gleichdick

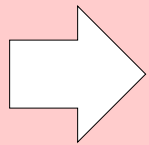
### INPUT

- $T_{en} = 50^\circ C$
- ISO VG 32
- $n = 4000 \text{ rpm}$
- $\bar{p} = 1.8 \text{ MPa}$
- [ $h_{min} = 7.5 \mu m$  bei  $0 \mu m$  Formabw.]
- Nominelle Welle

### ALP3T-Solver

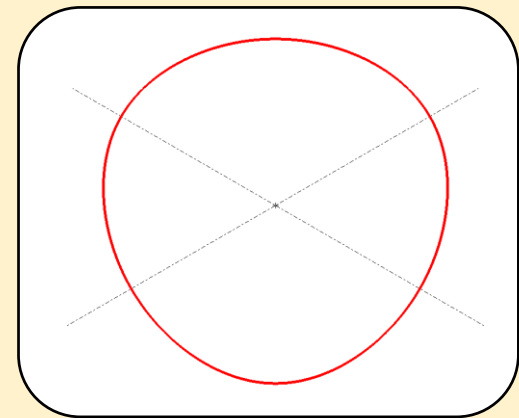
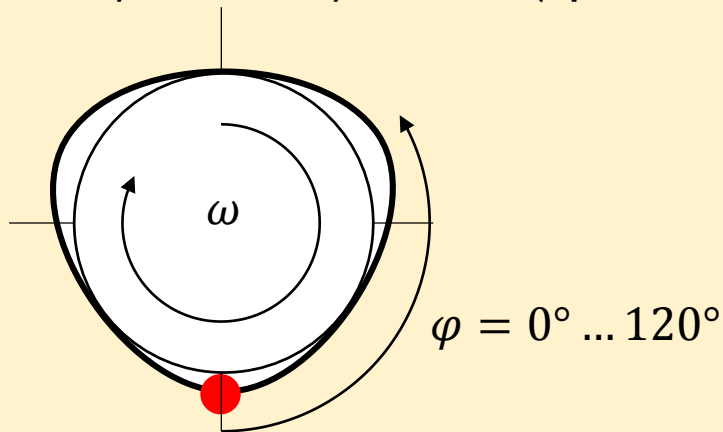
Lösung der Reynolds-  
Differentialgleichung für alle  
Punkte

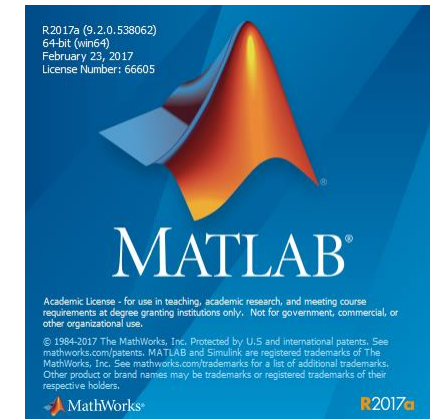
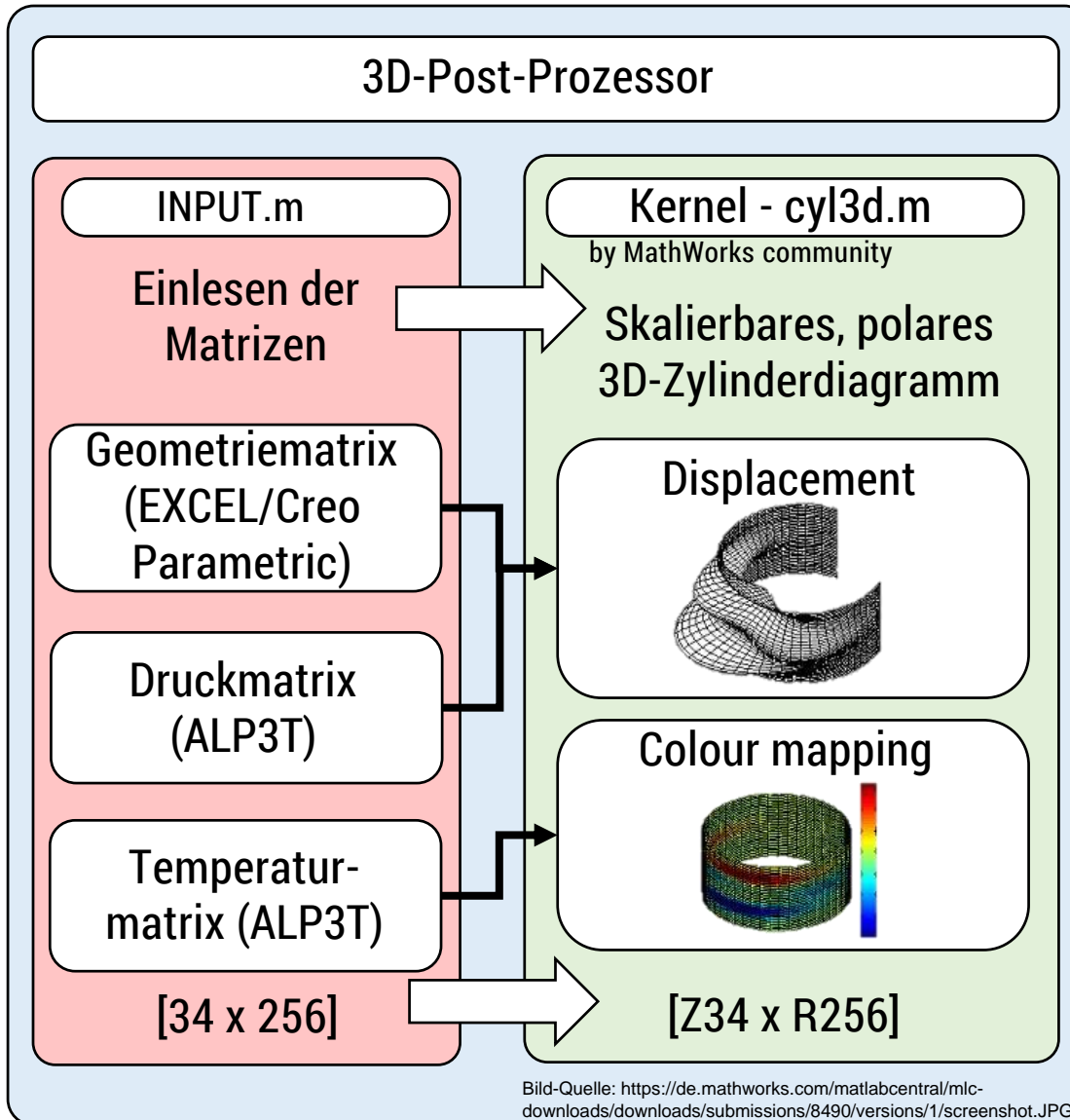
ALP3T model (numeric plain bearing simulation programme)



Simulation von  $0\mu m$  bis  $16\mu m$   
Formabweichung  
[Inkrement:  $0.5\mu m$ ,  $\varphi_i = 1.4^\circ$ ]

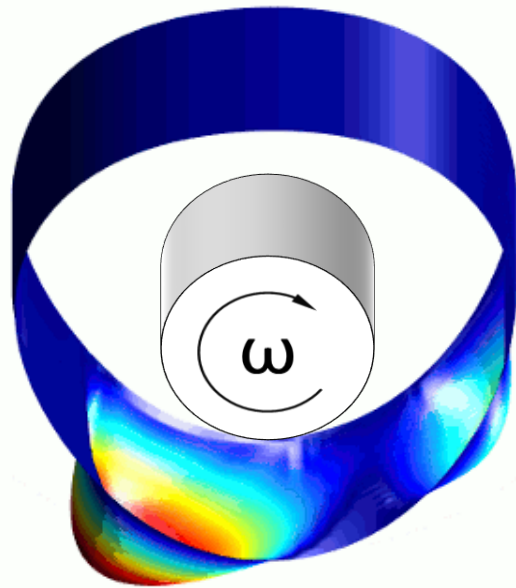
- Rotation der Formabweichung gegen die Drehrichtung der Welle  
[86 Schritte von  $\varphi = 0^\circ$  bis  $\varphi = 120^\circ$  (Spitze zu Spitze)]



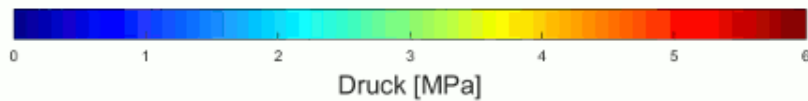


- Ergebnis bei 6  $\mu\text{m}$  Formabweichung für und Temperatur:

Max. Druck



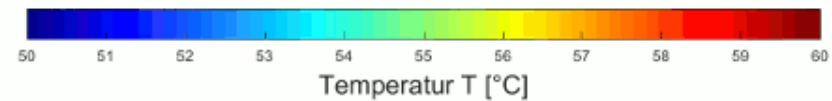
$p_{\text{max}} =$   
7.5682  
MPa



Max. Temperatur



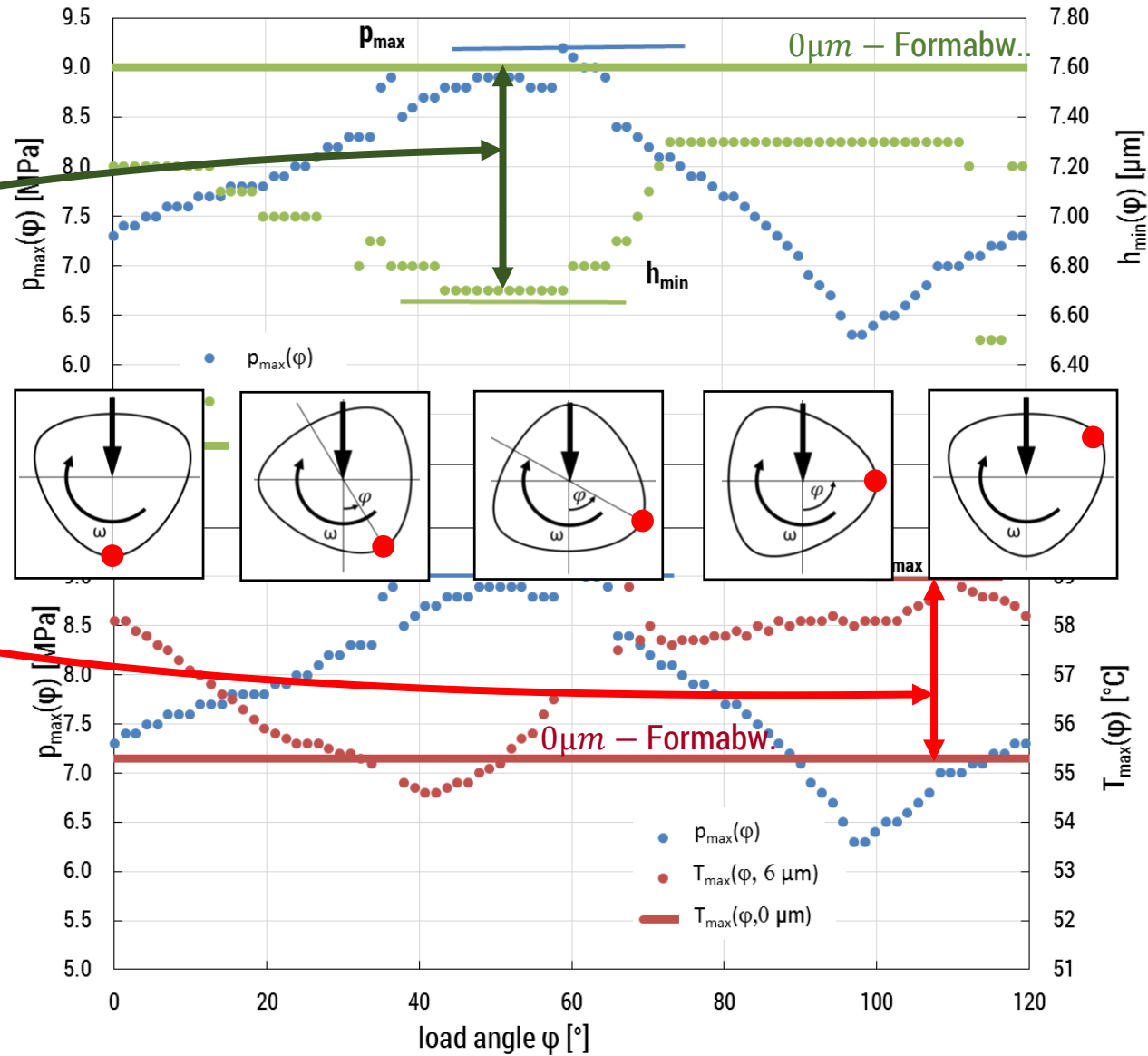
$T_{\text{max}} =$   
57.9314  
 $^{\circ}\text{C}$

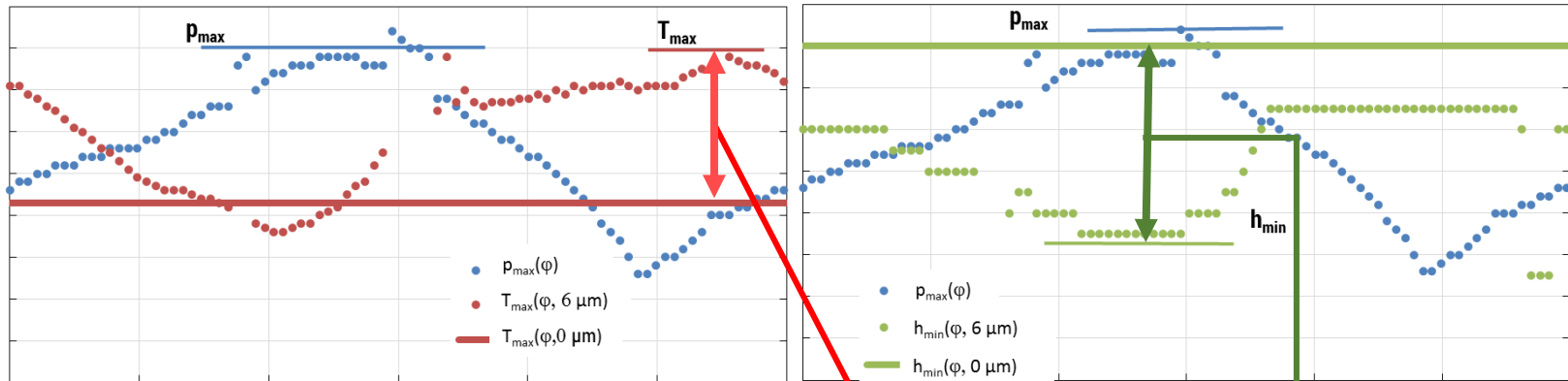


Min. Schmier-spalt

➤ Simulationsergebnis mit **6 μm** Formabweichung für Druck, minimale Schmier-spalthöhe und Temperatur. (Mitte des Lagers)

Temperatur





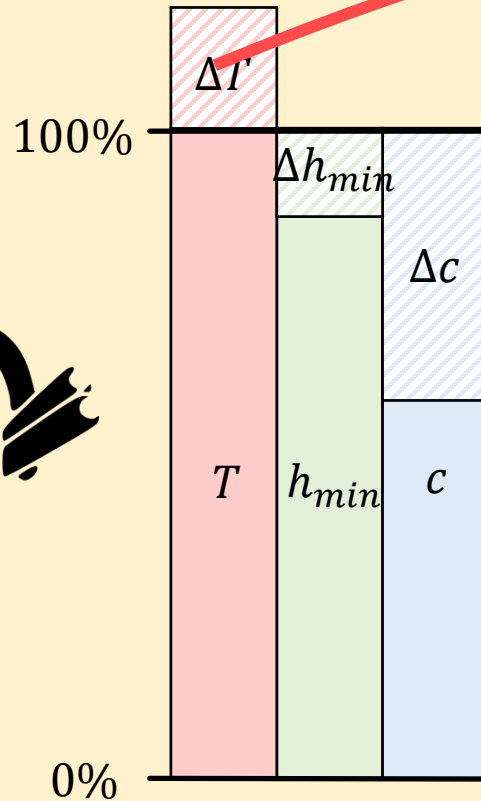
Der Worst-Case-Wert wird für jede Formabweichung in die Matrix überführt.

➔ Ausgewählte Parameter  
 $\Delta T [K]$   
 $\Delta h_{min} [\%]$   
 $\Delta c_{22} [\%]$

| bearing diameter<br>$\phi$ [mm] | specific bearing load with $b/d = 0,5$<br>$\bar{p}$ [Mpa] | speed<br>$n$ [rpm] | form deviation of roundness<br>$t_1$ [ $\mu m$ ] | temperature difference to the nominal bearing<br>$\Delta T$ [K] | reduction of the minimum lubrication gap<br>$\Delta h_{min}$ [%] | reduction of the stiffness in direction of load<br>$\Delta c_{22}$ [%] |
|---------------------------------|-----------------------------------------------------------|--------------------|--------------------------------------------------|-----------------------------------------------------------------|------------------------------------------------------------------|------------------------------------------------------------------------|
| $\psi = 2\text{‰}$              |                                                           |                    | 0                                                | 0                                                               | 0                                                                | 0                                                                      |
| 30                              | 1,8                                                       | 4000               | 0,5                                              | 0.1                                                             | 3                                                                | 3                                                                      |
|                                 |                                                           |                    | 1                                                | 0.3                                                             | 3                                                                | 6                                                                      |
|                                 |                                                           |                    | 2                                                | 0.7                                                             | 5                                                                | 16                                                                     |
|                                 |                                                           |                    | 4                                                | 1.8                                                             | 22                                                               | 62                                                                     |
|                                 |                                                           |                    | 6                                                | 3.5                                                             | 36                                                               | max                                                                    |
|                                 |                                                           |                    | 8                                                | 4.1                                                             | 59                                                               |                                                                        |
|                                 |                                                           |                    | 10                                               | max                                                             | 80                                                               |                                                                        |
|                                 |                                                           |                    | 12                                               |                                                                 | max                                                              |                                                                        |

## Nominelle Betriebsparameter

specific bearing load  $\bar{p}$   
 max. temp.  $T_{max}$   
 speed  $n$   
 bearing clearance  $h_{min}$   
 bearing stiffness  $c$

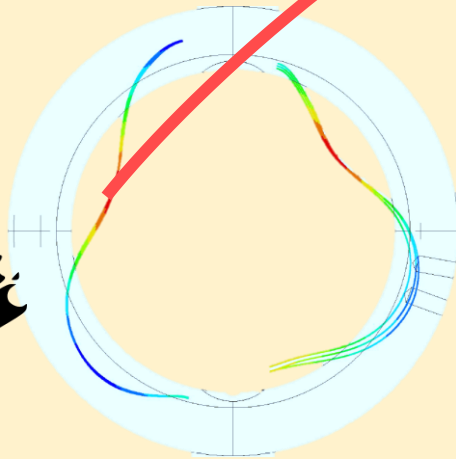


## Fall 1: Toleranzsynthese (Konstruktionsprozess)

| bearing diameter<br>$\phi$ [mm] | 0.008 |      | reduction of<br>the stiffness<br>direction of<br>load<br>$\Delta c_{22}$ [%] |
|---------------------------------|-------|------|------------------------------------------------------------------------------|
| 30                              | 1,8   | 4000 | 0                                                                            |
|                                 |       |      | 3                                                                            |
|                                 |       | 1    | 0.3                                                                          |
|                                 |       | 2    | 0.7                                                                          |
|                                 |       | 4    | 0.8                                                                          |
|                                 |       | 6    | 0.5                                                                          |
|                                 |       | 8    | 4.1                                                                          |
|                                 |       | 10   | max                                                                          |
|                                 |       | 12   | max                                                                          |
|                                 |       |      | 3                                                                            |
|                                 |       |      | 6                                                                            |
|                                 |       |      | 16                                                                           |
|                                 |       |      | 62                                                                           |
|                                 |       |      | max                                                                          |
|                                 |       |      | 59                                                                           |
|                                 |       |      | 80                                                                           |
|                                 |       |      | max                                                                          |

**Reale Geometrie**

diameter  $d$   
width  $b$   
roundness  $t_1$   
straightness  $t_2$   
parallelism  $t_3$



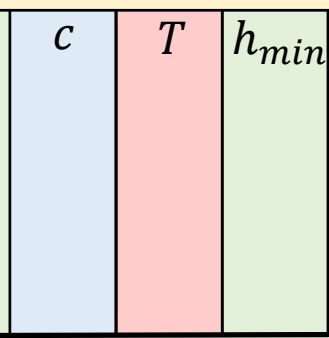
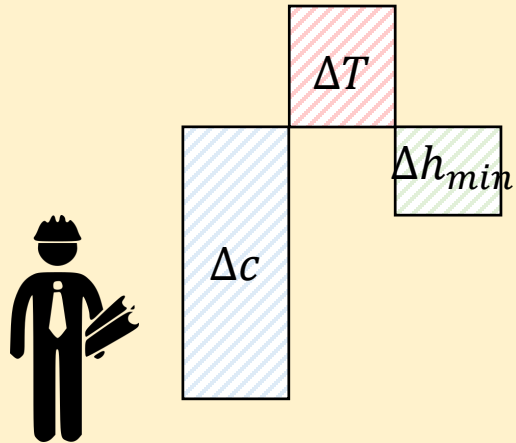
**Gemessenes  
Lager**

**Fall 2:  
Funktionale Analyse  
(Qualitätskontrolle)**

| bearing diameter<br>$\phi$ [mm] | specific bearing load with $b/d = 0,5$<br>$\bar{p}$ [Mpa] | speed<br>$n$ [rpm] | form deviation of roundness<br>$t_1$ [ $\mu\text{m}$ ] | temperature difference to the nominal bearing<br>$\Delta T$ [K] | reduction of the minimum lubrication gap<br>$\Delta h_{\min}$ [%] | reduction of the stiffness in direction of load<br>$\Delta c_{22}$ [%] |
|---------------------------------|-----------------------------------------------------------|--------------------|--------------------------------------------------------|-----------------------------------------------------------------|-------------------------------------------------------------------|------------------------------------------------------------------------|
| 30                              | 1,8                                                       | 4000               |                                                        | 0                                                               | 0                                                                 | 0                                                                      |
|                                 |                                                           |                    | 0,5                                                    | 0.1                                                             | 1                                                                 | 3                                                                      |
|                                 |                                                           |                    | 1                                                      | 0.3                                                             | 3                                                                 | 6                                                                      |
|                                 |                                                           |                    | 2                                                      | 0.7                                                             | 5                                                                 | 16                                                                     |
|                                 |                                                           |                    | <b>4</b>                                               | <b>1.8</b>                                                      | <b>22</b>                                                         | <b>62</b>                                                              |
|                                 |                                                           |                    | 6                                                      | 3.5                                                             | 36                                                                | max                                                                    |
|                                 |                                                           |                    | 8                                                      | 4.1                                                             | 59                                                                |                                                                        |
|                                 |                                                           |                    | 10                                                     | max                                                             | 80                                                                |                                                                        |
|                                 |                                                           | 12                 |                                                        | max                                                             |                                                                   |                                                                        |



### Zulässige Abweichungen der Betriebsparameter $\Delta$

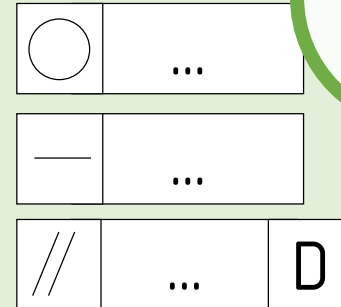


| bearing parameter | ISO bearing code with 2-5 digits | speed in 1/min | form deviation of hardness in μm | temperature difference to the normal bearing in °C | deviation of the mean lubrication gap in μm | residual of the stiffness in direction of load in % |
|-------------------|----------------------------------|----------------|----------------------------------|----------------------------------------------------|---------------------------------------------|-----------------------------------------------------|
| 0                 |                                  | 0              | 0                                | 0                                                  | 0                                           | 0                                                   |
| 0.5               |                                  | 0.5            | 0.5                              | 1                                                  | 3                                           | 3                                                   |
| 1                 |                                  | 1              | 0.3                              | 3                                                  | 6                                           | 6                                                   |
| 2                 |                                  | 2              | 0.7                              | 5                                                  | 16                                          | 16                                                  |
| 4                 |                                  | 4              | 1.8                              | 22                                                 | 62                                          | 62                                                  |
| 6                 |                                  | 6              | 3.5                              | 36                                                 | Max                                         | Max                                                 |
| 8                 |                                  | 8              | 4.1                              | 59                                                 | Max                                         | Max                                                 |
| 10                |                                  | 10             | Max                              | Max                                                | Max                                         | Max                                                 |

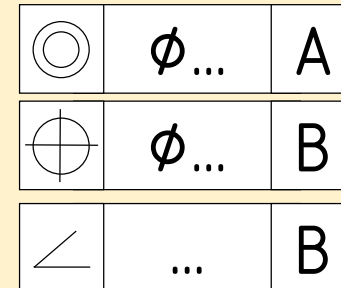
Wir wissen wie diese übersetzt werden können in ...

... aber wir wissen nicht wie diese übersetzt werden können in...

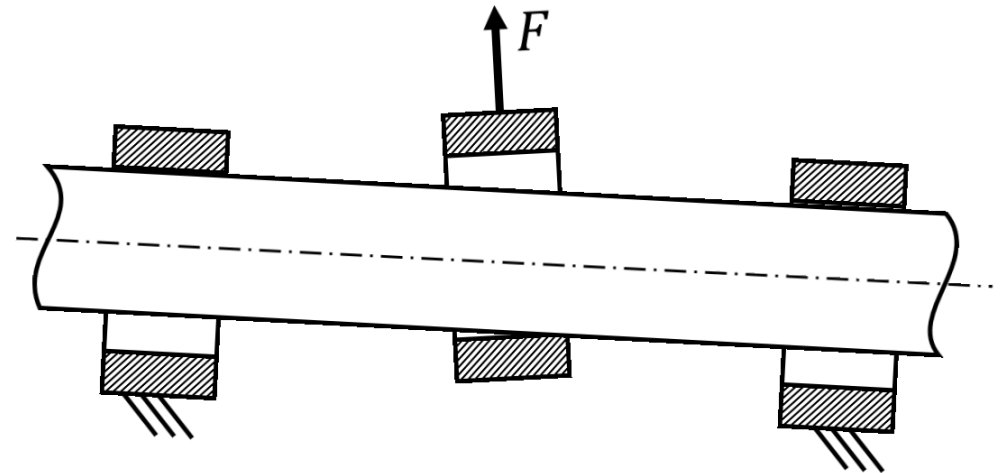
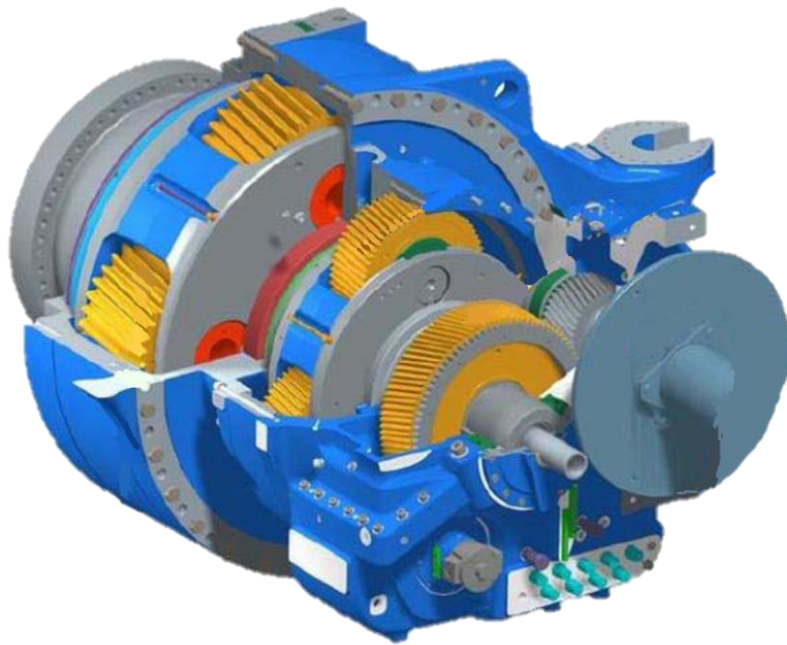
... maximale Formabweichungen...



... maximale Positions- und Richtungsabweichungen.



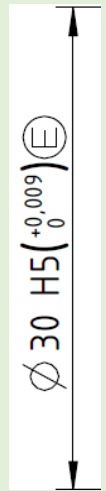
Einzellageranwendungen sind unüblich...



... Lager treten in Systemen auf.

## Geometrische Abweichungen an zylindrischen Gleitlagern

Dimension  
(Durchmesser)

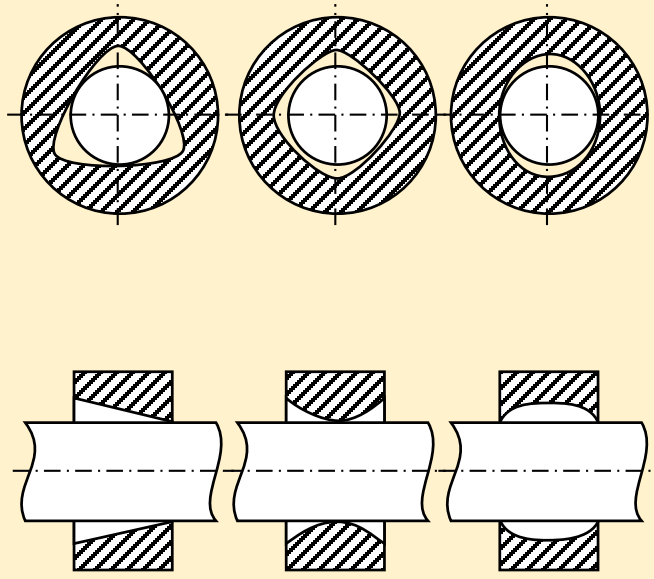


$\varnothing 30 H5 (+0,009 / 0) E$

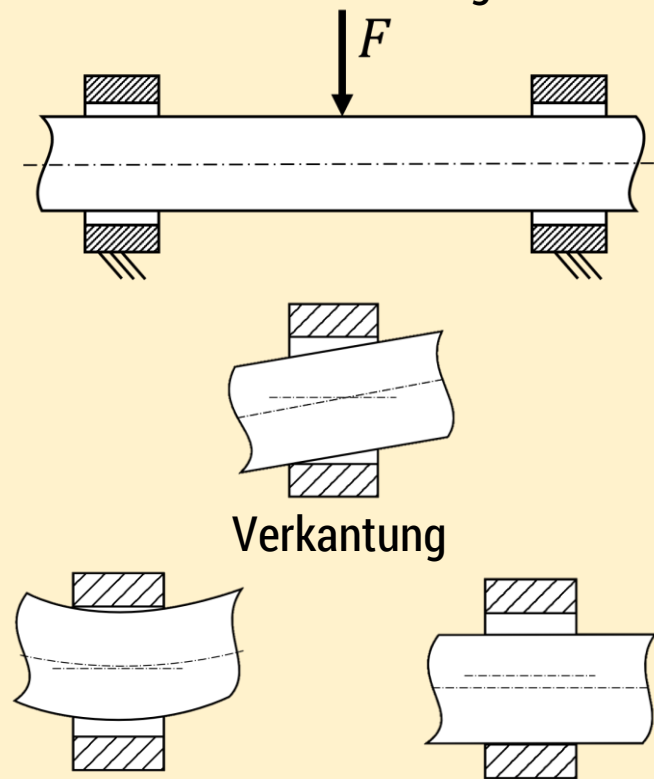
$\psi$

Relatives  
Lagerspiel

Formabweichungen (axial/radial)



Systemansatz  
-Ort und Richtung-



$F$

Verkantung

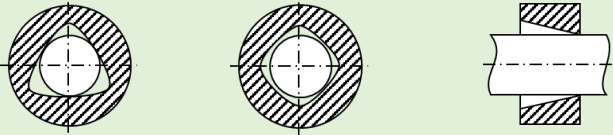
Biegung

Koaxialität

Oberflächengüte, Kantenbruch ...

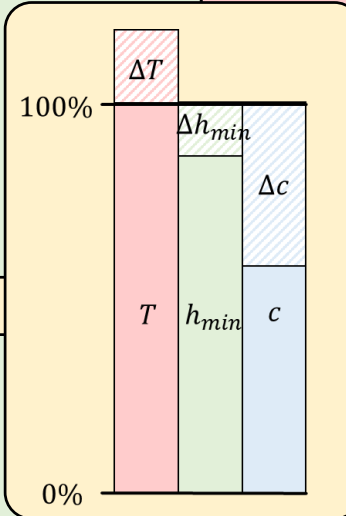
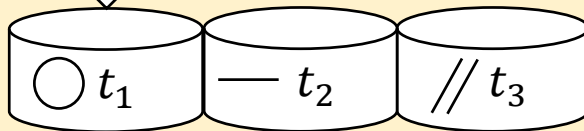
### Formabweichungen am Einzellager

Analyse von Formabw.

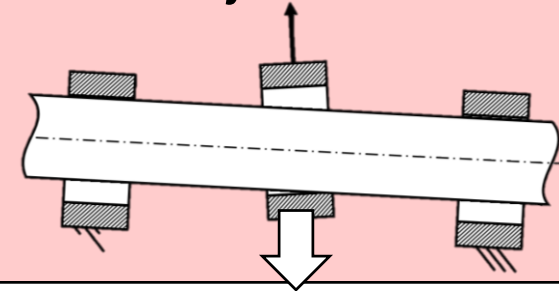


Parametervariation

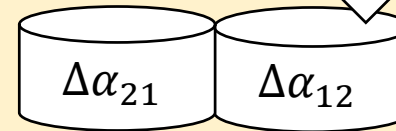
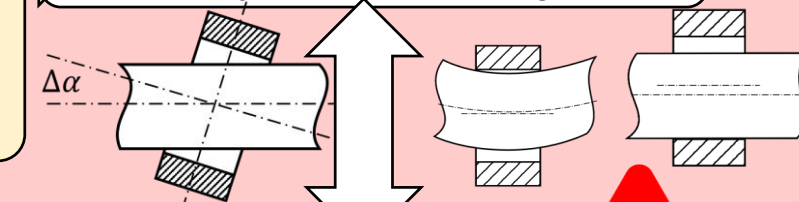
Worst-Case-Ableitung



### Geometrische Systemabweichungen

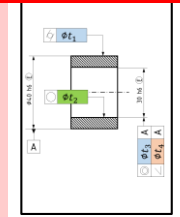
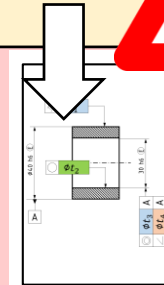
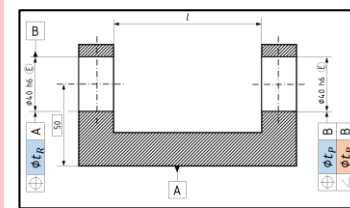
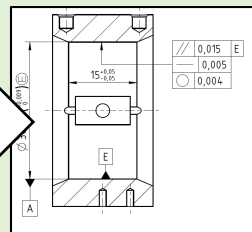


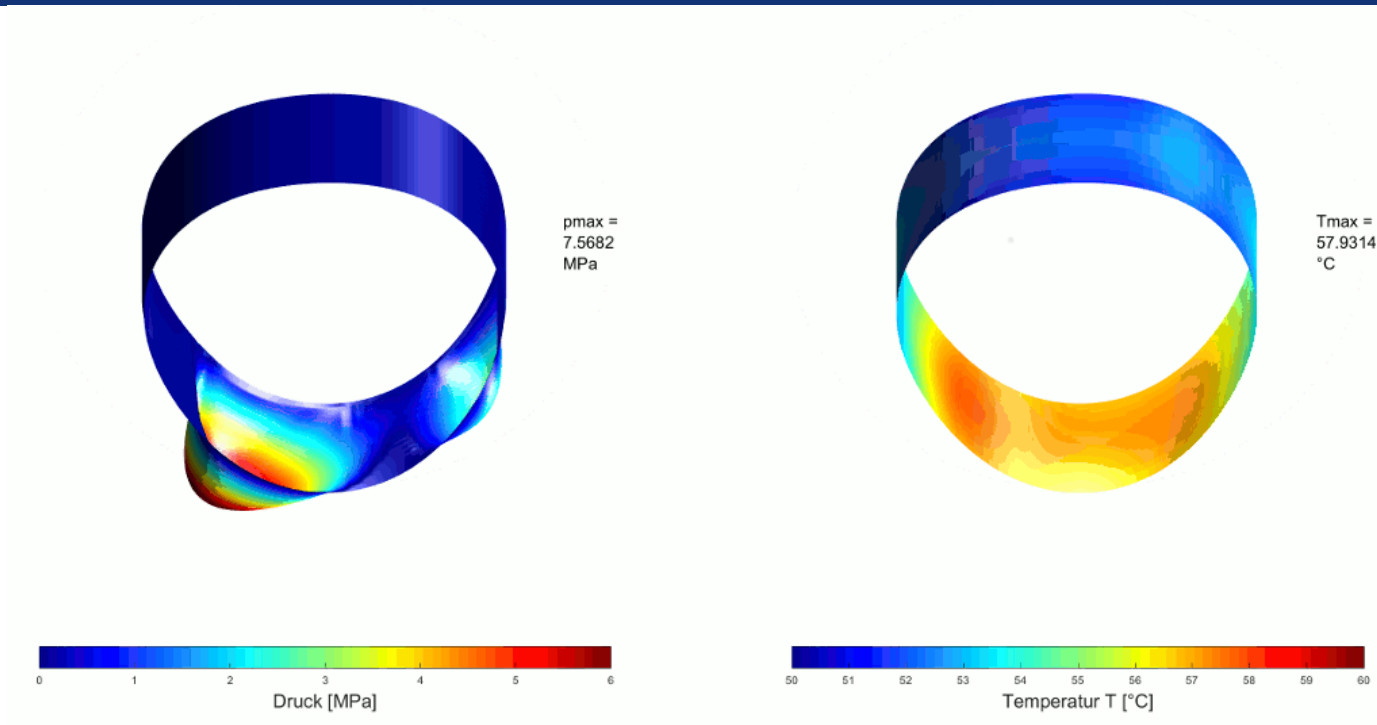
Werkzeugkasten für die Systemtolerierung



Datenbasis- Toleranzauswahlmatrix

0.008





## Vielen Dank für Ihre Aufmerksamkeit.

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