Layout process of a gear set – Step by Step
Layout process of a gear set

**Stage I**
Define Raw Dimensions
- \(a, b\)
  - (a: Centre distance)
  - (b: Face width)

**Stage II**
Define Macro Geometry
- \(m_n, z, \alpha, \beta, x, haP, hfP, \ldots\)

**Stage III**
Define Micro Geometry
- Step 1: Theoretical flank line modifications
- Step 2: Additional crowning to compensate tolerances
- Step 3: Profile modifications
Stage I

Layout process of a gear set: Stage I

**Input**
- Load, ratio
- Available space
- Material selection
- Design rules \((b/m_n, \ldots)\)

**Stage I**
Define Raw Dimensions
- \(a, b\)
  - \(a\): Centre distance
  - \(b\): Face width

**Optimisation aims**
- Weight
- Manufacturing costs
- Fitting into given space
Lay out of: Raw dimensions

Performances achieved by a raw sizing function
In a typical example here
Weight 19.5 .. 57.7 kg
(a: 220..355 mm; b: 35..135 mm)
Cost variation in the range of: 34-100% (with the same torque capacity)
Stage II

Layout process of a gear set: Stage II

**Input**
- Load, ratio
- Centre distance $a$
- Face width $b$
- Material

**Stage II**
- Define Macro Geometry
  - $m_n$, $z$, $\alpha$, $\beta$, $x$, $haP$, $hfP$, ...

**Optimisation aims**
- Torque capacity
- Lifetime
- Safety factors
- High efficiency
- High tooth profile
- ...

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Lay out of: Macro Geometry

Performances achieved by a Macro Geometry sizing function

In a typical example here

Torque capacity: 1020-1740 Nm ➞ 58-100%;
Losses: 0.12 - 0.50% ➞ 42-100%
Micropitting Slam: 0.7-2.7 ➞ 26-100% etc.

(with the same centre distance a and face width b)
Stage III: Layout of the Micro Geometry

The last phase in sizing a gear pair is to specify the flank line and profile modifications (also known as the "micro geometry").

To do so, the primary objective for which optimization has to be achieved: noise, service life, scuffing, micropitting or efficiency must be selected.

The calculation method for proving the effects achieved by micro geometry, the contact analysis under load ("Loaded Tooth Contact Analysis", or LTCA), is complex and time-consuming.

Unfortunately, the interpretation of LTCA results is not easy. All modifications applied on mating gears are interacting, so the decision of which modification to add or to change is difficult.
Stage III

Layout process of a gear set: Stage III

**Input**
- Macro geometry
- Manufacturing tolerances
- Shaft + Bearing
- Housing deformation

**Stage III**
- Define Micro Geometry
  - Step 1: Theoretical flank line modifications
  - Step 2: Additional crowning to compensate tolerances
  - Step 3: Profile modifications

**Optimisation aims**
- Even load distribution
- Compensate alignment errors by tolerances
- Noise, vibrations, losses, scoring, micropitting, ...
Stage III: Layout of the Micro Geometry

For a targeted sizing of the micro geometry, a step-by-step approach should be used, first specifying the flank line modification and then the profile modification.

A three-step process is proposed to perform a targeted sizing:

Step III/1: Layout of the theoretical flank line modifications
Step III/2: Including flank line manufacturing tolerances
Step III/3: Layout profile modifications
Step III/1: Layout of the theoretical flank line modifications

Proposition for an optimal flank line modification to get uniform load distribution for a single stage load (Input gear stage of the two-stage-industrial gearbox)
Step III/2: Including flank line manufacturing tolerances

Main manufacturing tolerances having impact on the load distribution (according ISO6336) are:
- $f_{Hb}$ for the lead variation of the gears ($f_{HbT1}+f_{HbT2}$)
- $f_{ma}$ for the axis misalignment in the contact plane

According ISO6336-1, Annex E, $K_{Hb}$ has to be calculated five times: Without tolerance, than with $+f_{Hb} \& +f_{ma}$, $+f_{Hb} \& -f_{ma}$, $-f_{Hb} \& +f_{ma}$, $-f_{Hb} \& -f_{ma}$. The highest $K_{Hb}$-value found will be used in the load capacity calculations.
Step III/2: Including flank line manufacturing tolerances

When no expertise is available, the following procedure can be applied. In ISO 6336-1, Annex B, for gears having a flank line modification to compensate for deformation, the crowning amount $C_b = f_{H\beta T}$

is proposed.

When such an additional modification is applied, clearly the load distribution over the face width as obtained in step 1 is not anymore uniform distributed. Therefore the face load factor $K_{Hb}$ will increase. The goal is to avoid edge contact in all possible combination of deviations.
Step III/2: Including flank line manufacturing tolerances

For all five combinations \((0, +f_{Hb} \& +f_{ma}, +f_{Hb} \& -f_{ma}, -f_{Hb} \& +f_{ma}, -f_{Hb} \& -f_{ma})\), the line load distribution in the operating pitch diameter has to be calculated and checked for edge contact.

Load distribution with different manufacturing deviation values.
Step III/3: Profile modifications

When the flank line modification is defined, the third step is to specify the profile modifications. Important features such as noise, losses, micropitting, scoring and wear can be improved by profile modifications. Therefore the layout criteria must be defined. Then the corresponding strategy is used.

Layout for low-noise:

Contact shock: Gear pair meshing and path of contact calculated with LTCA, showing the prolonged contact at start and end of the mesh.

PPTE: Peak-to-Peak Transmission error
Step 3: Use of a ‘modification sizing’ tool to find optimum design

Optimization of profile modifications in a case-by-case manner is extremely time-consuming and demanding.

“Analysis of modification variants” tool: Profile crowning variants

Tab. I: Contains all modifications which will not be changed

<table>
<thead>
<tr>
<th>No.</th>
<th>Gear</th>
<th>Flank</th>
<th>Type of modification</th>
<th>Value [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Gear 1</td>
<td>both</td>
<td>Crowning</td>
<td>15.00000</td>
</tr>
<tr>
<td>1</td>
<td>Gear 1</td>
<td>both</td>
<td>Helix angle modification, parallel</td>
<td>57.00000</td>
</tr>
<tr>
<td>1</td>
<td>Gear 2</td>
<td>both</td>
<td>Crowning</td>
<td>14.00000</td>
</tr>
<tr>
<td>1</td>
<td>Gear 2</td>
<td>both</td>
<td>Helix angle modification, parallel</td>
<td>40.00000</td>
</tr>
</tbody>
</table>

Tab. II: Definition of modifications which will be varied (here: Profile crowning)

<table>
<thead>
<tr>
<th>No.</th>
<th>Gear</th>
<th>Sync</th>
<th>Flank</th>
<th>Type of modification</th>
<th>Number of step</th>
<th>Value (min) [μm]</th>
<th>Value (max) [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Gear 1</td>
<td>1</td>
<td>both</td>
<td>Profile crowning (barreling)</td>
<td>7</td>
<td>40.00000</td>
<td>100.00000</td>
</tr>
<tr>
<td>2</td>
<td>Gear 2</td>
<td>2</td>
<td>both</td>
<td>Profile crowning (barreling)</td>
<td>7</td>
<td>25.00000</td>
<td>85.00000</td>
</tr>
</tbody>
</table>
Step III/3: Use of a ‘modification sizing’ tool to find optimum design

Table with numbered variants and selected main results
Step III/3: Use of a ‘modification sizing’ tool to find optimum design

Two charts with results (PPTE and efficiency) of 25 modification variants
Red: At 100 percent load; Blue: At 75 percent load
Step III/3: Use of a ‘modification sizing’ tool to find optimum design

“Analysis of modification variants” tool: Tip relief variants

Tab. I: Contains all modifications which will not be changed

<table>
<thead>
<tr>
<th>No.</th>
<th>Gear</th>
<th>Flank</th>
<th>Type of modification</th>
<th>Value [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Gear 1</td>
<td>both</td>
<td>Crowning</td>
<td>15.0000</td>
</tr>
<tr>
<td>1</td>
<td>Gear 1</td>
<td>both</td>
<td>Helix angle modification, parallel</td>
<td>57.0000</td>
</tr>
<tr>
<td>1</td>
<td>Gear 2</td>
<td>both</td>
<td>Crowning</td>
<td>14.0000</td>
</tr>
<tr>
<td>1</td>
<td>Gear 2</td>
<td>both</td>
<td>Helix angle modification, parallel</td>
<td>40.0000</td>
</tr>
</tbody>
</table>

Tab. II: Definition of modifications which will be varied (here arc-like tip relief)

<table>
<thead>
<tr>
<th>No.</th>
<th>Gear</th>
<th>Synchronize with</th>
<th>Flank</th>
<th>Type of modification</th>
<th>Number of steps</th>
<th>Value (min)</th>
<th>Value (max)</th>
<th>Factor 1 (min)</th>
<th>Factor 1 (max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Gear 1</td>
<td>1 both</td>
<td>both</td>
<td>Tip relief, arc-like</td>
<td>15</td>
<td>10.0000</td>
<td>150.0000</td>
<td>0.2000</td>
<td>2.5000</td>
</tr>
<tr>
<td>2</td>
<td>Gear 2</td>
<td>1 both</td>
<td>both</td>
<td>Tip relief, arc-like</td>
<td>15</td>
<td>10.0000</td>
<td>150.0000</td>
<td>0.2000</td>
<td>2.5000</td>
</tr>
</tbody>
</table>
Step III/3: Use of a ‘modification sizing’ tool to find optimum design

Display of 225 solutions, when the parameters (Tip relief (“Value mm”) and Length (“Factor 1”) of an arc-like tip relief are varied.

Here: Peak-to-Peak-Transmission-Error (PPTE)
Step III/3: Use of a ‘modification sizing’ tool to find optimum design

Display of 225 solutions, when the parameters (Tip relief (“Value mm”) and Length (“Factor 1”) of an arc-like tip relief are varied.

Here: **Maximum Hertzian Pressure**
Step III/3: Use of a ‘modification sizing’ tool to find optimum design

Display of 225 solutions, when the parameters (Tip relief (“Value mm”) and Length (“Factor 1”) of an arc-like tip relief are varied.

Here: Efficiency
Step III/3: Use of a ‘modification sizing’ tool to find optimum design

Display of 225 solutions, when the parameters (Tip relief (“Value mm”) and Length (“Factor 1”) of an arc-like tip relief are varied.

Here: Safety factor against Micropitting
Step III/3: Use of a ‘modification sizing’ tool to find optimum design

Display of 225 solutions, when the parameters (Tip relief (“Value mm”) and Length (“Factor 1”) of an arc-like tip relief are varied. Here: Safety factor against Tooth Flank Fracture (TFF)
Step III/3: Finish

End of Step III/3:
- Make a first selection of best variants (profile modifications)
- Check the LTCA results of these variants
- Choose the best over all variant
- Recheck load distribution *)

Method is successfully tested:
The time used by the design engineer to find optimum modifications for both stages of a gearbox was 15 minutes.

*) Normally the load distribution as defined in Step III/2 is typically not much changed by the added profile modifications.
Considering housing and/or planet carrier stiffness

In any KISSsys model the housing stiffness can be considered using a stiffness matrix imported from a FEM software. The resulting housing deformation at the bearing positions are shown in a results table. The deformations are assigned to the bearings (typically outer ring) in the shaft calculation and considered in the gear contact analysis.

<table>
<thead>
<tr>
<th></th>
<th>b1</th>
<th>b2</th>
<th>b1</th>
<th>b2</th>
<th>b1</th>
<th>b2</th>
</tr>
</thead>
<tbody>
<tr>
<td>s1</td>
<td>-0.21515</td>
<td>-0.24219</td>
<td>-0.2166</td>
<td>-0.24505</td>
<td>-0.22307</td>
<td>-0.24986</td>
</tr>
<tr>
<td>u_x</td>
<td>-0.14555</td>
<td>0.052544</td>
<td>-0.18155</td>
<td>0.17393</td>
<td>-0.12539</td>
<td>0.27237</td>
</tr>
<tr>
<td>u_y</td>
<td>0.3207</td>
<td>0.31393</td>
<td>0.11315</td>
<td>0.10758</td>
<td>-0.21719</td>
<td>-0.21053</td>
</tr>
</tbody>
</table>

Bearing outer ring displacements in mm (x, y: horizontal; z: vertical)
Example: Use of the 3-step-modification sizing procedure with a industrial 2-stage gearbox

For a typical industrial two-stage parallel shaft reducer the modifications are optimized using the 3-step method. The process is repeated twice, with and without considering housing stiffness, to get an indication on the influence of the housing.

First the load distributions of the two gear pairs without modifications are calculated. The face load factors are calculated according to Annex E in ISO6336-1, using the axis deformations from the shaft calculation.

<table>
<thead>
<tr>
<th>Gear Pair</th>
<th>$K_{Hβ}$ Without housing deformation</th>
<th>$K_{Hβ}$ With housing deformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSS (High speed stage)</td>
<td>1.17</td>
<td>1.16</td>
</tr>
<tr>
<td>HSS (Low speed stage)</td>
<td>1.30</td>
<td>1.32</td>
</tr>
</tbody>
</table>

Face load factors without flank line modifications
Proposed layout procedure Step III/1 to III/3

- The time used by the design engineer to find optimum modifications for both stages was 15 minutes.
- The optimum flank line modifications as defined in Step 1 are only slightly different when housing stiffness is considered (only 10% change in the helix angle modification value).
- The additional modifications in Step 2 and the profile modifications in Step 3 are identical with and without consideration of housing stiffness.
- The additional crowning added in Step 2 to compensate for manufacturing tolerances is much bigger (5 times) than the difference between modifications in Step 1 used to compensate shaft deflection with and without considering housing stiffness. Therefore, for practice-oriented solutions the influence of the housing stiffness is so small that it is negligible.
Conclusion

Raw sizing of major dimensions (Stage I), then fins sizing of macro geometry parameters (Stage II) and finally optimization of flank line and profile modifications (Stage III) is a very successful procedure to find the best gear pair for a specific application.

The last stage, optimization of micro modifications is a difficulty and time consuming task. The three-step methodology has proven highly successful since it was introduced two years ago. The layout of the modifications for an industrial gearbox shows that for a gearbox with parallel shafts including external forces acting on it, the housing deformations have an insignificant influence on the resulting gap in the meshing of the gears.

This method can also be used in applications such as wind power, ship transmission systems, or helicopters in which it is demanding to define the modifications due to the extreme load spectrum or high housing deflections.
THANK YOU for your attention!