KISSsoft 03/2016 – Instruction 068a

Sizing of Topological Modification of Bevel Gears

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Contents

1 Introduction

This instruction explains the background and the usage of the topological modification calculation for bevel gears. In order to use the calculation, experience on the 3D model generation in KISSsoft is pre-requisite. Please refer to [[1]] for the detailed instruction for generating 3D geometry of bevel gear.

2 Calculation instruction

2.1 User interface

The calculation is available under the menu Calculation > Topological modifications. Figure 1 shows the calculation window.

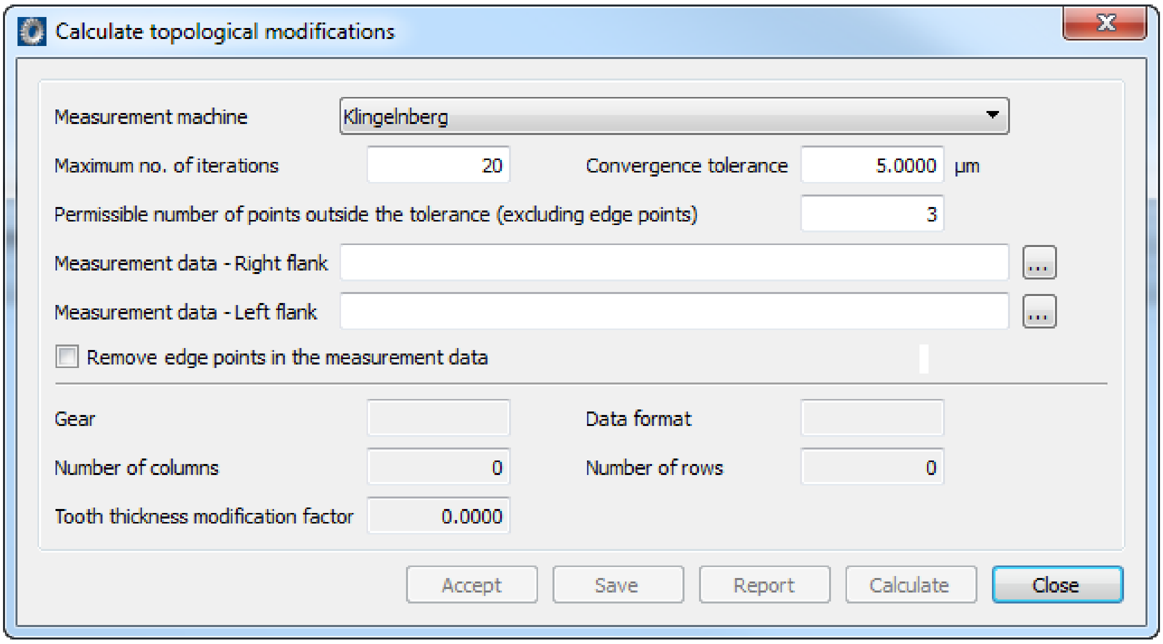


Figure 1 Input window for topological modification calculation

(1) The "**Measurement machine**" selects the format of the measurement data file. There four different types are available [Klingelnberg, Gleason, TBevel (Klingelnberg), TBevel (Gleason), Zeiss]. Here, the TBevel® types are the measurement report format from Wenzel [[2]] for Klingelnberg and Gleason machine. You should be very careful when you import the measurement grid data not to mix up the types and/or gears and/or flanks. Otherwise, the program will generate an error message.

(2) The "**Maximum no. of iterations**" sets the maximum number of iteration steps during the calculation. If the calculation doesn't converge until the maximum iterations, the calculation will stop and you will find the message in the report "NOT CONVERGED: Maximum iterations reached".

(3) The "**Convergence tolerance**" sets the maximum deviation between the given measurement data and the 3D geometry model with the topological modification. The deviation is defined as the minimum Euclidean distance between the given grid point to the modified surface.

(4) The "**Permissible number of points outside the tolerance**" sets the allowable number of points having bigger deviation than the convergence tolerance. For example, in some cases, only one or two points are exceeding the tolerance and blocks the program to converge. In that case, it's better to ignore these points if the points are from measurement noise.

(5) The “**Measurement data**” sets the full path of the measurement data files to be used as a target flank surface. In order to follow the convention, the Klingelnberg type machine has separate files for the right and the left flank, while Gleason and Zeiss machines have both flanks data in a single file.
(6) The “**Remove edge points in the measurement data**” option is used to ignore the edge points (at tooth ends and tip diameter) in the measurement data during the calculation. Refer to 2.2.2 for details.
(7) The “**Gear**” shows if the measurement data is for pinion or gear. This is determined from the measurement data.
(8) The “**Data format**” shows the actual data format of the defined measurement data by checking the coordinate system of the data. If the data format is conflicting with the setting of “**Measurement machine**”, the program will use the actual data format. However, it’s always recommended to check if your setting is correct, when you have the conflict.
(9) The “**Number of columns**” and “**Number of rows**” shows the data determined from the measurement data report.
(10) The “**Tooth thickness modification coefficient**” is calculated to give initial tooth thickness modification from the given measurement data. If you accept the calculated value, the program will proceed with the proposed value for the calculation. Otherwise, it will proceed with the original tooth thickness modification coefficient. Refer to 2.2.1 for details.
(11) You can do the calculation by the “**Calculate**” button. When the calculation finishes, whatever it’s converged or not, the “**Save**” and “**Report**” buttons are activated enabling to check the report. The “**Report**” button shows the deviation and the modification values for each steps with the convergence result. It also contains description of the reason for the error when it happens. The “**Save**” button saves the last step of the calculated topological modification for each flank, whatever the calculation converged or not. By default, the saved file has the name of “User defined name”+Gear1RF.dat for right flank of gear 1 and “User defined name”+Gear1LF.dat for left flank of gear 1. The “**Accept**” button is activated only after you saved the modification template. When you accept the result, the proposed tooth thickness modification coefficient (if you applied) and the topological modification templates are transferred to the main calculation file. In this case, all the previous modifications of the corresponding gear will be removed.

2.2 Calculation settings

2.2.1 Tooth thickness

KISSsoft does not allow negative values for the topological modification meaning that it does not allow to increase the tooth thickness by the modification and works as the way of removing the material from the initial model. Thus, the initial tooth thickness of the model should be big enough to completely cover the target tooth flank. The user can increase the tooth thickness either by changing the tooth thickness tolerance or by changing the tooth thickness modification coefficient. However, it’s recommended to set the tooth thickness tolerance to no backlash condition and then change only the thickness modification coefficient for simpler handling.
If you don’t have enough tooth thickness, the program will generate a warning message with the recommended modification coefficient as shown in Figure 2. You can select ‘Yes’ if you want to proceed the calculation with the recommended value, and then the value will be transferred to the main window when you accept the final modification template after the calculation. Please note that the value should be used only for the 3D model generation and not for other purposes such as strength calculation.

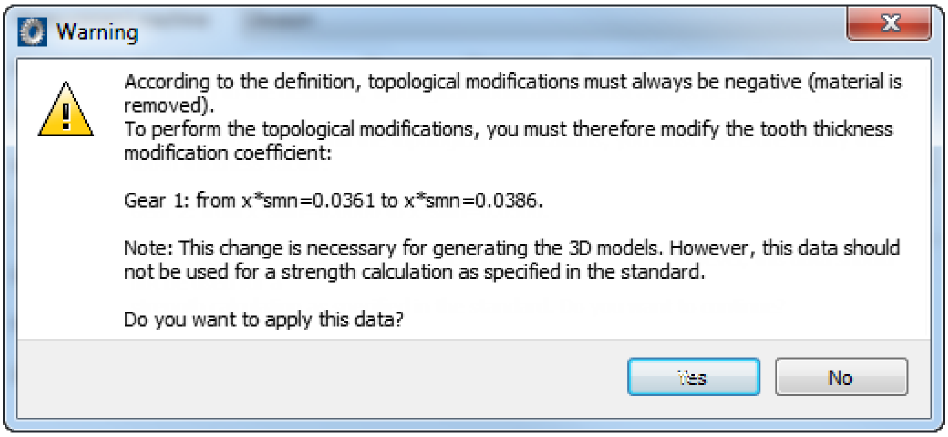
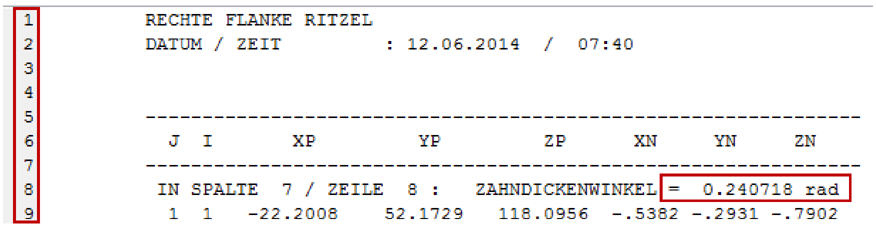


Figure 2 Warning message for tooth thickness modification coefficient

2.2.2 Standard format of measurement data

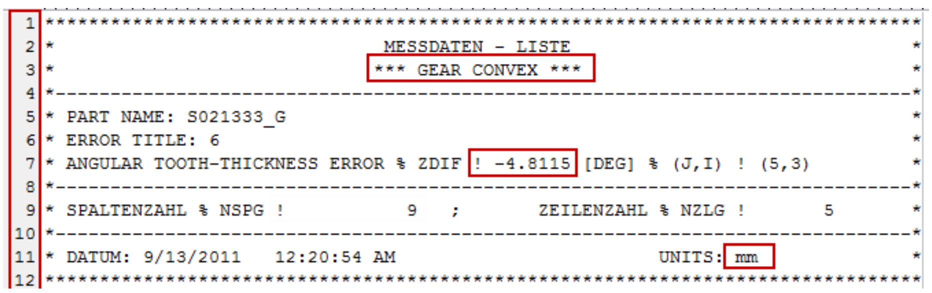
In order to read the measurement data correctly, the user should provide the data in a standard format. Especially the report header should have the correct standard format. Otherwise, the program will generate an error message or the calculation doesn't proceed correctly. The best practice is to refer the header of the measurement data report generated by KISSsoft. In the header format, it's most important to keep the correct line number, for example in the Klingelnberg data, the tooth thickness angle should be in line 8 as radian and the measurement data should start from line 9 as shown in Figure 3. The line numbers are shown only for the explanation and not included in the actual report.



```
1          RECHTE FLANKE RITZEL
2          DATUM / ZEIT          : 12.06.2014  /  07:40
3
4
5          ---------------------------------------------------------------
6            J  I       XP          YP          ZP       XN      YN      ZN
7          ---------------------------------------------------------------
8           IN SPALTE  7 / ZEILE  8 :   ZAHNDICKENWINKEL = 0.240718 rad
9            1  1    -22.2008     52.1729    118.0956  -.5382 -.2931 -.7902
```

Figure 3 Measurement report format of Klingelnberg machine

In the Gleason data, the calculation flank is classified by “GEAR CONVEX (or TELLERRAD KONVEX)”, “GEAR CONCAVE (or TELLERRAD KONKAV)”, “PINION CONVEX (or RITZEL KONVEX)”, “PINION CONCAVE (or RITZEL KONKAV)” as shown in line 3. Note that the Gleason report has both the convex and concave flank data in a single file. Then, the tooth thickness angle should be in the line 7 followed by ‘!’ in degrees and the units should be indicated in the header either as “mm” or “in”. The measurement data should start from line 15 as shown in Figure 4.



```
 1 ***************************************************************************
 2 *                             MESSDATEN - LISTE                            *
 3 *                            *** GEAR CONVEX ***                           *
 4 *--------------------------------------------------------------------------*
 5 * PART NAME: S021333_G                                                     *
 6 * ERROR TITLE: 6                                                           *
 7 * ANGULAR TOOTH-THICKNESS ERROR % ZDIF ! -4.8115 [DEG] % (J,I) ! (5,3)     *
 8 *--------------------------------------------------------------------------*
 9 * SPALTENZAHL % NSPG !          9    ;       ZEILENZAHL % NZLG !      5    *
10 *--------------------------------------------------------------------------*
11 * DATUM: 9/13/2011    12:20:54 AM                          UNITS: mm      *
12 ***************************************************************************
```

Figure 4 Measurement report format of Gleason machine

2.2.3 Validity of the measurement data

The calculation is using numerical optimization process based on the deviation between the given measurement data and the 3D model from KISSsoft. Thus, it can generate an error during the calculation caused from the original measurement data. So, you should note the following points very carefully.

(1) The calculation assumes the measurement data is defined for the nominal flank. Thus the data including the points outside the nominal flank, it's giving an error and stops the calculation.

(2) If the measurement data are highly irregular, the calculation may suffer from the convergence and give an error.

(3) When calculating the deviation, we add boundary values on the edges (side I and side II of the face width and at the root form and the tip diameters) automatically to calculation the modification template. The edge values are generated from linear extrapolation from the neighboring measurement data. Thus, if the given measurement data have the values close to the edges, it's prone to give an error during the calculation.

For example, if the measurement data have no margin from the side boundaries as shown in Figure 5, the calculated topological modification can give extremely high values on the edge as shown in Figure 6 (left). Note that even you can generate the model successfully with this modification, the model can have higher curvature changes on the surface which should be avoided in the manufacturing process. Instead, if the edge points are excluded in the calculation, the calculated topological modification shows much smoother result as shown in Figure 6 (right). Thus, it's highly recommended to provide the measurement data having enough margin from the edges to be on the safe side. If you can't provide the proper data, you can use the option "**Remove edge points in the measurement data**" to ignore the edge points during the calculation.

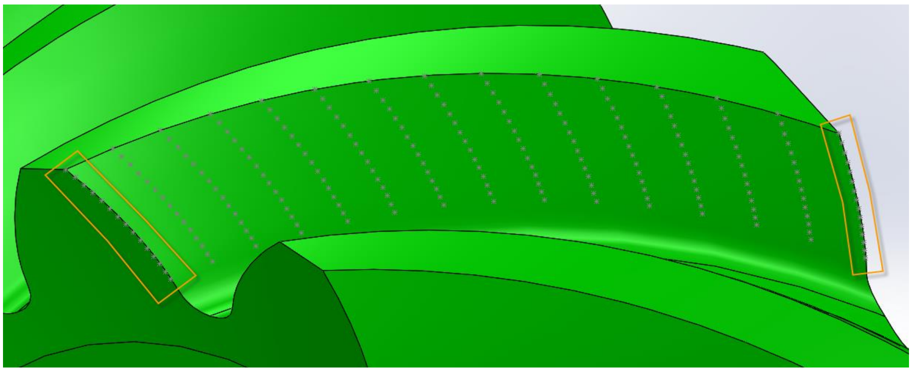


Figure 5 Measurement data having the points too close to the side boundaries

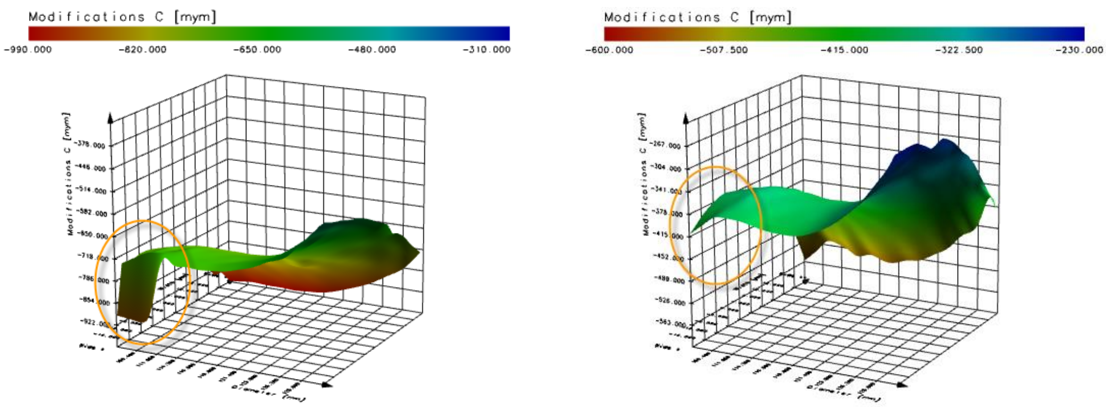


Figure 6 Topological modification with edges points (left) and without edge points (right)

(4) In addition, the calculation is based on the assumption that the reference point is positioned at the middle of the face width. The possible reason for this is that the measurement data have different margins on side I and II. In this case, the program is not working properly and need a new data having same margins and therefore the reference point is positioned at the middle of face width.

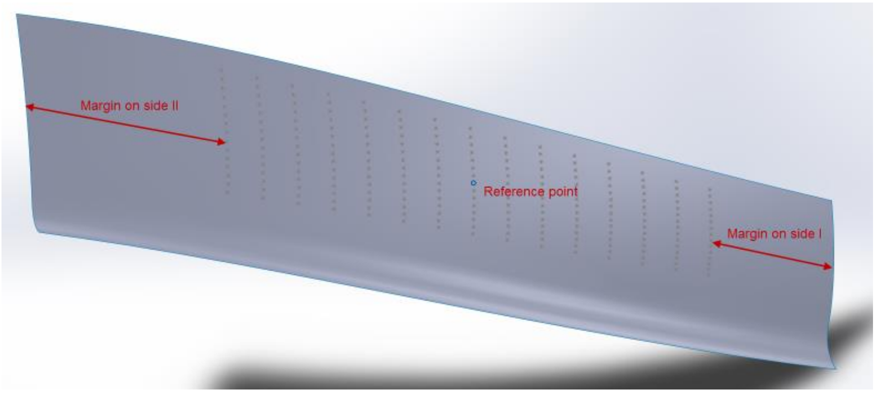


Figure 7 Margins for measurement data should be same at both sides

2.2.4 Applying calculated topological modifications

The topological modification calculation ignores the any type of predefined modifications during the calculation. When you accept the result, the proposed tooth thickness modification coefficient (if you applied) and the topological modification templates are added to the main calculation file with the corresponding link to the saved template file. Note that all the predefined modifications of the corresponding gear will be deactivated.

Gear	Flank	Type of modification	Value [µm]	Factor 1	Factor 2	Status	Information	Comment
Gear 1	right	Topological modification	1.0000			active	Drive flank (Concave)	C:\Topology template\ModificationGear1RF.dat
Gear 1	left	Topological modification	1.0000			active	Coast flank (Convex)	C:\Topology template\ModificationGear1LF.dat

Figure 8 Definition of the topological modification

2.3 Auxiliary settings

2.3.1 2D tooth form calculation

In order to generate the 3D geometry of bevel gear, KISSsoft calculates the 2D tooth forms at predefined sections along the face width. Then, the 2D tooth forms are approximated to the spline curves to be used for 3D geometry generation. We are using “Quadratic spline” as a default approximation type, but it’s recommended to use “Cubic spline” for the topological modification calculation especially when you are suffering from the tooth form calculation error. You can change the setting in the tab “Tooth form” as shown in Figure 9.

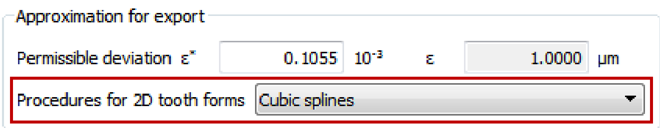


Figure 9 Settings for 2D tooth form calculation

Figure 10 shows an example for the topological modification to be applied, and you can see that the modification surface is highly nonlinear. Thus, the tooth form cannot be easily approximated by quadratic spline and the topological modification calculation often suffers from the tooth form calculation.

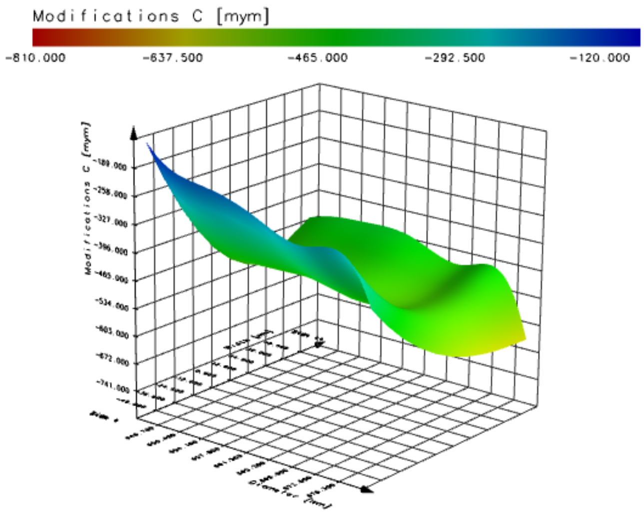


Figure 10 An example of topological modification

2.3.2 Settings for 3D geometry generation

Several settings for 3D geometry generation also affects the calculation and the result. You can find the setting in the Module specific settings window as shown in Figure 11.

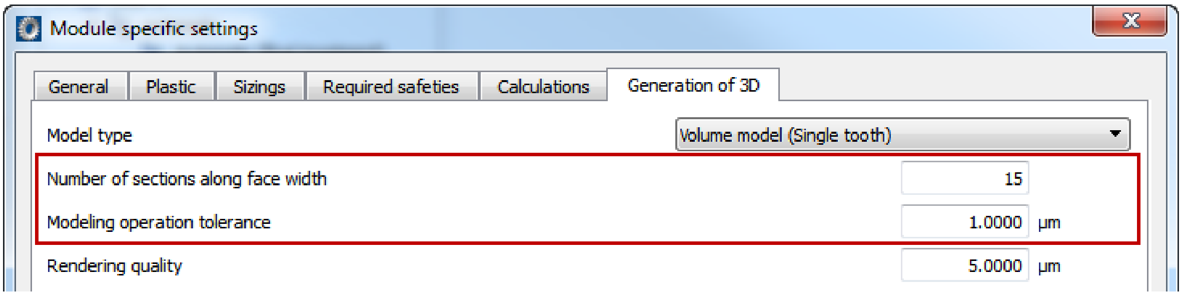


Figure 11 Settings for 3D geometry generation

The “**Number of sections along face width**” defines the number of sections to calculate the tooth form for the approximation of tooth flank form. The minimum value is 3, and the default value is 11. Normally, the quality of the final model can be increased with increasing the value, but it’s not recommended to use excessively many sections compared with the tooth dimension. However, if the measurement data has higher number of columns, for example 15x15, it’s recommended to use bigger number of sections than the columns.

The “**Modeling operation tolerance**” sets the tolerance for internal operations of 3D geometry generation process by Parasolid® kernel such as crash detection in Boolean operation or checking the intersection between objects. The default value is 1µm. You don’t need to change the value for the topological modification calculation in most cases, except the 3D model cannot be generated even without the modification.

3 Calculation procedure and results

The calculation iterates until the given acceptance criteria met. Please refer to Annex 1 for the detailed information about the calculation procedure.
In the first step, we measure the deviation by the normal distance between the measurement points with the flank of 3D model from KISSsoft. Then, we use the initial deviation as the initial topological template.
In our modeling strategy, we use slightly bigger surface area to cover the real gear surface, and it's not possible to measure correct distances at the borders. Thus, we ignore the border values in the acceptance checking in the calculation procedure and use the extrapolated values for the values.
After applying the topological modification of the first step, we build a new topological modification by linear summation of the deviation of each point and the last topological modification, that is, Modification2 = Modification1 + Deviation1.
In the successive steps, we build a new topological modification from the last topological modification by using empirical update formula with cubic polynomial regression fit to prevent higher nonlinearity in the resultant modification.

After finishing the calculation even when an error occurred, you can open a calculation report. The report shows the calculation history of the deviation and the modification of each step for all gears and all flanks. For example, "DEVIATION: STEP 0" shows the initial deviation between the given measurement data and the KISSsoft 3D model. Then, the program sets the topological modification as shown in "MODIFICATION: STEP 1" based on the previous deviations. Under the DEVIATION table of each step, you will find the "Number of points bigger than tolerance". This shows the count of the points that the corresponding deviation is exceeding the convergence tolerance. If the number keeps increasing or doesn't change over the steps, the program will stop the calculation and gives error message.
At the end of the report for each flank, the convergence result will be shown. If the calculation finished with error, the report shows the description of the description of the error. The following explains the convergence and error messages in the report.

3.1.1 Convergence criteria

Message: "CONVERGED!!!"
Condition: The calculated "Number of points bigger than tolerance" is smaller than the "**Permissible number of points outside the tolerance**" in the setting.

3.1.2 Error messages

Message: "PRE-PROCESSING ERROR: Error in nominal geometry calculation."
Condition: Main calculation gave an error.
Solution: Check if the main calculation is consistent.

Message: "PRE-PROCESSING ERROR: Error in nominal tooth form calculation."
Condition: Nominal geometry and/or tooth form calculation gave an error.
Solution: Check if the 2D and 3D geometry generation in the main calculation is possible.

Message: "CALCULATION ERROR: Error in tooth form calculation with topological modification."
Condition: Tooth form calculation with the topological modification gave an error.
Solution: Check if the 2D and 3D geometry generation in the main calculation is possible.
Check if the applied topological modification is highly nonlinear.

Message: "CALCULATION ERROR: Error in modification template factor calculation."
Condition: Calculation of length factor or width factor in the modification template gave an error.
Solution: The length and width factors are calculated from the supplied measurement data.
Check if the measurement grid data is correct.

Message: “CALCULATION ERROR: Error in the topological modification calculation.”
Condition: Calculation of the deviation of the modified surface gave an error.
Solution: Check if the deviation or the topological modification is highly nonlinear or too big.
Check if the tooth thickness modification factor is set reasonably.

Message: “NOT CONVERGED: Maximum iteration steps reached”
Condition: Maximum number of iterations reached
Solution: Increase the maximum number of iterations.
Increase the “**Convergence tolerance**”.
Increase the “**Permissible number of points outside the tolerance**”

Message: “NOT CONVERGED: Last three steps have same deviation”
Condition: The deviation values are not updated any more in last three steps.
Solution: Check if the deviation is having negative value or too big.
Check if the dimension of the gear and the measurement grid data is correct.
Check if the thickness modification factor is set reasonably.

Message: “NOT CONVERGED: Number of points bigger than tolerance increasing in last five steps”
Condition: The calculation is diverging.
Solution: Check if the deviation is having negative value or too big.
Check if the dimension of the gear and the measurement grid data is correct.
Check if the thickness modification factor is set reasonably.

Message: “FILE READING ERROR”
Condition: Reading measurement data report gives an error.
Solution: Check if the measurement data has wrong format.

4 Calculation Examples

Please contact to support@kisssoft.ch for more information.

References

[1] KISSsoft 03/2014 – Instruction 068, 3D Geometry of Bevel Gears
[2] http://www.wenzel-group.com/praezision/de/produkte/software/uebersicht/kmgsoftware.php

Annex 1

An approach of pairing bevel gears from conventional cutting machine with gears produced on 5-axis milling machine[1]

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Abstract

The authors developed a new method to automatically find the optimal topological modification from the predetermined measurement grid points for bevel gears. By using the method, it is possible to duplicate any flank form of a bevel gear given by the measurement points and to provide the 3D model for CAM machining in a very short time. This method not only allows the user to model existing flank forms into 3D models, but also can be applied for various other purposes, such as compensating hardening distortions and manufacturing deviations which are very important issues but not yet solved in the practical milling process.

1 Introduction

Recently, the cutting bevel gears on universal 5-axis milling machines has been widely accepted as a promising solution to replace the conventional cutting process. The process is highly flexible and does not require special tools. Thus, it is particularly suitable for small batches, prototypes, repairs in use having unacceptably high lead times. In order to apply the milling process for bevel gear cutting, we should provide feasible solid models. However, the kinematic geometry of the bevel gears is relatively complicated in accordance with the variety of the cutting method such as Gleason (fixed settings, Duplex® and Zerol®), Klingelnberg (Cyclo-Palloid® and Palloid®) and Oerlikon and it's not easy to generate the 3D geometry model proper for milling.

In the calculation software KISSsoft ([1]), the geometry calculation of straight and skew bevel gears for standard cone types has been available since many years in accordance with ISO 23509 ([2]). Then, the expansion to 3D models of spiral bevel gears was made covering all cone types four years ago. Since the 3D models of the spiral bevel gears are available, there has been much interest from many companies worldwide. The first prototype based on the 3D model from KISSsoft was machined by one of the major 5-axis milling machine manufacturers, Breton in Italy ([3]), and gave very satisfactory results. Then one of their customer who is using a 5-axis milling machine wanted to produce a very large bevel gear pair to replace an existing gear pair. However, they had a special problem hard to resolve. The problem was that the pinion shaft having 1500mm length was too long to be cut on the Breton machine. So the pinion was produced on a conventional Gleason machine, but the customer wanted to produce the gear (d_{e2} = 500mm) on the Breton machine. We always recommend our users that the model for the pinion and gear must be generated by the same software and thus the combination of a pinion, manufactured on a Gleason machine should not be combined with a gear based on the model from KISSsoft. But the customer insisted, so we had to invent something!

We got the basic gear data and the measurement grid points of the flank form of the gear produced by their Gleason software from the customer. However, the design data didn't include the formal definition of the flank modifications. Thus, the comparison of these measurement points with the 3D model from KISSsoft naturally showed small deviations. The deviation could not be eliminated easily by varying the geometric parameters and applying typical modifications such as barreling (profile crowning) and lead

[1] Revised from the original paper published in the International Gear Conference, 2014, Lyon, France

crowning. Thus, we developed a creative solution to generate a 3D model of the gear from KISSsoft and to adapt it to the given grid point from Gleason. In the following chapters, we will show the procedure of the method and the application results.

2 Topological modification of the 3D Model

The basic cone geometry of the bevel gear can be defined in accordance with ISO 23509, and the flank form is defined from the transverse tooth forms calculated along the face width. The trace form will be the extended epicycloid form by face hobbing process or circular form by face milling, as shown in Figure 12. In KISSsoft, the tooth form is supposed to the planar involutes of the virtual spur gear in transverse section. Then, the tooth flank surface is generated by splining the tooth forms of each section.

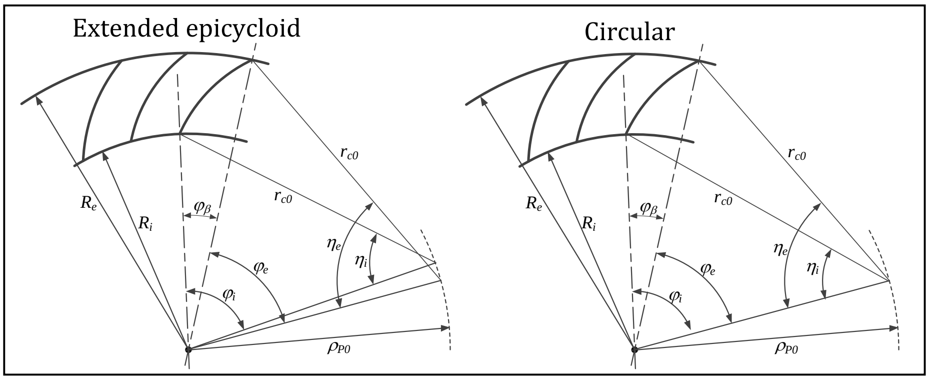


Figure 12. Face hobbing (left) and face milling (right) processes

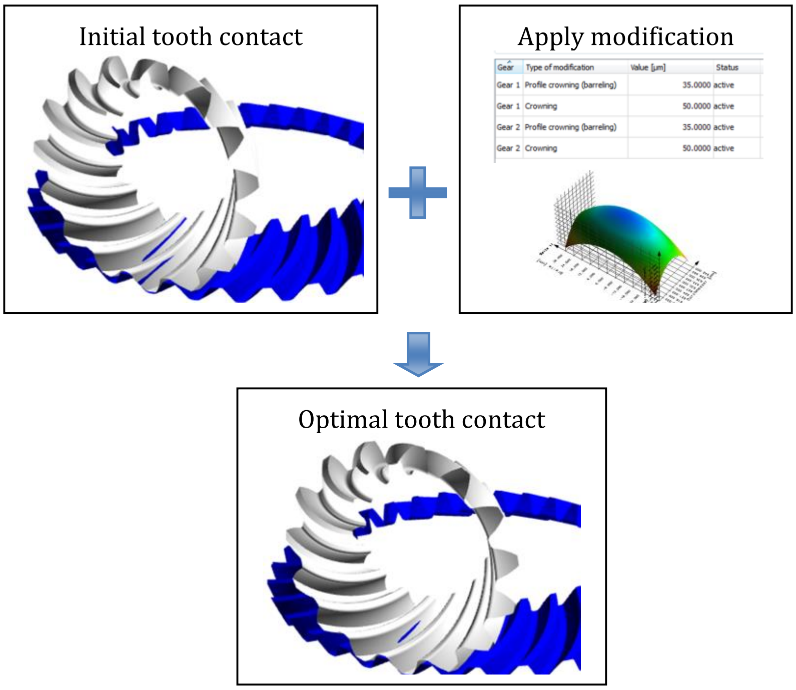
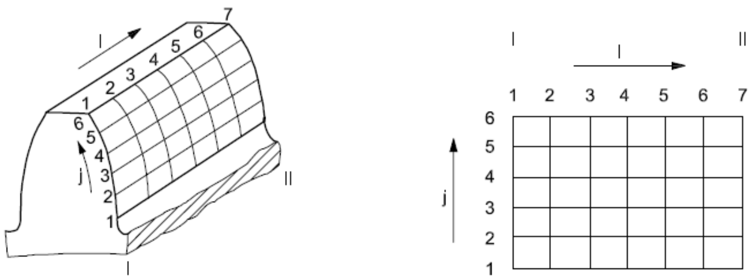


Figure 13. Optimal contact pattern with flank modifications

Bevel gear machine tool manufacturers (such as Klingelnberg and Gleason) have their own methods to generate the tooth form based on the generating motion of the cutter. The tooth form is known as octoid and is slightly different from spherical or planar involute tooth form. However, the difference of the tooth forms is normally less than the tolerance range and will have no problem in practical use. This can be verified from the fact that the bevel gears are always produced in pairs by the same process in order to

achieve a good contact pattern in practice. In order to validate the practical usage of the 3D model from KISSsoft, we compared our model with reference models of manufacturer programs and also carried out the contact pattern check with the actual model. The result showed the tooth flanks along the face width of the two models are very well matched with only slight differences ([4]).
It's one of the most important tasks to find the optimal modification to give good contact pattern in a bevel gear pair. In KISSsoft, the contact pattern of the bevel gear pair can be easily optimized by using proper modifications as shown in Figure 13. There are eight types of the modifications available for bevel gears in KISSsoft (profile crowning, eccentric profile crowning, pressure angle modification, helix angle modification, lead crowning, eccentric lead crowning, twist, and topological modification). The user can define different combination of modifications for drive and coast flanks to optimize the contact pattern separately.
However, if the target modification has highly non-linear or irregular pattern, the simple combination of the conventional modifications cannot be applied. In that case, the topological modification should be used to allow the user to freely define any type of modification that can't be covered by the conventional modifications. The user can define the modifications in a data map of factors at any position along the face width and along the tooth height by using the topological modification following the convention in ISO 21771 ([5]) as shown in Figure 14.



Key

$C_{i,j}$ amount of modification on point (i,j)[a]

[a] Transverse section i; flank line j. If necessary, interpolated points between the defined points (i,j) of a grid can be generated.

Figure 14. Definition of topological modification in ISO 21771 (5)

Figure 15 shows an example of the file structure of the modification used in KISSsoft. The example data map defines the progressive tip relief on side I and no modification on side II. Note that the modification values in the data map is normalized and the actual local modifications are calculated with Ca_local = fij * Ca, where fij is the modification factor at (i, j) node and Ca is the amount of modification. The intermediate values in between the data can be interpolated by linear, quadratic, or spline approximation along the tooth width and height respectively.
The adjustment of the bevel gear models to any predetermined measurement grid points should now be possible by applying the topological modification. That is, the modification can be calculated as the deviation between the surface of the 3D model from KISSsoft and the measurement grid points of the target model. The measurement grid points report contains the Cartesian coordinates and the normal vectors of the grid points with the format of [XP YP ZP XN YN ZN]. The reference coordinate system of the data is different according to the measurement machines. For example, the reference coordinate system of Klingelnberg format is using the convention shown in Figure 16. The order of the indexes for the points and the sections are defined according to ISO/TR 10064-6 ([6]) as well as the convention from the manufacturers such as Klingelnberg ([7]), here the index of the lines starts from the root to the tip, and the index of the columns from the side II (heel) to the side I (toe).
In applying the modification, however, various problems have shown up. The definition of topological modification surface in helical gears is located between the tip and the root form diameters, but the diameters over the tooth width for bevel gears are changing.

```
**************************************************************************************
COLUMNS= total number of columns including index column
DATA
index dummy bf1 bf2 ..... bfn
index lf1   f11 f12 ..... f1n
...
index lfm   fm1 fm2 ..... fmn
END

lfj : length factor (factor of length of path of contact)
    : lfj = 0.0 is at the root, lfj = 1.0 is at the tip
bfi : width factor (factor of face width)
    : bfi = 0.0 is on side I, bfi = 1.0 is on side II
fij : modification factor (local modification Ca_local = fij * Ca)
**************************************************************************************

COLUMNS=13
DATA
1   -1.000  0.000  0.100  0.200  0.300  0.400  0.500  0.600  0.700  0.800  0.900  1.000
2    1.000  1.000  0.988  0.951  0.891  0.809  0.707  0.588  0.454  0.309  0.156  0.000
3    0.900  0.810  0.800  0.770  0.722  0.655  0.573  0.476  0.368  0.250  0.126  0.000
4    0.800  0.640  0.632  0.609  0.570  0.518  0.452  0.376  0.291  0.198  0.100  0.000
5    0.700  0.490  0.484  0.466  0.437  0.396  0.346  0.288  0.222  0.151  0.076  0.000
6    0.600  0.360  0.356  0.342  0.321  0.291  0.255  0.212  0.163  0.111  0.056  0.000
7    0.500  0.250  0.247  0.238  0.223  0.202  0.177  0.147  0.114  0.077  0.039  0.000
8    0.400  0.160  0.158  0.152  0.143  0.129  0.113  0.094  0.073  0.049  0.025  0.000
9    0.300  0.090  0.089  0.086  0.080  0.073  0.064  0.053  0.041  0.028  0.014  0.000
10   0.200  0.040  0.040  0.038  0.036  0.032  0.028  0.024  0.018  0.012  0.006  0.000
11   0.100  0.010  0.010  0.010  0.009  0.008  0.007  0.006  0.005  0.003  0.002  0.000
12   0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000
END
```

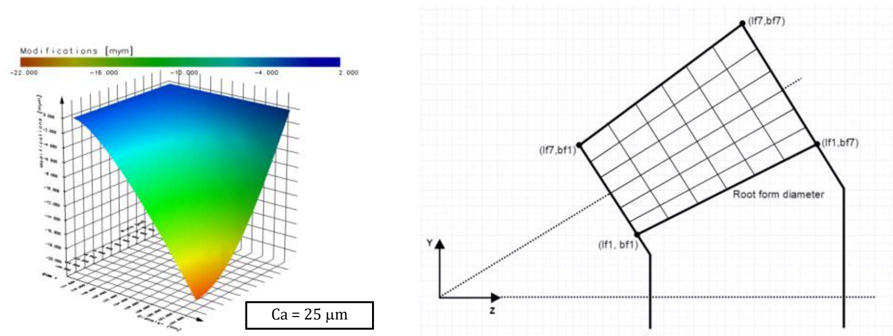
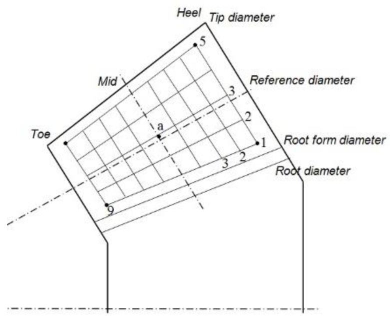


Figure 15. Definition of topological modification and an example




```
------------------------------------------------------------------
 J  I        XP          YP           ZP       XN      YN      ZN
------------------------------------------------------------------
 IN SPALTE  5 / ZEILE  3 :   ZAHNDICKENWINKEL =  0.266995 rad
 1  1    -18.2562    29.5731   180.8263  -.7138 -.3043 -.6306
 1  2    -18.6412    31.9205   180.3613  -.7532 -.1235 -.6460
 1  3    -18.6472    34.4531   179.8957  -.7657  .0144 -.6429
 1  4    -18.3081    37.1179   179.4362  -.7647  .1325 -.6305
 1  5    -17.6326    39.8802   178.9885  -.7545  .2376 -.6116
 2  1    -13.7726    30.6162   174.6872  -.7663 -.2239 -.6021
 2  2    -13.8719    32.9663   174.2261  -.7836 -.0300 -.6205
 2  3    -13.5611    35.4555   173.7642  -.7773  .1126 -.6189
 2  4    -12.8847    38.0330   173.3085  -.7594  .2324 -.6076
 2  5    -11.8565    40.6637   172.8649  -.7336  .3375 -.5897
```

Figure 16. Measurement grid convention of Klingelnberg machine format

On the other hand, the effort to transform the measured grid points to the format of the topological modifications is greatly increased. While the measurement direction of the distance between the two corresponding grid points for adjustment calculation is different from the normal of the tooth form (that is, the path of contact) along which the modification is applied. Moreover, even the deviation values are given correctly, we cannot easily reach to the exact surface points because the target modification can have highly nonlinear pattern.

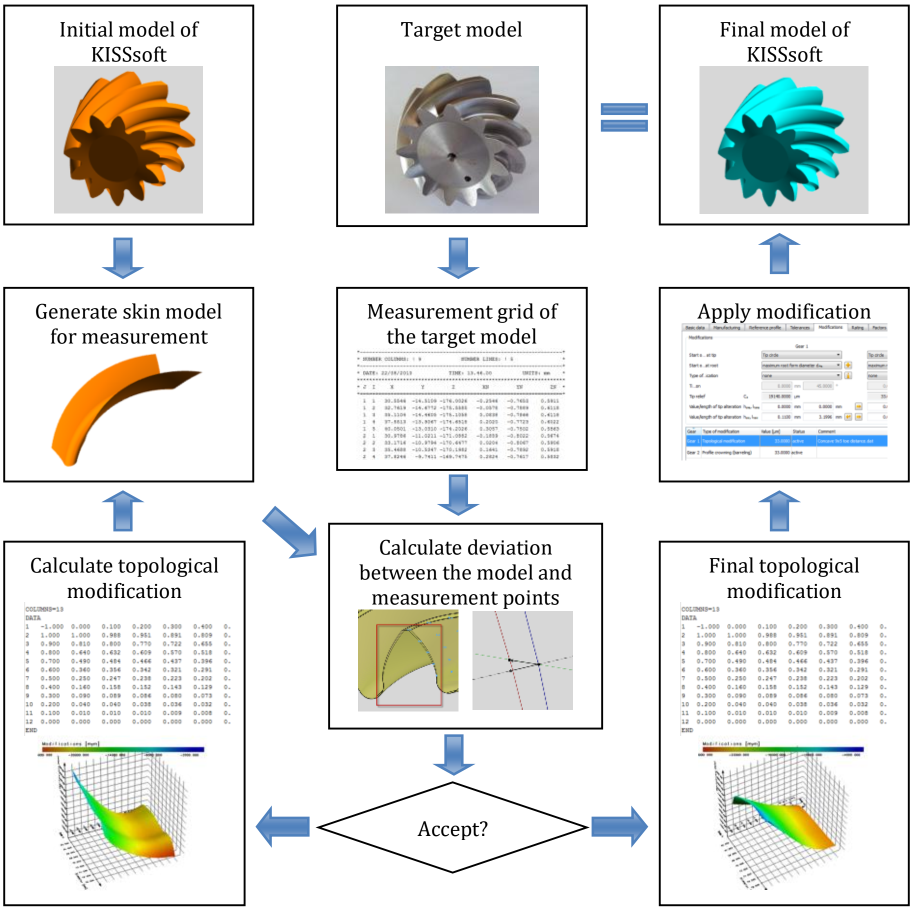


Figure 17. Procedure to get topological modification for target model

Thus, the procedure to get the topological modification, so that the final model becomes equivalent with the target model, cannot be finished in just a single step but need several iterations as shown in Figure 17. In each step, the distance between the corresponding measurement points are calculated and converted into the dimension in the virtual cylindrical gear. Then the topological modification is calculated based on these values and applied to generate a new measurement grid. The procedure iterates until the given acceptance criteria is met. The acceptance criteria is given as the maximum distance between the surface of the 3D model and the corresponding measurement points is smaller than the user-defined tolerance.

3 Application and Result

We used 11x7 points for the measurement and topology template definition, that is, 11 points starting from the side I (toe) to side II (heel), and 7 points from the root form diameter to the tip diameter without any margins. The position of each measurement point is defined as the length factor of the path of contact from the root form diameter to the tip diameter (column values in yellow in Table 1) and the face width factor from the side I to the side II (row values in yellow in Table 1).

3.1 Topological modification for the right flank

Table 1 shows the topological deviation and modification template values for the right flank according to the calculation steps. In the calculation, we set the acceptable maximum deviation to 5m.

Step 1

In the first step, we measure the deviation by the normal distance between the measurement points of the Gleason model with the flank surface of 3D model of KISSsoft (see Deviation 0 in Table 1). Then, we use the Deviation 0 as the initial topological template, Modification 1. The green-colored fields in the table indicates the border of the tooth flank. In our modeling strategy, we use slightly bigger surface area to cover the real gear surface, and it's not possible to measure correct distances at the borders. Thus, we ignore the border values in the acceptance checking in the calculation procedure and use the extrapolated values for the values. The maximum distance of the initial step gives 575µm at the position (0.965, 0.696). The deviation shows relatively big values because we intentionally increased the tooth thickness of the KISSsoft model to completely cover the surface of the target model and to give positive distances. Thus, the final model is compensating not only the topological deviation of the surface but also the tooth thickness deviation of the model.

Step 2

After applying the topological modification of the first step, the maximum distance at the position (0.965, 0.696) reduced to 65µm and the new maximum distance is 135µm at the position (0, 0.879) (see Deviation 1 in Table 1). From the Deviation 1, you will see the three points at (0, 0.089), (0.522, 0.089) and (0.965, 0.193) have the deviation less than the acceptance criteria of 5µm (values in blue). In this case, we use the same topological modification values of the last step at those positions. For the rest positions, we build a new topological modification by linear summation of the deviation of each point and the last topological modification, that is,

Modification2 = Modification1 + Deviation1.

Step 3

Now the Deviation 2 after applying the Modification 2 shows smaller distances than the Deviation 1 and more positions fitting into the acceptance deviation. The new maximum distance is 70µm at the position (0.965, 0.879) (see Deviation 1 in Table 1). However, the deviation in several positions, such as the positions at (0.956, 0.089) and (0.956, 0.193), increased because the surface is generated by spline approximation from the topological modification template (values in red). In this case, we build a new topological modification from the last topological modification by using empirical update formula.

Step 11 (Final step)

Then, we needed to iterate 11 steps until all the deviations fitting into the acceptance criteria. You can find the final topological modification as Modification 11 and the final deviation as Deviation 11 in Table 1. Now all the deviation values are less than the maximum deviation of 5µm except the values at the border.

The graphical comparison of the modification surfaces of Step 1 and the Step 11 (final step) are shown in Figure 12. As you can expect, the final modification surface doesn't not show regular pattern, and it's impossible to achieve the modification by simple combination of the conventional modification types such as crowning and barrelling.

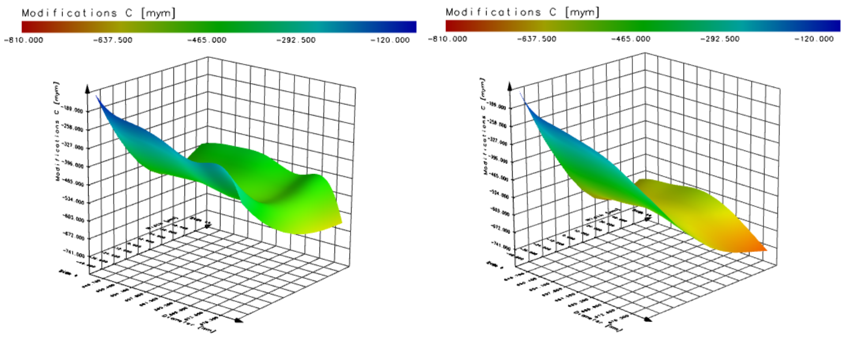


Figure 18. Modifications for right flank at Step 1 (left) and Step 11 (right)

3.2 Topological modification for the left flank

After finishing the calculation for the right flank, we applied the same procedure for the left flank. Table 2 shows the topological deviation and modification according to the calculation steps for the left flank.

Step 1

In the first step, the maximum distance of the left flank shows 570µm at the position (0.965, 0.789).

Table 1 Topological deviations and modifications according to iteration steps (right flank, values in µm)

Deviation 0	1	-1	0	0.089	0.193	0.297	0.399	0.5	0.599	0.696	0.789	0.879	1
Modification 1	2	1	395	446	496	536	567	591	608	619	626	629	631
	3	0.965	342	397	451	495	528	552	568	575	574	566	558
	4	0.744	289	348	407	453	489	514	527	530	523	504	484
	5	0.522	245	311	376	428	468	495	510	511	500	473	446
	6	0.301	207	280	353	412	458	490	508	510	498	467	436
	7	0.08	168	251	333	401	455	493	515	521	510	479	447
	8	0	129	222	314	390	451	495	523	532	522	490	459
Deviation 1	1	-1	0	0.089	0.193	0.297	0.399	0.5	0.599	0.696	0.789	0.879	1
	2	1	22	-7	-36	-18	-2	10	20	26	27	21	15
	3	0.965	19	12	4	19	33	46	56	65	71	72	73
	4	0.744	16	30	44	57	69	82	93	104	115	123	131
	5	0.522	-15	4	22	39	55	70	81	92	102	106	111
	6	0.301	-4	14	32	49	66	82	93	105	115	121	127
	7	0.08	-14	8	30	49	67	84	98	111	122	128	134
	8	0	-24	3	29	49	69	87	103	116	129	135	141
Modification 2	1	-1	0	0.089	0.193	0.297	0.399	0.5	0.599	0.696	0.789	0.879	1
	2	1	382	414	451	515	561	598	625	641	646	640	631
	3	0.965	373	409	451	514	561	598	624	640	645	638	629
	4	0.744	316	378	451	510	558	596	620	634	638	627	612
	5	0.522	237	311	398	467	523	565	591	603	602	579	548
	6	0.301	216	294	385	461	524	572	601	615	613	588	554
	7	0.08	170	259	363	450	522	577	613	632	632	607	573
	8	0	118	222	343	439	520	582	626	648	651	625	590
Deviation 2	1	-1	0	0.089	0.193	0.297	0.399	0.5	0.599	0.696	0.789	0.879	1
	2	1	-45	14	72	74	75	77	81	88	104	122	141
	3	0.965	-11	14	39	38	39	41	45	51	60	70	81
	4	0.744	22	14	6	1	2	6	10	13	16	18	20
	5	0.522	0	0	0	5	8	12	17	20	23	27	30
	6	0.301	4	5	6	11	12	15	19	23	27	30	34
	7	0.08	6	4	2	6	9	14	18	21	26	30	33
	8	0	7	2	-3	2	6	12	17	20	26	29	32
Modification 3	1	-1	0	0.089	0.193	0.297	0.399	0.5	0.599	0.696	0.789	0.879	1
	2	1	383	395	410	471	516	645	675	698	713	718	725
	3	0.965	377	395	416	476	522	639	669	691	705	708	712
	4	0.744	336	392	457	510	558	602	630	647	654	645	633
	5	0.522	237	311	398	467	531	577	608	623	625	606	580
	6	0.301	211	294	391	472	536	587	620	638	640	618	588
	7	0.08	170	259	363	456	531	591	631	653	658	637	609
	8	0	118	222	343	439	526	594	643	668	677	654	623
Modification 11	1	-1	0	0.089	0.193	0.297	0.399	0.5	0.599	0.696	0.789	0.879	1
(Final step)	2	1	376	432	498	555	602	645	675	698	713	726	744
	3	0.965	364	422	490	548	595	639	669	691	705	715	728
	4	0.744	288	357	438	505	552	602	630	647	654	645	633
	5	0.522	246	319	404	476	537	577	608	629	633	615	591
	6	0.301	218	298	391	472	536	587	620	638	640	625	605
	7	0.08	170	259	363	456	531	591	631	653	664	644	617
	8	0	123	225	343	439	526	594	643	667	683	660	629
Deviation 11	1	-1	0	0.089	0.193	0.297	0.399	0.5	0.599	0.696	0.789	0.879	1
(Final step)	2	1	19	10	1	-2	3	-5	0	2	6	-2	-11
	3	0.965	8	5	2	0	2	0	2	3	4	0	-3
	4	0.744	-2	1	4	2	2	5	4	4	2	3	4
	5	0.522	4	3	2	2	3	4	4	2	2	4	5
	6	0.301	3	3	2	2	1	1	2	2	3	0	-3
	7	0.08	5	3	0	1	1	0	3	4	2	1	1
	8	0	8	3	-2	1	1	0	3	5	0	2	4

Table 2. Topological deviations and modifications according to iteration steps (left flank, values in μm)

Deviation 0	1	-1	0	0.089	0.193	0.297	0.399	0.5	0.599	0.696	0.789	0.879	1
Modification 1	2	1	110	199	287	365	434	493	538	568	578	569	559
	3	0.965	145	225	306	375	438	490	531	558	570	564	558
	4	0.744	181	252	324	386	441	488	524	549	561	559	556
	5	0.522	219	281	344	397	444	484	515	537	548	549	549
	6	0.301	269	320	372	416	454	487	513	531	541	543	545
	7	0.08	342	382	423	456	486	511	531	544	552	555	559
	8	0	415	444	473	497	518	535	548	557	563	568	572
Deviation 1	1	-1	0	0.089	0.193	0.297	0.399	0.5	0.599	0.696	0.789	0.879	1
	2	1	63	62	60	63	67	70	77	87	105	120	135
	3	0.965	34	38	43	53	63	73	84	96	112	125	138
	4	0.744	4	15	27	44	59	77	92	106	119	130	141
	5	0.522	33	38	43	53	63	75	87	100	114	127	140
	6	0.301	35	40	46	57	68	80	91	105	118	132	145
	7	0.08	65	66	66	73	81	90	100	113	126	140	154
	8	0	95	91	87	90	94	100	109	121	135	149	163
Modification 2	1	-1	0	0.089	0.193	0.297	0.399	0.5	0.599	0.696	0.789	0.879	1
	2	1	188	262	349	428	501	563	615	654	682	689	698
	3	0.965	189	263	349	428	501	563	615	654	682	689	698
	4	0.744	195	267	351	430	500	565	616	655	680	689	701
	5	0.522	261	319	387	450	507	559	602	637	662	676	695
	6	0.301	310	360	418	473	522	567	604	636	659	675	697
	7	0.08	413	448	489	529	567	601	631	657	678	695	718
	8	0	514	535	560	587	612	635	657	678	698	717	743
Deviation 2	1	-1	0	0.089	0.193	0.297	0.399	0.5	0.599	0.696	0.789	0.879	1
	2	1	49	33	16	-2	1	16	30	36	36	34	32
	3	0.965	27	20	12	3	5	14	22	27	30	31	33
	4	0.744	6	7	7	7	9	11	14	18	23	28	33
	5	0.522	6	6	6	7	9	11	15	19	24	28	33
	6	0.301	1	3	5	8	11	15	18	22	26	30	35
	7	0.08	18	17	16	15	16	18	21	25	29	34	39
	8	0	35	31	27	23	21	21	23	27	33	39	44
Modification 3	1	-1	0	0.089	0.193	0.297	0.399	0.5	0.599	0.696	0.789	0.879	1
	2	1	218	284	361	427	500	577	638	682	713	720	730
	3	0.965	216	283	361	428	501	577	637	681	712	720	731
	4	0.744	202	274	358	437	509	576	630	673	703	717	736
	5	0.522	267	325	393	457	516	570	617	656	686	704	728
	6	0.301	310	360	418	481	533	582	622	658	685	705	732
	7	0.08	431	465	505	544	583	619	652	682	707	729	759
	8	0	548	566	587	610	633	656	680	705	731	756	790
Modification 14	1	-1	0	0.089	0.193	0.297	0.399	0.5	0.599	0.696	0.789	0.879	1
(Final step)	2	1	158	241	337	427	506	577	638	682	713	728	747
	3	0.965	166	246	340	428	506	577	637	681	712	727	747
	4	0.744	211	279	358	437	509	576	630	673	703	723	750
	5	0.522	267	325	393	457	516	570	617	656	686	710	742
	6	0.301	310	360	418	481	533	582	622	658	690	712	742
	7	0.08	436	474	518	546	583	619	652	682	714	738	770
	8	0	554	579	608	610	633	655	675	709	740	767	803
Deviation 14	1	-1	0	0.089	0.193	0.297	0.399	0.5	0.599	0.696	0.789	0.879	1
(Final step)	2	1	2	1	0	0	-1	2	5	6	5	0	-4
	3	0.965	0	1	2	1	1	2	3	4	4	1	-3
	4	0.744	-1	1	4	2	3	2	2	2	3	1	-2
	5	0.522	6	4	1	0	2	3	4	5	5	1	-4
	6	0.301	2	3	4	2	2	3	3	4	2	2	1
	7	0.08	6	3	1	3	4	3	4	5	2	3	3
	8	0	11	4	-3	5	5	3	5	5	2	4	5

Step 14 (Final step)

We could reach the final topological modification after 14 steps for the left flank. You can find the final modification as Modification 14 and the final deviation as Deviation 14. You can see all the deviation values are less than the maximum deviation of 5µm except the values at the border. The graphical comparison of the modification surfaces of Step 1 and the Step 14 (final step) are shown in Figure 19.

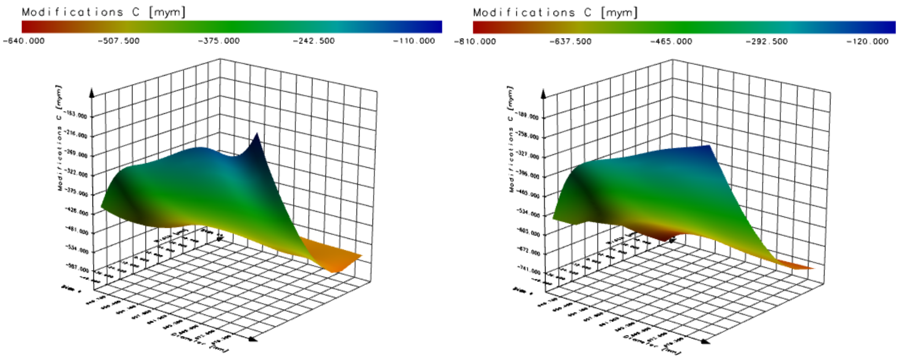


Figure 19. Modifications for left flank at Step 1 (left) and Step 14 (right)

4 Conclusions

The developed method makes it possible to incorporate any desired flank form of a bevel gear given by grid points, and provides the model for the CAM machining in a very short time from the simplest way. That is, the macro geometry is generally assumed by existing standards or data sheets, and the micro-geometry is created by a difference of unmodified real flank to the flank created by topological modifications with the help of KISSsoft. The results showed that the final flank with the topological modification gives the deviation of less than 5µm which can be ignorable considering the manufacturing tolerance in practical situation.

The presented method has considerably high potential for the practical usage, because it allows not only the modeling all existing flank forms into 3D models, but also can also be applied various other purposes, such as to compensate hardening distortions and cutting deviations of 5-axis milling models. These are very important features in practice, and were yet unresolved issues in the 5-axis milling process.

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