Shaft Positioning Tolerances for Bevel Gears

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QUESTION

Could you help me with a doubt? We know that for cylindrical gears we have the standard DIN 3964 for defining deviations of shaft center distance and shaft position tolerances of casings. And for bevel gears? Is there some specific standard for defining deviations of center distance and shaft position tolerances of casings (orthogonal shafts), as DIN 3964 do? Thank you for your help.

Response provided by Dr. Hermann J. Stadtfeld: For cylindrical gears, tolerances for deviation of shaft center distances and shaft position of casings are presented in DIN 3964 (Ref. 1). The DIN standard covers center distance and shaft inclination tolerances for involute cylindrical gears. The standard bases on the fact that spur and helical gears with an involute profile and a straight lead function behave very similar, across a wide range of modules, helix angles and face widths. The term "center distance insensitivity" of involute gears only refers to the transmission accuracy, which is not influenced within a certain range of center distance increase. However, if the center distance reduces, an interference condition will arise from a certain point on. An increase of center distance as shown (Fig. 1) has no impact on the transmission error between the driving and the driven member, yet, it will create an increased backlash which can cause rattle noise in light load conditions (Ref. 2).

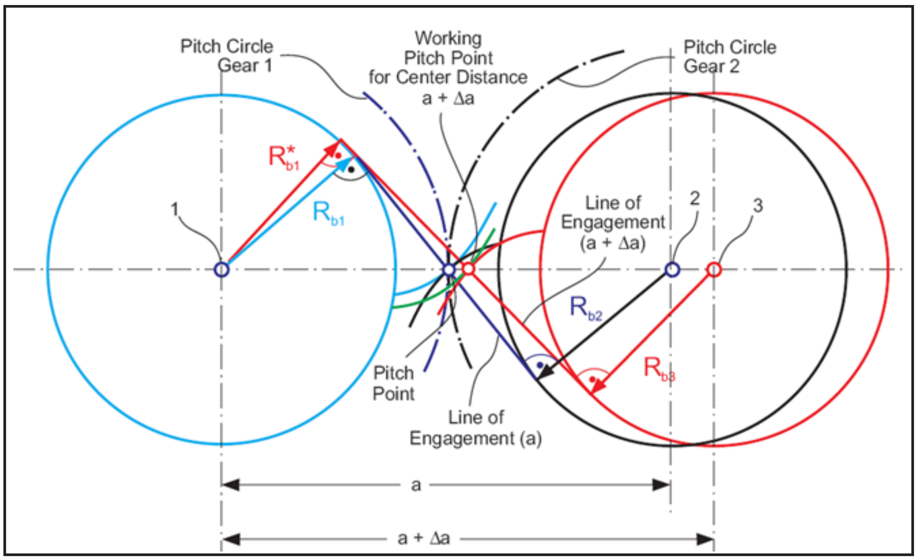

Figure 1 Center distance insensitivity of involute cylindrical gears.

The question, if a similar standard or guideline also exists for bevel gears must be answered with "no". The major reason for this is the wide range of different parameters which influence the sensitivity of a bevel gearset. The following parameters have a direct influence on the sensitivity and therefore on the permissible deviations of the bevel gear shafts:

- Spiral angle
- Lead function (straight, circular, epicycloidal, involute)
- Shaft arrangement (90°, angular, offset)
- Cutter diameter
- Crowning (length, profile, twist, higher order)

The Gleason Works developed a guideline with tolerances for allowable shaft positioning deviations of average bevel gearsets of the following categories:

- Miter straight bevel gears
- Straight bevel gears
- Miter spiral bevel gears
- Spiral bevel gears
- Hypoid gears
- Super reduction hypoids

The new Gleason guidelines are based on the Gleason backlash Table and on maximal shaft displacement recommendations (Ref. 3). An average bevel gearset is the gearset which is generated by the bevel gear design software when using default input parameters. It has to be acknowledged that particular applications of bevel and hypoid gears can be significantly more or less sensitive and would require their own custom set of tolerances.

Angular bevel gears have shaft angle not equal to 90°. As the shaft angle gets closer to zero the bevel gearset behaves more like a cylindrical gearset. In this case, the tolerances for cylindrical gears apply. As the shaft angle gets closer to 180°, the bevel gearset behaves more like a clutch and the tolerances of clutches can be applied.

Bevel and Hypoid Gear Sensitivity Evaluation

Bevel and hypoid gearsets have a very individual displacement behavior, which is why the national and international standards were not able to establish a set of tolerances which are generally applicable. The bevel and hypoid gear calculation programs use the so-called "V-H-Check," — introduced by Gleason in 1965 — in order to express the sensitivity of a bevel gearset. The shaft displacement in the directions E (offset), P (pinion axial), G (gear axial) and ALPHA (shaft angle) are sufficient for capturing the axis deflections in three linear and three angular directions (Fig. 2). A set of deflections f_α, $f_{\beta gear}$ and $f_{\beta pinion}$ can be converted into an equivalent set of deflections E*, P*, G* and ALPHA* as demonstrated (Fig. 3). For this reason the tolerances $f_{\beta gear}$ and $f_{\beta pinion}$ do not exist in reality.

The Gleason V-H-Check moves the contact pattern from a center position to a position between center and heel, and then to a position between center and toe (Fig. 4).

The difference between the axes positions in heel and toe position are the total V-H-displacement numbers. Bevel gear transmission housing designers use these total V-H-numbers in order to optimize the stiffness and the deflection characteristic of the transmission housing. As soon as a housing concept exists, finite element calculations of the gearbox deflection are used to calculate predicted shaft positioning deviations, which are then used as input to the contact analysis program in order to verify which influence the calculated deflections have on the position of the tooth contact. Depending on the resulting tooth contact, a tooth surface optimization has to be conducted in order to adjust the deflection characteristic to the transmission housing. This loop between transmission housing design and bevel gear optimization has to be repeated multiple times to assure a displacement characteristic of the bevel gearset which offsets the housing deflections.

The attempt to provide shaft deflection tolerances using the V-H-Check deflection numbers showed severe shortcomings, as the V-H-Check fails to identify the changing backlash. In cases of load-affected deflections, the increase of backlash is acceptable and does not present any obstacles. An exception is the case of coast-side operation, where the backlash reduces and severe flank surface damages can occur.

However, the general tolerances for the positioning of bevel and hypoid gear shafts has to be based on both — the contact movement as well as the allowable reduction or increase of the backlash as a result of the shaft miss-positioning.

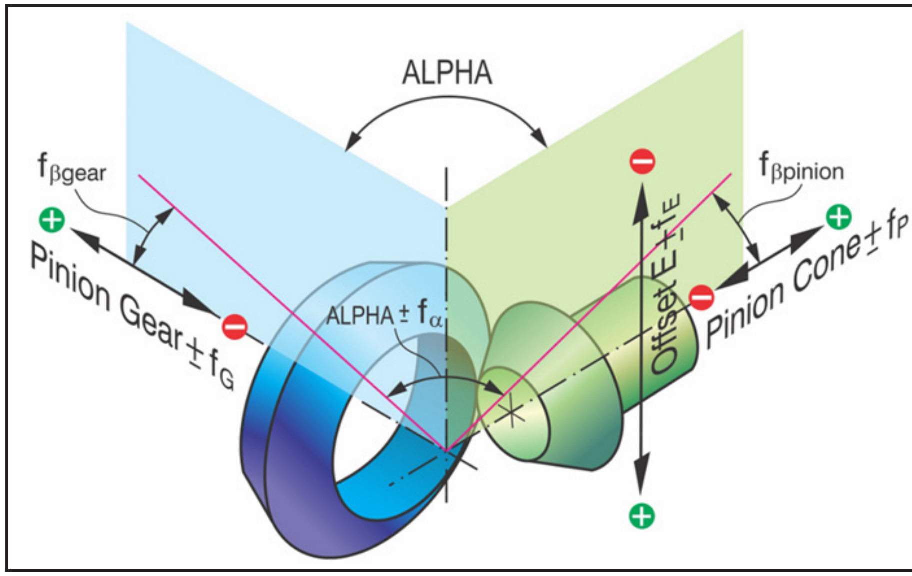

Figure 2 **Bevel gear axis definitions and nomenclature.**

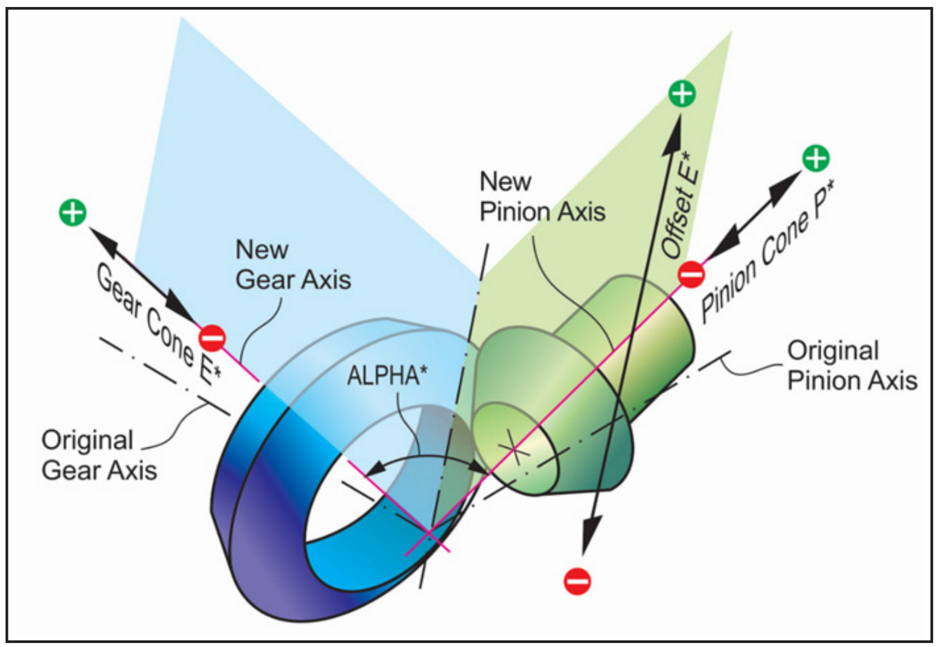

Figure 3 **Transformation of 6 deflections into 4 deflections.**

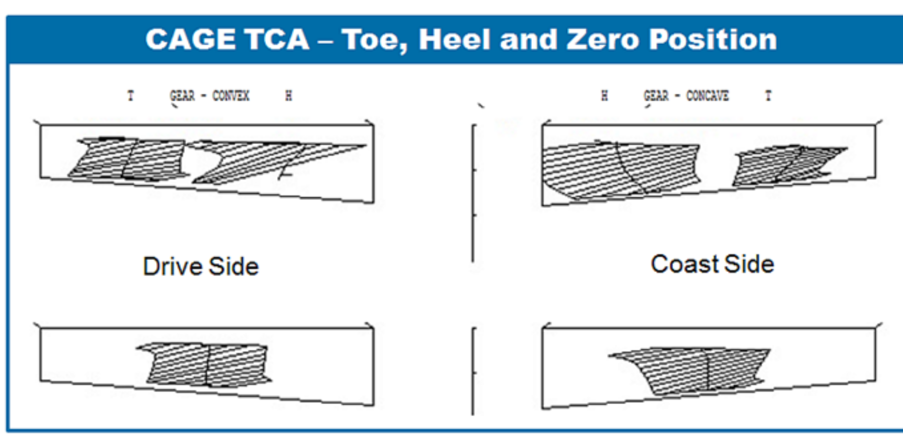

Figure 4 **Gleason V-H-Check.**

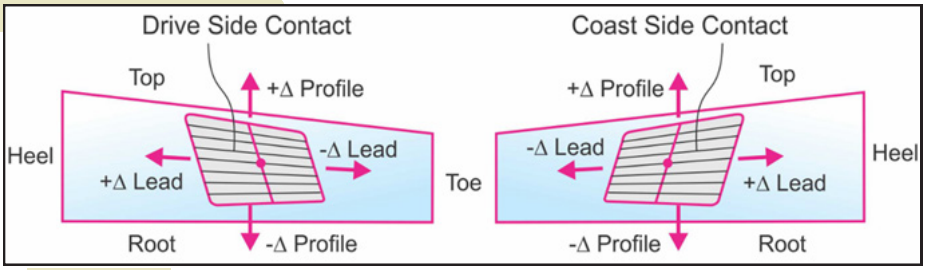

Figure 5 Contact movement in profile and lead direction.

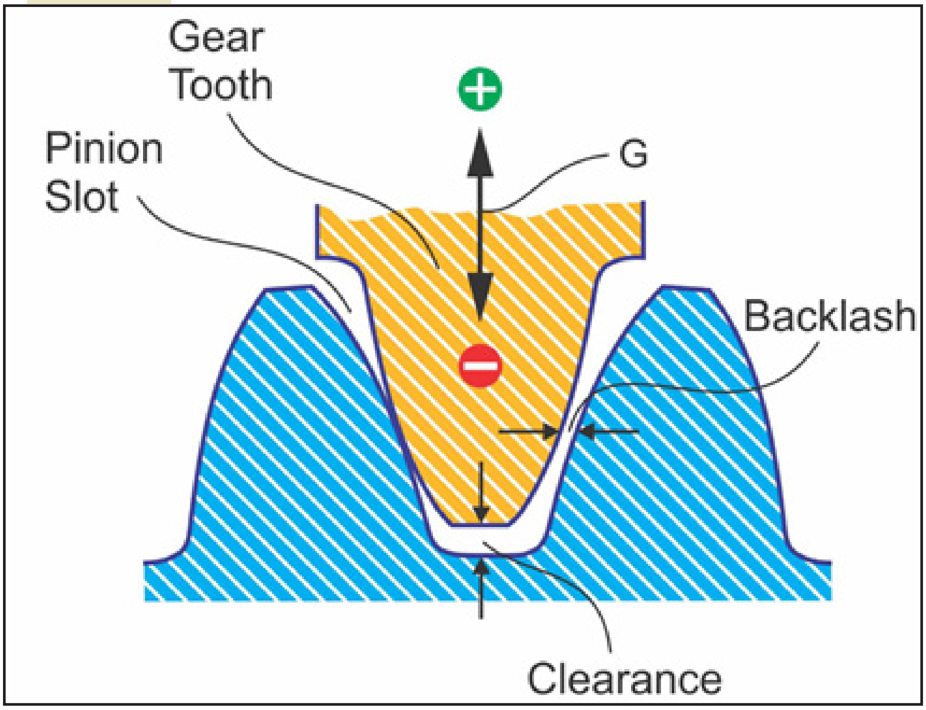

Figure 6 Change of backlash due to gear cone change G.

Table 1 Backlash ranges for bevel and hypoid gears, depending on module

Module [mm]	Diametral Pitch [1/inch]	Min. Backlash [mm]	Max. Backlash [mm]
0.21	120.00	0.008	0.018
0.31	81.00	0.013	0.025
0.62	41.00	0.025	0.051
1.27	20.00	0.051	0.102
2.54	10.00	0.076	0.127
3.18	8.00	0.102	0.152
4.23	6.00	0.127	0.178
5.00	5.00	0.152	0.203
6.35	4.00	0.178	0.229
7.26	3.50	0.203	0.279
8.47	3.00	0.254	0.330
10.00	2.50	0.305	0.406
12.70	2.00	0.356	0.457
14.51	1.75	0.406	0.559
16.93	1.50	0.457	0.669
20.32	1.25	0.508	0.762

Recommended Backlash and Tolerances

The Gleason backlash recommendation and its tolerance are not linked to a gear quality class. In Table 1, the backlash ranges have originally been defined for applications with medium speed and oil sump lubrication. Depending on the kind of transmission and the field of application, a manufacturer can deviate from the recommended values, utilizing data from their own testing. Backlash ranges are given from module 0.21 mm (DP 120/inch) up to module 20.32 mm (DP 1.25/inch). The Table is a conversion from the initial Imperial units, which explains the unusual decimal fraction of the SI units. For bevel and hypoid gears, the backlash is the most important basis of all shaft position tolerances. Common sense tells the gear engineer that each dimensional deviation, which impacts the shaft positioning within the backlash tolerances, is permissible.

Basis of Shaft Deviation Tolerances

In many cases of industrial gearbox design with bevel gears, the Gleason guideline with tolerances for the bevel gear shaft positioning tolerance can be very helpful. The tolerances which are compiled for average gearsets might not be the optimal numbers for the specific gearset a manufacturer is developing. Nevertheless, the Gleason tolerance guideline may be very useful at a stage when only few details of a new transmission are finalized.

In order to have a solid foundation for the shaft positioning tolerances, the impact onto the backlash as well as the contact pattern movement have been considered during the development of the tolerance tables. The contact movement definition is shown (Fig. 5). Contact movements in lead direction had been limited to 1.0 mm and profile movements were limited to 0.3 mm for medium-size bevel gearsets with module 4 mm.

A simplified graphic demonstrates (Fig. 6) the influence to the backlash if the gear cone distance G is changed. If the theoretical backlash is defined precisely in the middle of the tolerance given in Table 1, then any of the shaft positioning tolerances, or the worst-case combination of those tolerances, shall not change the backlash to a value outside of the given tolerances. The following shaft positioning tolerance tables are based on the maximally permissible contact movement and the maximally allowed backlash change. Both criteria are evaluated for each shaft deviation tolerance. The tolerance value was defined at the point when the permissible limit of one criterion was reached.

If the backlash is set in the transmission housing during assembly, e.g. — by a gear cone adjustment — then it appears always possible to obtain correct backlash independent from the shaft positioning tolerances. However, such a backlash adjustment would in case of shaft deviations, which exceed the recommended values in the following tables, result in unacceptably large tooth contact position errors and distortions. Therefore, the following tables are also valid in case of individual backlash setting in the transmission assembly.

Shaft Deviation Tolerances for Bevel and Hypoid Gears

The following tables for the different bevel gear types show, sorted by module, the E, P, G and ALHPHA tolerance values. The last row lists the expected but permissible contact movement in case of maximal shaft positioning errors, provided these are within the mentioned tolerance limits.

Table 2 was compiled for miter straight bevel gears. The offset tolerance allows equal positive and negative deviations, because the backlash increases in both directions. Miter bevel gears are bevel gears with a ratio of one. A major difference to bevel gearsets with ratios above 2.5 is setting the backlash; it is typical for ratios above 2.5 that a gear cone adjustment barely influences the contact pattern position, which is why the backlash adjustment in the assembly is done by shifting the gear axially (G) until the correct backlash is obtained. In case of miter gears, both the pinion axial position P and the gear axial position G influence the backlash equally. However, shifting only one of both will also change the contact pattern position. In case of small changes within the tolerances shown in Table 2 (equal for pinion cone P and gear cone G) the contact movements are within permissible limits.

Table 2 Miter straight bevel gear shaft positioning tolerance table

Module	2mm	4mm	6mm	12mm
E +1-	0.023mm	0.047mm	0.070mm	0.140mm
P +I-	0.011mm	0.023mm	0.034mm	0.068mm
G +1-	0.011mm	0.023mm	0.034mm	0.068mm
ALPHA +1-	0.035°/0.020°	0.035°/0.020°	0.035°/0.020°	0.035°/0.020°
Contact Displacement +/-	0.5mm	1.0mm	1.5mm	3.0mm

Table 3 Straight bevel gear shaft positioning tolerance table

Module	2mm	4mm	6mm	12mm
E +/-	0.023mm	0.047mm	0.070mm	0.140mm
P + (no minus)	0.027mm	0.054mm	0.080mm	0.160mm
G +/-	0.011mm	0.023mm	0.034mm	0.068mm
ALPHA +/-	0.035°/0.020°	0.035°/0.020°	0.035°/0.020°	0.035°/0.020°
Contact Displacement +/-	0 5mm	1.0mm	1.5mm	3.0mm

Table 4 Miter spiral bevel gear shaft positioning tolerance table

Module	2mm	4mm	6mm	12mm
E +/-	0.025mm	0.050mm	0.075mm	0.150mm
P +/-	0.015mm	0.030mm	0.045mm	0.090mm
G +/-	0.015mm	0.030mm	0.045mm	0.090mm
ALPHA +/-	0.035°/0.020°	0.035°/0.020°	0.035°/0.020°	0.035°/0.020°
Contact Displacement +/-	0.4mm	0.8mm	1.2mm	2.4mm

Table 5 Spiral bevel gear shaft positioning tolerance table

Module	2mm	4mm	6mm	12mm
E +/-	0.025mm	0.050mm	0.075mm	0.150mm
P + (no minus)	0.020mm	0.040mm	0.060mm	0.120mm
G +/-	0.011mm	0.022m	0.033mm	0.066mm
ALPHA +/-	0.035°/0.020°	0.035°/0.020°	0.035°/0.020°	0.035°/0.020°
Contact Displacement +/-	0.5mm	1.0mm	1.5mm	3.0mm

The tolerances in Table 3 were compiled for straight bevel gears. The offset tolerance allows equal positive and negative deviations. The pinion cone tolerance prohibits negative values due to the risk of metal-to-metal tooth jamming. The positive P tolerance is rather large, because of the small effect to the backlash. Backlash is commonly adjusted by changing the gear cone during the bevel gear assembly. A gear cone deviation tolerance which will change the backlash by +/-50% of the backlash range is shown in the Table (range equal maximum backlash — minimum backlash). The shaft angle allows a negative tolerance which will reduce the backlash by 40% of the backlash range and a positive tolerance which increases the backlash by 60% of the backlash range.

Miter spiral bevel gears are similar to straight bevel gears because the backlash setting should also be by increasing or reducing the pinion cone (P) and the gear cone (G) by equal amounts. Shifting only one of both will also change the contact pattern position. In case of small changes within the tolerances (Table 4) (equal for pinion cone P and gear cone G) the contact movements are within permissible limits.

In Table 5 the shaft positioning tolerances for average spiral bevel gears with a ratio in the vicinity of 3 are documented. Also, for the spiral bevel gear offset tolerances, E has equal positive and negative values because in both directions an increase of backlash can be noticed. In case of the pinion cone P tolerance, negative values are not permitted because of the risk of tooth jamming (similar to straight bevel gears, see Table 3). The gear cone G can be used for the adjustment of the gearset's backlash and has an equal positive and negative shaft positioning tolerance. The shaft angle tolerance always follows the same rule as explained with straight bevel gears (Table 3).

Also, the tooth contact displacement values for the given tolerances are equal to straight bevel gears. Although the tooth contact pattern position of spiral bevel gears reacts less sensitively to shaft deflections or positioning errors, the tolerances in Table 6 are very similar to the tolerances for straight bevel gears. The reason for this is the equal reaction to backlash changes, which is for both straight and spiral bevel gears, the limiting factor with respect to the shaft positioning tolerances.

For hypoid gearsets (Table 6), the offset tolerance E only allows positive deviations, as already small amounts of negative offset deviations would diminish the backlash rapidly. The tolerances for pinion cone P, gear cone G and shaft angle ALPHA are identical to spiral bevel gears. Different from spiral bevel gears is the contact displacement, which is 30% to 40% less for hypoid gears. The reason is 1) part that the tolerance in E direction is only positive and 2) that hypoid gears are typically less sensitive than spiral bevel and straight bevel gears.

The last bevel gear category covered in Table 7 of this guideline is super reduction hypoids (SRH). While the tolerance in offset (E) is equal to hypoid gears, the pinion cone tolerance (P) has a plus/minus value because of the slim pinion cone, which has only a very small influence on the backlash. The gear cone tolerance (G) is smaller than for hypoid gears, which is justified with the higher sensitivity regarding top-root contact and fillet transition interference. SRHs have the same shaft angle tolerances as all other bevel gear types, and contact displacement limits are identical to spiral bevel gears.

Table 6 Hypoid gear shaft positioning tolerance table

Module	2mm	4mm	6mm	12mm
E + (no minus)	0.025mm	0.050mm	0.075mm	0.150mm
P + (no minus)	0.020mm	0.040mm	0.060mm	0.120mm
G +/-	0.011mm	0.022m	0.033mm	0.066mm
ALPHA +/-	0.035°/0.020°	0.035°/0.020°	0.035°/0.020°	0.035°/0.020°
Contact Displacement +/-	0.3mm	0.6mm	1.0mm	2.0mm

Table 7 Super reduction hypoid gear shaft positioning tolerance table

Module	2mm	4mm	6mm	12mm
E + (no minus)	0.025mm	0 050mm	0.075mm	0 150mm
P +/-	0.020mm	0.040mm	0.060mm	0.120mm
G +/-	0.008m	0.016m	0.024mm	0.048mm
ALPHA +/-	0.035°/0.020°	0.035°/0.020°	0.035°/0.020°	0.035°/0.020°
Contact Displacement +/-	0.5mm	1.0mm	1.5mm	3.0mm

Table 8 Combination of tolerances

Direction	E	P	G	ALPHA
Straight & Spiral Miter	100% of Table Value	60% of Table Value	60% of Table Value	50% of Table Value
Straight & Spiral Ratio 2 to 5	100% of Table Value	75% of Table Value	55% of Table Value	50% of Table Value
Hypoid Ratio 2 to 5	100% of Table Value	75% of Table Value	60% of Table Value	60% of Table Value
SRH Ratio 5 to 50	100% of Table Value	100% of Table Value	60% of Table Value	60% of Table Value

Application of the Tolerances

The tolerance values in the tables for the specific gear types have been defined independently from each other to change the backlash not more than 50% of the backlash range defined in Table 1. If, for example, the entire negative tolerance for the root angle (ALPHA) and for the gear cone (G) is used simultaneously, then the backlash would be below the recommended minimal value; however, there will still be acceptable backlash available.

If a manufacturer can accept a backlash range which is twice the range shown in Table 1, then all the shaft positioning tolerances from the tables can be directly transferred in the housing print. If a manufacturer likes to control the backlash within the range of Table 1, then the values of the combined tolerances for the housing print have to be calculated by applying the axis-specific percentages from Table 8.

There are dependent and independent axis directions. The offset tolerance is independent from all other tolerances for all non-hypoid bevel gearsets because no backlash change can be noted within the amounts indicated in the tables. Pinion cone (P), gear cone (G) and shaft angle ALPHA are dependent axis directions because all three have an influence on the backlash. Table 8 considers the severity of these influences and recommends using only a specified percentage of the original, independent Table values.

References

[5] DIN 3964 "Deviations of Shaft Center Distances and Shaft Position Tolerances of Casings for Cylindrical Gears," Published by DIN Deutsches Institut für Normung e.V., Berlin, 1980.

[1] Stadtfeld, H.J. "Gleason Bevel Gear Technology - The Science of Gear Engineering and Modern Manufacturing Methods for Angular Transmissions," Expert Publishing, 2017, ISBN 978-3-8169-3283-3, Pages 357 to 373.

[6] N. N. "Bevel and Hypoid Gear Design," Company Publication, The Gleason Works, SD 3160-Feb. 1972-CAT, February 1972.

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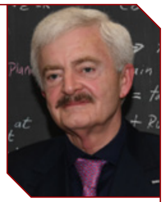

Dr. Hermann J. Stadtfeld is the Vice President of Bevel Gear Technology and R&D at the Gleason Corporation and Professor of the Technical University of Ilmenau, Germany. As one of the world's most respected experts in bevel gear technology, he has published more than 300 technical papers and 10 books in this field. Likewise, he has filed international patent applications for more than 60 inventions based upon new gearing systems and gear manufacturing methods, as well as cutting tools and gear manufacturing machines. Under his leadership the world of bevel gear cutting has converted to environmentally friendly, dry machining of gears with significantly increased power density due to non-linear machine motions and new processes. Those developments also lower noise emission level and reduce energy consumption.

For 35 years, Dr. Stadtfeld has had a remarkable career within the field of bevel gear technology. Having received his Ph.D. with summa cum laude in 1987 at the Technical University in Aachen, Germany, he became the Head of Development & Engineering at Oerlikon-Bührle in Switzerland. He held a professor position at the Rochester Institute of Technology in Rochester, New York From 1992 to 1994. In 2000 as Vice President R&D he received in the name of The Gleason Works two Automotive Pace Awards—one for his high-speed dry cutting development and one for the successful development and implementation of the Universal Motion Concept (UMC). The UMC brought the conventional bevel gear geometry and its physical properties to a new level. In 2015, the Rochester Intellectual property Law Association elected Dr. Stadtfeld the "Distinguished Inventor of the Year." Between 2015–2016 CNN featured him as "Tech Hero" on a Website dedicated to technical innovators for his accomplishments regarding environmentally friendly gear manufacturing and technical advancements in gear efficiency.

Stadtfeld continues, along with his senior management position at Gleason Corporation, to mentor and advise graduate level Gleason employees, and he supervises Gleason-sponsored Master Thesis programs as professor of the Technical University of Ilmenau—thus helping to shape and ensure the future of gear technology.