Application Examples from

Optimizing Gear Geometry for Minimum Transmission Error, Mesh Friction Losses and Scuffing Risk Through Computer- Aided Engineering

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Applications

A number of "real gear applications" were investigated as part of the X-GEAR project. A few are summarized below.

Wind turbine application. The original gear data and operating loads for this gear set are defined in Table 4. The calculated ISO 6336:2006 safety factors for the specified loads, speeds and life requirements (kA = 1.0) are displayed in Table 5, and show quite conservative values of SF1 = 3.50, SF2 = 3.74, SH1 = 1.56 and SH2 = 1.64. These values were used as benchmarking values for any changes in geometry that were investigated.

The *GATES* results in Table 5 show that without profile relief the maximum power loss is 9,131.10 W at 99.206%

Table 4—Wind turbine application example – geometry and operating conditions

Parameter	Original geometry		Revised geometry	
	Z 1	Z 2	Z 1	Z 2
Teeth (z)	19	90	25	116
Module (M_n)	9.00	9.00	7.00	7.00
Pressure angle (α_n)	20 °	20	20	20
Helix angle (β)	10°	10	10	10
Additional mod. coefficient (x)	0.13	0.88	0.13	–0.287
Outside diameter (d_a)	193.98	842.08	193.52	834.50
Root diameter (d_f)	150.78	798.88	159.92	800.90
Tooth height (h/M_n)	2.4	2.4	2.4	2.4
Root fillet radius (ρ_{ao})	0.35	0.35	0.35	0.35
Facewidth (b)	200	200	200	200
Accuracy	6	6	6	6
Profile crown (C_α)	–	–	–	–
Helix crown (C_β)	–	20	–	20
Tip relief	34	34	40	40
Operating speed (rev/min)	1000	211.1	1000	215.5
Torque (Nm)	10981.7	52018.5	10981.7	50955.0

Table 5—Wind turbine example – analysis results				
Parameter	No relief	Specified relief	Revised geometry	
			No relief	Ca = 40 Cb = 20
ISO 6336 Bending S_{F1} ISO 6336 Bending S_{F2}	3.50 3.74		2.84 2.91	
ISO 6336 Contact S_{H1} ISO 6336 Contact S_{H2}	1.56 1.64		1.52 1.60	
GATES				
Maximum contact load, N	753.4	653.0	725.2	713.5
Maximum contact stress, N/mm^2	1388.1	1024.1	1094.5	1017.4
Power loss, W (μm = 0.05)	9131.0	6460.8	7618.61	4709.1
Efficiency (μm = 0.05)	99.206%	99.397%	99.338%	99.591%
Peak power loss, W/mm	102.1 (195.5%)	52.2 (100%)	86.9 (166.5%)	31.7 (60.7%)
Transmission error, µm (pk–pk)	3.319	1.434	1.264	0.540

efficiency. With the specified relief, the efficiency improves to 99.438% as illustrated in Figure 16 (a saving of approximately 2,670 W), and peak contact load, contact stress and a peak power loss are significantly reduced.

The FZG work (Ref. 1) identified a significant increase in efficiency when reducing the module as it reduces maximum sliding speeds in a given application. Alternative gear macrogeometry, based on a 7.0-mm module gear, was investigated (see Table 4). The revised ISO 6336 safety factors in Table 5 are lower (up to 22% for bending), but this can be corrected by controlled shot peening of the tooth roots.

Table 5 shows lower TE (0.54 µm) and further improvements to efficiency to 99.591%. With the 40 µm tip relief applied, losses reduce to 4,709 W and the peak power loss is reduced from 52.2 W/mm by 66% to 31.7 W/mm. This demonstrates what can be achieved with minor changes to gear geometry without reducing other performance characteristics.

Automotive application. The geometry and operating conditions for this high-contact- ratio helical gear set are summarized in Table 6. The nominal transverse contact ratio is 1.593 and overlap ratio is 1.096, so these gears have optimized helix angle—but the high tooth height of 3.15 mn will provide a challenge for minimizing friction losses because of the high sliding speeds.

The *GATES* analysis is summarized in Table 7. Error-free and without flank corrections, a nominal gear set efficiency is calculated as 99.021% with 0.05 as the assumed coefficient of friction. The manufacturers specified a linear tip relief of 35 µm without helix crowning and thus the design is susceptible to alignment errors. The relief strategy improves the efficiency to 99.244% but does not reduce the high-peak power loss of 53.7 W/mm and contact stresses are high at 2,000 N/mm^2.

Investigations revealed a combination of 40 µm tip relief and 12 µm helix crowning improved the efficiency to

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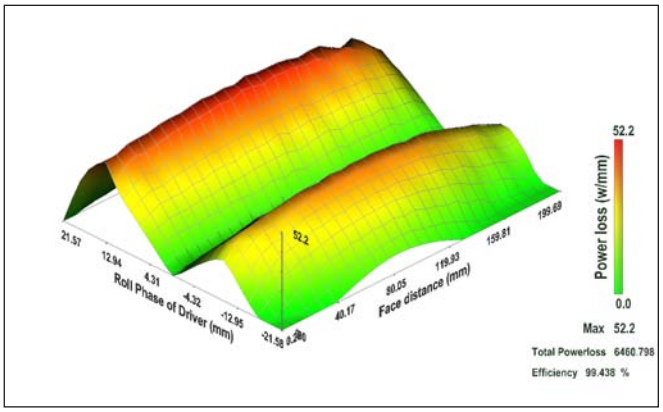

Figure 16—Wind turbine application: power loss for specified geometry and relief power loss.

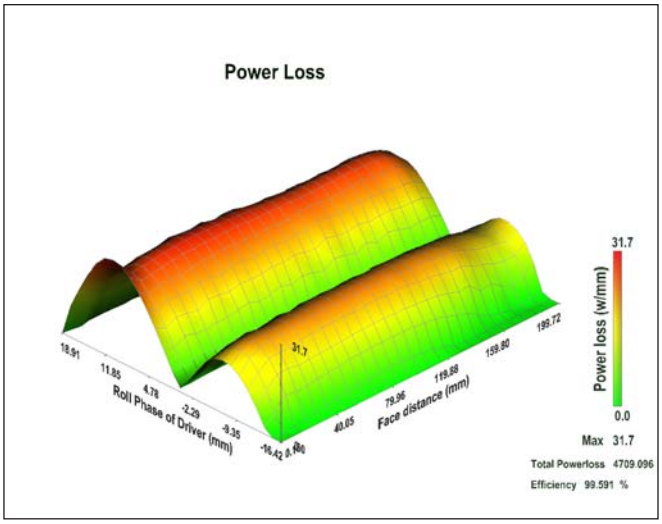

Figure 17—Wind turbine application friction loss: revised geometry and reliefs.

99.457% (Fig. 18), with the peak-power loss reduced from 53.7 W/mm to 15.7 W/mm, representing a significant reduction in potential scuffing risk.

The optimized geometry is also very insensitive to alignment errors (Table 8). A manufacturing error (fsh) of ± 20 µm, due to mesh alignment, potentially increases the scuffing risk by a max 66 W/mm on the specified relief strategy while the optimized design returned a maximum of 21.4 W/mm for the same error. The TE and contact stress are also relatively insensitive to alignment error.

Table 6. Automotive application geometry.

Parameter	160 mm center test gears	
	Z 1	Z 2
Teeth (z)	31	43
Module (M_n)	2.0	2.0
Pressure angle (α_n)	18 ˚	18 ˚
Helix angle (β)	22.5 ˚	22.5 ˚
Additional mod. coefficient (x)	-0.024	-0.024
Outside diameter (d_a)	72.412	98.389
Root diameter (d_f)	59.812	85.789
Tooth height (h / M_n)	3.150	3.150
Root fillet radius (ao)	0.39	0.39
Facewidth (b)	23.0	18.0
Accuracy	DIN 7	DIN 7
Profile crown (C_α)	–	–
Helix crown (C_β)	–	–
Tip relief	35 m (96%)	35 m (96%)
Operating speed (rev/min)	1500	1081.4
Torque (Nm)	280	388.69

In conclusion, small changes to the gear microgeometry improve losses by 0.2% with a reduction of the peak loss from 53.7 W/mm to 17.1 W/mm, significantly reducing the scuffing risk. Further improvements can be made by changing the gear macrogeometry and balancing the sliding speeds at the start and end of active profile by adjusting addendum modification coefficients, which will increase the efficiency.

High-speed application. This example illustrates the benefits that can be achieved in a high-speed test rig with pitch line speeds of 122 m/s by simply balancing the sliding speeds between entry and exit points on the mesh. The geometry in Table 9 shows the change in addendum modification factors, and the results from the *GATES* analysis are in Table 10. The reduction in friction power loss is from 9,861 to 7,037 W, and peak power loss is reduced from 383.7 W/mm to 240.0 W/mm.

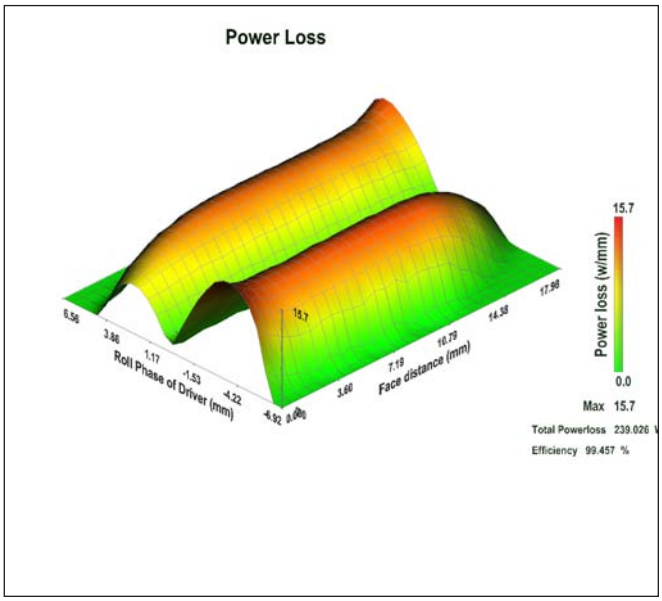

Figure 18—Automotive/friction loss: 40-mm tip relief and 12-mm crowning (relief starting at the HPSTC).

Table 7—Automotive – G A T E S analysis results

Parameter	No relief	Specified relief	Revised geometry
			Ca = 40 Cb = 1 2
ISO 6336 Bending S_{F1}	0.8		
ISO 6336 Bending S_{F2}	1.01		
ISO 6336 Contact S_{H1}	0.89		
ISO 6336 Contact S_{H2}	0.90		
GATES			
Maximum contact load, N	708.0	556.6	487.8
Maximum contact stress, N/mm^2	2027.0	2000.5	1612.8
Power loss, W (µm = 0.05)	430.6	332.6	239.0
Efficiency (µm = 0.05)	99.021%	99.244%	99.457%
Peak power loss, W/mm	50.4	53.7	15.7
Transmission error, µm (pk–pk)	1.08	1	0.76

Table 8. Automotive - GATES analysis results- effect of alignment errors

Parameter	Ca = 40 µm Cb = 12 µm + 20 f_{ma}	Ca = 40 µm Cb = 12 µm - 20 f_{ma}	Spec relief - 20 f_{ma}	Spec relief + 20 f_{ma}
ISO 6336 Bending S_{F1}	0.8			
ISO 6336 Bending S_{F2}	1.01			
ISO 6336 Contact S_{H1}	0.89			
ISO 6336 Contact S_{H2}	0.90			
GATES				
Maximum contact load, N	474.8	489.8	862.1	604.9
Maximum contact stress, N/mm^2	1614.1	1633.5	2181.3	2248.5
Maximum power loss (µ = 0.05)	261.225	263.627	335.656	335.441
Efficiency (µ = 0.05)	99.406%	99.401%	99.237%	99.237%
Peak power loss, W/mm	16.0	20.4	66.5	49.3
Transmission error, µm (pk-pk)	0.88	0.85	1.26	0.98

Table 9. High speed application – geometry &operating conditions

PARAMETER	Initial		Revised	
	Z 1	Z 2	Z 1	Z 2
Teeth (z)	45	92	45	92
Module (M_n)	5.00	5.00	5.00	5.00
Pressure angle (α_n)	20°	20°	20°	20°
Helix angle (β)	30°	30°	30°	30°
Additional mod coefficient, (x)	0.931	0.0	0.47	0.461
Outside diameter (d_a)	279.12	541.16	274.51	545.77
Root diameter (d_f)	255.12	517.16	250.51	521.77
Tooth height (h/M_n)	2.4	2.4	2.4	2.4
Root fillet radius (ρ_{ao})	0.39	0.39	0.39	0.39
Facewidth (b)	50.0	50.0	50.0	50.0
Accuracy	DIN 5	DIN 5	DIN 5	DIN 5
Helix crown (C_β)	10	–	10	–
Tip relief	25µm	25µm	25µm	25µm
Operating speed (rev/min)	9000	4402	9000	4402
Torque (Nm)	4160	8504	4160	8504

Table 10. High speed application - GATES analysis results

PARAMETER	Initial (no relief)	Initial (relief)	Revised (no relief)	Revised (relief)
Maximum contact stress, N/mm^2	746.2	766.7	750.7	784.6
Power loss, W (µ = 0.05)	14116	9861	11119	7037
Efficiency (µ = 0.05)	99.501%	99.651%	99.607%	99.751%
Peak power loss, W/mm	710.9	383.7	464.6	240.0
Transmission error, µm (pk-pk)	1.92	1.2	1.76	0.66

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