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Addendum modification of spur gears with equalized efficiency at the points where the meshing stars and ends

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1. Introduction

When determining the geometric dimensions of cylindrical spur gears, most often, specific addendum modifications are used. Their purpose is to obtain a well defined distance between the axes at the same time ensuring the correct meshing of teeth flanks over a longer time. The x_1 and x_2 addendum modification coefficients have influence on tooth shape and tooth thickness. Different assumptions or criteria can be used to determine their values as shown in [1] - [7]. Balancing or equalization of the sliding velocity [1], specific sliding [1, 2] or power lost by friction [3] are used to influence friction losses to obtain better efficiency, lower operating temperature, noise and wearing to increase the life of the gears. Instead of equalizing the power losses the paper presents a new method to establish the specific addendum modification coefficients using the equalization of the efficiencies, at the A and E points, where the meshing begins and ends (see Fig. 1). Compared to [2] this method is considering friction coefficients with distinct values between the teeth flanks at beginning and the end of the contact allowing to study the gear efficiency in a general case. Compared to [3] the method is dealing directly with the efficiency - the most important objective in the field of transmissions – and allows the study of the balanced gear efficiency for various friction coefficients and addendum modifications.

2. Efficiencies at the beginning and end of the teeth meshing

The efficiency of the teeth meshing is determined using the following general relation:

$$\eta = \frac{T_2\omega_2}{T_1\omega_1} = \frac{T_2 z_1}{T_1 z_2}, \quad (1)$$

where T_1 is the torque of the driving forces; T_2 the torque of the useful resistance forces; ω_1 the angular velocity of the driving wheel; ω_2 the angular velocity of the driven wheel; z_1 the number of teeth of the driving wheel; z_2 the number of teeth of the driven wheel.

Considering Fig. 1 the torque at the beginning of the teeth meshing, in point A, can be written with the following expressions:

$$T_1 = F_{nA}\left[r_{b1}\left(1-\mu_A\, tan\left(\alpha_w\right)\right)+\mu_A e_A\right] \quad (2)$$

and

$$T_2 = F_{nA}\left[r_{b2}\left(1-\mu_A\, tan\left(\alpha_w\right)\right)-\mu_A e_A\right]. \quad (3)$$

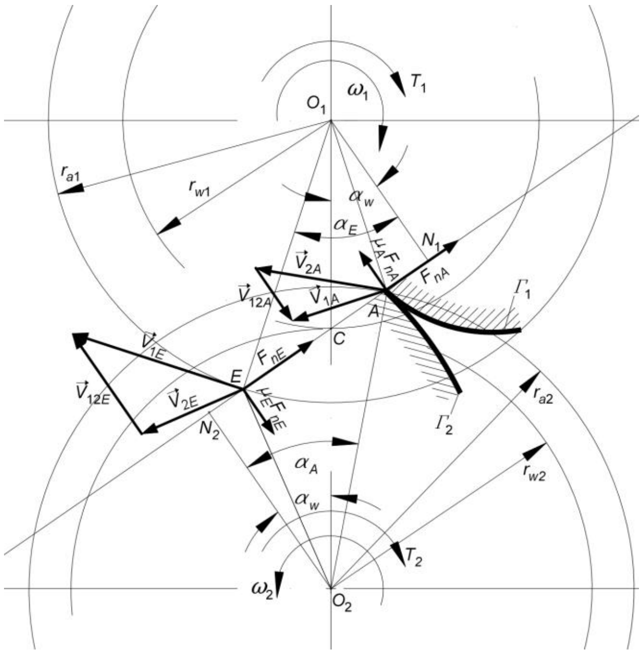

Fig. 1 Meshing of involute spur gears

where F_{nA} is the normal force in the A meshing point, r_{b1} and r_{b2} the base circles radii of the meshing gears with involute profiles ($r_{b2}\ z_1 = r_{b1}\ z_2$), μ_A the friction coefficient between the teeth flanks, in the A point, where the meshing begins, α_w the meshing angle, e_A the AC segment length from Fig. 1. From (2) and (3) the meshing efficiency in the A point becomes:

$$\eta_A = \frac{z_1\left(1-\mu_A\, tan\left(\alpha_A\right)\right)}{z_1\left(1-\mu_A\, tan\left(\alpha_A\right)\right)+z_2\mu_A\left(tan\left(\alpha_A\right)-tan\left(\alpha_w\right)\right)}. \quad (4)$$

Using the same methodology the torque is determined in the E point, where the meshing ends, thus:

$$T_1 = F_{nE}\left[r_{b1}\left(1+\mu_E\, tan\left(\alpha_w\right)\right)+\mu_E e_E\right] \quad (5)$$

and

$$T_2 = F_{nE}\left[r_{b2}\left(1+\mu_E\, \tan(\alpha_w)\right)-\mu_E e_E\right], \quad (6)$$

where F_{nE} is the normal force in the E meshing point, μ_E the friction coefficient between the teeth flanks, in the E point, e_E the EC segment length from Fig. 1.

From (5) and (6) the meshing efficiency in the E point becomes:

$$\eta_E = \frac{z_2\left(1+\mu_E\, tan\left(\alpha_w\right)\right)-z_1\mu_E\left(tan\left(\alpha_E\right)-tan\left(\alpha_w\right)\right)}{z_2\left(1+\mu_E\, tan\left(\alpha_E\right)\right)}. \quad (7)$$

In order to check the possibility of making equal the (4) and (6) expressions we will compute and plot these surfaces depending on x_1 and x_2 addendum modifications.

3. Computation and graphical representation of the efficiency

The numerical results for the (4) and (7) expressions are obtained using the following known formulae [6] from the spur gear geometry:

$$cos(\alpha_A) = \frac{r_2}{r_{a2}} cos(\alpha_0); \quad (8)$$

$$cos(\alpha_E) = \frac{r_1}{r_{a1}} cos(\alpha_0); \quad (9)$$

$$r_1 = \frac{mz_1}{2}; \quad (10)$$

$$r_2 = \frac{mz_2}{2}; \quad (11)$$

$$r_{a1} = \frac{m}{2}\left(z_1 + h_a^* + 2x_1 - 2k\right); \quad (12)$$

$$r_{a2} = \frac{m}{2}\left(z_2 + h_a^* + 2x_2 - 2k\right); \quad (13)$$

$$k = x_1 + x_2 - y; \quad (14)$$

$$y = \frac{z_1 + z_2}{2}\left(\frac{cos(\alpha_0)}{cos(\alpha_w)} - 1\right), \quad (15)$$

where α_w is computed from the following equation:

$$x_1 + x_2 = \left[\tan(\alpha_w) - \alpha_w - \left(\tan(\alpha_0) - \alpha_0\right)\right]\frac{z_1 + z_2}{2\tan(\alpha_0)}. \quad (16)$$

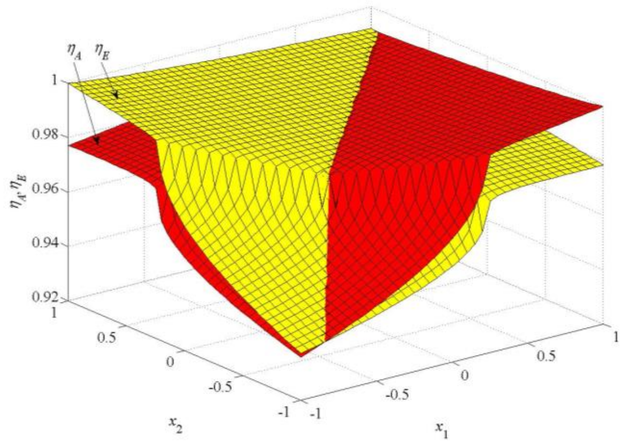

Fig. 2 The graphical representation of the (4) and (7) surfaces for $z_1 = 19$, $z_2 = 19$ and $\mu = 0.05$

In order to obtain the graphical representation of the (4) and (6) surfaces the following input data were considered: $\mu_A = \mu_E = \mu = 0.05$. The x_1 and x_2 values are in range [-1, 1] and the z_1 and z_2 values are fixed and the same for each surface representation. As seen in Fig. 2 the two surfaces intersect, so the equalization of the efficiencies, at the A and E points, have solutions. The curve from Fig. 3 was obtained using a Matlab code extracting the isoline of the intersection and then interpolating on surface (7). The results from these figures are however rough because:

- the solutions are obtained using Matlab facilities (surface intersection extraction and interpolation) instead of solving directly the (4) = (7) equation;
- in order to obtain results for the surfaces as Matlab requires, no limitations on the obtained results were applied; these concern the values of the meshing angle and the x_1 and x_2 values to avoid tooth undercut and sharpening.

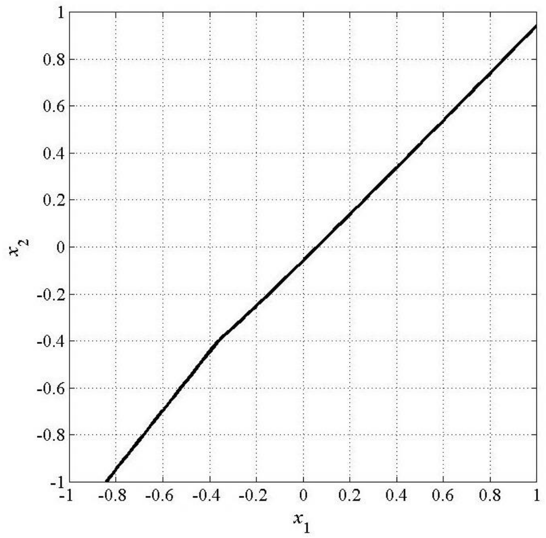

Fig. 3 The intersection curve of the (4) and (7) surfaces for $z_1 = 19$, $z_2 = 19$ and $\mu = 0.05$

4. Numerical results of the efficiency equalization

To avoid the tooth undercut and sharpening the following limitations were applied to the obtained x_1, x_2 results [1], [3]:

- for tooth undercut:

$$x_{1\,min} = \frac{17 - z_1}{17}; \quad (17)$$

$$x_{2\,min} = \frac{17 - z_2}{17}; \quad (18)$$

- for tooth sharpening by putting the following conditions:

$$d_{a1} \le d_{v1} - \frac{m}{6}; \quad (19)$$

$$d_{a2} \le d_{v2} - \frac{m}{6}; \quad (20)$$

we obtain:

$$x_{1\max} = \frac{d_{v1}}{2m} - \frac{1}{12} - \frac{z_1}{2} - h_a^* + k, \quad (21)$$

$$x_{2\max} = \frac{d_{v2}}{2m} - \frac{1}{12} - \frac{z_2}{2} - h_a^* + k, \quad (22)$$

with d_{a1} the outside circle diameter of wheel 1, d_{a2} the outside circle diameter of wheel 2, d_{v1} the sharp tip circle diameter of wheel 1, d_{v2} the sharp tip circle diameter of wheel 2.

Equalization of the (4) and (7) relations give the following equation:

$$\left[z_1\left(\mu_A \tan(\alpha_w)-1\right)-\mu_A z_2\left(\tan\left(\alpha_A-\tan(\alpha_w)\right)\right)\right]\times$$
$$\times\left[z_2\left(\mu_E \tan(\alpha_E)+1\right)-\mu_E z_1\left(\tan(\alpha_E)-\tan(\alpha_w)\right)\right]-$$
$$-z_1 z_2\left(\mu_A \tan(\alpha_A)-1\right)\left(\mu_E \tan(\alpha_E)+1\right)=0. \qquad (23)$$

The Matlab code is based on the following equalization algorithm:

```
ha=1;a0=deg2rad(20);miu=0.05;
z1=19;z2=21
x2in=-1.0;x2fin=1.0;n=41;
step=(x2fin-x2in)/(n-1);
plotcrt1x1=[];
plotcrt1x2=[];

for i=1:n
 x2=x2in+(i-1)*step;

% find alfa_left and alfa_right
%  for the bisection method implemented
%  in the bis function.
% equalization equation to be solve is
%  passed as parameter to the bis
%  solver function.
feq = (23)

% a_w is the solution of the (23)
%  equation
a_w=bis(@feq,alfa_left,alfa_right,x2,z1
,z2,miu,ha,a0,err);

% bisection_converge is true if
%  err is false
 if (bisection_converge)
   x1=(inv(a_w)-inv(a0))*(z1+z2)/2.
    /tan(a0)-x2; %from (15)
   ea=etaa(x1,x2,z1,z2,a0,miu,a_w);%(4)
   ee=etae(x1,x2,z1,z2,a0,miu,a_w);%(7)

% no_limitation is true if
%  aw in [14^0 ,32^0]
%  x1 in [x1min. x1max] %from (17), (18)
%  x2 in [x2min, x2max] %from (21), (22)
%  abs(ea-ea)<1e-7 %recheck convergency
   if (no_limitations)
    print i,x1_min(z1),x1,
     x1_max_v1(z1,z2,x1,x2),
     x2_min(z2), x2,
     x2_max_v1(z1,z2,x1,x2),a_w,ea,ee);
    plotcrt1x1=[plotcrt1x1 ; x1];
    plotcrt1x2=[plotcrt1x2 ; x2];
   end %if - no_limitations
 end %if - bisection_converge
end %for

try
 plot(plotcrt1x1, plotcrt1x2);
end
 catch err
end
```

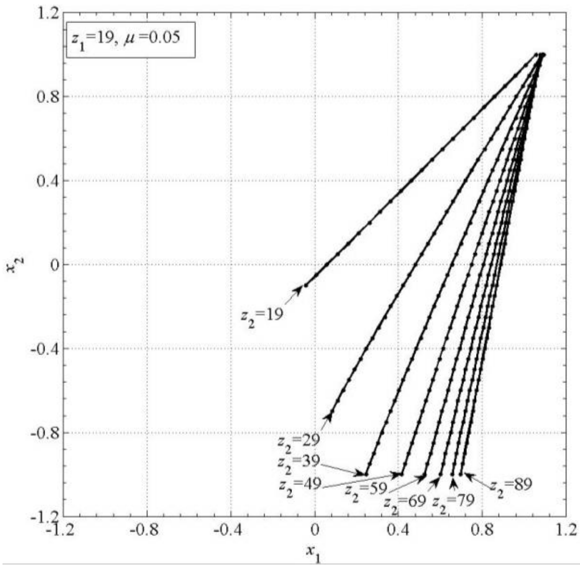

Fig. 4 The x_1 and x_2 plots for equalized efficiencies for z_1 = 19, z_2 = {19, 29, 39,…, 89} and μ=0.05

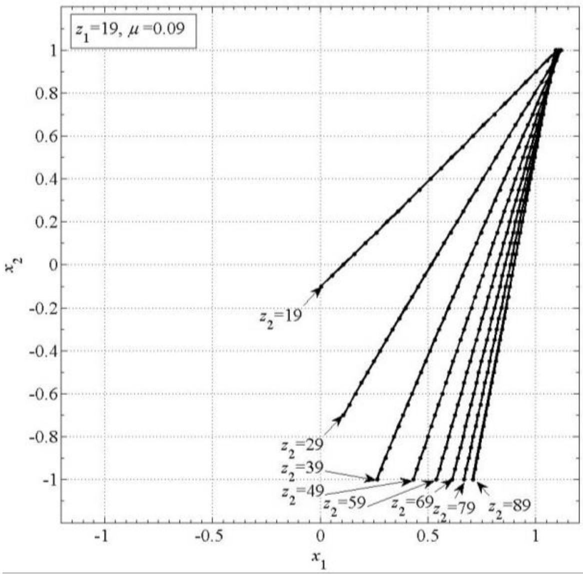

Fig. 5 The x_1 and x_2 plots for equalized efficiencies for z_1 = 19, z_2 = {19, 29, 39,…, 89} and μ = 0.09

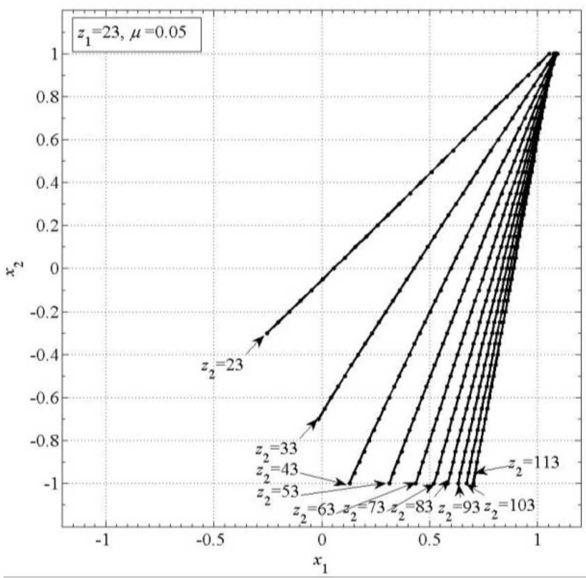

Fig. 6 The x_1 and x_2 plots for equalized efficiencies for z_1 = 23, z_2 = {23, 33, 43,…, 113} and μ = 0.05

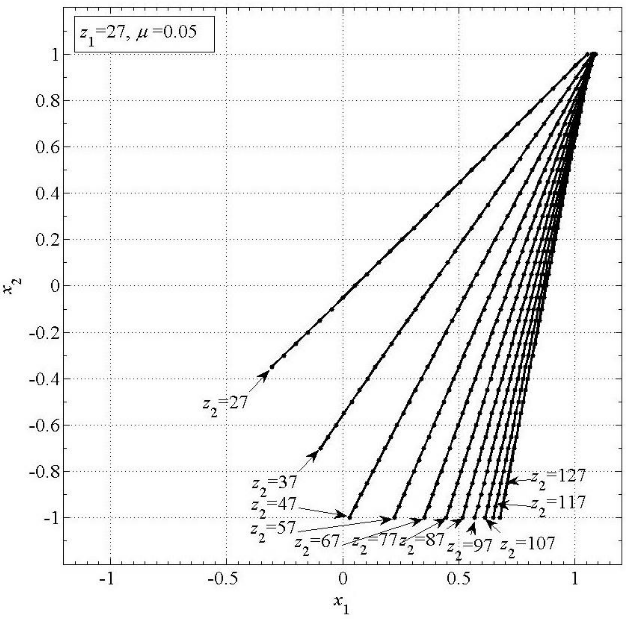

Fig. 7 The x_1 and x_2 plots for equalized efficiencies for z_1 = 27, z_2 = {27, 37, 47,…, 127} and μ = 0.05

The results from Table 1 are showing the raw data produced by the Matlab code. The [-1, 1] domain is divided into 41 points for x_2. Each solution is numbered from 1 to 41 in the i column of Table 1. Missing lines are representing a lack of solution for the (23) equalization equation. Some of the lines from Table 1 are eliminated in Table 2 as α_w must be over 14°. Table 2 to Table 5 are condensed versions of valid solutions and together with the plots from Fig. 4 to Fig. 7 allow making the following conclusions:

- higher μ friction coefficient will increase the number of valid solutions, however because the variation of the friction coefficient is very limited its influence is low;
- higher number of teethe as high ratio of numbers of teeth favor the number of solutions;
- the equalized efficiencies are maximum for the highest values of the positive of the x_1, x_2 pair solution;
- high ratio of numbers of teeth favors a higher value of the equalized efficiencies.

The x_1 and x_2 values are chosen independently under normal circumstances. Imposing the equalization condition a relationship between these to independent variables is defined and only one, of the two, will remain independent. As seen in the algorithm, the x_2 values are given, while the x_1 values result from the equalization condition if (23) has valid solutions.

Table 1

Equalized efficiencies for z_1 = 19, z_2 = 19 and μ = 0.05 with limitations

i	x_{1min}	x_1	x_{1max}	x_{2min}	x_2	x_{2max}	α_w, °	η_A	η_E
14	-0.11765	-0.30546	0.42089	-0.11765	-0.35000	0.39399	10.92986	0.98440	0.98440
15	-0.11765	-0.25140	0.38900	-0.11765	-0.30000	0.35982	13.38193	0.98521	0.98521
16	-0.11765	-0.19844	0.38076	-0.11765	-0.25000	0.34998	15.12985	0.98576	0.98576
17	-0.11765	-0.14612	0.38591	-0.11765	-0.20000	0.35393	16.52595	0.98620	0.98620
18	-0.11765	-0.09426	0.40005	-0.11765	-0.15000	0.36715	17.70443	0.98657	0.98657
19	-0.11765	-0.04274	0.42078	-0.11765	-0.10000	0.38716	18.73261	0.98690	0.98690
20	-0.11765	0.00851	0.44663	-0.11765	-0.05000	0.41246	19.64964	0.98720	0.98720
21	-0.11765	0.05953	0.47660	-0.11765	0.00000	0.44200	20.48055	0.98749	0.98749
22	-0.11765	0.11036	0.50998	-0.11765	0.05000	0.47508	21.24241	0.98776	0.98776
23	-0.11765	0.16102	0.54624	-0.11765	0.10000	0.51113	21.94746	0.98802	0.98802
24	-0.11765	0.21153	0.58499	-0.11765	0.15000	0.54975	22.60478	0.98827	0.98827
25	-0.11765	0.26190	0.62590	-0.11765	0.20000	0.59061	23.22136	0.98851	0.98851
26	-0.11765	0.31216	0.66872	-0.11765	0.25000	0.63344	23.80268	0.98875	0.98875
27	-0.11765	0.36231	0.71324	-0.11765	0.30000	0.67803	24.35311	0.98898	0.98898
28	-0.11765	0.41235	0.75928	-0.11765	0.35000	0.72419	24.87623	0.98921	0.98921
29	-0.11765	0.46231	0.80669	-0.11765	0.40000	0.77179	25.37501	0.98944	0.98944
30	-0.11765	0.51218	0.85536	-0.11765	0.45000	0.82067	25.85192	0.98966	0.98966
31	-0.11765	0.56197	0.90518	-0.11765	0.50000	0.87074	26.30905	0.98988	0.98988
32	-0.11765	0.61168	0.95604	-0.11765	0.55000	0.92190	26.74820	0.99010	0.99010
33	-0.11765	0.66133	1.00787	-0.11765	0.60000	0.97406	27.17092	0.99031	0.99031
34	-0.11765	0.71090	1.06060	-0.11765	0.65000	1.02715	27.57856	0.99053	0.99053
35	-0.11765	0.76042	1.11416	-0.11765	0.70000	1.08110	27.97229	0.99074	0.99074
36	-0.11765	0.80988	1.16850	-0.11765	0.75000	1.13586	28.35316	0.99095	0.99095
37	-0.11765	0.85928	1.22357	-0.11765	0.80000	1.19137	28.72207	0.99116	0.99116
38	-0.11765	0.90863	1.27931	-0.11765	0.85000	1.24758	29.07985	0.99137	0.99137
39	-0.11765	0.95792	1.33570	-0.11765	0.90000	1.30445	29.42724	0.99158	0.99158
40	-0.11765	1.00717	1.39268	-0.11765	0.95000	1.36195	29.76489	0.99179	0.99179
41	-0.11765	1.05637	1.45023	-0.11765	1.00000	1.42003	30.09340	0.99199	0.99199

Table 2

Equalized efficiencies for z_1 = 19, z_2 = 19 and μ = 0.05

i	x_1	x_2	α_w, °	$\eta_A = \eta_E$
19	-0.04274	-0.10000	18.73261	0.98690
20	0.00851	-0.05000	19.64964	0.98720
21	0.05953	0.00000	20.48055	0.98749
22	0.11036	0.05000	21.24241	0.98776
23	0.16102	0.10000	21.94746	0.98802
24	0.21153	0.15000	22.60478	0.98827
25	0.26190	0.20000	23.22136	0.98851
26	0.31216	0.25000	23.80268	0.98875
27	0.36231	0.30000	24.35311	0.98898
28	0.41235	0.35000	24.87623	0.98921
29	0.46231	0.40000	25.37501	0.98944
30	0.51218	0.45000	25.85192	0.98966
31	0.56197	0.50000	26.30905	0.98988
32	0.61168	0.55000	26.74820	0.99010
33	0.66133	0.60000	27.17092	0.99031
34	0.71090	0.65000	27.57856	0.99053
35	0.76042	0.70000	27.97229	0.99074
36	0.80988	0.75000	28.35316	0.99095
37	0.85928	0.80000	28.72207	0.99116
38	0.90863	0.85000	29.07985	0.99137
39	0.95792	0.90000	29.42724	0.99158
40	1.00717	0.95000	29.76489	0.99179
41	1.05637	1.00000	30.09340	0.99199

Table 3

Equalized efficiencies for z_1 = 19, z_2 = 89 and μ = 0.05

i	x_1	x_2	α_w, °	$\eta_A = \eta_E$
1	0.69735	-1.00000	19.07191	0.99578
2	0.71657	-0.90000	19.44898	0.99581
3	0.73575	-0.80000	19.81077	0.99585
4	0.75490	-0.70000	20.15867	0.99588
5	0.77402	-0.60000	20.49389	0.99592
6	0.79311	-0.50000	20.81751	0.99596
7	0.81219	-0.40000	21.13043	0.99599
8	0.83125	-0.30000	21.43347	0.99603
9	0.85030	-0.20000	21.72733	0.99608
10	0.86934	-0.10000	22.01267	0.99612
11	0.88838	0.00000	22.29003	0.99616
12	0.90741	0.10000	22.55994	0.99621
13	0.92644	0.20000	22.82286	0.99625
14	0.94547	0.30000	23.07920	0.99630
15	0.96450	0.40000	23.32933	0.99634
16	0.98354	0.50000	23.57361	0.99639
17	1.00259	0.60000	23.81235	0.99644
18	1.02164	0.70000	24.04583	0.99649
19	1.04070	0.80000	24.27433	0.99654
20	1.05978	0.90000	24.49808	0.99659
21	1.07886	1.00000	24.71732	0.99664

Table 4

Equalized efficiencies for z_1 = 27, z_2 = 27 and μ = 0.05

i	x_1	x_2	α_w, °	$\eta_A = \eta_E$
14	-0.30538	-0.35000	14.93574	0.98926
15	-0.25338	-0.30000	15.96645	0.98951
16	-0.20167	-0.25000	16.87081	0.98973
17	-0.15021	-0.20000	17.68081	0.98994
18	-0.09896	-0.15000	18.41716	0.99013
19	-0.04788	-0.10000	19.09416	0.99031
20	0.00305	-0.05000	19.72211	0.99049
21	0.05385	0.00000	20.30874	0.99066
22	0.10452	0.05000	20.85997	0.99082
23	0.15508	0.10000	21.38049	0.99098
24	0.20555	0.15000	21.87408	0.99114
25	0.25592	0.20000	22.34380	0.99129
26	0.30620	0.25000	22.79221	0.99145
27	0.35641	0.30000	23.22146	0.99160
28	0.40654	0.35000	23.63335	0.99175
29	0.45660	0.40000	24.02946	0.99189
30	0.50660	0.45000	24.41111	0.99204
31	0.55653	0.50000	24.77949	0.99219
32	0.60641	0.55000	25.13561	0.99233
33	0.65623	0.60000	25.48040	0.99248
34	0.70599	0.65000	25.81464	0.99262
35	0.75571	0.70000	26.13906	0.99276
36	0.80538	0.75000	26.45429	0.99291
37	0.85500	0.80000	26.76093	0.99305
38	0.90458	0.85000	27.05947	0.99319
39	0.95411	0.90000	27.35041	0.99333
40	1.00360	0.95000	27.63416	0.99347
41	1.05306	1.00000	27.91113	0.99361

Table 5

Equalized efficiencies for z_1 = 27, z_2 = 97 and μ = 0.05

i	x_1	x_2	α_w, °	$\eta_A = \eta_E$
1	0.56942	-1.00000	18.83493	0.99598
2	0.58231	-0.95000	19.01489	0.99599
3	0.59519	-0.90000	19.19121	0.99601
4	0.60806	-0.85000	19.36407	0.99603
5	0.62092	-0.80000	19.53362	0.99604
6	0.63377	-0.75000	19.70003	0.99606
7	0.64660	-0.70000	19.86342	0.99608
8	0.65943	-0.65000	20.02392	0.99609
9	0.67225	-0.60000	20.18165	0.99611
10	0.68507	-0.55000	20.33673	0.99613
11	0.69787	-0.50000	20.48926	0.99615
12	0.71067	-0.45000	20.63933	0.99617
13	0.72346	-0.40000	20.78705	0.99619
14	0.73625	-0.35000	20.93249	0.99621
15	0.74904	-0.30000	21.07574	0.99623
16	0.76182	-0.25000	21.21688	0.99625
17	0.77459	-0.20000	21.35598	0.99627

i	x_1	x_2	α_w, °	$\eta_A = \eta_E$
18	0.78737	-0.15000	21.49311	0.99629
19	0.80014	-0.10000	21.62834	0.99631
20	0.81290	-0.05000	21.76172	0.99633
21	0.82567	0.00000	21.89332	0.99635
22	0.83843	0.05000	22.02318	0.99637
23	0.85120	0.10000	22.15138	0.99640
24	0.86396	0.15000	22.27795	0.99642
25	0.87672	0.20000	22.40295	0.99644
26	0.88948	0.25000	22.52641	0.99646
27	0.90224	0.30000	22.64839	0.99649
28	0.91500	0.35000	22.76893	0.99651
29	0.92776	0.40000	22.88806	0.99653
30	0.94052	0.45000	23.00583	0.99655
31	0.95328	0.50000	23.12226	0.99658
32	0.96605	0.55000	23.23741	0.99660
33	0.97881	0.60000	23.35129	0.99663
34	0.99158	0.65000	23.46395	0.99665
35	1.00435	0.70000	23.57541	0.99667
36	1.01711	0.75000	23.68570	0.99670
37	1.02989	0.80000	23.79485	0.99672
38	1.04266	0.85000	23.90289	0.99675
39	1.05544	0.90000	24.00986	0.99677
40	1.06822	0.95000	24.11575	0.99680
41	1.08100	1.00000	24.22062	0.99682

5. Conclusions

The values of the specific addendum modifications x_1 and x_2 can be determined by this equalization procedure. A balanced efficiency will lead to balanced efficiency loss. As the efficiency loss is connected to sliding and rolling frictional losses the equalization will lead to a uniform wearing of teeth flanks at the points where the meshing ends and begins during load transmission. The algorithm allows finding a better balanced efficiency where the power losses are reduced. Reduced power losses lead to better operating conditions (lower operating temperature, noise and wear).

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ADDENDUM MODIFICATION OF SPUR GEARS WITH EQUALISED EFFICIENCY AT THE POINTS WHERE THE MESHING STARS AND

S u m m a r y

The paper gives a new method for obtaining the geometrical dimensions for involute spur gears based on the equalization conditions of the efficiencies, at the A and E points, where the meshing begins and ends. Numerical results and plots for the x_1 and x_2 addendum modifications are obtained, using the Matlab programming environment. The solutions are obtained for different pairs of teeth numbers, when the equalization condition stands, together with the limitations given by the teeth undercut, sharpening and operating pressure angle.

Keywords: spur gears, addendum modification, efficiency equalization.

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