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Contact Stress Analysis of Modified Straight Bevel Gear

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Abstract— The straight bevel gears are important mechanical element used in the industrial application for the purposes of transfer power and motion between two perpendicular shaft. Therefore, this study aims to increase the capability of the teeth to resist pitting failure and increase life of gears by modify the teeth profiles of standard (symmetric) straight bevel gear. The modification used in this study involve adopted the pressure angle of the teeth profile on unloaded side and fixed the pressure angle of the teeth profile on loaded side to establish a new geometry of modified (asymmetric) straight bevel gear . The first step used in the contact stress analysis is the generation of the tooth profile of standard and modified straight bevel gear, the generation process has been done by programming the parametric equation of the movement of the cutter by using MATLAB program (ver. 16), then the results obtain from parametric equation is import to the SOLIDWORKS program (ver.14) to generate the final form of standard and modified straight bevel gear. Then numerical investigation has been done on the model of the standard and modified straight bevel gear by using Finite Element Method (FEM) based on the ANSYS program (ver.16) to find the value of the contact stress. The results obtained from this study explained that there are a good enhancement in the value of the contact stress when using the modified straight bevel gear instead of standard case. The enhancement in the value of the contact about 19.601% for the case of modified straight bevel gear with unloaded pressure angle 35^0 when compared with standard case. Finally, verification on the numerical results of the contact stress has been done only for standard straight bevel gear by using analytical equation.

Keywords— Straight bevel gear, Standard (symmetric), Modified (asymmetric), Finite element method (FEM), Contact stress.

1. Introduction

Bevel gear drives are mostly used for the application of transfer power and motion between two perpendicular shafts, also few applications required a special design for the purposes of transfer power with shaft angle less or more than 90^0. There are different types of bevel gear such as straight, spiral, zerol, and hypoid bevel gear, the straight bevel gear which studied in this research was regarded as the simple types used in different application such automobile, marine, and lathe machine [3].

Pitting failure was regarded as the main types of failure that effected upon the working efficiency and corresponding effected up on the life of gear. Therefore, the requirement of increasing the ability of the teeth to resist the pitting failure were appear as the basic that interest the engineering design in the field of gear [7]. Accordingly, the modification on the involute teeth profile of straight bevel gear was regarded as the best way to increase the strength to resisting the pitting failure, this modification has been done by using asymmetric tooth profile by changing the working pressure angle for the unloaded side and fixed the working pressure angle of loaded side.

Ligata et al in [2] studied the contact stress of straight bevel gear generate by forging process forge with spherical involute tooth profile. The spherical involute form is not common in the industrial application, due to the fact that the machine don't have ability to cut this form of the tooth accurately. Then the contact analysis was done to compute the contact stress of the spherical involute tooth profile of straight bevel gear. Finally, the verification has been done to compare the results obtain from this study with the results from gear generated by rolling process. Zeyong et al in [14] introduced a new form of geometry of straight bevel gear and study the effect of this new geometry on the tooth contact stress and misalignment. The model of straight bevel gear was established and then the axial modification has been done done on the pinion and then the engagement between gear and pinion has been done to specify the contact region. The tooth contact stress of two interlock straight bevel gear was obtained by built software program in MATLAB. Deng et al in [12] studied the bending fatigue at the root of the tooth and contact fatigue on the tooth surface of the straight bevel gear by using finite element method, Also studied the variation in the contact fatigue and bending fatigue for different load condition. The value of contact and bending stress of two meshing tooth were done depending upon the stress life equation and nominal accumulative fatigue. Verification was done by using simulation procedure to increase the reliability of this method. The results of fatigue failure of the straight bevel gear was happen on the pinion derive. The contact fatigue and bending fatigue of the pinion was regarded as the main fatigue happen in two interlock straight bevel gear. KurlapKar and Merza in [11] studied two types of failure happen when a pair of bevel gear are meshing for the purposes of transfer power and motion, one include the bending failure due to bending stress ,and other include the pitting failure due to contact stress, Also studied the effect of different forces acting on the bevel gear. The Lewis bending equation was used to compute the bending stress of straight bevel gear, also the contact stress was computed by using Hertz equation. The results obtained for bending and contact stress of bevel gear by analytical method give good agreement when compared with the numerical results done by ANSYS. Kulkarni et al in [8] studied the bending stress and contact stress for the bevel gear for three different types of material theoretically and numerically by using finite element method. This study explains that the failure of the gear by the contact stress are higher when compared with bending stress, So that the maximum contact stress of bevel gear was computed by using finite element method and then the theoretical investigation was done by using Hertz contact equation. The results obtained for contact stress of bevel gear by numerical method gives good agreement when compared with the theoretical results. sandor in [1], studied the contact stress parameter such as normal stress, normal strain, and normal deformation of straight bevel gear as a function of number of teeth of the main gear. At first the model of straight bevel gear was generated by using a new software program which facilitate the procedure of calculation the dimension of the gears. Finally, the finite element method was done for five pairs of straight bevel gear to determine the normal stress, normal strain, and normal deformation at the contact region of every mating gears. Chen et al in [4] proposed an axial modification on the tooth profile of the straight bevel gear in order to improve the bearing capacity and meshing performance. In this study, two axial modification was done, one include tip end relief and second include symmetric crown modification, then meshing performance of the two gears were done by using finite element method. The results obtained from this study explained that the modification on the tip relief was regarded as optimum choice to enhancement the meshing performance for different installation of straight bevel gear with reduced transmission error, reduced bending and contact stress, and improve the distribution of the bending and contact strength.

Accordingly, this research aims to analyze the contact stress for standard and modified straight bevel gear for the purposes of increasing strength against pitting failure. modified straight bevel gear.

2. Generation of Standard and Modified Straight Bevel Gear

The first step used before analysis the contact stress involve the generation of the tooth profile of standard and modify straight bevel gear, this generation has been done by depending on the parametric equation describe the movement of the cutter during the operation of cutting process of the tooth of straight bevel gear as shown in the following equation [10]:

$$x_3 = x_2 cos\phi - y_2 sin\phi + (R - l)\phi\ tan\delta\ cos\phi - (R - l)tan\delta\ sin\phi \quad (1)$$

$$y_3 = x_2 sin\phi - y_2 cos\phi + (R - l)\phi\ tan\delta\ cos\phi - (R - l)tan\delta\ sin\phi \quad (2)$$

$$z_3 = z_2 + l \quad (3)$$

Then the parametric equation used to establish the standard form tooth profile of straight bevel gear has been modified to add the property of asymmetric form on the unladed side of tooth profile for straight bevel gear. There for the generation process can be divided into two parts, the first part include the generation of the loaded side as shown in the following equations [6]:

$$x_{3L} = x_{2L} cos\phi - y_{2L} sin\phi + (R - l)\phi\ tan\delta\ cos\phi - (R - l)tan\delta\ sin\phi \quad (4)$$

$$y_{3L} = x_{2L} sin\phi - y_{2L} cos\phi + (R - l)\phi\ tan\delta\ cos\phi - (R - l)tan\delta\ sin\phi \quad (5)$$

$$z_{3L} = z_{2L} + l \quad (6)$$

While, the second part have the generation process of the unloaded side of the tooth profile of straight bevel gear as shown in the following equations [6]:

$$x_{3u} = x_{2u} cos\phi - y_{2u} sin\phi + (R - l)\phi\ tan\delta\ cos\phi - (R - l)tan\delta\ sin\phi \quad (7)$$

$$y_{3u} = x_{2u} sin\phi - y_{2u} cos\phi + (R - l)\phi\ tan\delta\ cos\phi - (R - l)tan\delta\ sin\phi \quad (8)$$

$$z_{3u} = z_{2u} + l \quad (9)$$

3. Modeling of the Standard and Modified Straight Bevel Gear by Using Solidworks

Solidworks program ver. 14 has been used to generate the final shape of standard and modified straight bevel gear by depending upon different parameters shown in **Table (1)** like, gear module, addendum circle, dedendum circle, pitch circle, and reference cone angle.

Table 1: Gear and pinion parameters for speed ratio (SR =1).

Gear parameter	Gear and pinion
Pitch circle	d = 140 mm
Number of teeth	Z= 20
Gear module	m = 7 mm
Face width	f = 33 mm
Addendum	h_a = 7 mm
Dedendum	h_d = 8.75 mm
Pitch angle	$\delta = 45^0$
Distance of the cone	R = 98.994 mm
Angle of addedendum	$\theta_{a1} = 4.04^0$
Angle of dedendum	$\theta_{f1} = 5.05^0$
Tooth thickness	S = 10.9956 mm
Addendum circle	d_a = 149.899 mm

At first, the parametric equation describe the movement of cutter has been programming by using MATLAB program ver. 14 to get the profile of the involute teeth for standard and modified staright bevel gear.

The generation process for the straight bevel gear start by drawing the conical gear blank depending upon parameter shown in **Table (1),** then apply the instruction of revolved from 0^0 to 360^o to establish the final form of gear conical blank as shown in **Figure (1)** and **Figure (2).**

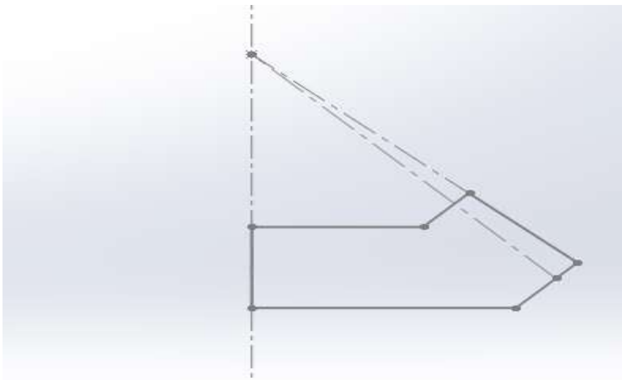

Figure 1 : 2D profile of conical gear blank.

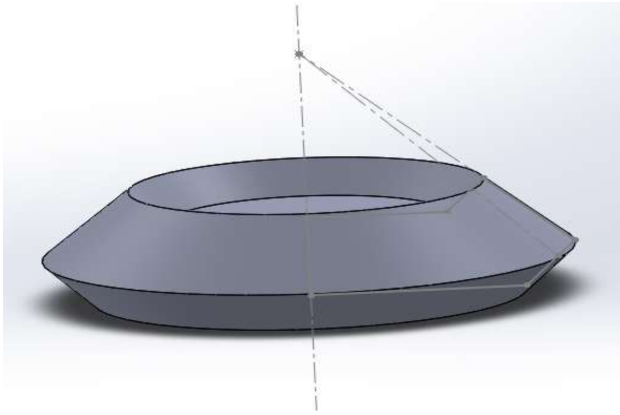

Figure 2 : 3D conical gear blank.

Then, imoport the involute profile of tooth of the gear found in MATLAB program to the SOLIDWORKS program to specify the tooth shape on the conical gear blank as shown in **Figure (3)**.

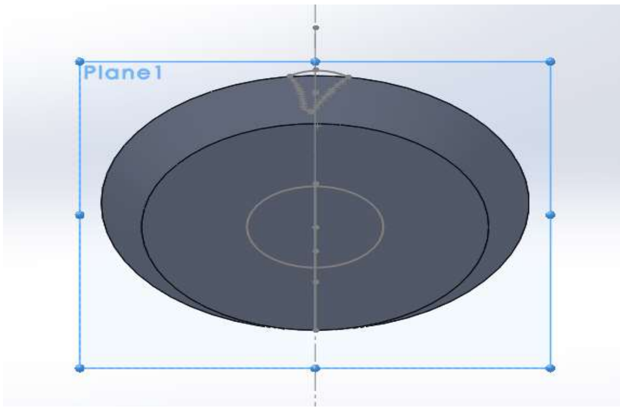

Figure 3 : Involute tooth profile fixed on the gear conical blank.

Using the lofted cut order on the involute profile of tooth according to reference point fixed on the line of intersection of center of gear with cone distance as shown in **Figure (4)**, the circular pattern order for 20 number of teeth and spacing 360 degree as shown in **Figure (5)** used to create the final shape of straight bevel gear.

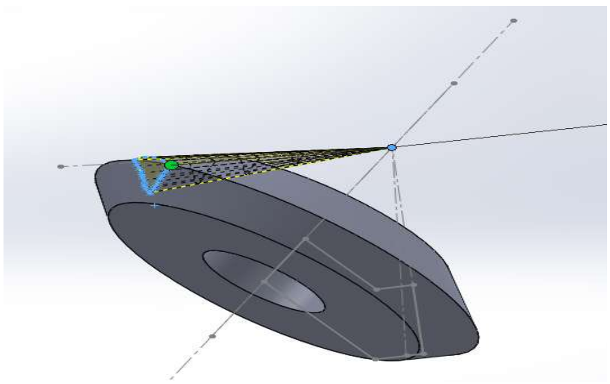

Figure 4 : Involute tooth profile fixed on the gear conical blank.

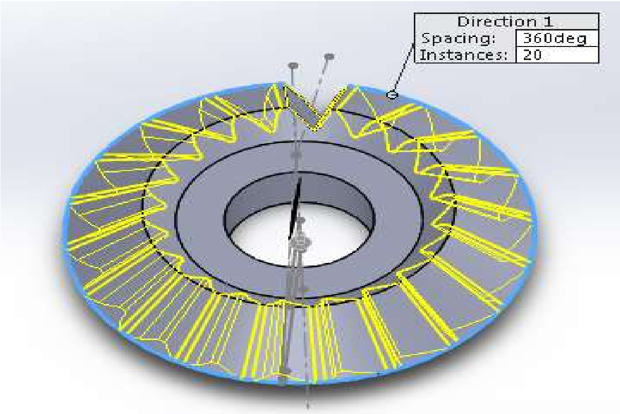

Figure 5 : Circular pattern done on the involute of the gear conical blank.

Finally, **Figure (6)** shows the full involute profile of straight bevel gear, then the order of revolved cut used to generate the final model used to obtain the contact stress of standard and modified straight bevel gear as shown in **Figure (7).**

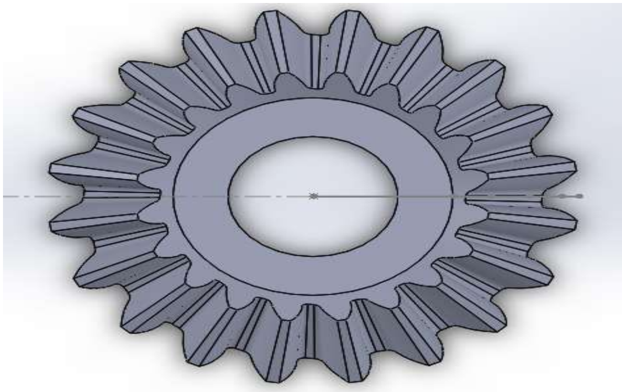

Figure 6 : 3D full straight bevel gear.

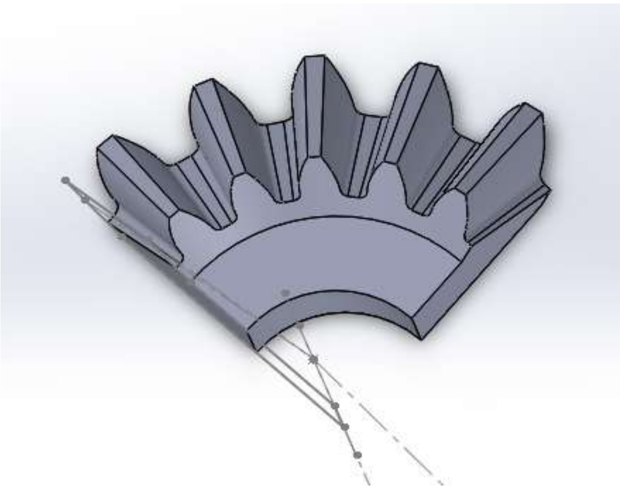

Figure 7 : Involute tooth profile fixed on the gear conical blank.

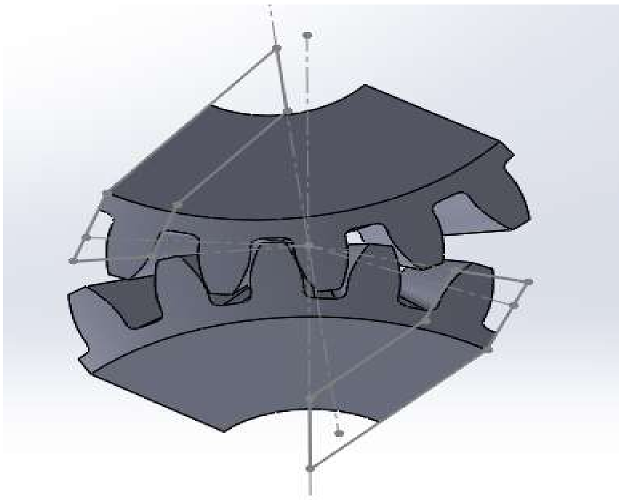

Figure 8 : Engagement of the two model of straight bevel gear.

4. Analytical Investigation into Contact Stress for Standard Straight Bevel Gear

The pitting failure is take place in the teeth of gear drives when the value of the contact stress on teeth surface is greater than the fatigue strength of the gear.

If a pair of tooth surface of gear drives are engage together the contact will be happen, the contact point between two engaged tooth move along tooth surface from top to bottom as shown in **Figure (9)**. The value of the contact stress depends on the number of pairs of the teeth in contact, so the maximum value of the contact stress was hapen when only one pair of teeth are in contact. **Figure (10)** shows the contact stress distribution along the tooth surface profile of straight bevel gear, from this figure its clear that the variation in the actual value of the contact stress from points a, b, and p, so point P (pitch point at middle surface) used to calculate the contact stress of a pairs of tooth of straight bevel gear are in contact. The Hertz equation is regard as a foundation used to determine the contact stress of gear drives as describe in the following equation [13]:

$$\sigma_c = Z_E\, Z_H \sqrt{\frac{4\, T_1}{\varphi\,.\,(1-0.5\varphi)\; {d_1}^3\; u}} \qquad (10)$$

Where

$$Z_E = \sqrt{\frac{1}{\pi\left[\frac{1-\mu_1^2}{E_1}+\frac{1-\mu_2^2}{E_2}\right]}} \qquad (11)$$

$$Z_H = \sqrt{\frac{2}{sin\beta.cos\beta}} \qquad (12)$$

$$\varphi = \frac{b}{R} \qquad (13)$$

σ_c: Contact stress (Mpa).

T_1: Torque applied at the pinion (N.mm).
μ_1, μ_2: Poisson's ratio of pinion and gear respectively.
E_1, E_2: Elastic modulus of pinion and gear respectively (Mpa).
d_1: Pitch diameter of the pinion (mm).
u: Gear ratio.
b: Face width (mm).
R: Cone distance (mm).
β: Pressure angle (degree).

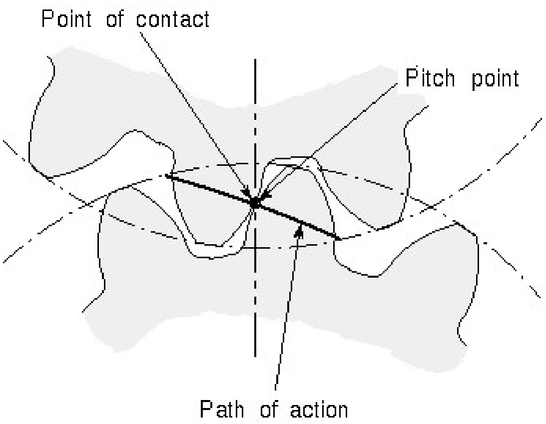

Figure 9 : Contact point of two matching straight bevel gear.

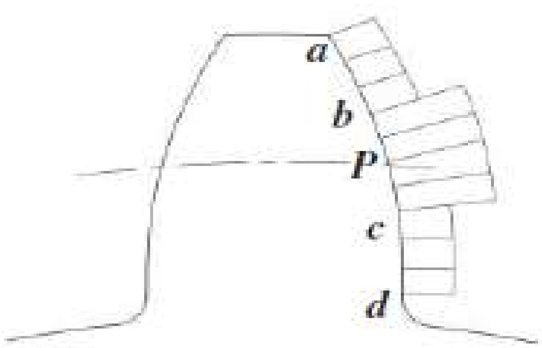

Figure 10 : Contact stress distribution on the tooth profile..

5. FEM Investigation into Contact Stress for Standard and Modified Straight Bevel Gear

The model of the teeth profile of standard and modified straight bevel gear was created in the SOLIDWORKS program (ver.14), then engagement of the two model has been done to study the contact stress. The model created in the Solidworks program include engagement of two straight bevel gear are importe to ANSYS program (ver.16), then the structural analysis has been done by using Finite Element Method (FEM) according to the following steps [5, 9].

The first step used in the contact stress analysis in ANSYS program is set engineering data with linear elastic properties, 6061 aluminum alloy material used with properties show in **Table (2)**.

Table 2: Properties of aluminum material used for study the contact stress.

Type of material	Elastic Modulus (Mpa)	Poisson's ratio	Yield strength (Mpa)
Aluminum	69	0.33	276

The second step carry out in the analysis is set the contact region between two interlock gear, using frictionless contact region for the contact body and target body for one tooth only as shown in **Figure (11)**.

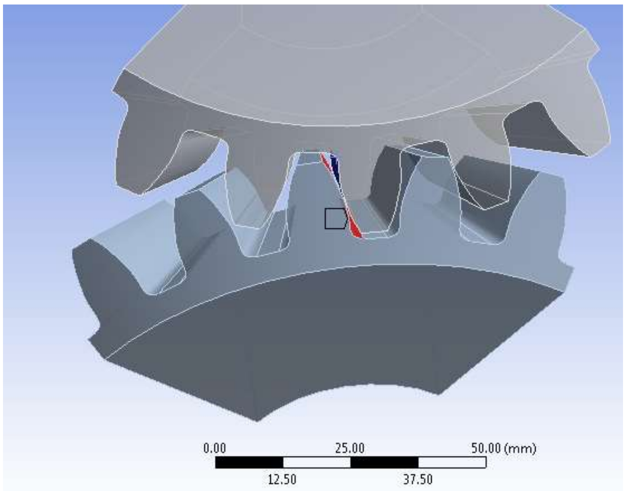

Figure 11 : Contact region of two engagement straight bevel gear.

The third step carry out in the analysis is set meshing to the model of the tooth profile of straight bevel gear, this meshing divided the model of the contact and target bodies to the number of small element with 1mm in size and then the sweep type of mesh is select. The elements in the expected region of maximum contact stress of the contact and target bodies was refined and then the size of element in this region is set 0.5mm, and finally the meshing operation has been done on the models as shown in **Figure (12)** having 242941 elements and 357324 nodes.

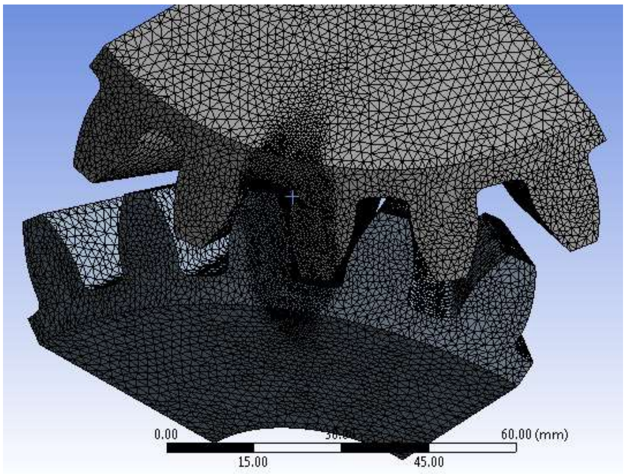

Figure 12 : Meshing performance of the two interlock straight bevel gear.

The fourth step carry out in the analysis is set the boundary condition on the rim of the engaged model of straight bevel gear, fixed boundary condition apply at the inner rim of the lower gear (target body) while frictionless support apply at the inner rim of the upper gear (contact body) to prevent radial translation and allow only to the rotational motion as shown in **Figure (13)**.

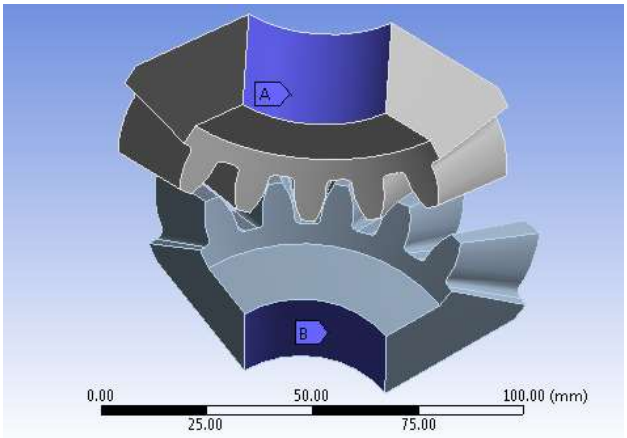

Figure 13: Boundary condition of two engagement straight bevel gear.

The fifth step carry out in the analysis is set the moment on the inner rim of upper gear (contact body) on the model of straight bevel gear with value equal to 8500 N.mm as shown in **Figure (14)**.

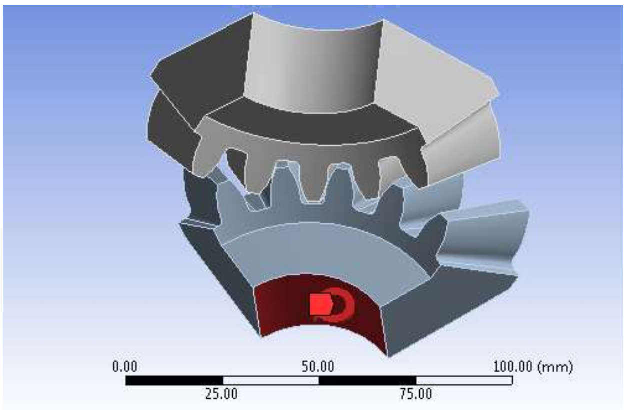

Figure 14: Loading condition of two interlock straight bevel gear.

Then the final step involves the solution of the model of the standard and modified tooth profile of straight bevel gear.

6. Results of the Contact Stress

The results of the contact stress consist of two parts, the first part deal with the analytical results for standard straight bevel gear, while the second part deal with the numerical results for standard and modified straight bevel gear.

6.1 *Analytical Results*

In this study, the analytical results can be find for standard straight bevel gear, while in the case of modified straight bevel gear, there is no clear theoretical equation used to obtain the contact stress due to complexity in the geometry of teeth profile. The main purposes of the analytical result of standard straight bevel gear are using to verify the numerical results of standard straight bevel gear, and this also give good indication to the validity of the numerical results for modified straight bevel gear.

Figure (15) shows the effect of loading condition on the value of the contact stress. From this figure, it's clear that the increase in the value of loading will cause increase in the value of the contact stress, this behavior can attribute due to the fact that the loading is directly related the induced contact stress of straight bevel.

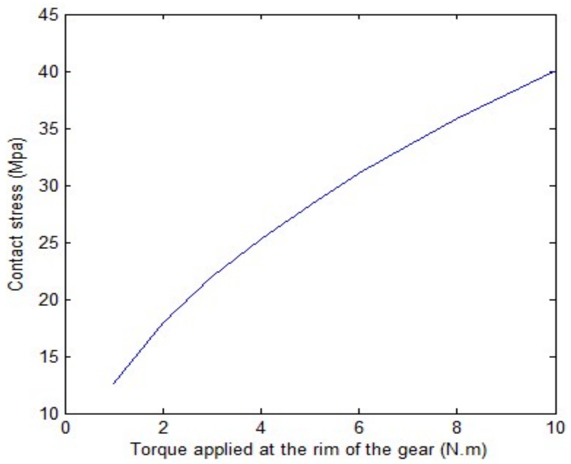

Figure 15: Effect of the loading on the value of the contact stress for straight bevel gear with 14.5^0 loaded pressure angle on both side.

Figure (16) shows the effect of pressure angle on the value of the contact stress. From this figure, it's clear that the increase in the value of pressure angle will cause decrease in the value of the contact stress, this behavior can attribute due to the fact that the increase in the pressure angle lead to increase in the contact area and this lead to increase the radius of curvature of straight bevel.

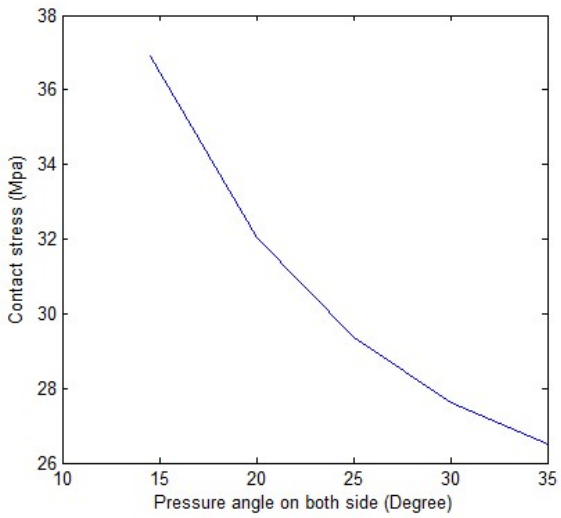

Figure 16: Effect of pressure angle on the value of the contact stress for straight bevel gear.

Figure (17) shows the effect of speed ratio on the value of the contact stress. From this figure, it's clear that the increase in the value of speed ratio will cause decrease in the value of the contact stress, this behavior can attribute due to the fact that the increase in the speed ratio lead to increase in the contact area and this lead to increase the radius of curvature of straight bevel.

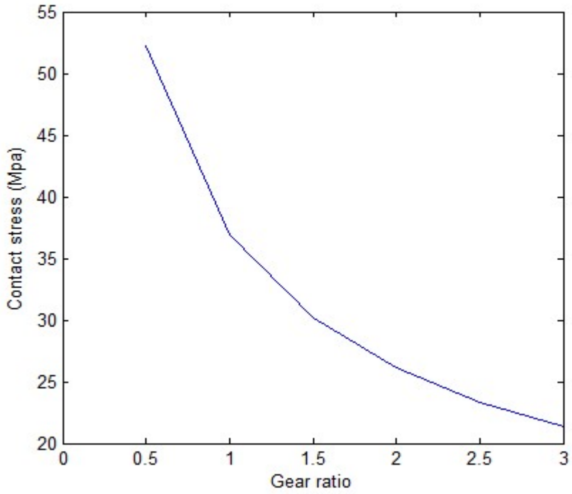

Figure 17: Effect of the gear ratio on the value of the contact stress for straight bevel gear.

6.2 *Numerical Results*

Figures (18,19,20,21,22) explain the contact stress distribution on the tooth profile of two engagement standard and modified straight bevel gear for five selected examples of case studies of **Table (3)**.

Table 3: Sample case studies

Case study	Loaded pressure angle (β_l)	Unloaded pressure angle (β_u)
Case (1)	14.5^0	14.5^0
Case (2)	14.5^0	20^0
Case (3)	14.5^0	25^0
Case (4)	14.5^0	30^0
Case (5)	14.5^0	35^0

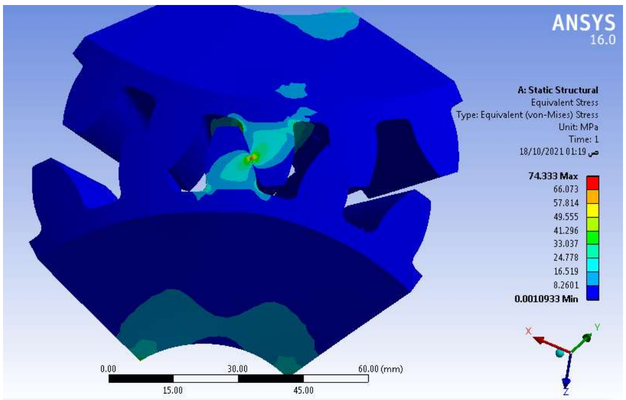

Figure 18: Contact stress of standard straight bevel gear.

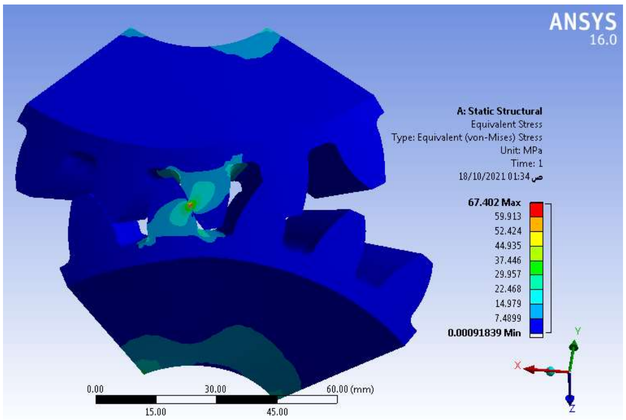

Figure 19: Contact stress of modified straight bevel gear (β_l=14.5^0 and β_u=20^0).

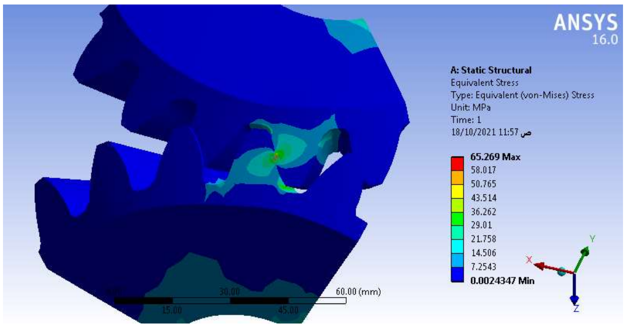

Figure 20: Contact stress of modified straight bevel gear (β_l=14.5^0 and β_u=25^0).

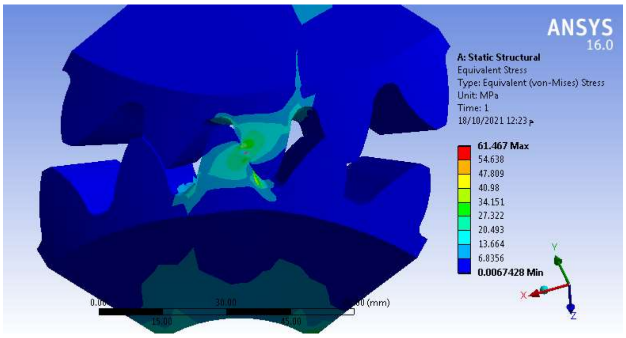

Figure 21: Contact stress of modified straight bevel gear (β_l=14.5^0 and β_u=30^0).

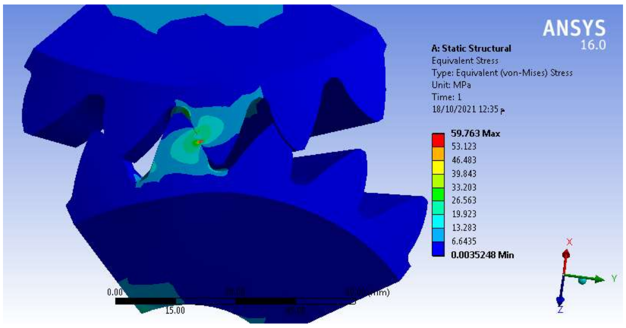

Figure 22: Contact stress of modified straight bevel gear (β_l=14.5^0 and β_u=35^0).

Table (4) explains the numerical results of contact stress (maximum stress) on the tooth profile for standard and modified straight bevel gear according to the moment load applied at rim of the gear with its enhancement percentage in the value of contact stress when using modified (asymmetric) straight bevel gear of all case studied describe in **Table (1)** when compared to the reference (standard) case study (1).

Table 4: Numerical results of contact stress with enhancement percentage.

Case study	Contact stress (Mpa)	Enhancement percentage (%)
Case (1)	74.333	0 %
Case (2)	67.402	9.3243%
Case (3)	65.269	12.1938%
Case (4)	61.467	17.3086%
Case (5)	59.763	19.601%

From **Table (4)** and **Figure (15-19)**, one can conclude that there is clear enhancement in the value of the contact stress for all case studies of modified straight bevel gear when compared with standard case, this behavior due to the fact that using modified tooth profile of straight bevel gear lead to increase stiffness distribution in the tooth body, and this stiffness in body of the tooth increase when increasing the pressure angle of the unloaded side of modified straight bevel gear.

Table (5) shows the comparison between numerical results and analytical results for standard bevel gear drive with percentage error less than 1%.

Table 5: Comparison between numerical and analytical results.

Analytical contact stress (Mpa)	Finite element (Mpa)	Percentage error (%)
73.7743	74.333	0.75%

7. Conclusion

The results of the contact stress of standard and symmetric straight bevel gear lead to fixed the following facts:

1. The model of standard tooth profile of straight bevel gear can be generated by using the parametric equation of the movement of the cutter, then this parametric equation is modified to establish the modified tooth profile of straight bevel gear.
2. The modification on the tooth profile of straight bevel gear has been done by changing the working pressure angle of the unloaded side and fixed the working pressure angle of the loaded side at standard value.
3. There are a significant enhancement in the value of the contact stress (increase strength against pitting failure) when using modified teeth profile of straight bevel gear when compared with the standard case.
4. The enhancement percentage in the value of the contact stress when using modified straight bevel gear with unloaded pressure angle (20^0, 25^0, 30^0, 35^0) and 14.5^0 loaded pressure angle are (9.3243%, 12.1938%, 17.3086%, 19.601%) according to reference standard case study.

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Nomenclature

d_I Pitch diameter (mm).

l	Distance between reference point and coordinate of the cutter (mm).
R	Cone distance (mm).
T_1	Torque transmitted (N.mm)
u	Gear ratio
x_2,y_2,z_2	Coordinate of cutter (mm)
x_3,y_3,z_3	Coordinate of gear (mm).)
Z_H	Zone factor
Z_E	Elastic coefficient
E_1, E_2	Elastic modulus of pinion and gear respectively (Mpa).
b	Face width (mm).
R	Cone distance (mm).

Greek symbols

ϕ	Angular position of blank coordinate system relative to the reference coordinate (degree).
φ	Ratio of face width to the cone distance.
σ_c	Contact stress (Mpa).
μ_1, μ_2	Poisson's ratio of pinion and gear respectively.
δ	Reference pitch angle (degree).

Subscripts

C	Contact
L	Loaded side
U	Unloaded side

تحليل اجهاد التلامس للترس المخروطي المعدل

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الخلاصة – التروس المخروطية المستقيمة هي اجزاء ميكانيكية مهمة تستخدم في التطبيقات الصناعية لغرض نقل الطاقة والحركة بين جزء واخر. لذلك هذه الدراسة تهدف الى زيادة قدرة الاسنان لمقاومة فشل النقر وزيادة العمر بتعديل ملامح الاسنان القياسية (المتناظرة) للترس المخروطي المستقيم. التعديل المستخدم في هذه الدراسة يتضمن تحويل زاوية الضغط للجانب غيرالمحمل وتثبيت زاوية الضغط للجزء المحمل لتكوين شكل هندسي جديد من الترس المخروطي المعدل (غير متناظر). الخطوة الاولى المستخدمة في تحليل اجهاد التلامس هي توليد سن الترس المخروطي القياسي والترس المخروطي المعدل, هذا التوليد يطبق باستخدام برنامج SOLIDWORKS (النسخة 14) طبقا للمعادلات البارامترية. ثم يتم تطبيق التحليل العددي على النموذ القياسي والمعدل للترس المخروطي المستقيم باستخدام طريقة العناصر المحدودة (FEM) طبقا لبرنامج ANSYS (ver.16) لايجاد قيمة اجهاد التلامس. النتائج التي تم الحول عليها من هذه الدراسة تبين ان هنالك تحسين جيد في قيمة اجهاد التلامس عندما يتم استخدام الترس المخروطي المعدل بدل الحالة القاسية. هذه التحسينات في قيمة اجهاد التلامس يتم توضيحها جيدا في حالة الترس المخروطي المعدل بزاوية ضغط 35 درجة على الجانب غير المحمل وبنسبة تحسين 19,601 %. اخيرا,تم التحقيق على النتائج العددية لاجهاد التلامس للترس المخروطي القياسي باستخدام المعادلة التحليلية.

الكلمات الرئيسية – الترس المخروطي المستقيم, القياسي (المتناظر), المعدل (الغير متناظر), طريقة العناصر المحددة, اجهاد التلامس