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Design and Optimization of Bevel Gear Actuator

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Abstract: Actuators are Mechanical devices specially intended to control, direct, start, stop, settling the flow and pressure of a process liquids. An actuator comprises of a bevel gear & pinion. The objective of this study is to find out the how much load is acting on the bevel gear and pinion i.e., tangential, dynamic, wear, and endurance strength of tooth load. This work covers design and optimization of bevel gear actuator operated by manual hand wheel. Bevel Gear Actuator is designed using manual dimensions analytically and geometric modeling is carried out in UGNX7.5. Optimization of Bevel Gear and Pinion is carried out by changing the teeth on Gear and Pinion.

Keywords: Actuator, Bevel Gear & Pinion, UG-NX.

I. INTRODUCTION

An actuator is a form of device that controls components or frameworks. It takes hydraulic fluid, electric current and flow or unlike sources of energy and advocates the energy to encourage the movement. Actuators are to great degree helpful appliances and have a differing scope of employments in fields engineering, electronic designing, printers, autos or plate drives. Most actuators create straight (straight line), rotational (round) or oscillatory movement.

Classification of Actuators:

There are 4 key varieties of actuators: Manual, Hydraulic, Pneumatic & Electric.

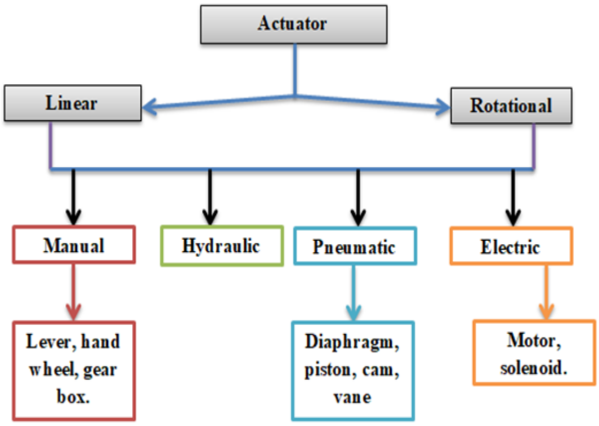

Fig. 1.Classification of Actuators

Types of bevel gear:

It is categorized into four types, according to teeth it classified.

a) Straight
b) Spiral
c) Zerol &
d) Hypoid Bevel Gears

Bevel gear:

"A cone shaped gear which conveys control among two intersecting axles." Bevel gears are typically mounted on shafts that are 90^0 separated however can be proposed to work at different angles too.

Fig.2 Bevel gear

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Nomenclature of bevel gear:

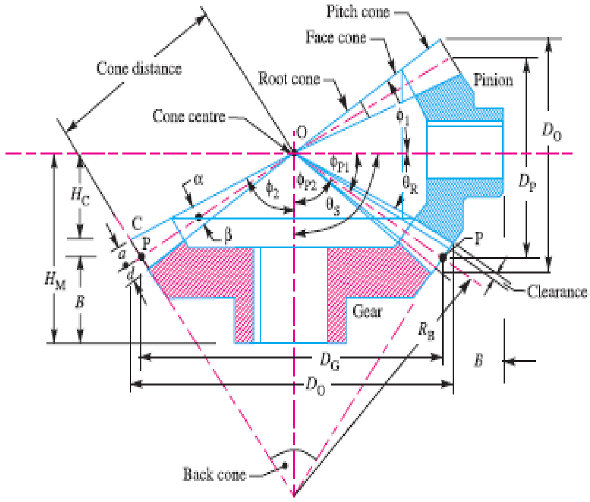

Fig.3 Nomenclature of bevel gear

a. Pitch cone:

"It is a cone containing the pitch elements of the teeth."

b. Cone Centre:

"It is the apex of the pitch cone. It may be clear as that point where the axes of two mating gears meet each other."

c. Pitch angle:

"It is the angle made by the pitch line with the axis of the shaft". It is indicated by 'θ_P'.

d. Cone distance:

"It is the length of the pitch cone part, denoted by 'O_P'." Mathematically, represented as

$$O_p = \frac{pitch\ radius}{sin\theta_p} = \frac{\left(\frac{D_P}{2}\right)}{sin\theta_{p1}} = \frac{\left(\frac{D_G}{2}\right)}{sin\theta_{p2}}$$

e. Addendum angle:

"The angle subtended by the addendum of the tooth at cone centre."

f. Dedendum angle:

"It is an angle subtended by the dedendum of the tooth at cone centre."

g. Face angle:

"The angle subtended by the face of the tooth at the cone centre & the face angle is equal to the pitch angle plus addendum angle" denoted by 'φ'.

h. Root angle:

"It is the angle subtended by the root of the tooth at the cone centre & it is equal to the pitch angle minus dedendum angle," indicated by 'θ_R'.

i. Back (or normal) cone:

"It is an imaginary cone, perpendicular to the pitch cone at the end of the tooth."

j. Back cone distance:

"It is the length of the back cone called as back cone radius," indicated by 'R_B'.

k. Backing:

"Distance of the pitch point (P) from the back of the boss, parallel to the pitch point of the gear."

l. Crown height:

"The distance of the Crown Point (C) from the cone centre (O), parallel to the axis of the gear (H_C)."

m. Mounting height:

"It is the distance of the back of the boss from the cone centre (H_M)."

n. Pitch diameter:

"The diameter of the largest pitch circle is pitch diameter."

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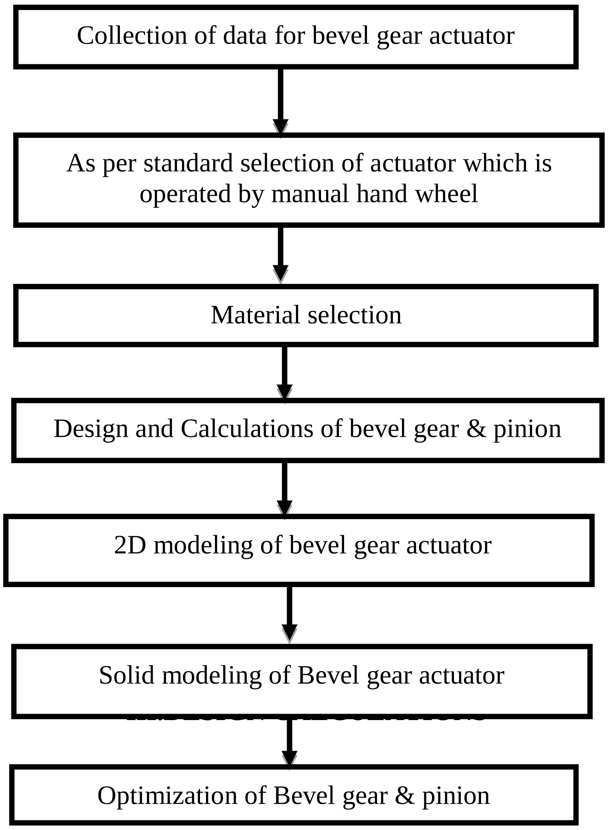
II. METHODOLOGY



Scopes for bevel gear:

The scopes for the bevel gears can be chosen as follows:

Addendum, a = 1 **m.**
Dedendum, d= 1.2 **m.**
Clearance, = 0.2 **m.**
Working depth = 2 **m.**
Thickness of tooth = 1.5708 **m.**

where "**m**" is the module.

Strength of bevel gears:

The strength of a bevel gear tooth is achieved in a related way as deliberated. The altered form of Lewis equation for the tangential tooth load is specified as follows.

$$W_T = (\sigma_0 * C_v)\, b.\Pi.m.Y' \left(\frac{L-b}{L}\right)$$

Where $\sigma_0 = Allowable\ static\ stress,$

$C_v = Velocity\ factor,$

$= \frac{3}{3+v}, for\ teeth\ cut\ by\ form\ cutters,$

$= \frac{6}{6+v}, for\ teeth\ produced\ for\ machines,$

$v = Peripheral\ speed\ in\ m/s,$

$b = Face\ width\ in\ mm,$

$m = Module\ in\ mm,$

$Y' = Tooth\ form\ factor\ for\ the\ corresponding\ no.of\ teeth,$

$$L = Slant\ height\ of\ pitch\ cone = \sqrt{\left(\frac{D_G}{2}\right)^2 + \left(\frac{D_P}{2}\right)^2}$$

where $D_G = Pitch\ diameter\ of\ gear$, and

$D_P = Pitch\ diameter\ of\ pinion.$

Dynamic load bevel gear:

$$W_D = W_T + W_I$$

where W_I is Incremental Load $\boldsymbol{W_I}\ \frac{21v\,(b.C+W_T)}{21v+\sqrt{b.C+W_T}}$

where C, Deformation factor $\boldsymbol{C} = \frac{0.00535}{\frac{1}{E_P}+\frac{1}{E_G}}$

where E_P and E_G are Young's Modulus

Wear load of bevel gear:

The maximum wear load for bevel gears is specified by; $\boldsymbol{W_w} = \frac{\boldsymbol{D_p.b.Q.K}}{\boldsymbol{\cos\theta_{p1}}}$

where D_p, b, Q and K have normal denotations as deliberated here except that Q is based on equal no. of teeth,

where Q, Ratio factor; $\boldsymbol{Q} = \frac{\boldsymbol{2T_{EG}}}{\boldsymbol{T_{EG}+T_{EP}}}$

where K, factor dependent upon form of teeth;

$$\boldsymbol{K} = \frac{\sigma_{se}^2\times 0.3}{1.4}\left(\frac{1}{E_1}+\frac{1}{E_2}\right)$$

Design and Calculations for Bevel Gear & Pinion:

No. of teeth for Bevel Pinion $\mathbf{Z_1}$=15

No. of teeth for Bevel Gear $\mathbf{Z_2}$=30

Diameter of Bevel Pinion $\mathbf{d_1}$=46mm

Diameter of Bevel Gear $\mathbf{d_2}$=92mm

Module $\boldsymbol{m} = (\frac{Z_2}{d_2}) = (\frac{92}{30}) = 3.06 \cong 3.5$mm

Addendum a=1m=1×3.5=3.5mm

Dedendum, d = 1.2 m = 1.2×3.5 = 4.2m

Velocity factor;

$$\boldsymbol{C_V} = \frac{6}{6+v} = \frac{6}{6+0.048} = 0.99$$

$$\boldsymbol{v} = \frac{\pi d_1 N_1}{60\times10^3} = \frac{\pi\times46\times20}{60\times10^3} = 0.048\ m/s$$

$$\boldsymbol{\theta_{p1}} = \tan^{-1}\frac{\sin\theta_s}{2+\cos\theta_s};\ \theta_s = 90^0$$

$$\boldsymbol{\theta_{p1}} = \tan^{-1}\frac{\sin 90^0}{2+\cos 90^0} = 26.56^0$$

$$\boldsymbol{\theta_{p2}} = 90^0 - 26.56^0 = 63.43^0.$$

Equivalent no. of teeth for pinion & gear correspondingly (Tredgold's Approximation)

$$\boldsymbol{T_{E1}} = T_1\ \sec\theta_{p1} = 15\times\ \sec 26.56^0 = 17\ \ or\ 18$$

$$\boldsymbol{T_{E2}} = T_2\ \sec\theta_{p2} = 30\times\ \sec 63.43^0 = 67.07 \cong 68$$

Tooth form factor;

$$\boldsymbol{Y_1'} = \mathbf{0.154} - \frac{\mathbf{0.912}}{\boldsymbol{T_{E1}}} = 0.1033$$

$$\boldsymbol{Y_2'} = \mathbf{0.154} - \frac{\mathbf{0.912}}{\boldsymbol{T_{E2}}} = 0.1405$$

Bevel factor

$$\boldsymbol{B.F} = \frac{\boldsymbol{L-b}}{\boldsymbol{L}} = \mathbf{0.523}$$

where **L** = Slant height of pitch cone== 51.42mm

$Face\ width\ \boldsymbol{b} = 6.3m\ to\ 9.5m = 7m = 24.5mm$

Tangential load:

$$\boldsymbol{W_T} = (\boldsymbol{\sigma_0} * \boldsymbol{C_v})\,\boldsymbol{b.\Pi.m.y'}\ (\boldsymbol{B.F})$$

$$\boldsymbol{W_{T1}} = 2017.20\ N$$

$$\boldsymbol{W_{T2}} = 1371.81N$$

$W_{T1} > W_{T2}$; condition for design its means that pinion teeth are weaker than gear teeth.

Dynamic load:

$$\boldsymbol{W_D} = \boldsymbol{W_T} + \boldsymbol{W_I}$$

$$\boldsymbol{W_I} = \frac{21v\,(b.C+W_T)}{21v+\sqrt{b.C+W_T}}$$

where $\boldsymbol{C} = \frac{\mathbf{0.00535}}{\frac{1}{E_P}+\frac{1}{E_G}} = 321\text{N/mm}$

$$\boldsymbol{W_{I1}} = 99.210N$$

$$\boldsymbol{W_{I2}} = 95.810\text{N}$$

$$\boldsymbol{W_{D1}} = W_{T1} + W_{I1} = 2116.411N$$

$$\boldsymbol{W_{D2}} = W_{T2} + W_{I2} = 1467.68N$$

Endurance Strength:

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$$W_s = \sigma_e . b. \Pi. m. y' \left(\frac{L-b}{L}\right)$$
$$W_{s1} = 1833.81\ N$$
$$W_{s2} = 1662.80\ N$$

Wear Load:

$$W_w = \frac{D_p.b.Q.K}{\cos\theta_{p1}};\ where\ Q = \frac{2T_{EG}}{T_{EG}+T_{EP}} = 1.58$$
$$K = \frac{\sigma_{se}^2 \times 0.3}{1.4}\left(\frac{1}{E_1}+\frac{1}{E_2}\right) = 1.18\ N/mm^2$$
$$W_{w1} = 2349.08\text{N}$$
$$W_{w2} = 9401.24\text{ N}$$

$$\left.\begin{matrix} W_{W1} > W_{T1} \\ W_{W2} > W_{T2} \end{matrix}\right\}; \text{design condition}$$

Design is in safe hands i.e. acceptable from the normal point of wear.

Assembly of bevel gear actuator:

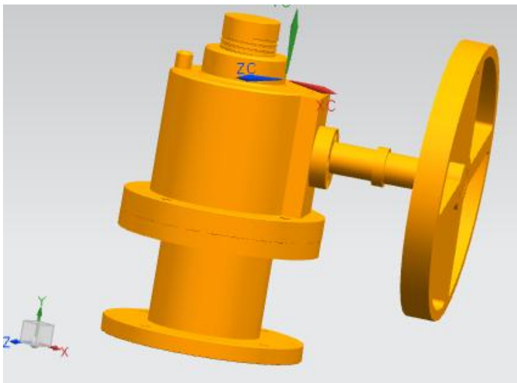

Fig. 5.Assembly of bevel gear actuator

IV. DESIGN AND OPTIMIZATION

First Optimization of Bevel Gear & Pinion:

Gear Teeth Z_2=32
Pinion teeth Z_1=16
Diameter of Pinion $\mathbf{d_1}$=50mm
Diameter of Gear $\mathbf{d_2}$=100mm
Module $\boldsymbol{m} = (\frac{Z_2}{d_2}) = (\frac{100}{32}) = 3.125 \simeq 3.5mm$

Velocity factor;

$$C_V = \frac{6}{6+v} = \frac{6}{6+0.048} = 0.99$$
$$v = \frac{\pi d_1 N_1}{60\times10^3} = \frac{\pi\times46\times20}{60\times10^3} = 0.048\ m/s$$

Equivalent no. of teeth for pinion & gear correspondingly (Tredgold's Approximation)

$$T_{E1} = T_1 \sec\theta_{p1} = 16\times \sec 26.56^0 = 17\ or\ 18$$
$$T_{E2} = T_2 \sec\theta_{p2} = 32\times \sec 63.43^0 = 67.07 \cong 68$$

Tooth form factor;

$$Y_1' = 0.154 - \frac{0.912}{T_{E1}} = 0.1033$$
$$Y_2' = 0.154 - \frac{0.912}{T_{E2}} = 0.1413$$

Bevel factor;

$$B.F = \frac{L-b}{L} = 0.6055$$

$where\ \boldsymbol{L} = Slant\ height\ of\ pitch\ cone = 55.902mm$
$Face\ width\ \boldsymbol{b} = 6.3m\ to\ 9.5m = 6.3m = 22.05mm$

Tangential load:

$$W_T = (\sigma_0 * C_v)\, b. \Pi. m. y' \,(B.F)$$
$$W_{T1} = 2101.86N$$
$$W_{T2} = 1437.52N$$

$W_{T1} > W_{T2}$; condition for design its means that pinion teeth are weaker than gear teeth.

Dynamic load:

$$W_D = W_T + W_I$$

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$$W_I = \frac{21v\,(b.C+W_T)}{21v+\sqrt{b.C+W_T}}$$
$$C = \frac{0.00535}{\frac{1}{E_P}+\frac{1}{E_G}} = 321\text{N/mm}$$
$$W_{I1} = 104.037N$$
$$W_{I2} = 100.163N$$
$$W_{D1} = W_{T1} + W_{I1} = 2205.89N$$
$$W_{D2} = W_{T2} + W_{I2} = 1537.183N$$

Endurance Strength:

$$W_s = \sigma_e\,.\,b.\Pi.m.y'\left(\frac{L-b}{L}\right)$$
$$W_{s1} = 1910.78\ N$$
$$W_{s2} = 1742.45\ N$$

Wear Load:

$$W_w = \frac{D_p.b.Q.K}{\cos\theta_{p1}};\ where\ Q = \frac{2T_{EG}}{T_{EG}+T_{EP}} = 1.6$$
$$K = \frac{\sigma_{se}^2\times 0.3}{1.4}\left(\frac{1}{E_1}+\frac{1}{E_2}\right) = 1.18\ N/mm^2$$
$$W_{w1} = 2326.08\text{N};$$
$$W_{w2} = 9307.23\ \text{N}$$
$$\left.\begin{matrix} W_{W1} > W_{T1} \\ W_{W2} > W_{T2} \end{matrix}\right\}\text{; design condition}$$

Design is in safe hands i.e. acceptable from the normal point of wear.

Second Optimization of Bevel Gear &Pinion:

Gear Teeth Z_2=26
Pinion teeth Z_1=13
Diameter of Pinion $\mathbf{d_1}$=39mm;
Diameter of Gear $\mathbf{d_2}$=78mm
Module $m = (\frac{Z_2}{d_2}) = (\frac{78}{26}) = 3mm$

Velocity factor;

$$C_V = \frac{6}{6+v} = \frac{6}{6+0.0408} = 0.99$$
$$\textbf{where } v = \frac{\pi d_1 N_1}{60\times 10^3} = \frac{\pi\times 60\times 20}{60\times 10^3} = 0.0408m/s$$
$$\theta_{p1} = \tan^{-1}\frac{\sin\theta_s}{2+\cos\theta_s};\theta_s = 90^0 = 26.56^0;$$
$$\theta_{p2} = 90^0 - \theta_{p1} = 63.43^0$$

Equivalent no. of teeth for pinion & gear correspondingly (Tredgold's Approximation):

$$T_{E1} = T_1\sec\theta_{p1} = 13\times\sec 26.56^0 = 14.5 \cong 15$$
$$T_{E2} = T_2\sec\theta_{p2} = 26\times\sec 63.43^0 = 58.12 \cong 60$$

Tooth form factor;

$$Y_1' = 0.154 - \frac{0.912}{T_{E1}} = 0.0932$$
$$Y_2' = 0.154 - \frac{0.912}{T_{E2}} = 0.1388$$

Bevel factor;

$$B.F = \frac{L-b}{L} = 0.56.$$

where **L** = Slant height of pitch cone;$= 43.60 \cong 44$mm
$Face\ width\ \boldsymbol{b} = 6.3m\ to\ 9.5m = 6.3m = 18.5 \cong 19$

Tangential load:

$$W_T = (\sigma_0 * C_v)\,b.\Pi.m.y'\,(B.F)$$
$$W_{T1} = 1313.869N$$
$$W_{T2} = 978.35N$$

$W_{T1} > W_{T2}$; condition for design its means that pinion teeth are weaker than gear teeth.

Dynamic load:

$$W_D = W_T + W_I$$
$$W_I = \frac{21v\,(b.C+W_T)}{21v+\sqrt{b.C+W_T}}$$
$$C = \frac{0.00535}{\frac{1}{E_P}+\frac{1}{E_G}} = 321\text{N/mm}$$

$$\boldsymbol{W_{I1}} = 73.04N$$
$$\boldsymbol{W_{I2}} = 71.35N$$
$$\boldsymbol{W_{D1}} = W_{T1} + W_{I1} = 1386.729N$$
$$\boldsymbol{W_{D2}} = W_{T2} + W_{I2} = 1049.70N$$

Endurance Strength:

$$\boldsymbol{W_s} = \boldsymbol{\sigma_e . b. \Pi. m. y'} \left(\frac{L-b}{L}\right)$$
$$\boldsymbol{W_{s1}} = 1194.42\ N$$
$$\boldsymbol{W_{s2}} = 1185.88\ N$$

Wear Load:

$$\boldsymbol{W_w} = \frac{D_p.b.Q.K}{\cos \theta p1} where\ Q = \frac{2T_{EG}}{T_{EG}+T_{EP}} = 1.6$$
$$\boldsymbol{K} = \frac{\sigma_{se}^2 \times 0.3}{1.4}\left(\frac{1}{E_1} + \frac{1}{E_2}\right) = 1.18\ N/mm^2$$
$$\boldsymbol{W_{w1}} = 1564.06\text{N}$$
$$\boldsymbol{W_{w2}} = 6255.47\text{ N}$$
$$\left.\begin{matrix}\boldsymbol{W_{W1} > W_{T1}} \\ \boldsymbol{W_{W2} > W_{T2}}\end{matrix}\right\}; \text{design condition}$$

Therefore Design is in safe hands i.e. acceptable from the normal point of wear.

V. RESULTS AND DISCUSSION

Table 1 Results and Discussion

Type of Norms		Tangential load (W_T) N	Dynamic load (W_D) N	Endurance strength (W_S) N	Wear load (W_W)
Manual	Pinion	2017.2	2116.41	1833.18	2390.08
	Gear	1371.81	1467.68	1662.80	9401.24
Trail 1	Pinion	2101.86	2205.89	1910.78	2326.08
	Gear	1437.52	1547.18	1742.45	9307.23
Pinion	**% variation**	**4.02**	**4.05**	**4.06**	**0.97**
Gear		**4.57**	**5.13**	**4.57**	**0.01**
Manual	Pinion	2017.2	2116.41	1833.18	2390.08
	Gear	1371.81	1467.68	1662.80	9401.24
Trail 2	Pinion	1313.86	1386.72	1194.42	1564.06
	Gear	978.35	1049.7	1185.88	6255.47
Pinion	**% variation**	**34.86**	**34.47**	**34.84**	**34.56**
Gear		**28.68**	**28.47**	**28.68**	**33.46**

VI. CONCLUSION

For first comparison of bevel pinion and gear, there is 4.02% & 4.5% increase in tangential load, for dynamic load 4.05% & 5.13% in increase, 4.06% & 4.57% increase in endurance strength and in wear load there is little bit decrease 0.97% & 0.01%.

For second comparison of bevel pinion and gear, there is 34.86% & 28.68% of decrease in tangential load, for dynamic load 34.47% & 28.47% in decrease, 34.84% & 28.68% of decrease in endurance strength, 34.56% & 33.46% decrease in wear load.

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