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Optimization of powertrain of jib crane

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Abstract - *To optimize the power transmission system for the slewing motion of a jib crane, including the gear, pinion, and geared motor, for all coordinates of the lifted load from the pillar center, the entire system needs to be carefully analyzed and refined. This involves selecting suitable gears, pinions, and a geared motor that can handle the load requirements and desired range of motion. The design should consider factors like torque, speed, efficiency, and safety. it is necessary to perform a comprehensive analysis and implement topology optimization techniques for the ring gear.*

A boom of jib crane experiences a maximum load when the load is acting at the maximum span / Outreach of the crane from pillar centre. Hence the motor and gearbox for jib crane is designed according to the beam under maximum possible loading condition.However, the actual movement of load happens at various coordinates from centre of the pillar which is different from the maximum value. The aim of this project is optimization of complete power transmission for slewing motion of jib crane which includes the gear, Pinion, and Geared Motor for all coordinates of the lifted load from pillar centre.

Key words*: jib crane , ring gear , Optimization.*

1. INTRODUCTION

1.1 Jib crane

A jib crane is a crane which has cantilevered beam which consists of a hoisting mechanism and trolley. It is attached to a building column or either to a cantilever beam from an independent column mounted on the floor.

It is a type of crane which is most often fixed near certain workstation so that the load movement in the specific zone is catered to.

Jib cranes can be wall or Pillar (Tower) mounted. All jib cranes swivel and can lift and carry loads. Most jib cranes also traverse, in that the job crane can traverse the beam from the center of the circle to the edge of the circle created by the jib as the jib crane rotates.

The jib arm is usually mounted on a vertical pole or column (tower) and sometimes on an inclined jib. In other outriggerless structures such as derricks, the load is suspended directly from the outriggers (usually often called jibs).

Crane companies in India sell its global products in Jib crane segment, and they want to localise the design as well as manufacturing and supply chain so as to make the design suitable to India market. It also will then cater to Indian standards, and the direct and indirect costs will also come down. This is the basic concept behind starting with this project.

At present, while standardizing the gearbox, many factors like country standards, material available for fabrication & manufacturing, specifications of geared motor from the motor catalogue, material standards, lifting load variations and its frequency of operations are to be considered which cannot be followed directly from the global product for the Indian standards.

1.2 Elements of jib crane

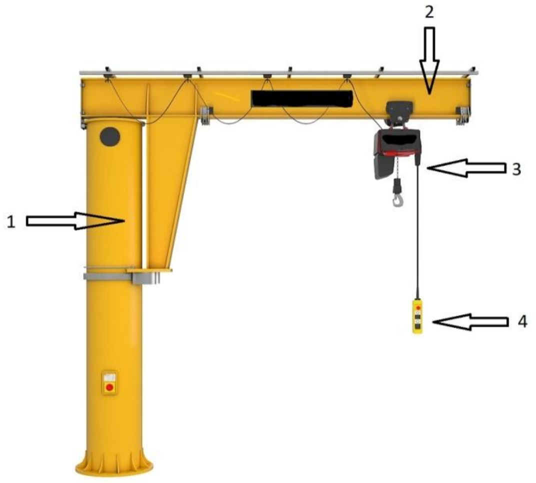

Fig -1: Elements of jib crane

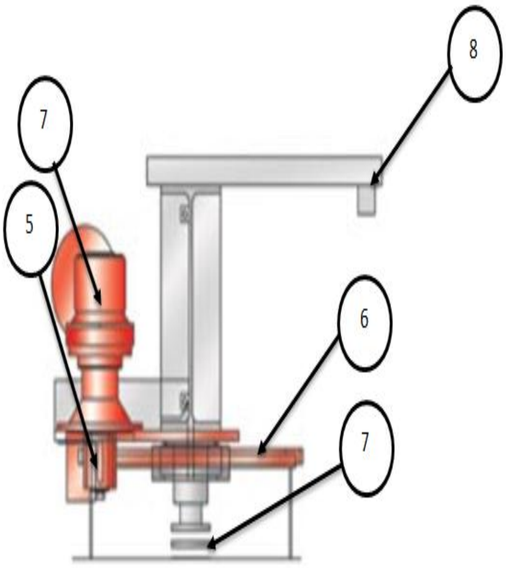

Fig -1: Elements of gearbox

1) Pillar: Vertical Member of jib crane which support the complete Jib
2) Jib Arm: Horizontal member on which the Hoist travel. Hoist: Lifting machine which lifts the load. It has 2 motions a) Lifting/ Lowering , b) Travelling.
3) Pendant: It is one of the devices which gives control signals to the jib crane, other devices are Radio remote, Joystick etc…
4) Pinion: It engages with the Gear ring which revolves and rotates giving slewing motion to the Jib arm.
5) Gear Ring: The Gear is fixed to pillar and pinion revolve around the gear to give slewing motion to jib arm.
6) Slip Ring assembly: Slip Ring assembly is needed to deliver the power supply to the other machineries as the jib cranes rotates 360 degrees.
7) Festoon System: System delivering power to the hoist based C track and power supply trolleys.

1.2 Calculations

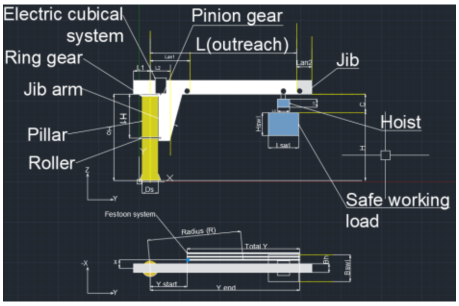

Fig -2: front view and top view of jib crane

Table -1 Terminologies and abbreviations

Term	**abbreviation**	**Hoist dimensions**	**abbreviation**
Safe working load(SWL)	GL	Length-	LH
Out reach	L	Width-	BH
Hook approach _Inner	Lan 1	Jib Slewing rpm-	n
Hook approach _Outer	Lan 2	Safe Working Load (SWL) dimensions-	
Beam Overhang on rear side	L1	Length	L swl
Position of Arm	L2	Width	B swl
Arm Height	H1	Height	H swl
Diameter of Pillar	Ds	Height	H swl
Hook path above floor	H		
Hoist Head Room	C		
Floor to bottom of beam	Ho = H+C		
Hoist weight	Gh		

Total cycles- 25000

Jib rpm = 1

Total duration = 25000 min

Total duration in h = 4166.67

2. Types of loads acting on jib crane-

1.Uniformly Distributed Load (UDL) (Festoon system)

2.Point Load

3. Live Load

4.Fixed Crane Load

2.1.Calculations for UDL (festoon system) -

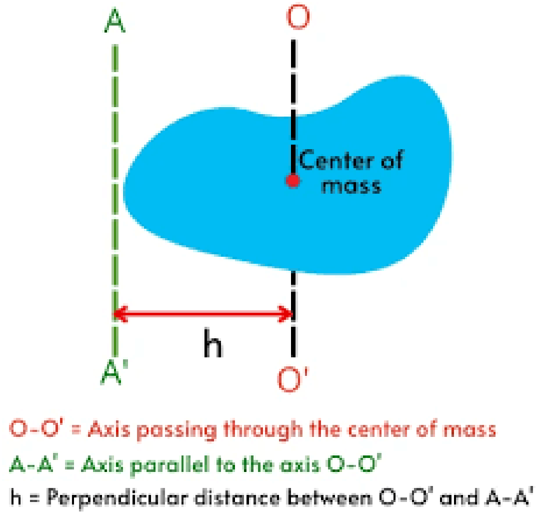

Fig -3: MOI explaination

UDL= $l\ kg/m$

length of UDL = $a\ m$

Width of UDL = b m

∴Point load=$m = la \ \times mass\ factor\ (\ kg)$

Horizontal distance of CG of udl =x

Vertical distance of CG of udl =y

Distance of CG of UDL from pillar $= r = \sqrt{x^2+y^2}$

Ic = MMI of UDL around CG = $\frac{(a^2+b^2)m}{12}$

Io = $Ic + mh^2$

Moment about pillar = $UDL\ force\ \times x$

2.2 Calculations for point load & fixed crane loads-

Load = m kg

∴Total load = M = m * Mass factor

Length of load = a m

Width of load = b m

Diatance of x coordinate = x

Distance of y coordinate = y

∴Radius = $r = \sqrt{x^2+y^2}$

∴ Ic = $\frac{M\times(a^2+b^2)}{12}$

Io = Ic +Mr^2

Moment around pillar = $M\ \times y$

2.3 Calculations for live load

Iteration 1-

Total load = M = SWL + Hoist load

Radius = R1 m

Ic swl = $\frac{SWL(Lswl^2+Wswl^2)}{12}\ kgm^2$

Ic hoist = $\frac{Hoist\ load(Lhoist^2+Whoist^2)}{12}\ kgm^2$

∴Io1= $\text{Ic swl} + \text{Ic hoist} + MR1^2$

∴Moment around pillar =M1 = $M \times\ R1\quad Nm$

Iteration 2-

$R2 = \ R1 + \frac{L-R1}{4}$

∴Corresponding Io2= Ic swl + Ic hoist + $MR2^2$

∴Moment around pillar =M2 = $M \times\ R2\quad Nm$

Iteration 3-

$R3 = \ R2 + \frac{L-R2}{4}$

∴Corresponding Io3 = Ic swl + Ic hoist + $MR3^2$

∴Moment around pillar =M3 = $M \times\ R3\quad Nm$

And so on for further iterations

∴Max. Io = $Io\ corresponding\ to\ max.radius\ kgm^2$

∴RMS Io = $\sqrt{\frac{Io1^2+Io2^2+Io3^2+\cdots}{no.of\ iterations}}\ kgm^2$

Max. Moment =$moment\ corresponding\ to\ max.radius\ Nm$

∴RMS moment = $\sqrt{\frac{M1+M2+M3+\cdots}{no.of\ iterations}}\ Nm$

∴Total MMI = $Io(point\ load) + Io(fixed\ crane\ load) + Io(Live\ load) + Io(UDL)\ kgm^2$

∴Total axial force = $9.81(UDL + point\ load + fixed\ crane\ load + live\ load)N$

∴Total Moment around pillar = $\sum Moment(UDL + point\ load + fixed\ crane\ load + live\ load)\ Nm$

Arm height = H1 m

∴ Radial force = $\frac{Total\ momet\ around\ pillar}{arm\ height}\ N$

Total acceleration torque= $Total\ MMI\ \times angular\ acceleration$

Frictional force = $\frac{(travel\ resistance\ of\ selected\ roler \times (radial\ force)}{9.81}\ N$

∴ Frictional torque = $Frictional\ force\ \times (diameter\ of\ pilar)\ \ Nm$

Axial torque= $Total\ axial\ force\ \times \mu(roller\ bearing) \times \frac{inner\ diameter + ouetr\ diameter}{2} Nm$

∴Total torque = Frictional torque + axial torque + acceleration torque Nm

Set motor rpm =$Motor\ rpm\ \times set\ point$

Total ratio = $\frac{set\ motor\ rpm}{jib\ rpm}$

∴$torque\ refered\ to\ motor = \frac{total\ torque}{total\ ratio}\ Nm$

∴power = $torque\ refered\ to\ motor\ \times \frac{set\ motor\ rpm}{60}\ W$

Total efficiency = $efficiency\ of\ system\ \times\ Effciency\ Gear\ \times\ Effciency\ Gearbox$

∴ Final motor power = $\frac{Power}{total\ efficiency}$ kW

Optimization of power of motor

Table -2: Input constants –

Hook approach _Inner	Lan 1	750 mm
Hook approach _Outer	Lan 2	250 mm
Beam Overhang on rear side	L1	350 mm
Position of Arm	L2	600 mm
Arm Height	H1	1030 mm
Diameter of Pillar	Ds	670 mm
Hook path above floor	H	3000 mm
Hoist Head Room	C	300 mm
Floor to bottom of beam	Ho=H+C	3300 mm
Hoist weight	Gh	600 kg
Hoist dimensions-		
Length	LH	350 mm
Width-	BH	350 mm
Jib Slewing rpm-		1
Safe Working Load (SWL) dimensions-		
Length	L swl	1581 mm
Width	B swl	255 mm
Height	H swl	1581 mm

2. HEADING 2

Using maximum method-

UDL (Uniformly Distributed Load) -

Festoon 1

UDL=5 kg/m
Width of UDL= 50 mm= 0.05 m= b
UDL start(Y start)= 200 mm
UDL end(Y end)= 6000 mm
Total Y= $Yend - Ystart$
= 6000-200
=5800 mm
= 5.8 m
= a

CG of Y= $Ystart + \frac{(totalY/)}{2}$
= 3100 mm
= Y coordinate

Distance of festoon 1 from jib arm
= 500 mm
= X coordinate

(x,y)=(500,3100)

∴Radius=$\sqrt{500^2 + 3100^2}$

= 3140.1 mm

R = 3.14 m

∴Total load =length of UDL × UDL

=total Y × UDL

= 5.8 × 5

= 29 kg

Mass factor(M.F.) = 1.1

∴Load with M.F = total load × MF

∴M =31.9 kg

∴**MR^2**= 31.9×3.14^2

= 314.5 kgm^2

∴**Self MR^2= Ic** =MMI about CG of festoon1

$$= \frac{M(a^2+b^2)}{12} = \frac{31.9(5.8^2+0.05^2)}{12}$$

Ic =89.4 kgm^2

∴**MMI about pillar=**$Io = Ic + MR^2$

= 89.4+ 314.5

= 404 kgm^2

∴**Moment about Pillar** =

$$\frac{M * 9.81 * CG\ Y}{1000} = \frac{31.9 * 9.81 * 3100}{1000}$$

=970.1 Nm

Festoon 2-

For festoon 2,

Distance of festoon 1 from jib arm

= 750 mm

= X coordinate

(x,y) = (750,3100)

∴Radius= 3189.4 mm

M =31.9 kg

∴**MR^2=** 31.9* 3.189^2

= 324.5 kgm^2

∴**Self MR^2 =Ic=** MMI about CG of festoon2

$$= \frac{M(a^2+b^2)}{12} = \frac{31.9(5.8^2+0.05^2)}{12}$$

=89.4 kgm^2

∴**MMI about pillar = Io** $= Ic + MR^2 = 89.4 + 324.5^2$

= 413.9 kgm^2

∴**Moment about Pillar =** $\frac{M * 9.81 * CG\ Y}{1000} = \frac{31.9 \times 9.81 \times 3100}{1000}$

= 970.1 Nm

$$\sum MR^2 = 639\ kgm^2$$

$$\sum Ic = 178.9\ kgm^2$$

$$\sum Io = 817.9\ kgm^2$$

$$\sum Moment = 1940.2\ Nm$$

Table -3 Point loads

Name of Load	Point load1	Point load2	**Point load 3**	
Discription	Electric cubical	Canopy	Drives	
Load ‘L’ (kg)	500	0	57	
Length a’(mm)	500	1000	250	
Width’b’(mm)	250	500	250	
X coordinate (mm)	750	0	500	
Y coordinate (mm)	500	0	0	
Radius ’R’ (mm) $(\sqrt{x^2+y^2})$	901.4	0	500	
Mass factor (MF)	1	1	1	
Load with M.F.’M’(kg) $(MF \times L)$	500	0	57	Σload=557 kg

MR^2 $M(\frac{R}{1000})^2 \quad kg\,m^2$	406.3	0	14.3	$\sum MR^2 = 420.5 \ \ kgm^2$
Self MR^2 'Ic' $\frac{M}{12}\times(\frac{a}{1000}^2+\frac{b}{1000}^2) \quad kgm^2$	13	0	0.6	$\sum Ic = 13.6\, kgm^2$
Total Mr^2 'Io' $(Ic + MR^2)\, kgm^2$	419.3	0	14.8	$\sum Io = 434.1\, kgm^2$
Moment (Nm) $\frac{M \times 9.81 \times Y\ Coordinate}{1000}$	2452.5	0	0	$\sum$ Moment = 2452.5 Nm

Table -4 Fixed crane load

Name of Loads		Point load 1	Point load 2	
Discriptions		Jib	Arm	
Load'L'(kg)		785	150	
Length(a)	L+Lan2+L1	6600	400	
Width(b)		250	250	
X coordinate		0	0	
Y coordinate		(L+Lan2+L1)/2-L1 = 2950	L2= 600	
Radius (mm)	$M = (\sqrt{x^2 + y^2})$	2950	600	
Mass Factor 'MF'		1.3	1.3	
Load with MF 'M'(kg)	$(MF \ \times L)$	1020.5	195	
MR^2	$M(\frac{R}{1000})^2$	8880.9	70.2	$\sum MR^2 = 8951.1 \ \ kgm^2$
Self MR^2 (kgm^2)	$Ic = \frac{M}{12}\times(\frac{a}{1000}^2+\frac{b}{1000}^2)$	3709.7	3.6	$\sum Ic = 3713.3 \ \ kgm^2$
Total Mr^2 (kgm^2)	Io =$(Ic + MR^2)$	12590.6	73.8	$\sum Io = 12664.4\, kgm^2$
Moment (Nm)	$\frac{M \times 9.81 \times Y\ Coordinate}{1000}$	29532.75	1147.7	$\sum$ Moment = 30680.52 Nm

- **Live load-**

Iteration 1

- **Max. outreach= 6000 mm**
- **Max. Load = 5000 kg**

Hoist load = 600 kg

∴Total load= 5600 kg

Iteration1-
SWL=5000 kg
Hoist Load= 6000 kg
Total Load= SWL + Hoist load
M = 5600 kg
Distance of SWL & Hoist load from pillar=
Max. of outreach/2 & position of arm
=max $(\frac{L}{2}\ \&\ L2)$
=max $(\frac{6000}{2}\ \&\ L2)$
= 3000 mm
= R1

∴ MR^2= $M \times \frac{R}{1000}^{2}$
= $5600 \times \frac{3000^2}{1000}$
= 50400 kgm^2

∴Self MR^2 of SWL= Ic1=$\frac{SWL\left(Lswl^2+Bswl^2\right)}{12}$
=$\frac{5000(\frac{1581}{1000}^2+\frac{Bswl}{1000}^2)}{12}$
=1068.58 kgm^2

∴ Self MR^2 of hoist= Lc2=$\frac{Hoist\ load\ \left(Lswl^2+Bswl^2\right)}{12}$
=$\frac{600(\frac{350}{1000}^2+\frac{350}{1000}^2)}{12}$
=12.25 kgm^2

∴Total MR^2 around the pillar
= Io
= MR^2 + Ic1 + Ic2
=50400 + 1068.58 + 12.25
= 51480.8 kgm^2

Moment around jib arm
=$\frac{total\ load \times 9.81 \times R}{1000}$
=$\frac{5600 \times 9.81 \times 3000}{1000}$
=164808 Nm

Iteration 2-
Self MR^2 of SWL= Ic1
=1068.58 kgm^2

∴ Self MR^2 of hoist= Lc2
= 12.25 kgm^2

R2 = $R1 + \frac{L-R1}{4} = 3000 + \frac{6000-3000}{4}$

= 3750 mm
= 3.75 m

∴ MR^2 =5600×3.75^2
= 78750 kgm^2

∴ Total MR^2 = MR^2 + Ic1 + Ic2
= 78750 + 1068.58 + 12.25
= 79830.8 kgm^2

∴ Moment = $total\ load \times 9.81 \times R2$
= $5600 \times 9.81 \times 3.75$
= 206010 Nm

Iteration3-

Self MR^2 of SWL= Ic1
=1068.58 kgm^2

∴Self MR^2 of hoist= Lc2
= 12.25 kgm^2

R3 = $R2 + \frac{L-R2}{4} = 3750 + \frac{6000-3750}{4}$
= 4500 mm
= 4.5 m

∴MR^2 =5600×4.5^2
= 113400 kgm^2

∴Total MR^2 = MR^2 + Ic1 + Ic2
= 113400 + 1068.58 + 12.25
= 114480.8 kgm^2

∴Moment = $total\ load \times 9.81 \times R2$
= $5600 \times 9.81 \times 4.75$

= 247212 Nm

Iteration 4-

Self MR^2 of SWL= Ic1
=1068.58 kgm^2

∴Self MR^2 of hoist= Lc2

= 12.25 kgm^2

R4 =$R3 + \frac{L-R3}{4} = 4500 + \frac{6000-4500}{4}$

= 5250 mm
= 5.25 m

∴MR^2 = 5600×5.25^2
= 154350 kgm^2

∴Total MR^2 = MR^2 + Ic1 + Ic2
= 154350 + 1068.58 + 12.25
= 155430 kgm^2

∴Moment =
$total\ load\ \times 9.81 \times R4 = 5600 \times 9.81 \times 5.25$

= 288414 Nm

Iteration 5-
Self MR^2 of SWL= Ic1
=1068.58 kgm^2

∴Self MR^2 of hoist= Lc2
= 12.25 kgm^2

R5 = $R4 + \frac{(L - R4)}{4} = 5250 + \frac{6000-5250}{4}$

= 6000 mm
= 6 m

∴MR^2 = 5600×6^2
= 201600 kgm^2

∴Total MR^2 = MR^2 + Ic1 + Ic2
= 201600 + 1068.58 + 12.25
= 202680 kgm^2

∴Moment
$= total\ load\ \times 9.81 \times R5 = 5600 \times 9.81 \times 6$

= 329616 Nm

Table -5 MMI and moment using maximum and RMS method

	MMI around the pillar of total load kgm^2	**Square**	**Moment around the pillar (Nm)**	**Square**
Iteration1	51480.8000000	2650275600.08476	164808.000000000	27161676864
Iteration2	79830.8	6372961019.33476	206010	42440120100
Iteration3	114480.8	13105859865.08480	247212	61113772944
Iteration4	155430.8	24158742137.33480	288414	83182635396
Iteration5	202680.8	41079517836.08480	329616	108646707456
	Max. MMI = 202680.8 kgm^2	**RMS MMI = 132187.3** kgm^2	**Max. Moment = 329616 Nm**	**RMS Moment= 253986 Nm**

Similarly we can find Max. and RMS Io and MMI & compare togrther

Table - 6 RMS power calculated using different iterations

Safe Working Load(SWL)(kg)	Outreach(m)	Hoist load(kg)	Max. MMI kgm^2	RMS MMI kgm^2	Max. moment Nm	RMS Moment Nm
5000	6	600	202680	132187	329616	253986
1000	6	600	57826	37692	94176	75267
2000	6	600	94039	61315	153036	117922
3000	6	600	13053.4	84939	211896	163276

Table – 7 Power calculated using maximum method

Load (kg)	2	2.5	3	3.5	4	4.5	5	5.5	6
500	0.029	0.037	0.046	0.056	0.066	0.078	0.090	0.103	0.116
1000	0.037	0.048	0.059	0.072	0.086	0.101	0.118	0.135	0.153
1500	0.045	0.058	0.073	0.089	0.106	0.125	0.146	0.167	0.19
2000	0.053	0.069	0.086	0.106	0.127	0.149	0.174	0.199	0.227
2500	0.061	0.079	0.1	0.122	0.147	0.173	0.201	0.232	0.264
3000	0.069	0.090	0.113	0.139	0.167	0.197	0.229	0.264	0.301
3500	0.076	0.1	0.127	0.156	0.187	0.221	0.257	0.296	0.338
4000	0.084	0.111	0.140	0.172	0.207	0.245	0.285	0.329	0.375
4500	0.092	0.121	0.154	0.189	0.227	0.269	0.313	0.361	0.411
5000	0.1	0.132	0.167	0.205	0.247	0.293	0.341	0.39S3	**0.4478**

Table – 8 Comparison with power calculated using RMS method

	Outreach (m)								
Load (kg)	2	2.5	3	3.5	4	4.5	5	5.5	6
500	0.025	0.031	0.038	0.046	0.054	0.063	0.072	0.082	0.093
1000	0.030	0.039	0.048	0.058	0.068	0.080	0.092	0.105	0.119
1500	0.036	0.046	0.058	0.07	0.083	0.097	0.112	0.128	0.145
2000	0.042	0.054	0.067	0.082	0.097	0.114	0.032	0.150	0.171
2500	0.048	0.062	0.077	0.094	0.112	0.131	0.151	0.173	0.197
3000	0.054	0.07	0.087	0.106	0.126	0.148	0.171	0.196	0.223
3500	0.06	0.077	0.097	0.118	0.14	0.165	0.191	0.219	0.249
4000	0.065	0.085	0.106	0.13	0.155	0.182	0.211	0.242	0.0275
4500	0.071	0.093	0.116	0.733	0.169	0.199	0.231	0.265	0.301
5000	0.077	0.1	0.126	0.154	0.184	0.216	0.251	0.288	**0.32**

% Decrease in power for maximum Load & outreach conditions-

% Decrease in power (kW)=

Conclusion- For each iteration of load vs outreach data, Root Mean Square method power is coming to be minimum for corresponding iteration for maximum method.

Thus, power required to rotate the jib is reduced by 28.41%

Validation using Tooth root stress -

Known data –

Module = m= 6

Pressure angle = 20 deg

Helix angle = 0 deg

Pinion gear = gear 1

Ring gear = gear 2

$$\therefore PCD1 = \frac{\mathrm{Z1*m}}{\cos(\textbf{Helix angle})}\ mm$$

$$\mathrm{V1} = \text{ pitch line velocity} = \frac{\pi \times PCD1 \times N1}{60 \times 1000}\ m/s$$

Tangential force transmitted = Wt1$= \frac{power\ transmitted\ by\ motor \times 1000}{Pitch\ line\ velocity\ (V1)}$

Velocity factor$= \frac{6}{6+V1}$

Kv1$= \frac{6}{6+ +0.023}$

Permissible stress $= \sigma p1 \ = \frac{Wt1}{Kv \times m \times y \times Fw1}$

BHN$= \frac{Sut\ of\ pinion\ gear\ material}{3}\ Mpa$

Infinite life strength for tooth root stress$= Sut\ \times 0.3$

∴Syt

$= Infinite\ life\ strength\ \times \text{Stress concentration factor}$

Factor of safety = $\frac{Syt}{\sigma p1}$

∴ Balanced FOS$= \frac{FOS}{requird\ \min\ FOS}$

∴ Transmittable power =
$motor\ power \times balanced\ FOS$

∴Calculation accuracy
$= \frac{power\ in\ validation\ software}{transmittable\ power}\ kW$

Validation using flank strength -

Contact strength = Sc = $2.76\ BHN1 - 70$

CL =Life Factor

CH= Hardness factor

CT =Temperature Factor

CR = Reliability Factor

AGMA stress ratio = $\frac{CL \times CH \times Sc}{CT \times CR}$

∴Dynamic factor = Kv1 = $\sqrt{\frac{50}{50+(200 \times pitch\ line\ velocity)}}$

∴Safety factor =
$\text{Overload correction factor} \times \text{ Load distributionn factor}$

∴Geometrical factor =
$\frac{\cos(pressure\ angle\ ) \times \sin(pressure\ angle)}{2} \times \frac{m}{m+1}$

∴Weight force transmitted = Wtf=
$\frac{Sc^2 \times Kv1 \times FW2 \times PCD1 \times geometrical\ factor}{\text{Elastic coefficient}^2}\ N$

∴Safety factor = $\frac{Wtf}{\text{Tangential force transmitted}}$

∴ Transmittable power = $\text{Safety factor} \times \text{motor power}$

∴ Calculation accuracy

$= \frac{power\ in\ validation\ software}{transmittable\ power}\ kW$

3. CONCLUSIONS

The accuracy coming from method of tooth root stress is around 85% for gear 1(pinion) while for some gear of is of 115%

While using flank strength method the accuracy for gear 1 is coming to be 81% and for gear 2 it is around 150%.

In general validation unsung tooth root stress is considerable and can be used for optimization of ring gear.

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