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Torque Measurement in Epicyclic Gear Train

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***Abstract:** Gears are used to transmit power and rotary motion from the source to its application with or without change of speed or direction. Gears trains are mostly used to transmit torque and angular velocity from one shaft to another shaft, whenever there is large speed reduction requirement within confined space. In epicyclic gear trains there is relative motion between axes which useful to transmit very high velocity ratio with gears of smaller sizes in lesser space. In this research paper torque calculations are done for epicyclic gear train. Input torque, output torque and holding or braking torque are calculated experimentally using experimental set up and analytically using tabular formulas for rpm range starting from 1000 rpm to 2800 rpm. Finally the experimental and analytical torque values are compared which shows error ranging from 6 % to 8% which is due to some frictional losses and mechanical losses.*

***Keywords:** Epicyclic gear train, output torque, holding torque.*

I. INTRODUCTION

A gear train is combination of gears used to transmit motion from one shaft to another shaft. It becomes necessary when it is required to obtain large speed reduction within small space. Combinations of gear wheels used to increase or decrease speed of driven shaft is known as gear system. The prime movers like steam or gas turbines run at very high speed. The speed of turbine output is required to be reduced considerably by means of gear train; such gear train is known as reduction gear train. There are mainly four types of gear train: Simple gear train, Compound gear train, Reverted gear train, Planetary or Epicyclic gear train.

A gear train having a relative motion of axis is called planetary or an epicyclic gear train or simply epicyclic gear or train. In an epicyclic train the axis of at least one of the gears also moves relative to the frame. For Simple gear train, compound gear train and reverted gear train axes of motion of wheel are fixed in position and gears rotate about their respective axes. In case of epicyclic gear train the axis of shaft on which gears are mounted may move relative to fixed axis. However, in epicyclic gear train axes of some wheels are not fixed but rotate around the other wheels with which they mesh [1-3]. Epicyclic gear trains are useful to transmit very high velocity ratio with gears of smaller sizes in lesser space.

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II. CONSTRUCTION OF EPICYCLIC GEAR TRAIN

As shown in Figure 1, there are two gear wheels S and P, the axis of which are connected by an arm or carrier a. If the arm A is fixed then wheels S and P constitute simple gear train.

However if the wheel S is fixed so that the arm can rotate about the axis of S, the wheel P would also move around S. Therefore, it is an epicyclic train. In epicyclic gear one wheel is usually fixed. However it is not necessary at all and wheel S can have rotations in any direction about its axes i.e. clockwise or anticlockwise direction .Usually, the wheel P is known as epicyclic wheel [2-4]. The term epicyclic emerges from fact that wheel P rolls outside another wheel and traces an epicyclic path.

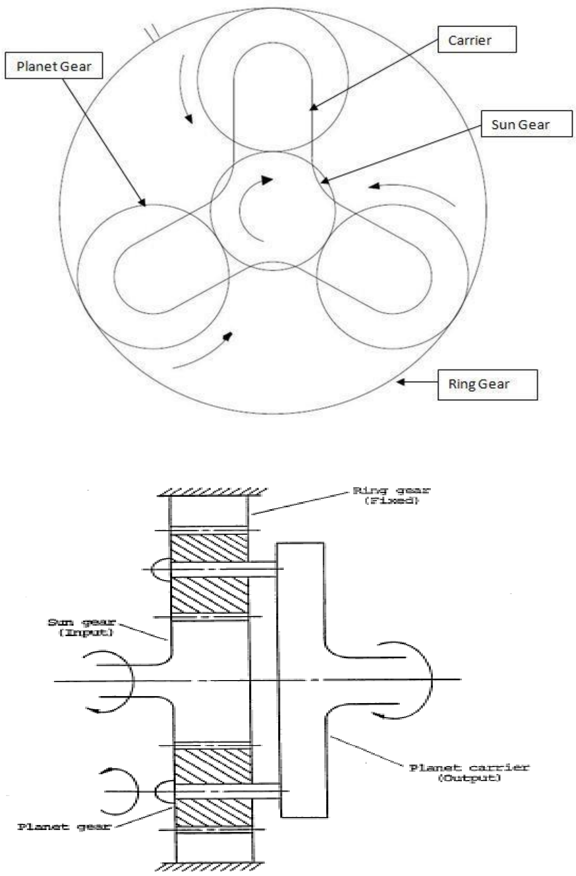

Figure.1 Construction of epicyclic gear train

Large speed reductions are possible with epicyclic gear train and if the fixed wheel is annular more compact unit could be obtained. Important applications of epicyclic gears are in transmission, computing devices and so on. It is also used in wrist watches, mills, clocks, Back gear of lathe, differential gears of automobile, Hoists, pulley blocks, aircrafts.

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III. ANALYSIS OF EPICYCLIC GEAR TRAIN

Epicyclic gear trains usually have complex motion. Therefore comparatively simple methods are used to analyse epicyclic gear trains, which don't require accurate visualization of motion. We are assuming arm is fixed and turn S through x revolutions in clockwise direction. The sign convention followed as clockwise as positive and anticlockwise direction as negative.

Revolutions of arm a = $N_a = 0$

Revolutions of sun S = $N_s = x$

Revolutions of planet P = $N_p = -(T_s/T_p)\,x$

Revolutions of ring gear or Annulus A = $N_A = -(T_s/T_A)\,x$

Now, the mechanism is locked together and turned through number of revolutions, the relative motion between a, S, P will not change. Now the locked system is turned through y revolutions in clockwise direction.

Revolutions of arm a = $N_a = y$

Revolutions of sun S = $N_s = y + x$

Revolutions of planet P = $N_p = y - (T_s/T_p)\,x$

Revolutions of ring gear or Annulus A = $N_A = y - (T_s/T_A)\,x$

Here, Revolutions of planet P is $Np = y - (T_s/T_p)\,x$ shows revolutions in space or relative to fixed axis of S. Thus if revolutions made by any of two element is known x and y can be solved and revolutions made by third can be determined.

The procedure for analysis of simple epicyclic gear train can be summarised as shown in Table 1.

Table 1. Procedure for analysis of simple epicyclic gear train

Sr no.	Action	N_a	N_s	N_p	N_A
1	Arm fix, S rotates through 1 revolutions	0	1	$-(T_s/T_p)$	$-(T_s/T_A)$
2	Arm fix, S rotates through x revolutions	0	x	$-(T_s/T_p)\,x$	$-(Ts/T_A)\,x$
3	Add y revolutions	y	y	y	y
4	Total revolutions	y	y + x	$y - (T_s/T_p)\,x$	$y - (T_s/T_A)\,x$

1. Lock the arm and assume other wheel is free to rotate.
2. Turn any convenient gear through one revolution in clockwise direction and record the number of revolutions made by each of other wheel.
3. Multiply all above reading by x and write same in second row. This is equivalent to statement that chosen wheel gives x revolutions in clockwise direction keeping arm fixed.
4. Add y to all quantities in second row and make recording in third row. This amount to fact that by locking whole system it is turned through y revolutions in clockwise direction. Thus arm makes y revolutions and the chosen wheel makes y+ x revolutions.
5. Apply the given conditions and find the vales of x and y. Now having the values of x and y revolutions made by any wheel can be known. Here revolutions of planet P given in third row of table is the number of revolutions of planet P in space or relative to fixed axis of wheel S and not about its own axis. [5-6]

Revolutions of planet P about its own axis = Total revolutions of P about axis of arm – revolutions of arm.

$= [y - (T_s/T_p)\,x] - y = -(T_s/T_p)\,x$

IV. TORQUES IN EPICYCLIC GEAR TRAIN

Analytical torque calculation in epicyclic gear is done under certain assumptions. Torque is transmitted from one element to another element when geared system transmits power. Following assumptions made while calculating torques in epicyclic gear train.

Assumptions:

1. All wheels of gear train rotate at uniform speed i.e. accelerations are not involved.
2. Each wheel is in equilibrium under action of torques acting on it.

Let,

N_s, N_a, N_p, and N_A are revolutions made by sun, arm, planet and annulus respectively.

T_s, T_a, T_p, and T_A are number of teeth on sun, arm, planet and annulus respectively.

Now considering above two assumptions we can take,

Summation of all torques = 0.

$$T_s + T_a + T_p + T_A = 0 \qquad \text{..........Eq. (1)}$$

Here we can observe thing that S and a are connected to machinery outside system and thus transmits external torque. The planet P can rotate on its own pin fixed to arm a, but it is not connected to anything outside. Therefore planet P does not transmit any external torque. The annulus is either locked by an external torque or transmitting power or torque either to or from system through external teeth. If annulus A is fixed T_A is known as braking torque or holding torque or fixing torque. Out of Ts and Ta one will be driving torque and other as an output or resisting torque. [7-8]

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Assuming no power losses in power transmission, energy of gear train will become zero if all losses due to friction etc. are neglected. Then,

$$T_S N_S + T_A N_A + T_A N_A = 0 \quad \text{....... Eq. (2)}$$

If the annulus A is fixed, $N_A = 0$.
And equation will become,

$$T_S N_S + T_A N_A = 0. \quad \text{....... Eq. (3)}$$

Proper directions and sign conventions of speed and torque considered .Gear train is in equilibrium under influence three torques namely driving / input torque, output /driven torque, holding /fixing/braking torque.

V. EXPERIMENTAL SET UP FOR TORQUE MEASUREMENT

In this apparatus internal type epicyclic gear train is demonstrated. It consists of sun gear mounted on the input shaft. Two planet gears are on the both sides meshes with sun gear and which also meshes with the internal teeth's of annular gear. Two planet gears are mounted on the pins which are fixed into both ends of the arm. Output shaft is connected to the arm on which the drum is fixed. We have used belt and spring balance arrangement to measure output torque and holding torque

Specifications of the motor, control panel and important input parameters for the experimentation are as follows.

1. Epicyclic gear train ratio 1: 9.
2. 1 HP D.C. motor, 3000 rpm, 230 Volt, 4 Amp.
3. Control panel with dimmer (D.C.) for speed variation and ammeter, voltmeter to get input power
4. Internal epicyclic gear consists of; 1) Ring gear having 80 teeth, 2) sun gear having 10 teeth, 3) Planet gear having 35 teeth.

VI. EXPERIMENTAL PROCEDURE

After checking the experimental set up, give supply to motor from control panel. As shown in figure 2, Start the motor and measure the input and output shaft speeds. Output drum rotational motion is opposed by the belts provided which carries spring balance system. As we go on turning the wheel it will create frictional force through belt to output drum, which opposes the output drum motion. Apply the torque by turning the wheel at output drum location just to hold the braking drum which carries annulus inside. The corresponding spring balance reading is taken given at braking drum. We have applied the torque to output drum till the spring at braking drum location becomes exactly vertical and it is full of tension. This is done very carefully. We have increased the motor speed from 1000 rpm to 2800 rpm and ten corresponding spring balance reading are taken at output drum and holding drum. Following are some input parameters and formulas used for torque calculation.

1. R = radius of output drum = 80 mm.
2. r = radius of holding drum = 65 mm.
3. Input torque = (60*voltage*current)/ (2*22/7*input speed)
4. Output torque = Spring balance reading at output drum (kg) *9.81* R
5. Holding torque =Spring balance reading at output drum (kg) *9.81* r.

Observation table for corresponding rpm is shown in Table 2.

Table 2. Experimentally torque calculations

Sr no.	Speed		Voltage	Current	Torque (Nm)		
	Input speed N1 (rpm)	Output speed N2 (rpm)	Volt	Amp	Input torque (Nm)	Output torque (Nm)	Holding torque (Nm)
1.	1000	110	47	0.976	0.4379	3.6256	3.2931
2.	1200	133	54	1.023	0.4394	3.6384	3.3002
3.	1400	155	61	1.07	0.4450	3.6848	3.3433
4.	1600	178.10	68	1.117	0.4531	3.7521	3.3976
5.	1800	199.20	75	1.164	0.4630	3.8333	3.4584
6.	2000	222	82	1.211	0.4739	3.9242	3.5013
7.	2200	244.10	89	1.258	0.4858	4.0223	3.5918
8.	2400	266.20	94	1.305	0.4879	4.0397	3.6256
9.	2600	288.80	101	1.352	0.5013	4.151	3.7535
10.	2800	312	108	1.399	0.5151	4.2649	3.8096

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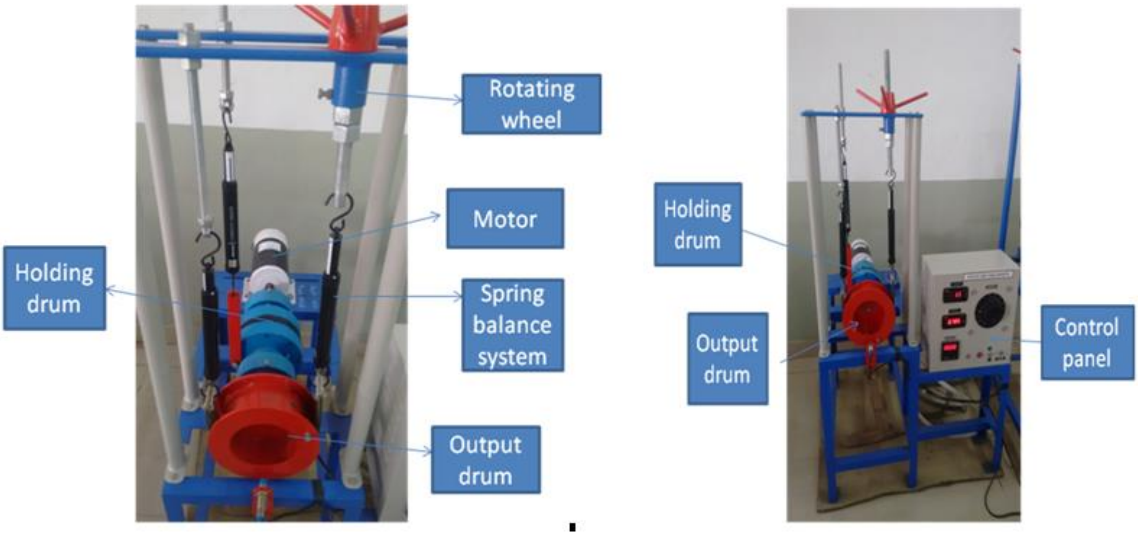

Figure 2. Experimental setup.

VII. ANALYTICAL CALCULATIONS

As we are having input speed, output speed, voltage and current for corresponding rpm reading we can calculate input torque, output torque and holding torque by using following formulas.

1. Input torque = (60*voltage*current)/ (2*22/7*input speed)
2. Output torque = (60*voltage*current)/ (2*22/7*output speed)
3. Holding torque = Output torque – Input torque.

Observation table for corresponding rpm is shown in Table 3.

Table 3. Analytically torque calculations

Sr no.	Speed		Voltage	Current	Torque (Nm)		
	Input speed N1 (rpm)	Output speed N2 (rpm)	Volt	Amp	Input torque (Nm)	Output torque (Nm)	Holding torque (Nm)
1.	1000	110	47	0.976	0.4379	3.9408	3.5030
2.	1200	133	54	1.023	0.4394	3.9548	3.5154
3.	1400	155	61	1.07	0.4450	4.0052	3.5602
4.	1600	178.10	68	1.117	0.4531	4.0783	3.6252
5.	1800	199.20	75	1.164	0.4630	4.1666	3.7036
6.	2000	222	82	1.211	0.4739	4.2655	3.7915
7.	2200	244.10	89	1.258	0.4858	4.3721	3.8863
8.	2400	266.20	94	1.305	0.4879	4.3910	3.9031
9.	2600	288.80	101	1.352	0.5013	4.5119	4.0106
10.	2800	312	108	1.399	0.5151	4.6358	4.1207

VIII. RESULTS AND DISCUSSION

Comparison of analytical and experimental results for torque shows error of 5.99 % to 7.54 %.It means that efficiency of experimental set up that we have used is not 100 %.There are some frictional losses and mechanical losses occurs. Various parameters affect the torque results like motor efficiency, frictional losses occurring between belt and rope drum, spring stiffness used for measurement.

Table 4. Comparison between experimental torque and analytical torque

Sr no.	Speed		Voltage	Current	Experimental	Analytical	
	Input speed N1 (rpm)	Output speed N2 (rpm)	Volt	Amp	Holding torque (Nm)	Holding torque (Nm)	Error (%)
1.	1000	110	47	0.976	3.2931	3.5030	5.99
2.	1200	133	54	1.023	3.3002	3.5154	6.12
3.	1400	155	61	1.07	3.3433	3.5602	6.09
4.	1600	178.10	68	1.117	3.3976	3.6252	6.27
5.	1800	199.20	75	1.164	3.4584	3.7036	6.62

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6.	2000	222	82	1.211	3.5013	3.7915	7.65
7.	2200	244.10	89	1.258	3.5918	3.8863	7.57
8.	2400	266.20	94	1.305	3.6256	3.9031	7.11
9.	2600	288.80	101	1.352	3.7535	4.0106	6.41
10.	2800	312	108	1.399	3.8096	4.1207	7.54

IX. CONCLUSION

In this paper, it was attempted to calculate holding or braking torque in epicyclic gear train both by using experimental and analytical method. The results are nearly equal to each other. The error between experimental and analytical method is due to mechanical and frictional losses that are occurring while performing the experiment. We can verify the experimental and analytical results further in modeling software like Catia, UG, and solid works as future scope of this experimentation.

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