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Study of Gyroscopic effects on a disc

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Abstract

Background/Objectives: Gyroscopic couple is a reactive couple which opposes any changes of the spinning motion of the spinning axis. The study aims to perform the experimental analysis of gyroscopic effects on a disc using the experimental setup available in machine dynamics laboratory at Mechanical Engineering Department, Jamia Millia Islamia, New Delhi. **Method:** The mass is kept in the pan at a fixed distance from rotor and the applied couple is calculated. The Gyroscopic couple is also found with the help of mass moment of inertia, rotor speed and precession speed. **Findings:** The author recorded the observations of various spinning speeds (881,1608,2004 and 2546 RPM) for 45°, 90°, 135° and 180° precession angle with a set of externally applied load of 1kg, 2kg, 3kg and 4 kg. The author verifies the gyroscopic couple, compares it with the applied couple and suggested the precession speeds along with the externally applied load to achieve the minimum error (mention the minimum error value). **Novelty:** The study will be useful for researchers in avoiding errors in the initial stage of their research work.

Keywords: Gyroscopic couple; applied couple; precession speed; precession angle

1 Introduction

If a body is moving linearly through a curved path then a centripetal force is necessary to apply on the body. This centripetal force is also known as active force. But if a body at its own, moves through a circular path, a radially outward force also known as reactive force acts on it. The term "gyroscope", conventionally referred to the mechanical class of gyroscopes. Gyroscope applications are mainly for navigation and control systems in aviation as well as space engineering. In[1] demonstrated angular velocity interpretation of gyroscope using Euler rotations and finds a systematic error in sensor orientation. They suggested that this systematic error should not be confused to other sources of sensor inaccuracies like output bias drift, sensitivities and alignment of sensor axes. They validated their findings using real-case measurements. With the ongoing researches in gyroscope manufacturing technology, their applications in various sectors is observably increasing[2–6]. In[7] presented an overview of gyroscopes and their applications. The studied mechanical gyroscopes as well as optical gyroscopes. The important properties of considered gyroscopes and their technologies were related to their performance.[8] gave rough idea that may be implemented on bike which can be balanced itself without any support. The authors[9] studied thermal contact conditions subjected to heating. They used thermal contact of a gyro-unit platform assembly considering qualitative and quantitative characteristics of thermal contacts conductance. Authors in[10] reported on designing a single-structure tri axes MEMS capacitive gyroscope. They used a Z-shaped beam to support the coupling spring to suppress and eliminate the stress effects on the spring ends. They used COMSOL Multi physics and Matlab for simulation and to decrease the vacuum level in fabrication. In[11] discussed the finite element methods for computing nonlinear coefficients in systems. Authors in[12] discussed circular plates of non-uniform thickness in the z− direction, and other complex geometries. Authors in[13] presented a new theoretical method for drilling operation using finites element of beam design with the help of gyroscopic effect. In[14] discussed gyroscopes and its effects in most of the fields of everyday life like wheels, gears, shafts, rotors, bicycles, motorcycles and children toys etc.[15] discussed the precision and accuracy of MEMS vibratory gyroscopes.[16] discussed vibratory gyroscopes is a challenging task involving the precise matching of high-Q modal frequencies. In[17] developments in micro-electro-mechanical-system (MEMS) vibratory gyroscopes, which have shown great potential due to their small dimensions, favorable power consumption, and high quality factors. There are number of devices used in the military, and their design is based on the principles of gyroscopes and discussed electromechanical systems[18,19] [20]. In[21] studied unknown properties of gyroscope. He discussed that the nature of gyroscope effects, mathematical models and theories do not match the actual motions of the gyroscopic effects. In[22] studied experimentally of a gyroscopic beam system. First, they studied a simple two-degree of freedom model for simple understanding governing design. After that, they carried out experiment tests at different velocities of the gyroscopic actuator to measure the deflection.[23] used a smart phone for the identification of Atrial Fibrillation (AFib) to use the built-in accelerometer and gyroscope sensors. In[24] studied with inertial measurement units of drones. They used the latest inventions in micro-electro-mechanical systems manufacturing processes due to which size, power consumption, and cost of sensors minimized to great extent. They discussed a new method to jointly calibrate the accelerometer, gyroscope, and magnetometer. In[25] suggested a system for vehicle velocity and acceleration monitoring. They validated their suggested system with that of accelerometer sensor embedded in cellular telephone using accelerometer analyzer software. In[26] discussed the safety of two-wheeler on road using the application of gyroscopes. They have designed a self balancing two-wheeler with the help of gyroscopic principle. In[27] suggested a cost-effective experiment to understand the gyroscopic effect. The suggested experiment is easy, simple and reliable to conduct in understanding the gyroscopic effect. In[1,28], De Felice, A., Sorrentino, S., Worked on analyzing the gyroscopic effects on rotor system stability. In[29] GRAY, R., suggested various applications of gyroscopic principles.

A number of researchers have studied gyroscopic systems along with its properties. But, most of the work that has been carried out is theoretical and difficult to apply experimentally. Therefore, author, performed the experiment in the machine dynamics laboratory to relate both the theory and practical.

2 Materials and Methodology

Fig 1. Motorized Gyroscopic test rig available in machine dynamics laboratory

Motorized Gyroscope Apparatus available in machine dynamics laboratory is shown in Figure 1. The motor is coupled to the disc rotor that is statically and dynamically balanced. The disc shaft rotates about X-X axis in two ball bearings housed in the Horizontal frame. This frame can swing about Y-Y axis in bearing provided in the yoke type frame. In steady position, horizontal frame is balanced by providing a weight on the opposite side of the motor. The yoke frame is free to rotate about vertical axis Z-Z. Thus, freedom of rotation about three perpendicular axes is given to the rotor. There are some weights to apply the torque and mechanical or optical tachometer for speed measurement.

The mass is kept in the pan at a fixed distance from rotor and the applied couple is calculated. The Gyroscopic couple is also found with the help of mass moment of inertia, rotor speed and precession speed. We keep rotor at zero position. The variable motor is started with the help of rotary switch. We increased the speed of variable motor gradually and let to stable and measured its speed as 881 rpm with the help of tachometer. Now, we put the 1 kg weight in the weight pan and yoke rotate in counter clockwise direction recorded the time taken for the rotation of angle 45°, 90°, 135° and 180° using stop watch. Now, at the same speed (881 rpm), we increased the external weight from 1 kg to 2 kg and recorded the time taken again in rotation of angle 45°, 90°, 135° and 180°. Similarly, at the same speed (i.e. 881 rpm), we recorded the third and fourth observations at 3 kg and 4 kg respectively for the rotation of 45°, 90°, 135° and 180° each time. The author recorded all these four observations in Table 1.

Now, we increase the rotor rpm up to 1608 rpm and at this constant speed, the time taken for the second set of observations for external weight of 1kg, 2kg, 3kg and 4 kg is recorded for rotation of angle 45°, 90°, 135° and 180° for each mass in Table 2. Similarly, third and fourth set of observations at constant speeds of 2004 rpm and 2546 rpm, recorded in Tables 3 and 4 respectively.

Nomenclature and Formulas

I = Mass moment of inertia of disc or rotor about Z axis in kg.m^2.

N = Speed of motor in RPM.

ω = Angular velocity of spinning rotor in rad/sec.

ω_p = Angular velocity of precession of yoke about vertical axis in rad/sec.

dθ = Angle of precession in degree.

dt = Time required for this precession angle in sec.

M = Mass of the disc or rotor in kg.

m= External mass applied in the pan in kg.

L = Distance of bolt of Weight pan from disc Centre in m.

R = Radius of rotor, in m.

C = Reactive or Gyroscopic couple = I. ω. ω_p in N. m.

T = Active or Applied couple = W.L = m.g.L in N. m.

D = Diameter of the disc or rotor in m.

R = Radius of the disc or rotor in m.

Observations

D= Rotor Diameter = 300 mm = 0.3m, L = Distance of bolt of Weight pan from disc Centre =197 mm, M = Mass of the disc or rotor = 6.5 kg, I = M.D^2/8 = 0.073 kg.m^2, m_1 =1 kg, m_2 =2 kg, m_3 =3 kg, m_4 =4 kg, T1=1.933 N.m, T2=3.865 N.m, T3=5.799 N.m, T4=7.732 N.m.

Table 1. observations at spinning speed, n= 881 rpm.

S. N.	θ (deg)	dt_1 (at m=1 kg)	dt_2 (at m=2 kg)	dt_3 (at m=3 kg)	dt_4 (at m=4 kg)
1	45	2.15	1.38	1.09	0.67
2	90	4.4	2.68	1.93	1.35
3	135	6.79	4.08	2.73	2.12
4	180	10.02	5.42	3.6	2.84

Table 2. observations at spinning speed, n= 1608 rpm.

S. N.	θ (deg)	dt_1 (at m=1 kg)	dt_2 (at m=2 kg)	dt_3 (at m=3 kg)	dt_4 (at m=4 kg)
1	45	3.94	2.25	1.55	1.09
2	90	8	4.69	2.85	2.41
3	135	12.94	6.68	4.17	3.59
4	180	17.42	9.48	6.12	4.59

Table 3. observations at spinning speed, N= 2004 RPM

S. N.	θ (deg)	dt_1 (at m=1 kg)	dt_2 (at m=2 kg)	dt_3 (at m=3 kg)	dt_4 (at m=4 kg)
1	45	6.4	2.78	2.12	1.53
2	90	12.76	5.54	4	2.77
3	135	19.45	8.29	6.07	4.44
4	180	27.27	11.15	8.01	5.97

Table 4. observations at spinning speed, N= 2546 RPM.

S. N.	θ (deg)	dt_1 (at m=1 kg)	dt_2 (at m=2 kg)	dt_3 (at m=3 kg)	dt_4 (at m=4 kg)
1	45	7.41	3.7	2.11	1.99
2	90	14.66	7.08	4.07	3.59
3	135	22.98	10.45	6.46	5.23
4	180	31.9	14.11	8.8	6.82

3 Results and Discussion

The results and various calculations at spinning speed (N) 881 rpm are recorded in Tables 5, 6, 7 and 8. In each Table, ω_{p1}, ω_{p2}, ω_{p3} and ω_{p4} are angular precession speeds for precession angles at 45°, 90°, 135° and 180° for externally applied weight of 1kg, 2kg, 3kg and 4 kg respectively. Similarly, C1, C2, C3 and C4 are the reactive or gyroscopic couples (C) for precession angle of 45°, 90°, 135° and 180° for externally applied weight of 1kg, 2kg, 3kg and 4 kg respectively. The active couple or applied torques due to externally applied weights of 1kg, 2kg, 3kg and 4 kg are ; T1=1.933 N.m, T2=3.865 N.m, T3=5.799 N.m and T4=7.732 N.m respectively.

We observe from Table 5 that for precession angle 45°, the percentage error in measuring the gyroscopic couple at externally applied load of 1kg, 2kg, 3kg and 4 kg is 27.26, 0.65, 16.9 and 2.3 respectively. We also note that for precession angle 90°, the percentage error in measuring the gyroscopic couple at externally applied load of 1kg, 2kg, 3kg and 4 kg is 24.67, 2.2, 5.35 and 1.53 respectively. While the same percentage error for 135° and 90° , are 21.06,0.65,0.4,3.0 and 9.16,1.16,1.48,3.51 respectively for the externally applied load of 1kg, 2kg, 3kg and 4 kg. The average percentage error at an externally applied load of 1kg at precession angles of 45°, 90°, 135° and 180° is 20.54. Similarly, the average percentage errors at an externally applied load of 2kg, 3kg and 4 kg at precession angles of 45°, 90°, 135° and 180° are 1.16,5.86 and 2.58 respectively. The authors note down from Figure 2 that the precession angular velocity at 881 rpm spinning speed remains uniform at externally applied load of 2kg.

The author observes from Table 6 that for precession angle 45°, the percentage error in measuring the gyroscopic couple at externally applied load of 1kg, 2kg, 3kg and 4 kg is 26.74, 11.25, 7.55 and 14.71 respectively. We also note that for precession angle 90°, the percentage error in measuring the gyroscopic couple at externally applied load of 1kg, 2kg, 3kg and 4 kg is 25.20, 6.98, 16.98 and 3.72 respectively. While the same percentage error for 135° and 90° , are 15.88,12.29,19.93,4.50 and 14.85,5.56,8.96,9.03 respectively for the externally applied load of 1kg, 2kg, 3kg and 4 kg. The average percentage error at an externally applied load of 1kg at precession angles of 45°, 90°, 135° and 180° is 20.69. Similarly, the average percentage errors at an externally applied load of 2kg, 3kg and 4 kg at precession angles of 45°, 90°, 135° and 180° are 9.02,13.37 and 7.99 respectively. We note down from Figure 3 that the precession angular velocity at 1608 rpm spinning speed remains uniform at externally applied load of 1kg.

It is clear from Table 7 that for precession angle 45°, the percentage error in measuring the gyroscopic couple at externally applied load of 1kg, 2kg, 3kg and 4 kg is 2.74, 12.03, 2.0 and 1.78 respectively. We also note that for precession angle 90°, the percentage error in measuring the gyroscopic couple at externally applied load of 1kg, 2kg, 3kg and 4 kg is 2.22, 12.55, 3.88 and 12.52 respectively. While the same percentage error for 135° and 90° , are 3.77,12.81,2.69,5.28 and 8.43,11.77,3.76,4.37 respectively for the externally applied load of 1kg, 2kg, 3kg and 4 kg. The average percentage error at an externally applied load of 1kg at precession angles of 45°, 90°, 135° and 180° is 4.29. Similarly, the average percentage errors at an externally applied load of 2kg, 3kg and 4 kg at precession angles of 45°, 90°, 135° and 180° are 12.29,3.08 and 5.98 respectively. We note down from Figure 4 that the precession angular velocity at 2004 rpm spinning speed remains uniform at externally applied loads of 1kg as well as 2 kg.

Table 8 reveals that for precession angle 45°, the percentage error in measuring the gyroscopic couple at externally applied load of 1kg, 2kg, 3kg and 4 kg is 7.09, 7.11, 25.11 and 6.23 respectively. We also note that for precession angle 90°, the percentage error in measuring the gyroscopic couple at externally applied load of 1kg, 2kg, 3kg and 4 kg is 8.12, 11.77, 29.71 and 10.32 respectively. While the same percentage error for 135° and 90° , are 3.46,13.58,22.59,13.55 and 0.67,12.29,19.98,16.14 respectively for the externally applied load of 1kg, 2kg, 3kg and 4 kg. The average percentage error at an externally applied load of 1kg at precession angles of 45°, 90°, 135° and 180° is 4.5. Similarly, the average percentage errors at an externally applied load of 2kg, 3kg and 4 kg at precession angles of 45°, 90°, 135° and 180° are 11.26,24.34 and 11.56 respectively. We note down from Figure 5 that the precession angular velocity at 2546 rpm spinning speed remains almost uniform at externally applied loads of 1kg as well as 2 kg.

Table 5. Results and discussion at spinning speed, n= 881 rpm.

SN	1	2	3	4	Avg
θ (deg	45	90	135	180	
m in kg	1	2	3	4	
ω_{p1}(rad/s)	0.365	0.357	0.347	0.314	
ω_{p2}(rad/s)	0.569	0.586	0.578	0.58	
ω_{p3}(rad/s)	0.721	0.814	0.863	0.873	
ω_{p4}(rad/s)	1.172	1.164	1.111	1.106	
C_1(N-m)	2.46	2.41	2.34	2.11	2.33
C_2(N-m)	3.84	3.95	3.89	3.91	3.896
C_3(N-m)	4.86	5.489	5.821	5.885	5.514
C_4(N-m)	7.91	7.85	7.5	7.46	7.68
%ErrorC_1	27.26	24.67	21.06	9.16	20.54
%ErrorC_2	0.65	2.2	0.65	1.16	1.16
%ErrorC_3	16.19	5.35	0.400	1.48	5.86
%ErrorC_4	2.30	1.53	3.00	3.51	2.58

Table 6. Results and discussion at spinning speed, n= 1608 rpm.

S.N.	1	2	3	4	Avg
θ (deg)	45	90	135	180	
m in kg	1	2	3	4	
ω_{p1}(rad/s)	0.199	0.196	0.182	0.18	
ω_{p2}(rad/s)	0.349	0.335	0.353	0.331	
ω_{p3}(rad/s)	0.507	0.551	0.565	0.513	
ω_{p4}(rad/s)	0.721	0.652	0.656	0.684	
C_1(N-m)	2.45	2.42	2.24	2.22	2.333
C_2(N-m)	4.3	4.12	4.34	4.08	4.21
C_3(N-m)	6.237	6.784	6.955	6.319	6.574
C_4(N-m)	8.87	8.02	8.08	8.43	8.35
%ErrorC_1	26.74	25.20	15.88	14.85	20.69
%ErrorC_2	11.25	6.98	12.29	5.56	9.02
%ErrorC_3	7.55	16.98	19.93	8.96	13.37
%ErrorC_4	14.71	3.72	4.50	9.03	7.99

Table 7. Results and discussion at spinning speed, n= 2004 rpm.

S.N.	1	2	3	4	Avg
θ (deg)	45	90	135	180	
m in kg	1	2	3	4	
ω_{p1}(rad/s)	0.123	0.123	0.121	0.115	
ω_{p2}(rad/s)	0.283	0.284	0.284	0.282	
ω_{p3}(rad/s)	0.37	0.393	0.388	0.392	
ω_{p4}(rad/s)	0.513	0.567	0.531	0.526	
C_1(N-m)	1.88	1.89	1.86	1.77	1.85
C_2(N-m)	4.33	4.35	4.36	4.32	4.34
C_3(N-m)	5.683	6.024	5.955	6.017	5.919
C_4(N-m)	7.87	8.7	8.14	8.07	8.195
%ErrorC_1	2.74	2.22	3.77	8.43	4.29
%ErrorC_2	12.03	12.55	12.81	11.77	12.29
%ErrorC_3	2.00	3.88	2.69	3.76	3.08
%ErrorC_4	1.78	12.52	5.28	4.37	5.98

Table 8. Results and discussion at spinning speed, n= 2546 rpm.

S.N.	1	2	3	4	Avg
θ (deg)	45	90	135	180	
m in kg	1	2	3	4	
ω_{p1}(rad/s)	0.106	0.107	0.103	0.098	
ω_{p2}(rad/s)	0.212	0.222	0.225	0.223	
ω_{p3}(rad/s)	0.372	0.386	0.365	0.357	
ω_{p4}(rad/s)	0.517	0.438	0.451	0.461	
C_1(N-m)	2.07	2.09	2.00	1.92	2.02
C_2(N-m)	4.14	4.32	4.39	4.34	4.296
C_3(N-m)	7.255	7.522	7.109	6.958	7.211
C_4(N-m)	7.68	8.53	8.78	8.98	8.4925
%ErrorC_1	7.09	8.12	3.46	0.67	4.5
%ErrorC_2	7.11	11.77	13.58	12.29	11.26
%ErrorC_3	25.11	29.71	22.59	19.98	24.34
%ErrorC_4	6.23	10.32	13.55	16.14	11.56

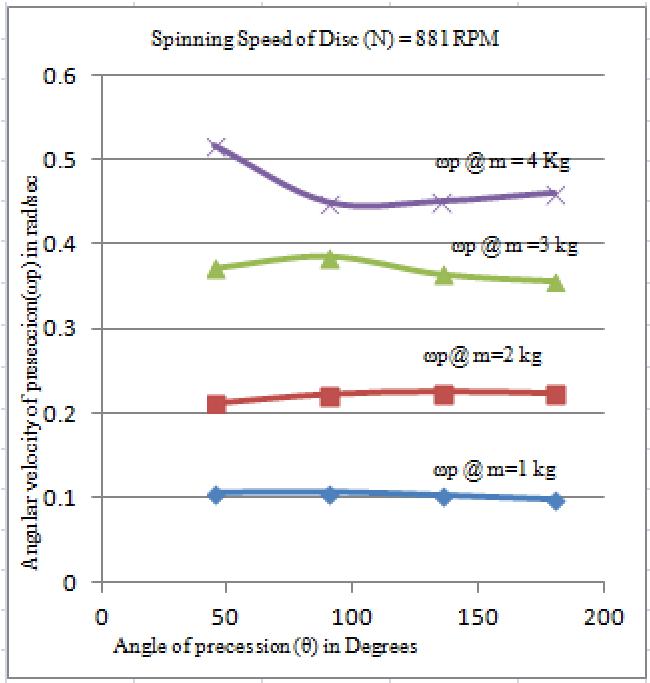

Fig 2. Variation in Angular Precession Velocity at Different External Applied Load at Spinning Speed of Disc, N=881 RPM

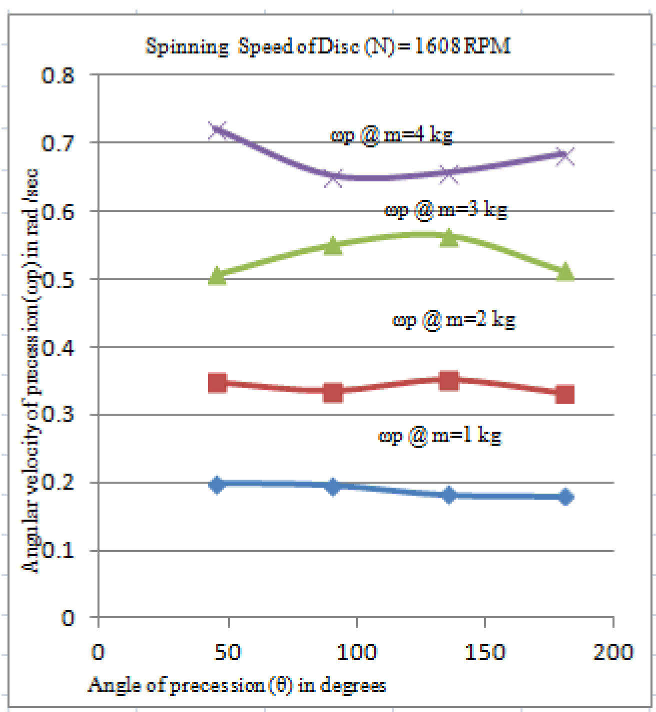

Fig 3. Variation in Angular Precession Velocity at Different External Applied Load at Spinning Speed of Disc, N=1608 RPM

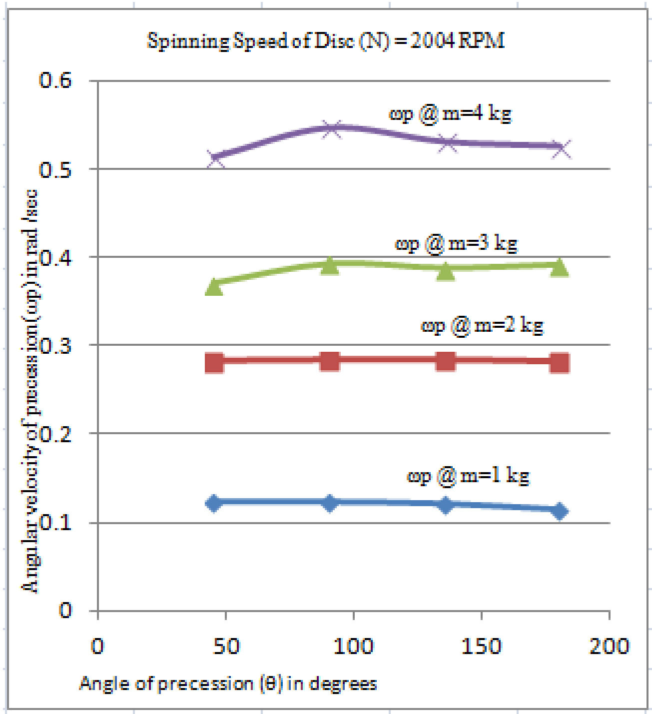

Fig 4. Variation in Angular Precession Velocity at Different External Applied Load at Spinning Speed of Disc, N=2004 RPM

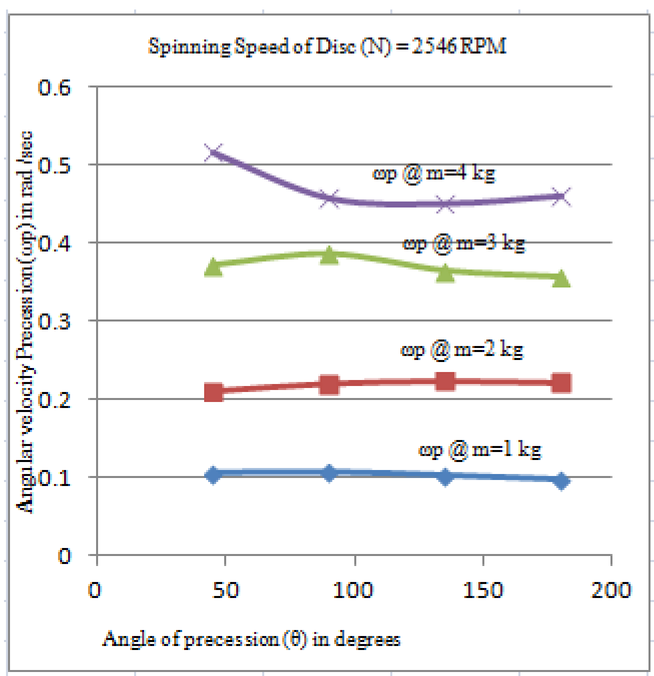

Fig 5. Variation in Angular Precession Velocity at Different External Applied Load at Spinning Speed of Disc, N=2546 RPM

4 Conclusions

It is clear from Table 5 that at precession angular velocity of 92.26 rad/s, minimum error is 0.65 % at an externally applied load of 2kg. Also, the average minimum error is 1.16 % at a load of 2kg for angular precession from 45° to 180°. It is clear from Table 6 that at precession angular velocity of 168.39 rad/s, the average minimum error is 7.99 % at a load of 4kg for angular precession from 45° to 180°. It is clear from Table 7 that at precession angular velocity of 209.86 rad/s, the average maximum error is 12.29 % at a load of 2 kg for angular precession from 45° to 180°. It is clear from Table 8 that at precession angular velocity of 266.62 rad/s, the average minimum error is 4.5 % at a load of 1 kg for angular precession from 45° to 180°. Finally, we conclude that at lower precession angular speed, there is maximum error using the lower externally applied load. We should use higher external load at lower precession speed. But, as we increase the precession speed, we obtained minimum error at lower external loads also. With the increase of angular precession speeds, we get the average error within permissible limits. In short, we conclude from Figure 6 that the gyroscopic law is best verified at spinning speed of 1608 rpm while the externally applied load is 2 kg. In other words, the gyroscopic law is best verified at spinning speeds greater than 1500 rpm at externally applied torque of 3.865 N.m.

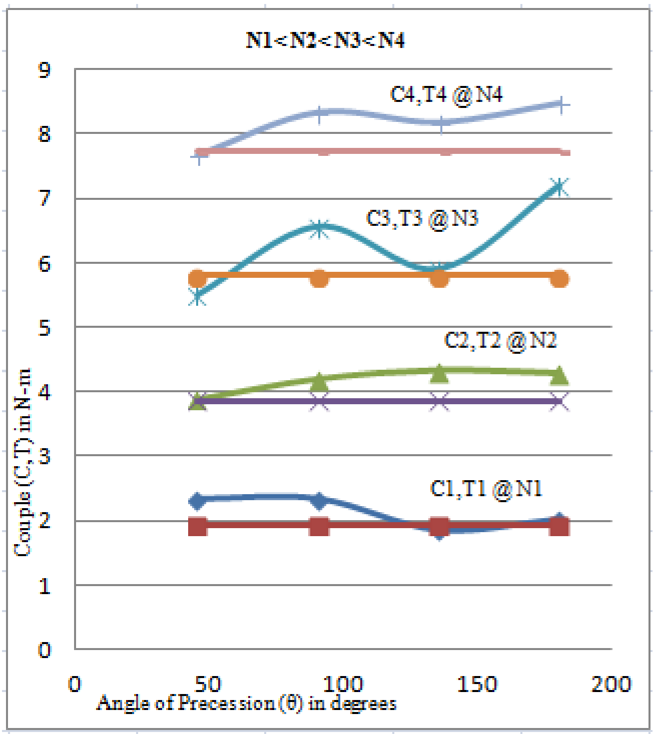

Fig 6. Variations between Active Couple (T) and Reactive Couple (C) at various Spinning speeds

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