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Objective

This lab session focuses on the completion of the following objectives:

- Determination and assessment of torque as the function of the distance between force action point and origin coordinates.
- Determination and assessment of torque as a function of force

Theoretical background

Torque is defined as the force that causes rotation in a body and it is the product of force and the moment arm. Torque is also known as the twisting force. The magnitude of the torque can be computed using the given relation:

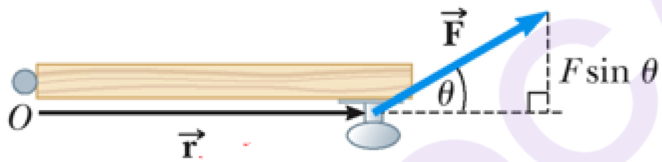

Figure 1 Torque application visualization

And mathematically, torque is given as:

$$\tau = rFsin\theta \quad (1)$$

In the above equation,

- τ represents the torque
- r represents the moment arm
- F represents the acting force

This lab session focuses on static equilibrium, which means the object under observation doesn't move either linearly or rotationally because of the balanced sum of forces and torques on the objects. For static equilibrium, two main conditions include the sum of forces should be zero and the sum of torques should be zero. They are written as:

$$\sum F = 0 \quad (2)$$

$$\sum \tau = 0 \quad (3)$$

The assembly used for this experiment is provided in the figure below with their associated equations:

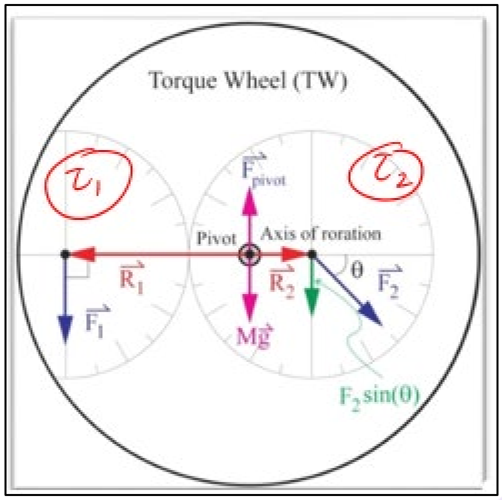

Figure 2 Torque wheel assembly

The first equilibrium condition that the sum of forces should be equal to zero is given as:

$$\sum F = 0$$
$$Mg_{TW} + F_2 sin\theta + F_1 - F_{pivot} = 0 \quad (4)$$

The second equilibrium condition that the sum of torques should be equal to zero is given as:

$$\sum \tau = 0$$
$$\tau_1 + \tau_2 = 0 \quad (5)$$
$$R_1 \times F + R_2 \times F_2 = 0$$

Procedure and Equipment

The equipment used for performing the experiment includes the following components:

- Torque wheel
- Stands
- Mainframe
- Spring scales
- Masses
- Hanger

The figure of apparatus used for experimentation:

Figure 3 Apparatus Diagram

The following steps were followed for performing the experiment:

- All the components were collected and assembled. All the connections were made and the assembly was prepared for the experiment.
- The strings were attached at two points on the torque wheel. One end with connected to a stand with a spring scale while the second one has a spring scale attached with a hanger on which masses were applied.
- The torque was computed with the introduction of variation in distance and mass.
- Firstly, the mass of 100 g was attached while the distance R2 was set to 12 cm. The distance R1 was varied and static equilibrium was achieved by balancing out the torques and the resulting values of parameters were measured and tabulated.
- Secondly, the distances R1 and R2 were set to 9cm and 6cm. Then, the mass values were varied and static equilibrium was achieved along with the determination of required parameters.
- All the recorded data were tabulated and used for performing further calculations.

Data Table

Table 1 Measured torque as a function of distance

R_1 (m)	F_2 (N)	$\tau_2 = R_2F_2$ (N.m)	$\tau_1 = R_1F_1$ (N.m)
0.03	0.23	0.0276	0.0294
0.06	0.54	0.0648	0.0588
0.09	0.77	0.0924	0.0882
0.12	1.07	0.1284	0.1176
0.13	1.14	0.1368	0.1274

Table 2 Measured torque as a function of force

m (kg)	$mg = F_1$ (N)	F_2 (N)	$\tau_2 = R_2F_2$ (N.m)	$\tau_1 = R_1F_1$ (N.m)
0.040	0.39	0.6	0.036	0.035
0.050	0.49	0.72	0.043	0.044
0.060	0.59	0.87	0.052	0.053
0.070	0.69	1.07	0.064	0.062
0.100	0.78	1.19	0.071	0.071

Graph

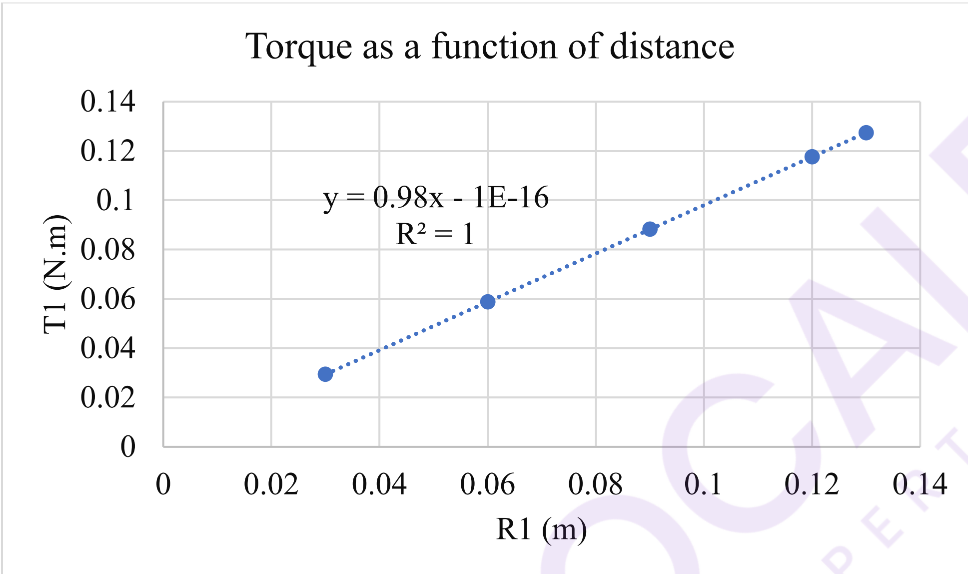

Figure 4 Torque as a function of distance

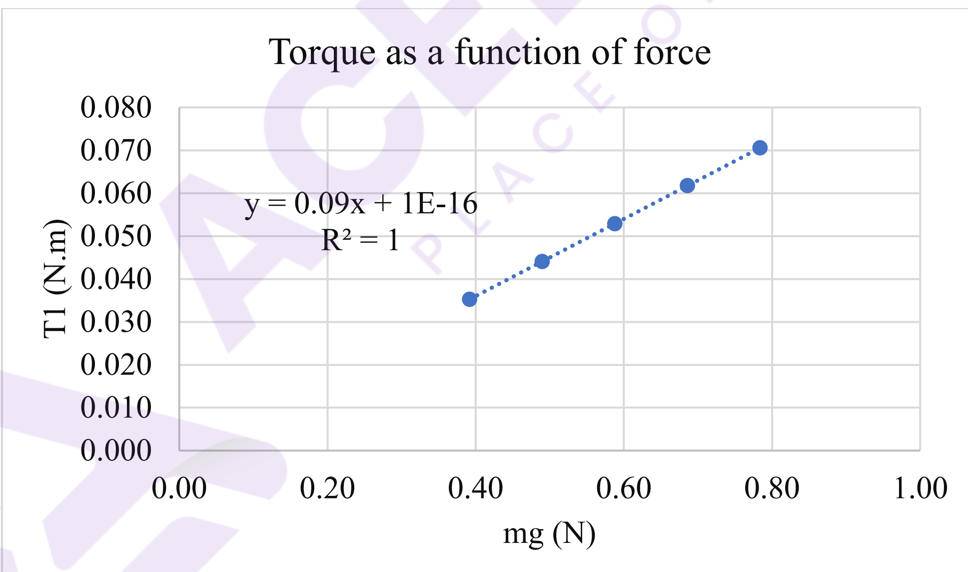

Figure 5 Torque as a function of force

Error Analysis

a. The estimated uncertainty (Δm) in the mass (m) is 0.001 Kg.

b. The estimated uncertainty (Δg) in the gravitational acceleration is 0.1 m^2/s.

c. The estimated uncertainty (ΔR) in the (R) is 0.001 m.

d. The error in the force is evaluated as following

$$\Delta F_1 = \Delta mg = \sqrt{(m.\Delta g)^2 + (g.\Delta m)^2}$$

$$\Delta F_1 = \Delta mg = \sqrt{\left(\frac{\delta mg}{\delta m}\Delta m\right)^2 + \left(\frac{\delta mg}{\delta g}\Delta g\right)^2}$$

$$\Delta F_1 = \Delta mg = \sqrt{(0.04 \times 0.1)^2 + (9.81 \times 0.001)^2} = 0.01\ N$$

e. The error in the torque (τ_1) is evaluated as following

$$\Delta \tau_1 = \sqrt{(R_1.\Delta F_1)^2 + (F_1.\Delta R_1)^2}$$

$$\Delta \tau_1 = \sqrt{\left(\frac{\delta F_1 R_1}{\delta F_1}\Delta F_1\right)^2 + \left(\frac{\delta F_1 R_1}{\delta R_1}\Delta R_1\right)^2}$$

$$\Delta \tau_1 = \sqrt{(0.09 \times 0.01)^2 + (0.39 \times 0.001)^2} = 0.035\ Nm$$

f. The error in the torque (τ_2) is evaluated as following

$$\Delta \tau_2 = \sqrt{(R_2.\Delta F_2)^2 + (F_2.\Delta R_2)^2}$$

$$\Delta \tau_2 = \sqrt{\left(\frac{\delta F_2 R_2}{\delta F_2}\Delta F_2\right)^2 + \left(\frac{\delta F_2 R_2}{\delta R_2}\Delta R_2\right)^2}$$

$$\Delta \tau_2 = \sqrt{(0.06 \times 0.01)^2 + (0.6 \times 0.001)^2} = 0.036\ Nm$$

The error percentage between the theoretical and experimental value is given by:

$$\%\ Error\ in\ F_1 = \frac{Theoretical\ value - Experimental\ value}{Theoretical\ value} \times 100\%$$

Percentage error in $F_1 = \left|\frac{0.98-0.98}{0.98}\right| = 0\%$

$$\% \, Error \, in \, R = \frac{Theoretical \, value - Experimental \, value}{Theoretical \, value} \times 100\%$$

$$\text{Percentage error in } F_1 = \left| \frac{0.09 - 0.09}{0.09} \right| = 0\%$$

Discussion & Conclusion

In this experiment, static equilibrium is studied and achieved experimentally. Two different conditions are verified. In the first condition, equilibrium is achived by adjusting the forces in such a way that there sum is zero. This provides the linear hindrance to the movement of object. In the second condition, summation of all the torques is taken as zero. Hence, static equilibrium is achieved in which sum of forces as well as torques is zero.Two graphs are plotted between torque as a function of distance (R_1) & Torque as a function of force. Both graphs are found to be linear and slope of the graphs are found using linear line equation. Error analysis is carried and step by step procedure is shown above. Results are found to be accurate without the percentage error in experimental and theoretical results.

A detailed discussion was done covering theoretical and practical concepts relevant to static equilibrium and torques. A torque wheel assembly was used for performing the experiment and the torque as a function of the distance between the point of force application and origin was computed, discussed, and analyzed along with torque as a function of force. Graphs were plotted between torque with force and torque with distance. An error analysis was performed for computing errors in forces, mass, gravity readings, and radius.