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Energy in a Flywheel Technical Report

Further Science for Engineers (ACHA4007)

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1 Introduction

Flywheels have been used since the earliest days of mechanical system as a means to smooth the operation of power impulses in a machine and also act as an energy storage device (Dresig & Holzweissig, 2010). The flywheel was a fundamental component of large slow cycle steam engines which formed the basis of the industrial revolution. Since then, flywheels have become common place in multiple applications from the gyroscopic action of stabilisation apparatus to kinetic energy recovery in the latest motorsport technology (Collins, 2011).

The theory of flywheels is, therefore, important in the understanding and design of many components used in motorsport applications.

This report investigates the kinetic energy of a flywheel and losses of potential energy which occur when potential energy from an energy source is transferred to the flywheel and then back to potential energy.

This report describes the experimental methodology used and calculates various parameters, including the Moment of Inertia (I) of the flywheel. Results are tabulated and calculations clearly described. Photographs and diagrams are included where appropriate and conclusions drawn.

Finally, some suggestions are made as to the sources of energy loss in the system and how these might be avoided.

2 Experimental Procedure

The experiment was set up using a standard kit (ES9) supplied by TecQuipment Limited. Instructions for the construction of the experiment and the execution of the experiment itself were closely followed to achieve the best possible results (TecQuipment Ltd., 2012).

2.1 Apparatus

The apparatus consists of a flywheel attached by means of a shaft which passes through a bearing block, with a thumbscrew brake, and terminated with a machined pulley opposite the flywheel, Figure 1.



Figure 1 Apparatus components

The bearing block is mounted to a drilled steel plate by means of screws and the steel plate is held vertically by two triangular feet. This allows the pulley and flywheel to be mounted at a height greater than 300mm above the laboratory table, Figure 2.



Figure 2 Mounting of bearing block to steel plate

Attached to the pulley is a cord and at the bottom of the cord is a flat hanger which can carry small weights. The flat hanger acts as a reference point against a magnetic steel ruler. The ruler is carefully positioned behind the hanger in order that it can be read against the bottom of the hanger with minimum parallax error and such that the zero marking coincides with the bottom of the hanger, Figure 3.



Figure 3 Cord, ruler and hanger positioning

Weights can then be added to the hanger in 100g increments and the cord wound on to the pulley until the bottom of the hanger is at the level of the 280mm mark on the ruler, Figure 4.



Figure 4 Positioning of weight hanger at 280mm above rest position

At this time the apparatus is ready for the experiment to be performed

2.2 Method

The principal of the experiment is to allow the weight to fall under the influence of gravity. This fall unwinds the cord around the pulley and transfer the potential energy of the weight on the hanger into kinetic energy of the rotation of the flywheel.

This transfer of energy continues until the weight hanger reaches the bottom of its travel and the cord is completely unwound. At that point the angular momentum of the flywheel continues the flywheel spinning and the cord is rewound back on to the pulley until the movement stops, Figure 5 (Tecquipment Ltd., 2012).

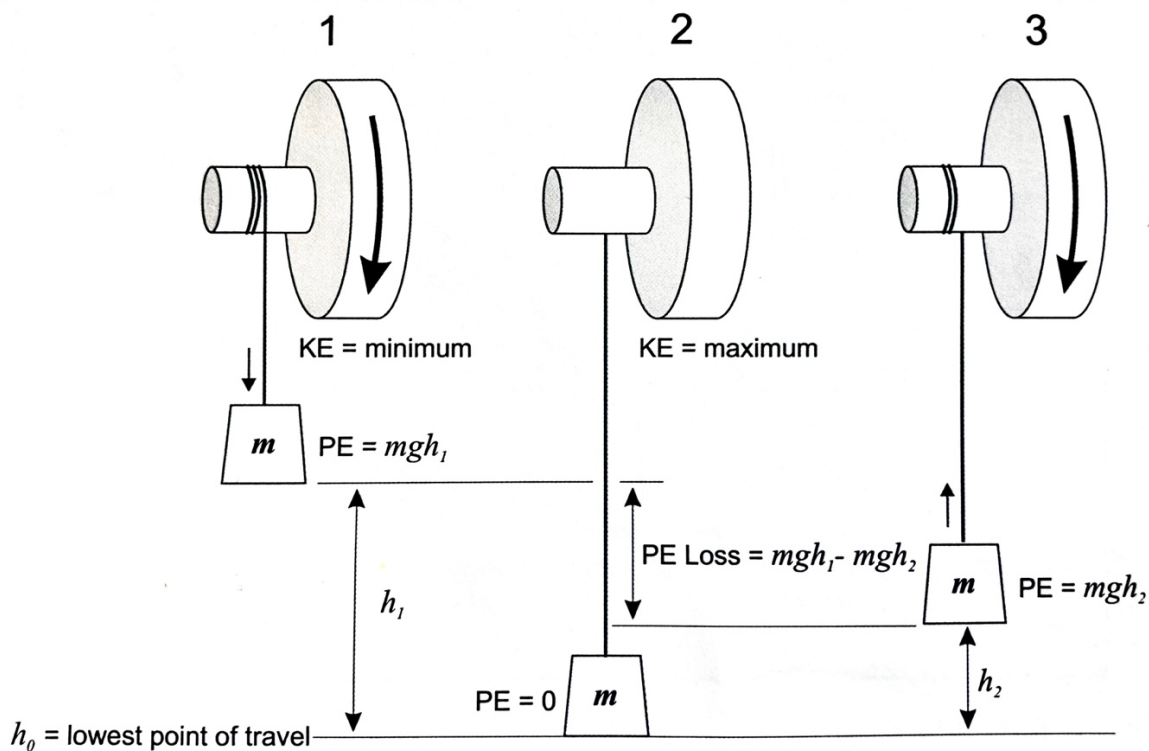


Figure 5 Schematic of the experimental measurements (Tecquipment Ltd., 2012)

The thumbscrew brake can then be applied to the shaft and the height to which the bottom of the hanger plate measured against the magnetic rule.

The time taken for the full cycle of the 280mm fall, h_1 , and the return to height, h_2 , is measured with a stopwatch.

The difference in height between the start point and the end point corresponds to energy losses which occur in the system.

The amount of time taken for the full cycle allows calculations to be made for angular velocity, acceleration and the moment of Inertia of the flywheel.

The cycle was performed three times for each weight, starting at 100g and increasing by 100g incrementally to 500g.

Results were tabulated in an Excel spreadsheet and then formulae were input to the spreadsheet to calculate the following parameters for each weight:

- Mean fall and rise time (t_f)
- Mean rise height (h_2)
- Adjusted PE loss (during fall)
- Fall time
- Acceleration
- Velocity
- Angular Velocity
- Torque
- Angular Acceleration
- Kinetic Energy of the Flywheel

Plotting a graph of Torque versus Angular Acceleration for each weight allowed a best fit line to be inserted, the gradient of which is the Moment of Inertia of the flywheel derived experimentally. This could then be compared against the nominal Moment of Inertia stated for the flywheel in the kit.

3 Results

Table 1, below, contains the results measure for each of three complete cycles of the experiment at each weight from 100g to 500g in 100g increments.

Table 1 Measured results for flywheel system

Mass m (kg)	PE mgh (J)	Time to fall and rise t_f (seconds) 1st	Time to fall and rise t_f (seconds) 2nd	Time to fall and rise t_f (seconds) 3rd	h_2 (m) 1st	h_2 (m) 2nd	h_2 (m) 3rd
0	0	0	0	0	0	0	0
0.1	0.27468	4.54	4.05	4.6	0.23	0.232	0.236
0.2	0.54936	3	2.99	3.23	0.25	0.253	0.255
0.3	0.82404	2.98	2.39	2.38	0.253	0.255	0.255
0.4	1.09872	2.06	2.09	1.96	0.258	0.26	0.255
0.5	1.3734	1.86	1.83	1.74	0.243	0.245	0.23
Constants	Value						
h_1 (m)	0.28 drop height						
g (m.s ⁻²)	9.81 gravity						
c (m)	0.04084 circumference of pulley						

The total time from the start of the drop until the end of the rewind was measured to reduce the proportional effect of error in pressing the stopwatch button. The time taken purely for the fall is shorter than the total time so the percentage error in measurement could be greater.

A mean was calculated from these results, and this was used for the next stage of the analysis.

4 Analysis

Table 2 contains the calculations performed against the results tabulated in section 3 of this report. The analysis uses standard equations of motion for both linear and rotational systems (Bolton, 2021). Calculation was performed by input of the relevant formulae to apply to the results contained within the Excel spreadsheet.

Table 2 Analysis of Flywheel Parameters

Time to fall and rise t_f (seconds)	h_2 (m)	mean	mg (N)	PE Loss Adjusted (J)	Falling Time t_f (seconds)	Acceleration a (m.s ⁻²)	Velocity v (m.s ⁻¹)	Angular Velocity ω (rad.s ⁻¹)	Torque T (Nm) (mg-ma).r	Angular Acceleration α (rad.s ⁻²) (a/r)	KE (J)
0.000	0.000	0	0	0	0	0	0	0	0	0	0
4.397	0.233	0.981	0.025360572	2.40130039	0.097116952	0.233206975	35.87861505	0.006313265	14.94132729	0.271960725	0.271960725
3.073	0.253	1.962	0.028189937	1.615519399	0.214567367	0.346637744	53.32980363	0.012473847	33.01093361	0.537344227	0.537344227
2.583	0.254	2.943	0.039582707	1.35371179	0.305587513	0.413677419	63.64377775	0.018533285	47.01427453	0.798370649	0.798370649
2.037	0.258	3.924	0.045638091	1.060632362	0.497803882	0.527986907	81.23015609	0.024211292	76.58653365	1.042965965	1.042965965
1.810	0.239	4.905	0.107544801	0.975866496	0.588040464	0.573848987	88.28598248	0.029970851	90.46932432	1.291074335	1.291074335

To calculate the PE loss during the time to fall, it is assumed that the losses experienced during the fall are equivalent to the losses experienced during the rise of weights. Such losses could be caused by various factors such as friction in the bearing block, air resistance or stiction in the movement of the cord.

Thus, the adjusted PE loss (for the fall) can be calculated as follows:

$$\text{Adjusted PE loss} = (mgh_1 - mgh_2) \times h_1 / (h_1 + h_2)$$

Similarly, the falling time can be calculated using the same assumption:

$$\text{Fall time } t_f = t_i \times h_1 / (h_1 + h_2)$$

From this the linear acceleration of the weight hanger can be calculated using:

$$s = ut + \frac{1}{2} at^2 \text{ (initial velocity } u \text{ is zero)}$$

$$a = 2s/t^2$$

$$a = 2 \times h_1 / t_f^2$$

The linear velocity of the weight hanger at the lowest point can be calculated using:

$$v = u + at \text{ (initial velocity is zero)}$$

$$v = at_f$$

Since the linear velocity of the falling hanger is the same as the tangential velocity of the perimeter of the flywheel pulley, it is possible to calculate the angular velocity ω of the flywheel, since the pulley and flywheel are mounted on the same shaft and are rotating at the same speed.

$$\omega = 2\pi \times \text{velocity/circumference}$$

Assuming the cord does not stretch, from the linear acceleration it is possible to calculate the angular acceleration α as follows:

$$\alpha = a/r$$

It is also possible to calculate the torque applied to the system, Figure 6 (Tecquipment Ltd., 2012), as follows:

$$F = mg - ma$$

but

$$T = F \times r$$

so

$$T = (mg - ma) \times r$$

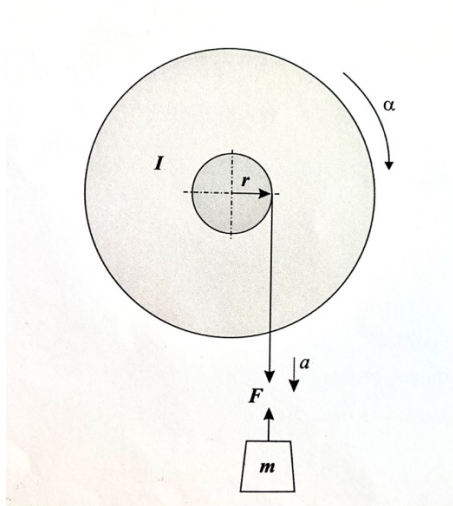


Figure 6 Calculation of Applied Torque (Tecquipment Ltd., 2012)

Since we know that:

$$T = I \times \alpha$$

We can see that plotting a graph of torque against angular acceleration allows us to derive the moment of inertia I from the gradient of the graph.

$$T = (mg - ma) \times r = I \times (a/r)$$

$$I = \frac{(mg - ma) \times r}{(a/r)}$$

5 Conclusion

Using the graphing function of the Excel spreadsheet the calculated torque at each of the weight increments was plotted against the calculated angular acceleration, Figure 7. It was then possible to plot a best fit line and derive the equation of that line.

The line equation was found to be:

$$y = 0.00033889x$$

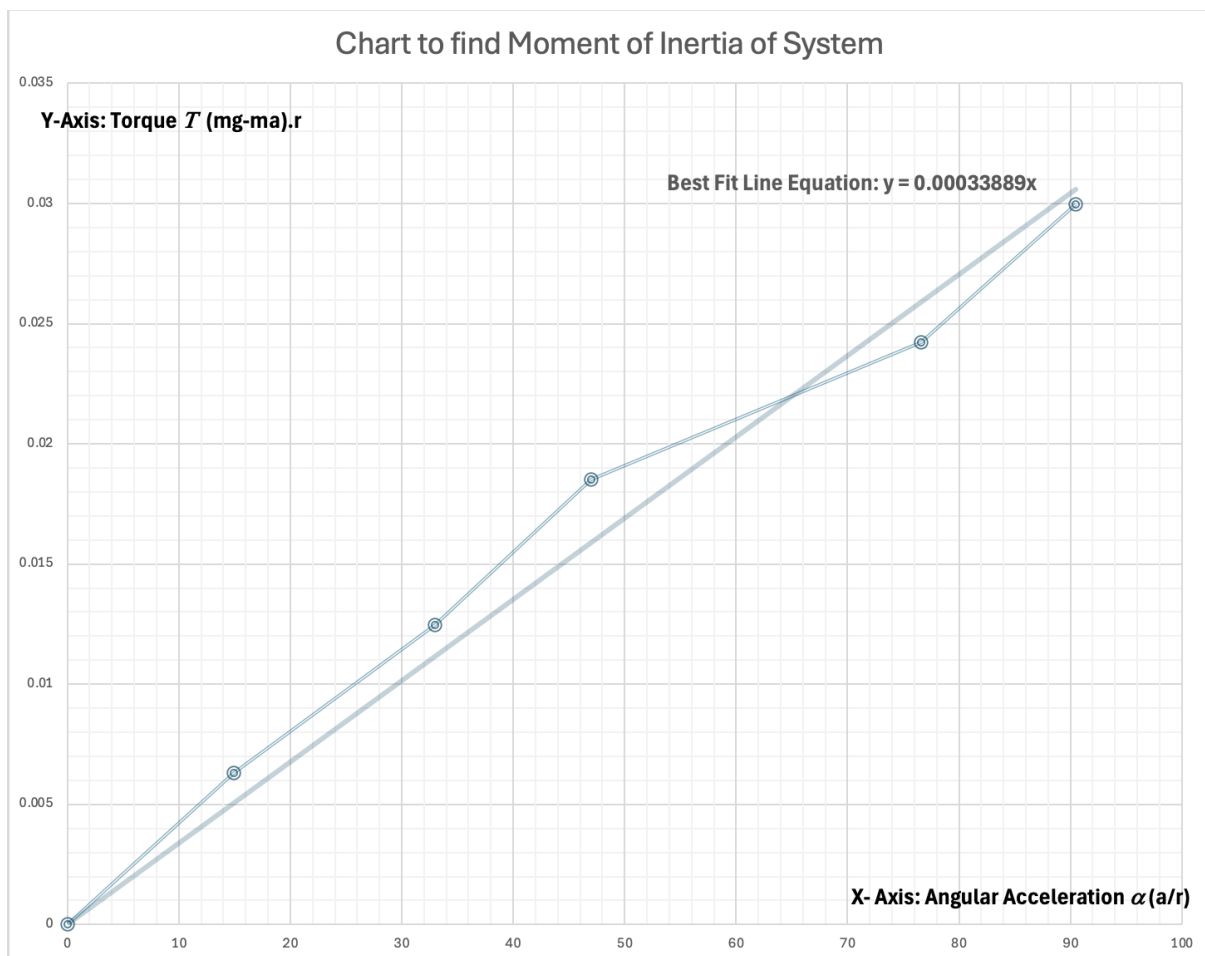


Figure 7 Plot of Torque versus Angular Acceleration to find Moment of Inertia

Using the standard equation for a straight line:

$$y = mx + c \text{ (where } m \text{ is the gradient)}$$

It can be seen that the calculated value for the moment of inertia of the flywheel system is $0.33889 \times 10^{-4} \text{ kg/m}^2$ or $3.33899 \times 10^{-4} \text{ kg/m}^2$ in standard form notation.

This compares with the stated nominal moment of inertia for the system which was $4.696 \times 10^{-4} \text{ kg/m}^2$.

6 Evaluation

Care was taken during the experiment to allow the cord and hanger to hang vertically downwards rather than pushing the cord back towards the ruler which would have given an incorrect reading at the bottom of the hanger.

Readings of heights h_1 and h_2 were taken at eye-level to minimise parallax error.

The experiment was repeated three times for each weight increment and an arithmetic mean taken for the height and time results at each of these increments.

It was assumed that the causes of PE losses were equivalent in both falling and rising directions.

The time taken for the fall was calculated by a ratio of the fixed drop height of 280mm against the total distance moved (h_1+h_2). This minimises the proportion of the error contributed by human reaction time.

Measuring the total time rather than the drop time also avoids error in estimating when the fall has actually ended and the rise begun.

This same ratio was used for the same reasons to calculate the adjusted PE loss.

7 Further Work

This experiment has clearly demonstrated that energy can be retained in a flywheel system, but that energy losses can be significant if the system is not carefully designed, (Pullen, 2019). As discussed, such losses could come from various sources including friction in bearings, air resistance and stiction in connecting equipment, such as the cord in this experiment.

If time and money were no object, then the experiment could be dramatically improved. Examples of such improvements could be.

- Reducing bearing friction to a minimum, such as by using magnetic suspension bearings which have no contact.
- Air resistance effects could be minimised by performing the experiment within a vacuum chamber.
- The timing equipment could be automated with a photocell detecting the point at which the drop ends.
- Stiction and elongation errors could be minimised by using a high tensile, extremely thin fibre such as Kevlar or carbon.
- All components could be accurately weighed and measured using scientific measuring equipment.

8 References

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