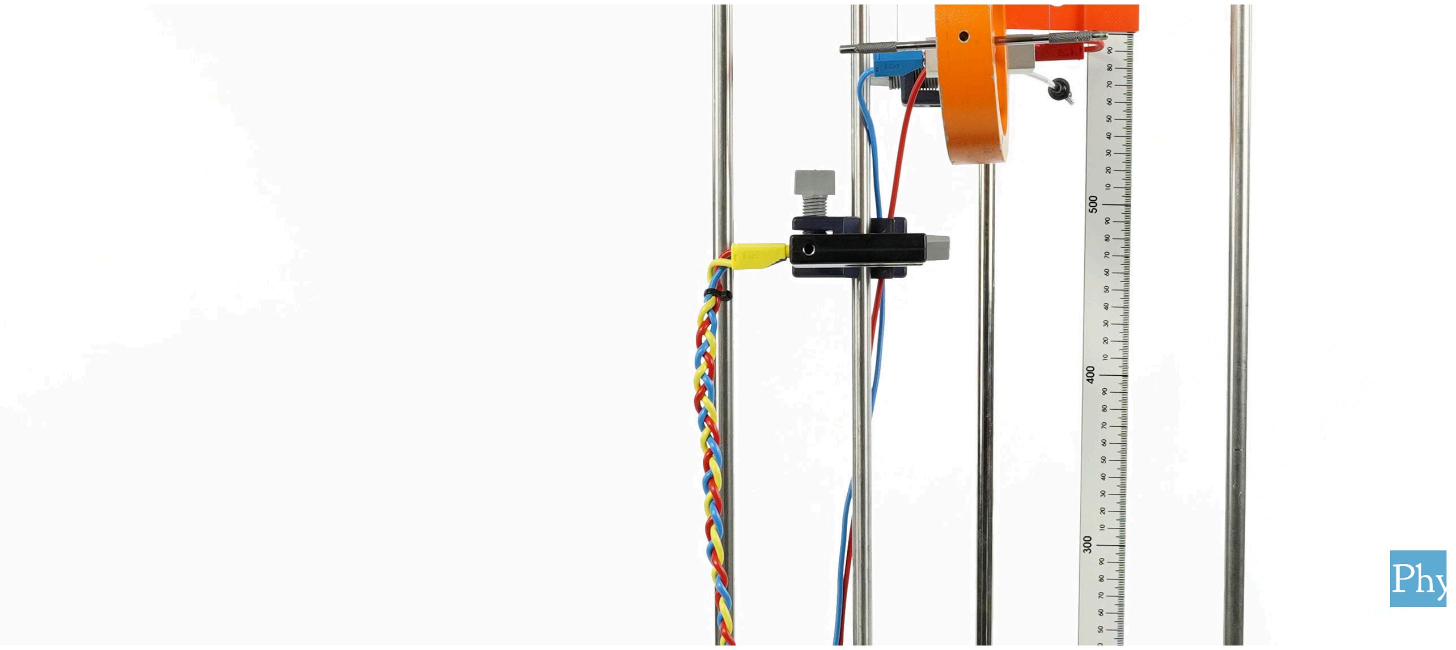
Mechanical conservation of energy/ Maxwell's wheel



The goal of this experiment is to demonstrate the conservation of energy in mechanical systems.

Physics > Mechanics > Circular motion & rotation

Difficulty level	Group size	Preparation time	Execution time
easy	-	20 minutes	10 minutes

General information

Application

Experimental setup

The conservation of energy is one of the fundamental laws of thermodynamics. This law also holds in mechanical systems.

This experiment can be used to demonstrate the conservation of energy in such mechanical system.

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Other information (1/2)

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Prior knowledge

There is no prior knowledge necessary.

Main principle

A disk, which can unroll with its axis on two cords, moves in the gravitational field. Potential energy, energy of translation, and energy of rotation are converted into one another and are determined as a function of time.

Other information (2/2)

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Learning objective

The goal of this experiment is to demonstrate the conservation of energy in mechanical systems.

Tasks

The moment of inertia of the Maxwell disk is determined. Using the Maxwell disk,

1. the potential energy,
2. the energy of translation, and
3. the energy of rotation

are determined as a function of time.

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Theory (1/2)

The total energy E of the Maxwell disk, with mass m and moment of inertia I_Z around the axis of rotation, consists of the potential energy E_P, the energy of translation E_T and the energy of rotation E_R:

$$E = m \cdot \vec{g} \cdot \vec{s} + \frac{m}{2}\vec{v}^2 + \frac{I_Z}{2}\vec{\omega}^2 \ .$$

Here, $\vec{\omega}$ stands for the angular velocity, $\vec{v}$ for the translational velocity, $\vec{g}$ for the acceleration due to gravity, and $\vec{s}$ for the (negative) height.

With the notation of Fig. 1,

$$d\vec{s} = d\vec{\varphi} \times \vec{r}$$

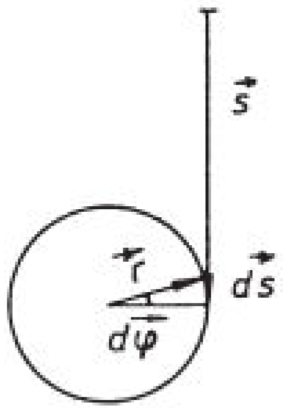

Fig. 1: Relation between the increase in angle d φ and the decrease in height ds in the Maxwell disk.

Theory (2/2)

and $\vec{v} \equiv \frac{d\vec{s}}{dt} = \frac{d\vec{\varphi}}{dt} \times \vec{r} = \vec{\omega} \times \vec{r}$,

where $\vec{r}$ is the radius of the spindle.

In the present case, $\vec{g}$ is parallel to $\vec{s}$, and $\vec{\omega}$ is perpendicular to $\vec{r}$, so that

$$E = -m \cdot g \cdot s(t) + \frac{1}{2} \cdot (m + I_Z/r^2)(v(t))^2 .$$

Because the total energy E is constant over time, differentiation gives

$$\frac{dE}{dt} = 0 = -m \cdot g \cdot v(t) + (m + I_Z/r^2) v(t) \cdot v(t).$$

For $s(t=0) = 0$ and $v(t=0) = 0$, one obtains

$$s(t) = \frac{1}{2} \frac{m \cdot g}{m + I_Z/r^2} \cdot t^2 \qquad (1)$$

and

$$v(t) \equiv \frac{ds}{dt} = \frac{m \cdot g}{m + I_Z/r^2} \cdot t$$

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Equipment

Position	Material	Item No.	Quantity
1	Support base DEMO	02007-55	1
2	Support rod, stainless steel, 1000 mm	02034-00	3
3	Right angle clamp expert with fulcrum screw	02054-00	6
4	Meter scale, l = 1000 mm	03001-00	1
5	Cursors, 1 pair	02201-00	1
6	Maxwell wheel	02425-00	1
7	Connecting cord, 32 A, 1000 mm, red	07363-01	2
8	Connecting cord, 32 A, 1000 mm, yellow	07363-02	1
9	Connecting cord, 32 A, 1000 mm, blue	07363-04	2
10	Light barrier, compact	11207-20	1
11	Holding device with cable releasee	02417-04	1
12	PHYWE Timer 2-1	13607-99	1
13	Plate holder	02062-00	1
14	Support rod, stainless steel, l=370 mm, d=10 mm	02059-00	1
15	Support rod, stainless steel, 750 mm	02033-00	1
16	Rod M 6x250 stainless steel	329829	1

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Setup and Procedure

Setup (1/3)

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The experimental set-up is as shown in Fig. 2 and Fig. 3. Using the adjusting screw on the support rod, the axis of the Maxwell disk, in the unwound condition, is aligned horizontally. When winding up, the windings must run inwards.

The winding density should be approximately equal on both sides. It is essential to watch the first up and down movements of the disk, because incorrect winding (outwards, crossed over) will cause the "gyroscope" to break free.

Fig. 2: Experimental set-up for investigating the conservation of energy, using the Maxwell disk.

Setup (2/3)

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The release switch, controlling the pin to be placed in a hole of the disk, is used to release the disk mechanically and to start the counter when determining distance and time.

The release switch could be adjusted in way that the disk does not oscillate or roll after the start. Furthermore, the cord should always be wound in the same direction for starting.

Please connect release switch with the trigger input of the the Timer 2-1 as shown in Fig. 3 and Fig. 4

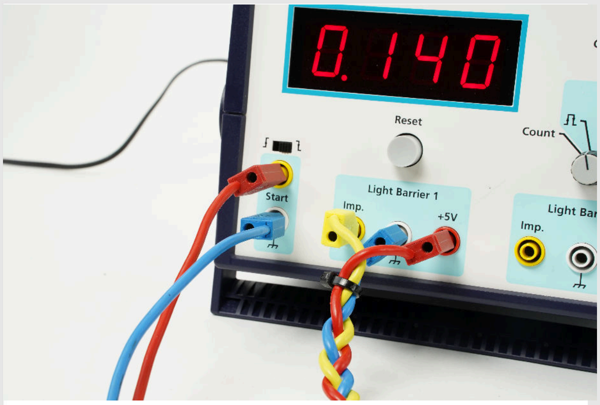

Fig. 3: Connection of the light barrier (Lb).

Setup (3/3)

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Connect the release switch with the blue and the red cable (Fig. 4). .According to the colors of the connection lines connect the light barrier with the Timer 2-1.

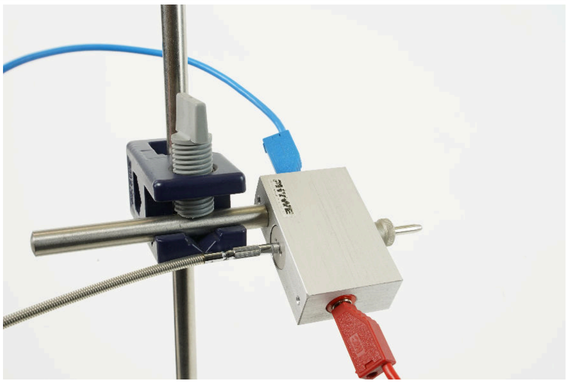

Fig. 4: Connection of the release switch

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Procedure (1/3)

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Measurement of the time t

- Connect the release switch to the Timer 2-1 as it is shown in Fig. 3 and Fig. 4
- Press the wire release and lock the position.
- Set the selection key of the Timer 2-1 to 
- Press the "Reset" button of the light barrier.
- Loosening the wire release stopper sets the wheel into motion and the counter of the light barrier starts.
- **After the wheel has passed the needle of the holder, the wire release is pressed again and locked before the light barrier is interrupted.**
- The counter stops as soon as the axis of rotation enters the path of light of the light barrier.

Procedure (2/3)

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Measurement of Δt

- Fix the wheel in the start position by means of the holder.
- Set the switch of the Timer 2-1 to 
- Press the "Reset" of the Timer 2-1
- Loosening the wire release stopper sets the wheel into motion, the counter of the light barrier does not start yet.
- As soon as the axis of rotation enters the light barrier, the counter starts and stops when it moves past the light barrier.

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Procedure (3/3)

The velocity at the time $t + \frac{\Delta t}{2}$ is determined from the measured time Δt by

$$v = \left(t + \frac{\Delta t}{2}\right) = \frac{\Delta s}{\Delta t}$$

Since distance s and time t can be measured relatively accurately, independently of one another, equation (1) below is most suitable for determining the moment of inertia. The times Δt generally have less accuracy. Therefore, it is not appropriate to derive further values (e.g. I_Z from equation (2)) from these data. They are, however, useful for checking the energy values obtained and calculated from the distance-time measurement.

Evaluation

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Evaluation (1/3)

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In the measurement example, the mass $m = 0.436\,\mathrm{kg}$ and the radius of the spindle $r = 2.5\,\mathrm{mm}$ were obtained.

From the regression line to the measured values of Fig. 4, with the exponential expression

$Y = A \cdot X^B$

one obtains

$B = 1.99 \pm 0.01$ and

$A = 0.0196 \pm 0.0015\,\mathrm{m/s^2}$

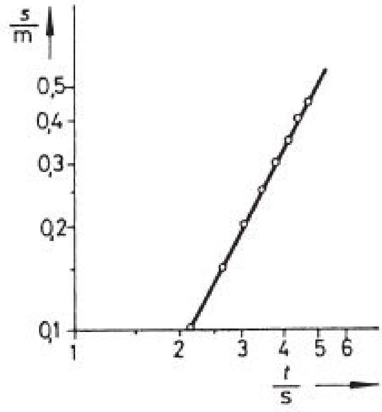

Fig. 4: Distance travelled by the centre of gravity of the Maxwell disk as a function of time.

Evaluation (2/3)

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With eq. (1), there follows a moment of inertia

$I_Z = 9.84 \cdot 10^{-4}\,\mathrm{kg\,m^2}$.

From the regression line to the measured values of Fig. 5, with the exponential expression

$Y = A \cdot X^B$

one obtains

$B = 1.03 \pm 0.015$ (see eq. (2)).

As can be seen in Fig. 6, the potential energy is almost completely converted into rotational energy.

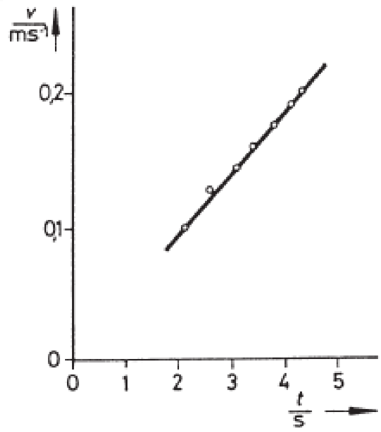

Fig. 5: Velocity of the centre of gravity of the Maxwell disk as a function of time.

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Evaluation (3/3)

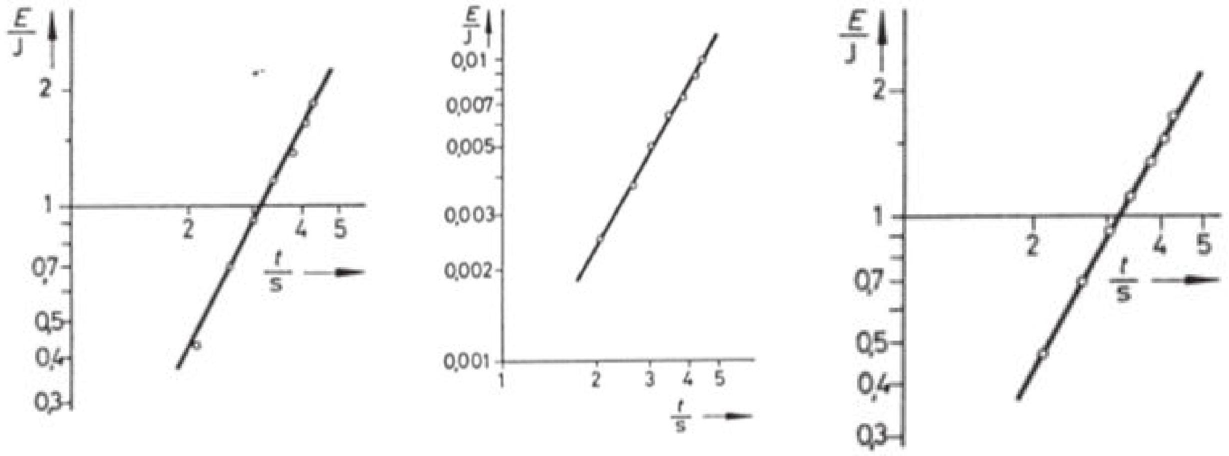

Fig. 6: Energy of the Maxwell disk as a function of time. 1) Negative potential energy, 2) energy of translation, and 3) energy of rotation.

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