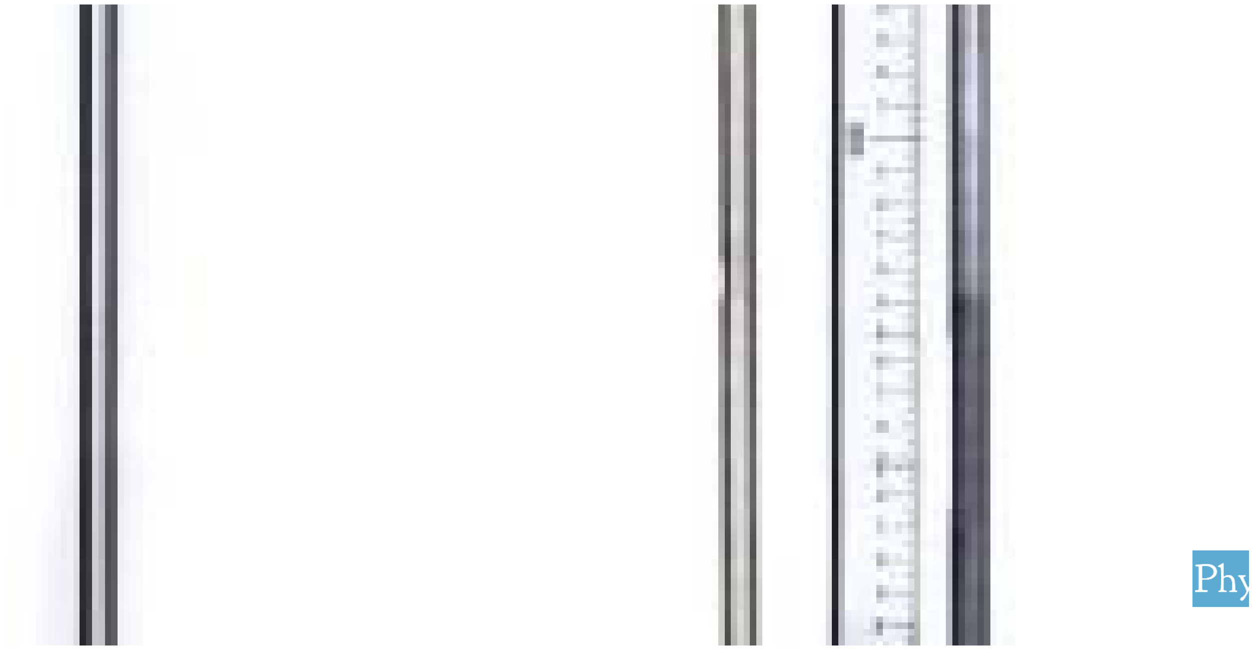
Mechanical conservation of energy/ Maxwell's wheel with measure Dynamics



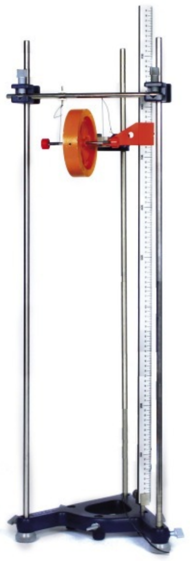
The goal of this experiment is to demonstrate the conversation of energy in mechanical systems.

Physics › Mechanics › Circular motion & rotation

Difficulty level	Group size	Preparation time	Execution time
hard	2	10 minutes	20 minutes

General information

Application



Experimental setup

The conversation 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 conversation 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 conversation of energy in mechanical systems.

Tasks

1. Determination of the moment of inertia of the Maxwell wheel by way of the distance-time relationship.
2. Determination of the moment of inertia of the Maxwell wheel by way of the velocity-time relationship.
3. Graphical representation of the potential energy, kinetic energy, and rotational energy 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,

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

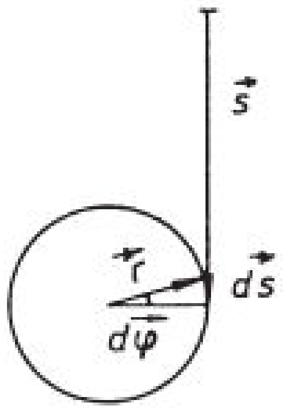

Fig. 1: Relation between the increase in angle d φ and the decrease in height ds in the Maxwell disk.

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

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

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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	02054-00	3
4	Meter scale, l = 1000 mm	03001-00	1
5	Maxwell wheel	02425-00	1
6	Holding device with cable releasee	02417-04	1
7	Plate holder	02062-00	1
8	Software "Measure Dynamics", single user	14440-61	1

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Setup and Procedure

Setup

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Set the experiment up as shown in Figure 2. Use the adjustable screw on the support rod for the horizontal alignment of the axis of the Maxwell wheel in the unwound state. Then, wind the Maxwell wheel uniformly up on both sides. When doing so, ensure that the windings run inwards. It is essential to observe the first up and down movement of the wheel, since incorrect winding (outwards, crossed) may cause the Maxwell wheel to break free.

The release switch, i.e. the pin that is located in a hole of the Maxwell wheel, is used for releasing the wheel. Adjust the release switch so that the wheel neither oscillates nor rolls after it has been released. In addition, ensure that the cords are always wound in the same direction for the experiments.

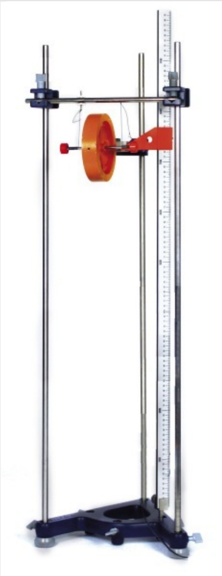

Fig. 2: Experimental setup

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Procedure (1/2)

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In terms of the video that will be recorded, the following must be taken into consideration concerning the setting and positioning of the camera:

- Set the number of frames per second to approximately 30 fps.
- Select a light-coloured, homogeneous background.
- Provide additional lighting for the experiment.
- The experiment set-up should be in the centre of the video. To ensure this, position the video camera on a tripod centrally in front of the experiment set-up.

Procedure (2/2)

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- Film the experiment from the side.
- The experiment set-up should fill the video image as completely as possible.
- The optical axis of the camera must be parallel to the experiment set-up (no movement in the x-direction).
- For scaling, position a scale next to the experiment set-up by way of a support base, support rod, right-angle clamp, and plate holder.

Then, the video recording process and the experiment can be started.

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Evaluation

Evaluation (1/9)

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The second experiment evaluation requires the following data: The mass m of the wheel during the experiment is = 0.436 kg. The radius of the wheel is = 2.5 mm.

Transfer the video that has been recorded to the computer. Then, start "measure Dynamics" and open the video under "File" – "Open video ...". Mark the start of the experiment ("Start selection" and "Time zero") and the end of the experiment ("End selection") in the video for further analysis via the menu line above the video. The experiment begins when the Maxwell wheel starts to unroll and it ends when the first turning point is reached.

Then, mark the scale with the scale that appears in the video by way of "Video analysis" – "Scaling ..." – "Calibration" and enter the resulting length into the input window. In addition, enter the frame rate that has been set for the recording process under "Change frame rate" and position the origin of the system of coordinates at the centre of the Maxwell wheel at the beginning of the experiment under "Origin and direction".

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Evaluation (2/9)

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Then, the actual motion analysis can be started under "Video analysis" – "Automatic analysis" or "Manual analysis". For the automatic analysis, we recommend selecting "Motion and colour analysis" on the "Analysis" tab.

Under "Options", the automatic analysis can be optimised, if necessary, e.g. by changing the sensitivity or by limiting the detection radius. Then, look for a film position in the video where the centre of the Maxwell wheel is perfectly visible. Click the centre. If the system recognises the object, a green rectangle appears and the analysis can be started by clicking "Start".

If the automatic analysis does not lead to any satisfying results, the series of measurements can be corrected under "Manual analysis" by manually marking the centre of the Maxwell wheel.

Evaluation (3/9)

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Add a new column to the worksheet by clicking "New column" in the table menu line. Enter the distance "s" that has been covered into the new column (unit: "m"; formula: "-y").

In order to display the curve of the distance covered as a function of time, select "Display" and "Diagram", click "Options", delete all of the already existing graphs, and select the graph t (horizontal axis) – s (vertical axis). This leads to:

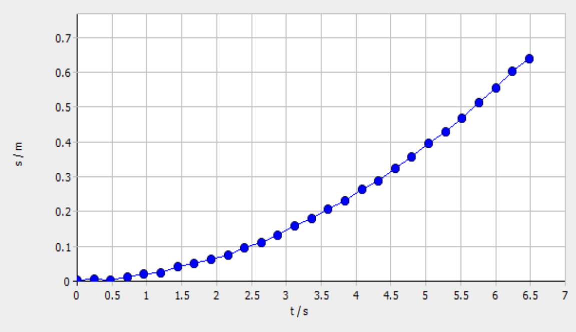

Figure 3: Distance covered s as a function of time t.

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Evaluation (4/9)

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As it could have been expected from equation (1), Figure 3 shows a quadratic relationship. In order to examine it in greater detail, it is advisable to consider the dependence of the distance covered on the square of the time.

To be able to visualise this is graphical form, the worksheet must be extended by clicking "New column" in the table menu line in order to add a new column. Then, enter the square of the time "t2" (unit: "s^2"; formula: "t^2") into the new column. As a result, the t^2-s diagram can be displayed in the same way as the t-s diagram. The following results:

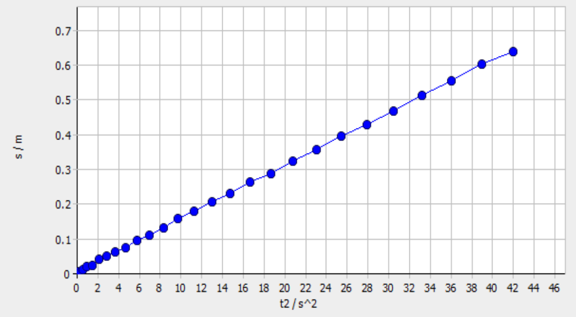

Figure 4: Distance covered s as a function of the square of the time t.

Evaluation (5/9)

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As shown in Figure 4, the distance covered is linear with regard to the square of the time. Clicking "Options" in the menu line of the diagram and selecting the tab "Linear regression" will add a regression line to the diagram so that the regression line of the distance s as a function of the square of the time t2 can be determined. The result is a gradient of 0.0152.

(1) leads to a moment of inertia of

$I_z = 8.77 \cdot 10^{-4}\,\mathrm{kgm}^2$

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Evaluation (6/9)

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It is also possible to determine the moment of inertia via the representation of the velocity of the centre of gravity of the Maxwell wheel as a function of time. Add another new column to the worksheet by clicking "New column" in the table menu line.

Enter the velocity "v" (unit: "m/s"; formula: "-v_y") into the new column. In order to display the curve of the velocity of the centre of gravity of the Maxwell wheel as a function of time, select "Display" and "Diagram", click "Options", delete all of the already existing graphs, and select the graph t (horizontal axis) – v (vertical axis).

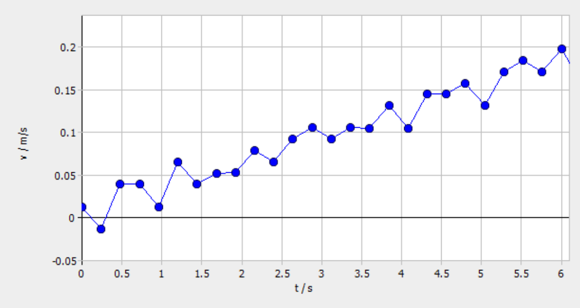

Figure 5: Velocity v as a function of time t.

Evaluation (7/9)

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As it could have been expected from equation (2), Figure 5 shows a linear relationship. Clicking "Options" in the menu line of the diagram and selecting the tab "Linear regression" will add a regression line to the diagram so that the regression line of the velocity as a function of time can be determined. The result is a gradient of 0.0303.

(2) leads to a moment of inertia of

$$I_z = 8.80 \cdot 10^{-4}\,\mathrm{kgm}^2$$

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Evaluation (8/9)

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In order to visualise the (negative) potential energy (name: "-E_pot"; unit: "J"; formula: "0.436*9.81*s"), kinetic energy (name: "E_kin"; unit: "J"; formula: "0.5*0.436*(v_y)^2"), and rotational energy (name: "E_rot"; unit: "J"; formula: "0.5*8.77*10^(-4)*(v_y)^2/(2.5*10^(-3))^2") graphically, another new column must be added to the worksheet for each of these types of energy.

The graphical representation of the energy types as a function of time leads to:

(Figures 6 and 7 show that the potential energy is nearly completely converted into rotational energy.)

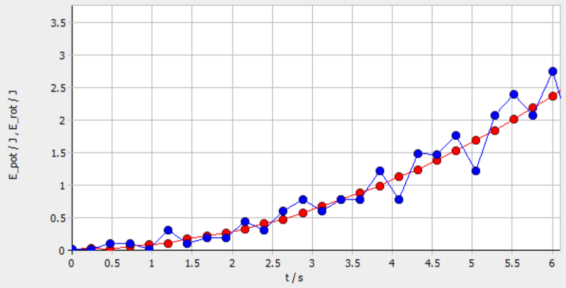

Figure 6: The potential energy (red) and rotational energy (blue) as a function of time t.

Evaluation (9/9)

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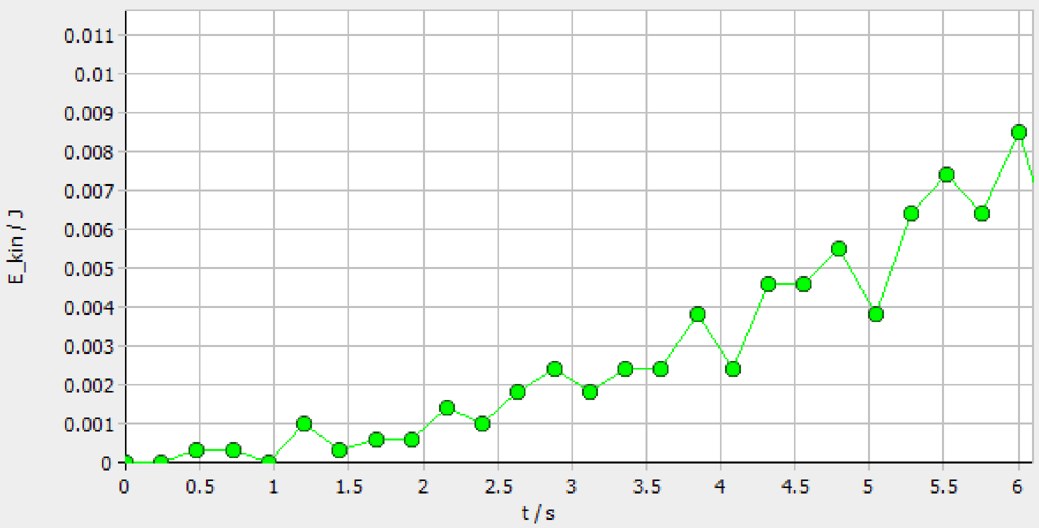
Figure 7: Kinetic energy as a function of time t.



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