24th International Young Physicists’ Tournament

POLAND
15. Slow Descent

Design and make a device, using one sheet of A4 80gram per m² paper that will take the longest possible time to fall to the ground through a vertical distance of 2.5m. A small amount of glue can be used. Investigate the influence of the relevant parameters.
Interpretation of the task

- No initial velocity
- Single device
- Whole sheet

No confetti
Plan of the presentation

- The types of motion performed by rectangular piece of paper
- Kutta-Joukowski Theorem
  - Experimental check
- Turbulent flow
  - Drag considerations
- Minor improvements
The presentation of the final device
Forces on a body moving in fluid medium

Lift and drag will be studied separately
Types of card’s motion

Tumbling

Fluttering

We will study and use autorotation as the source of lift force
We studied images appearing on the screen in order to find out how the air flows around the strip.
Image on the screen – front edge
The air would accelerate along the front edge, which indicates pressure reduction along the front edge.
Image on the screen – back edge
Whirlpool indicates there is an area of reduced pressure at the top of the trailing edge
Sustaining the rotation

Green – described torques increase angular velocity
Blue – described torques decrease angular velocity

As green corresponds to higher velocity than blue, the net torque tends to increase the angular velocity, counter the drag and sustain stable rotation.
Lift force on a rectangular body

The lift force on a rotating rectangular body moving through a fluid can be found using Kutta-Joukowski theorem.

\[ F_{\text{lift}} = 4\pi a^2 b \omega V \rho \]

Assumptions: very long body, ideal fluid with no viscosity.

How does this correspond to a real, viscous situation?
Lift force experimental setup

Scales indication changes were measured versus the voltage and wind generator setting
Lift force experimental setup

Angular velocity was found as a function of voltage by means of stroboscopic measurement.

Flashing diode

The velocity of wind was found using a Venturi tube with a manometer.
Lift force measurements results

Lift force was found to be linearly dependent on $V\omega$. 

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Reynolds number is a parameter, describing a flow in given setup.

\[ \text{Re} = \frac{\text{inertia force}}{\text{viscous force}} \]

Reynolds number describes the flow in given setup.
Reynolds number in our case is given by:

\[ \text{Re} = \frac{2aV}{\nu} \]

- **2a** – side of the rectangle
- **V** – velocity of the body
- **\( \nu \)** – kinematic viscosity of the medium

Theory and experiments described in the presentation will discuss motions with **Re** of order of $10^3$ to $10^4$
Vortexes can be seen behind the body
Aerodynamic drag

The value of aerodynamic drag for discussed motion can be approximated as (David L. Finn, ”Falling paper and flying business cards”):

\[ F_d = \frac{1}{2} C_d \rho AV^2 \]

- \( C_d \) – dimensionless drag coefficient
- \( \rho \) – air density
- \( A \) – area perpendicular to \( V \)
- \( V \) – velocity of the body with respect to air

In this problem \( A \) has an upper bound of 624 square centimeters.
Theoretical parameters of steady motion

\[ \text{drag} \propto abV^2 \]

\[ \text{lift} \propto a^2 b \omega V \]
Theoretical parameters of steady motion

\[ \tan \alpha = \frac{\text{drag}}{\text{lift}} \propto \frac{abV^2}{a^2b\omega V} = \frac{V}{a\omega} \]

\[ \text{drag} \propto abV^2 \]

\[ \text{lift} \propto a^2b\omega V \]
Direct measurements of tumbling bodies

- Air motion protection
- Distance scale
- 1000 W lamp
- High-speed camera

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Measured parameters of motion:

- Linear velocity
- Angular Velocity
- Angle of descent

Studied body made of playing card

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The plot is not linear but it is increasing, so a moderate agreement with the theory was achieved.
Optimisation of aspect ratio

For rigid cards lowest downward velocity are obtained for lowest aspect ratio
Bending of paper

Unlike playing cards, paper strips tend to bend during the fall.

![Typical bending](image1)

For 3 connected strips, bending makes the motion unstable.

The core of our device is two glued halves of A4 sheet.
Optimisation – longer edges folded

Typical bending during tumbling of paper with $a/b=1/6$

With longer edges folded, it has increased stiffness so that bending is rarely observable.
Optimisation – shorter edges folded

The core of the device are two glued halves of A4 sheet

Instabilities (chaotic motion) occur less frequently for paper with shorter edges folded
The experiment determining the influence of winglets on falling time
The falling time of our final device

Histogram of falling times of the device without winglets – 110 falls

- The mean fall time – 3.66s
- Standard deviation – 0.52s
- Highest fall time – 5.9s
- Lowest fall time – 2.4s
The falling time of our final device

Histogram of falling times of the device with winglets – 110 falls

- The mean fall time – 5.49s
- Standard deviation – 0.69s
- Highest fall time – 7s
- Lowest fall time – 3.4s
The final design
Conclusions

1. During the fall of thin rectangular bodies, autorotation may arise and so lift force may be generated.

2. Simple theoretical treatment allows to qualitatively predict the parameters of motion.

3. Rigid cards with biggest aspect ratio allow slowest fall. However, aspect ratio is limited by bending.
• P. Dupleich, *Rotation in free fall of rectangular wings of elongated shape*, NACA Technical Memo No. 1201 (1941)


Turbulent flow

In turbulent flow is characterized by the lack of stream lines.
Aerodynamic drag experiment

The sheet of paper was observed to fall from 2.5m in approximately 3 seconds.