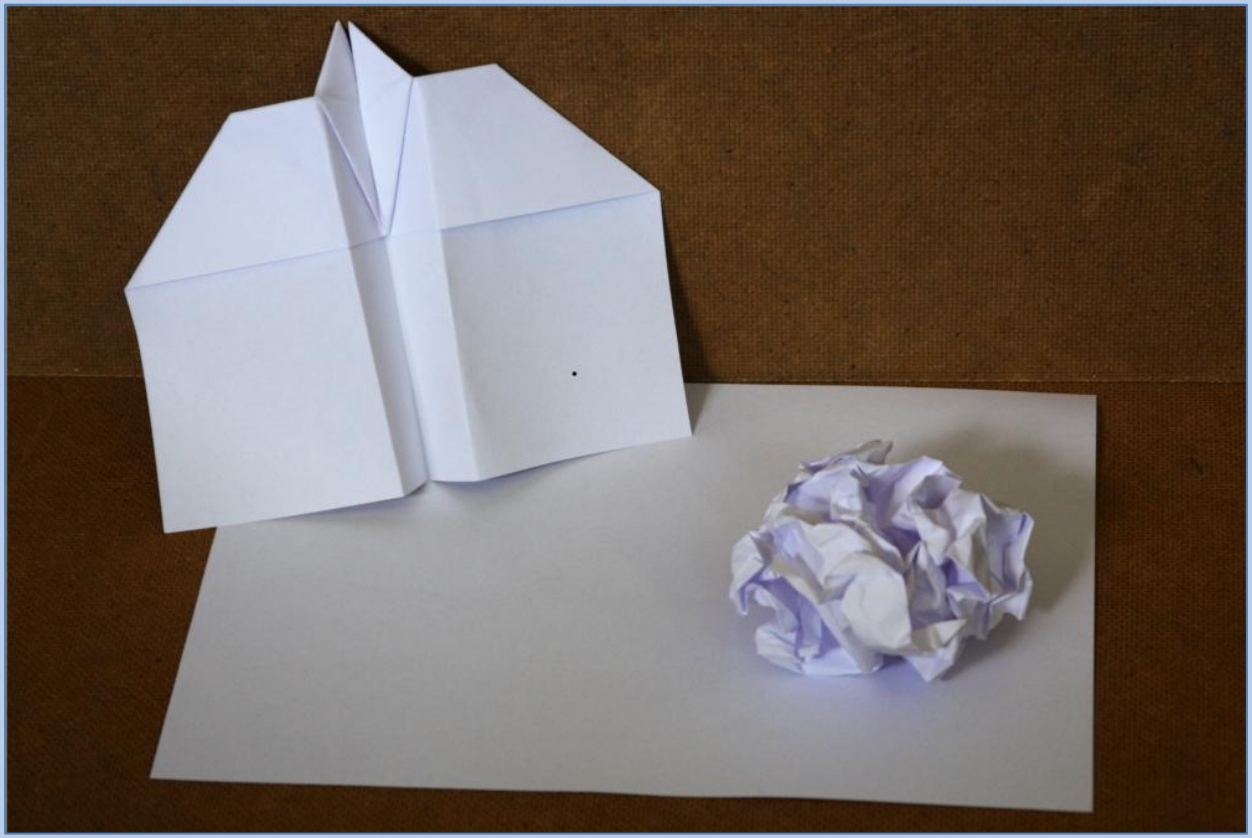
24th International Young Physicists' Tournament

POLAND

15. Slow Descent



Design and make a device, using one sheet of A4 80gram per m^2 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

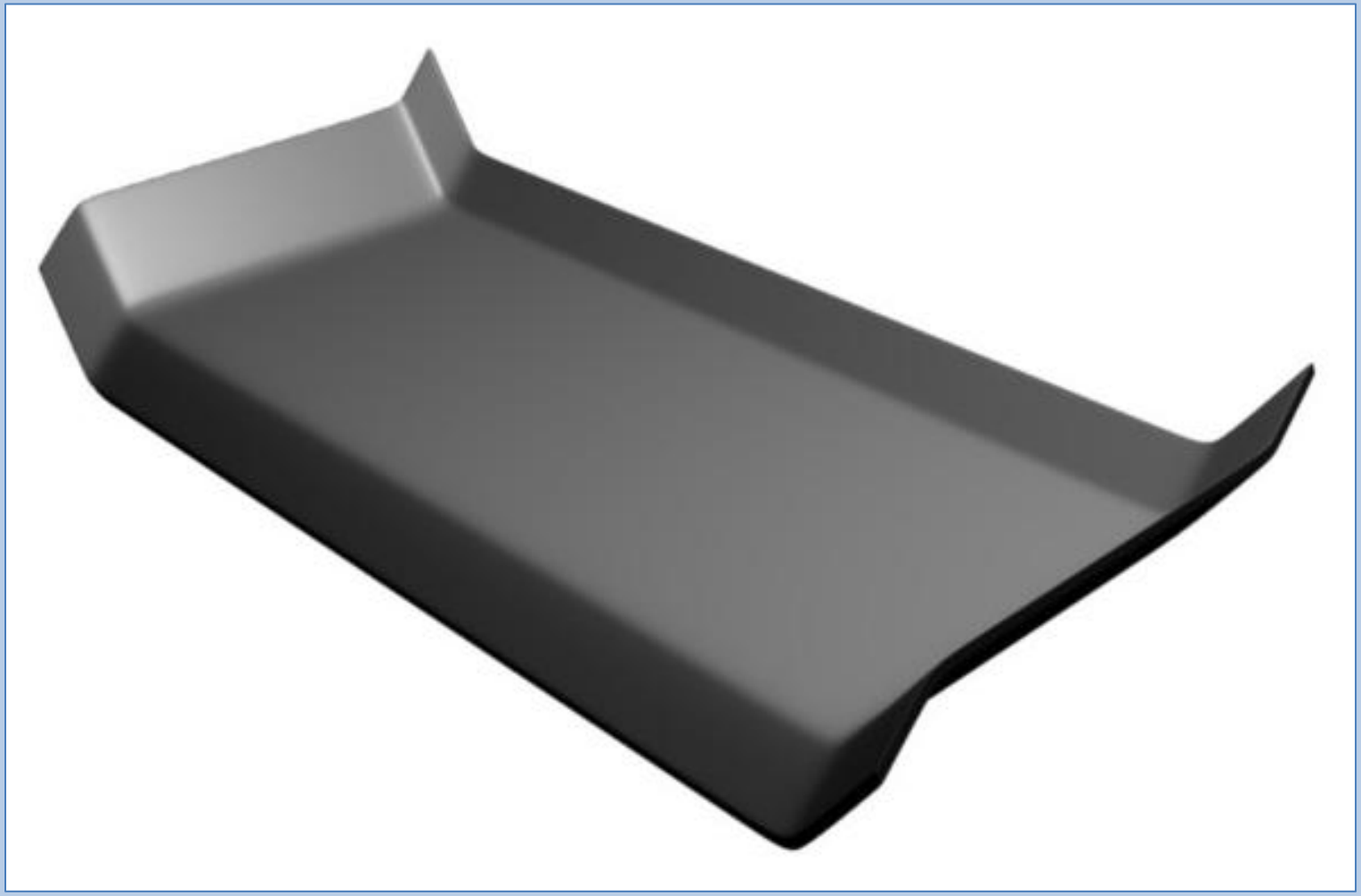
- The types of motion performed by rectangular piece of paper

- Kutta-Joukowski Theorem
- Experimental check

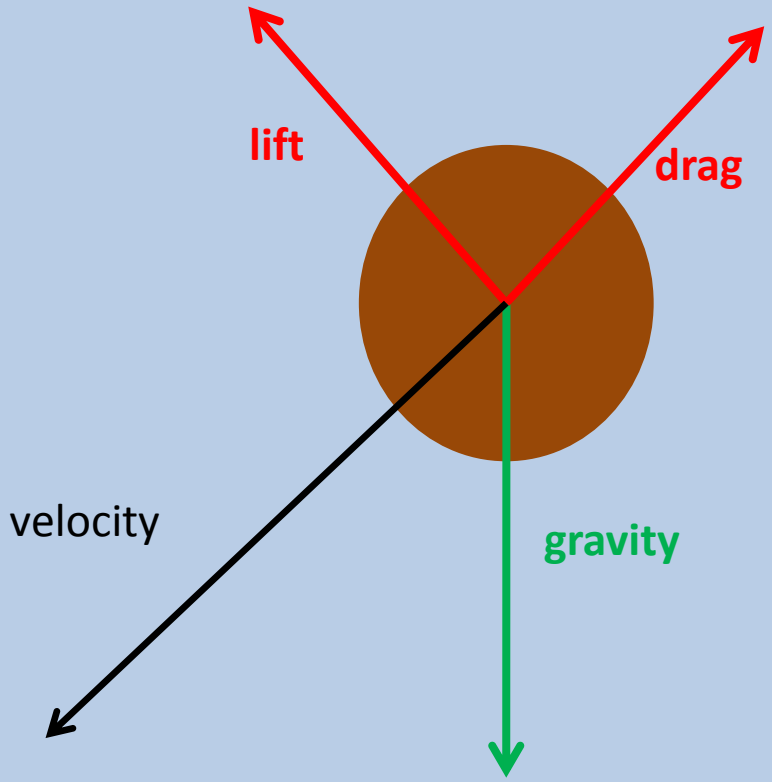
- Turbulent flow
- Drag considerations

- Minor improvements

The presentation of the final device

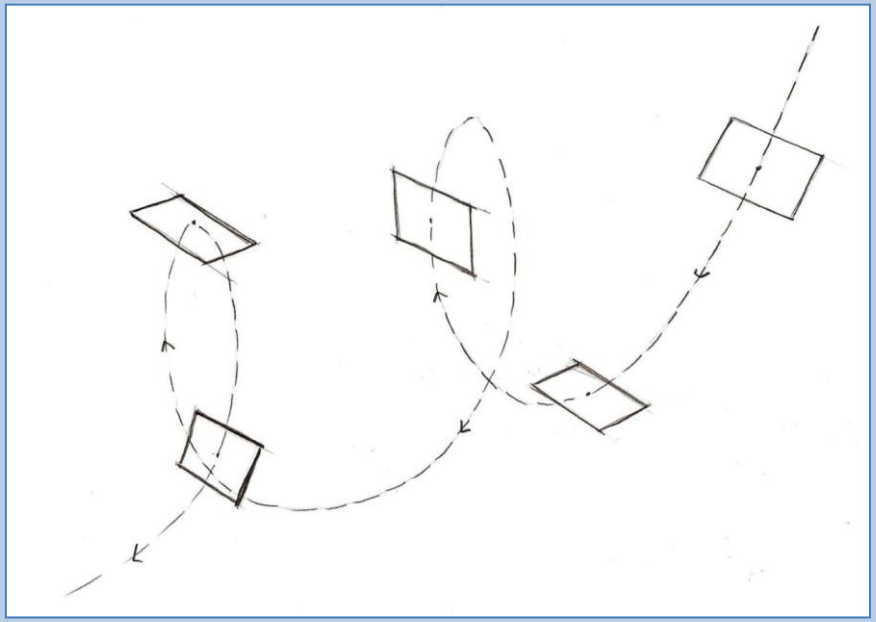


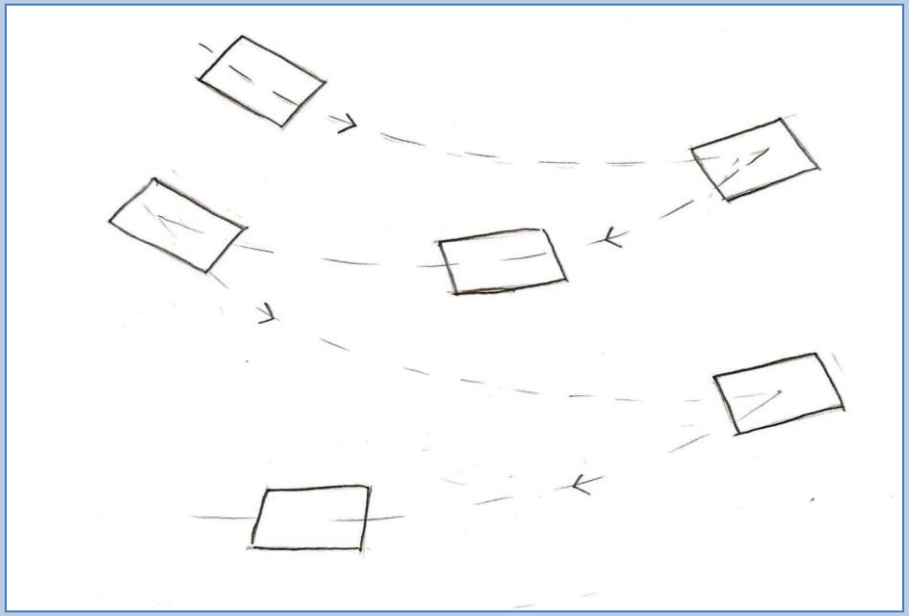
Forces on a body moving in fluid medium



Lift and drag will be studied separately

Types of card's motion



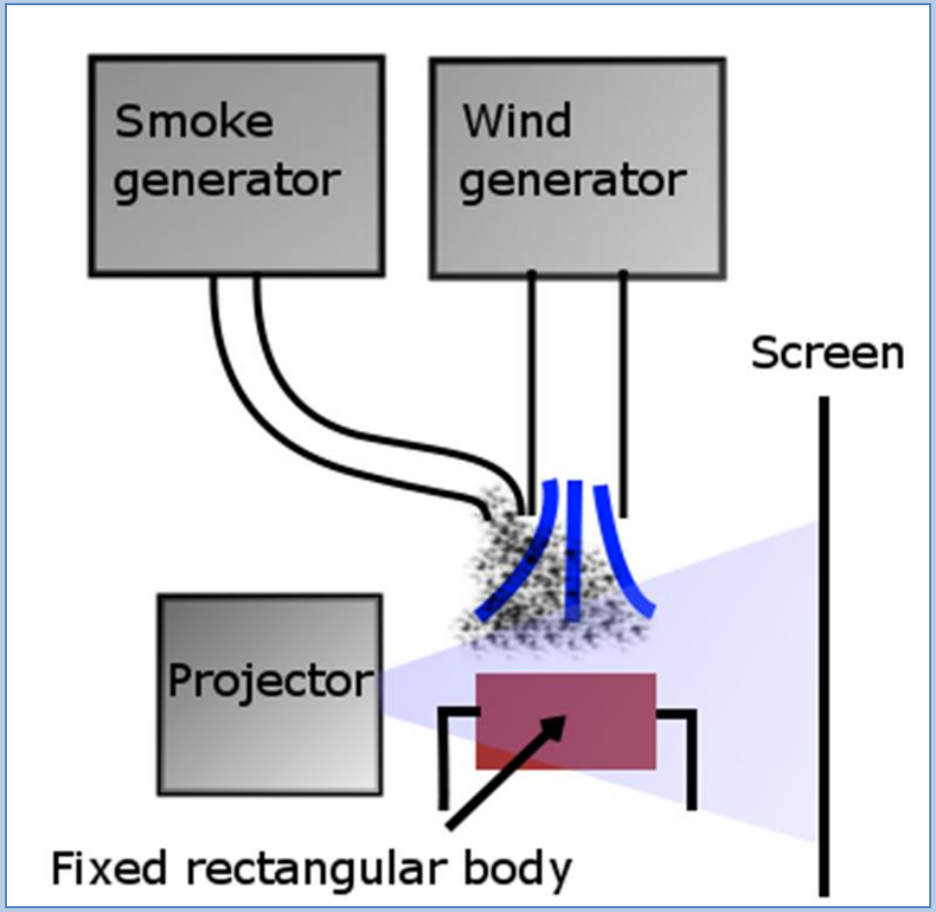


Tumbling

Fluttering

We will study and use autorotation as the source of lift force

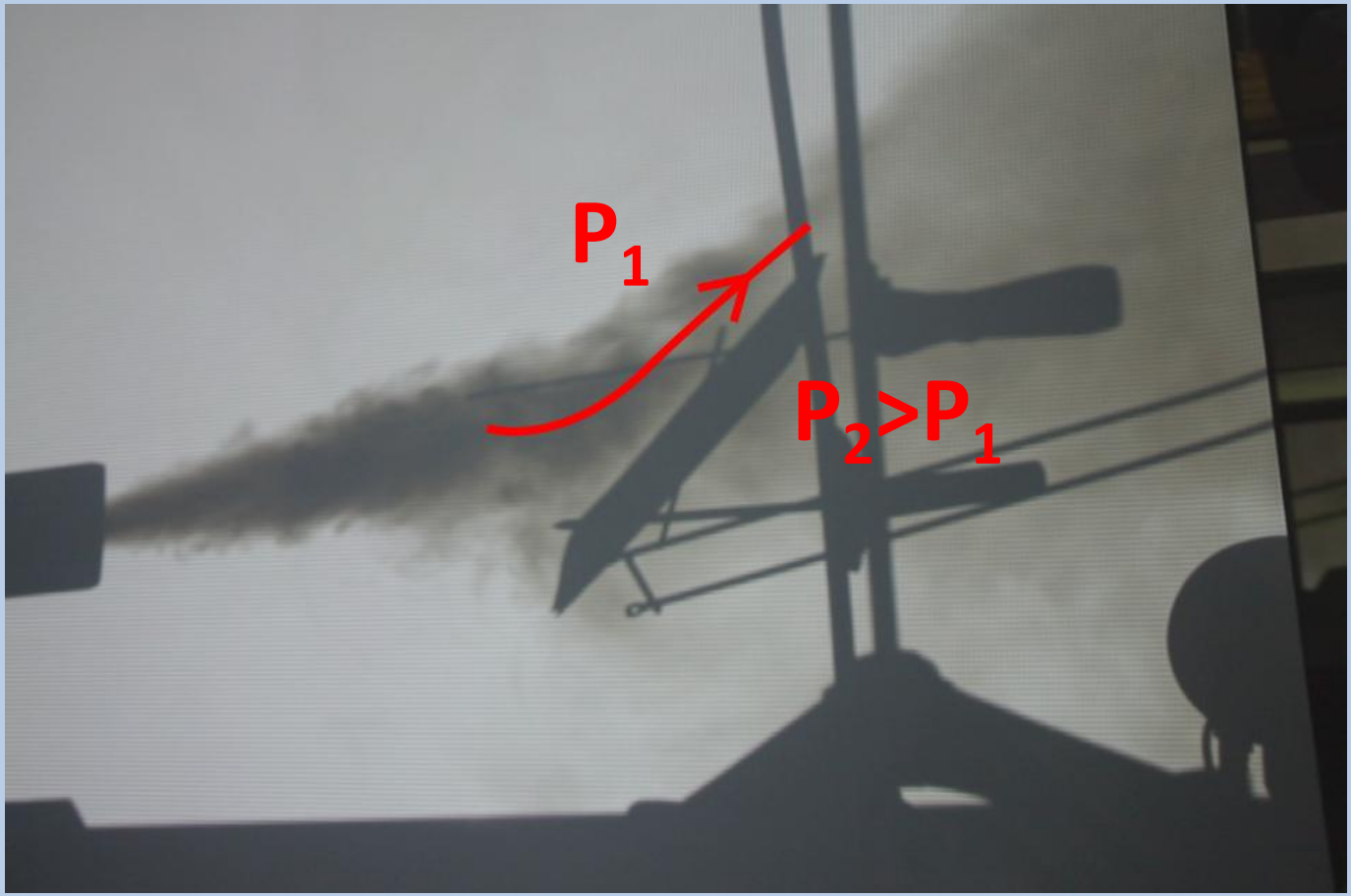
Experimental setup



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

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

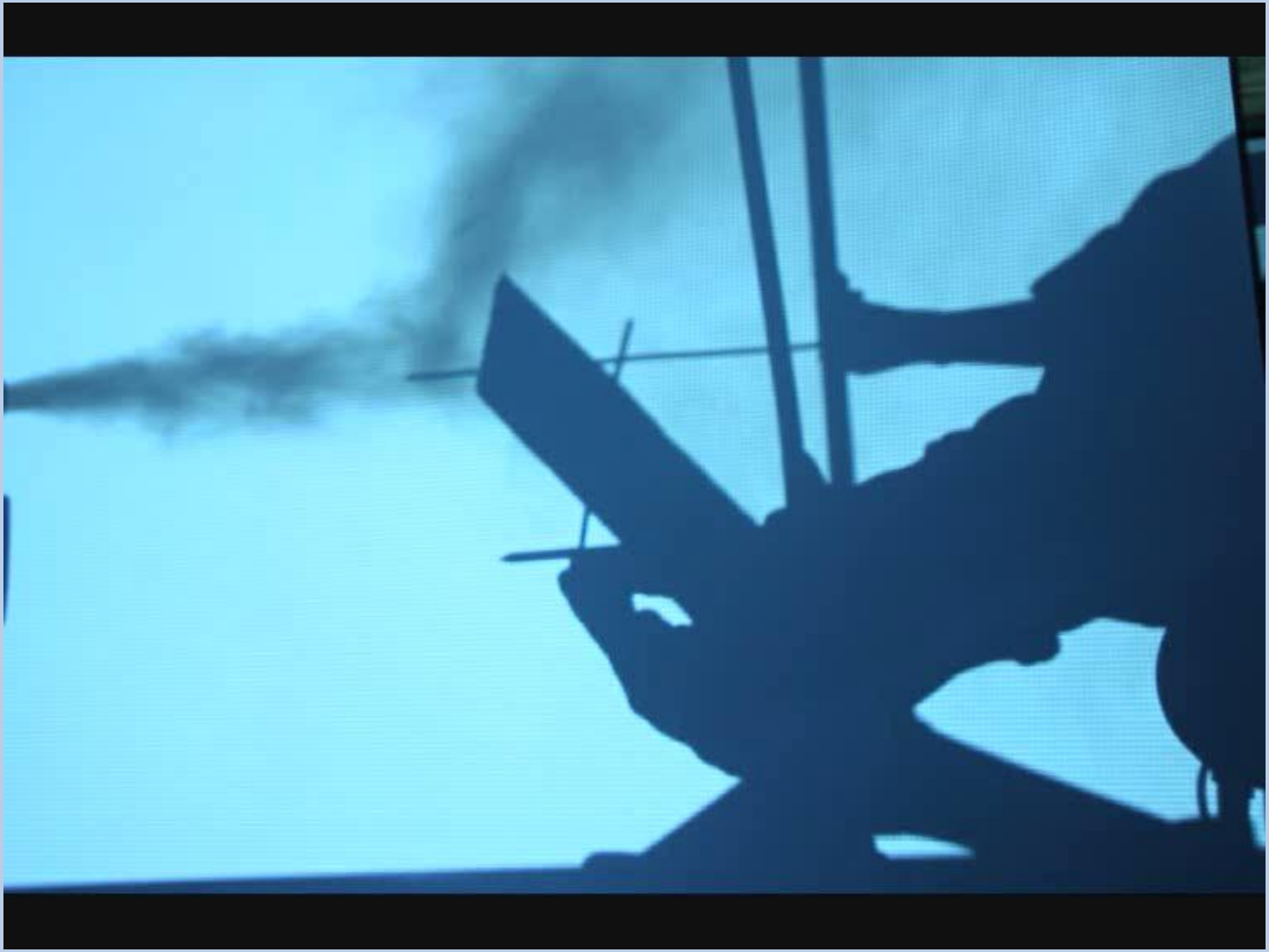
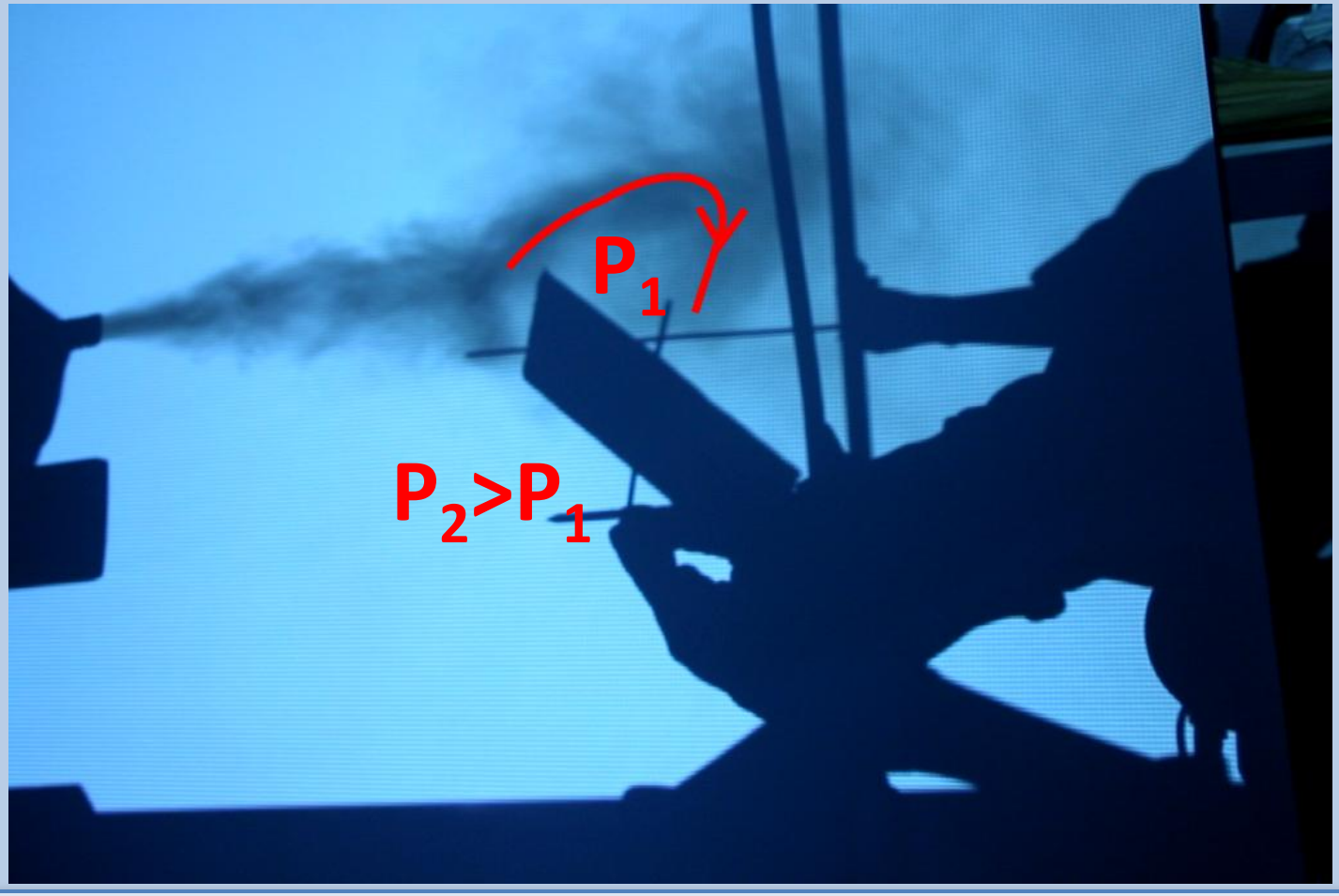
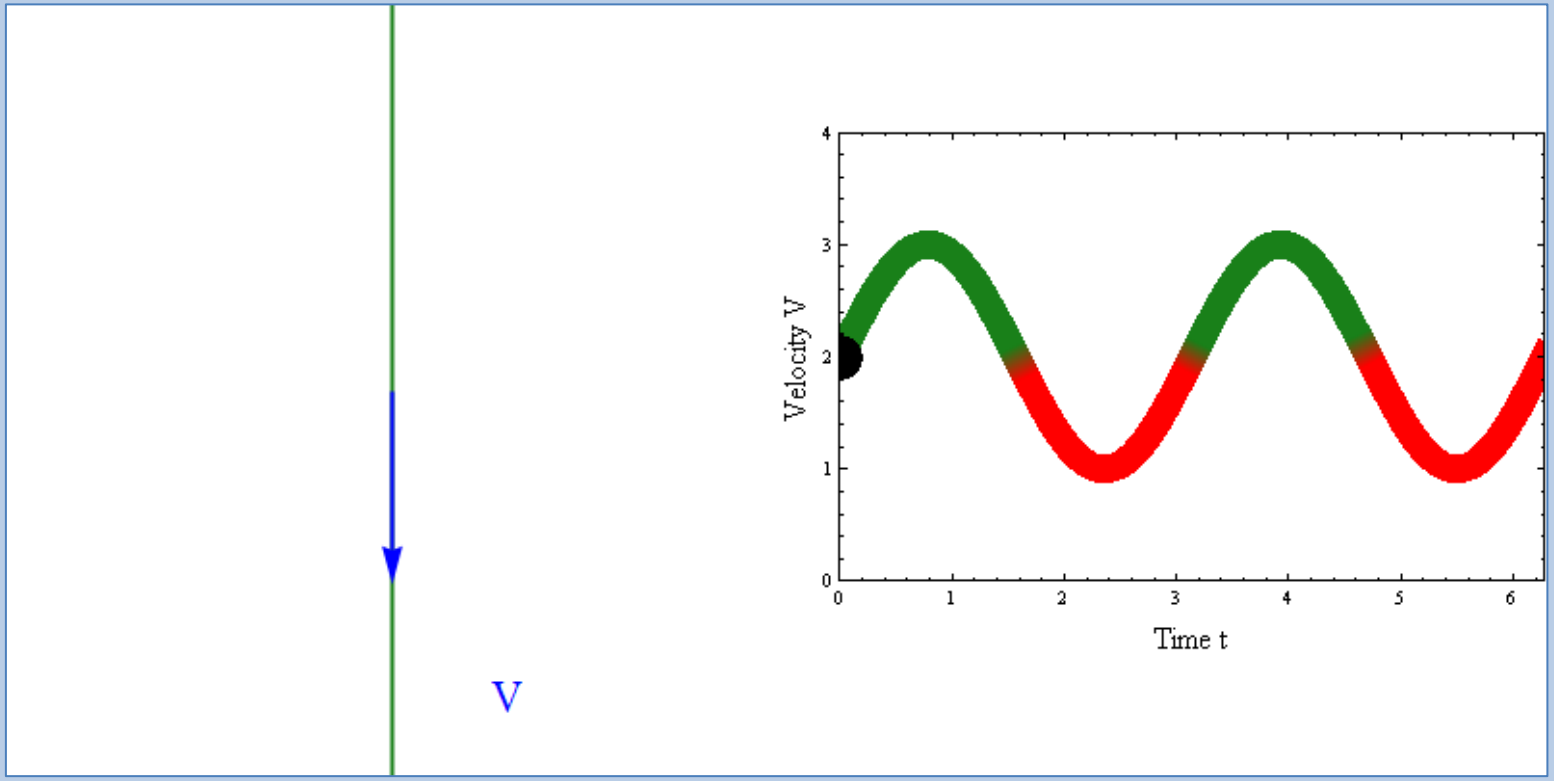


Image on the screen – back edge



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

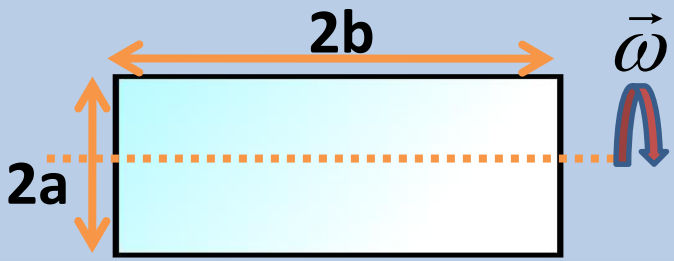
As **green** corresponds to higher velocity than **blue**, the net torque tends to **increase** the angular velocity, counter the drag and sustain stable rotation

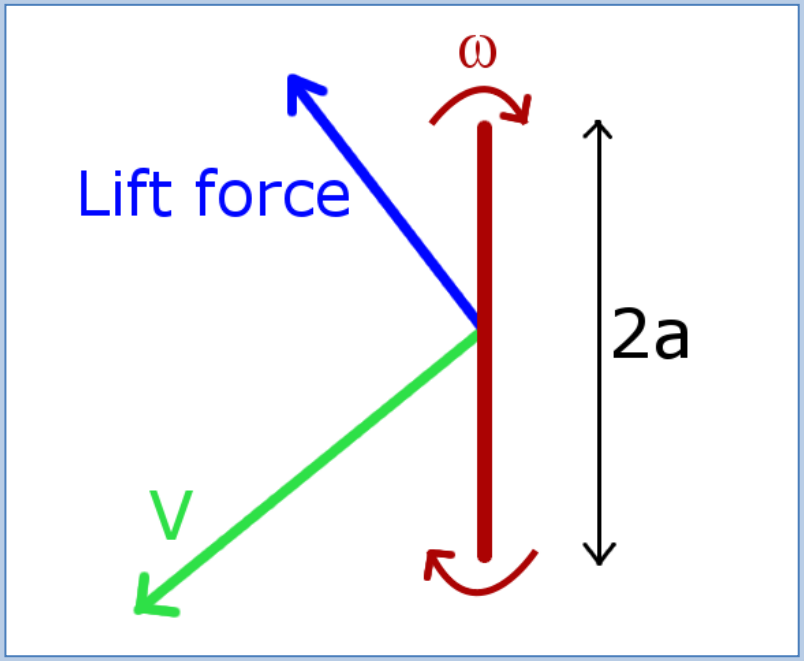
Lift force on a rectangular body

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

$$F_{lift} = 4\pi a^2 b \omega V \rho$$

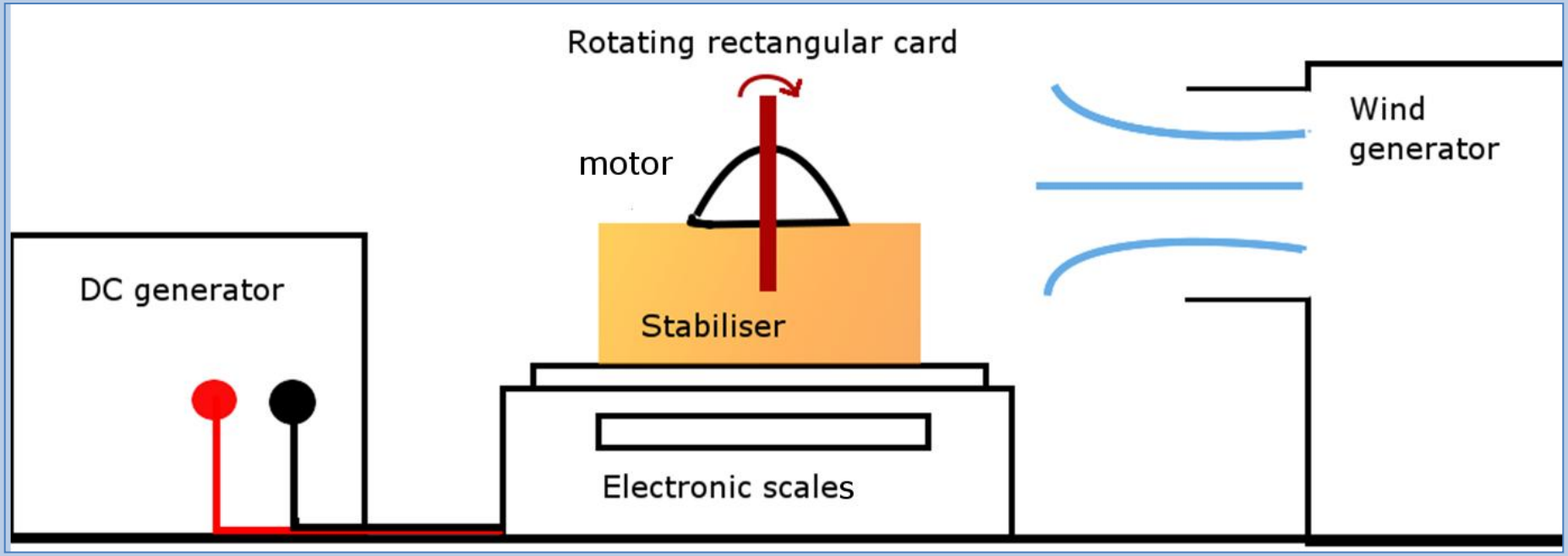
Assumptions: very long body, ideal fluid with no viscosity





How does this correspond to a real, viscous situation?

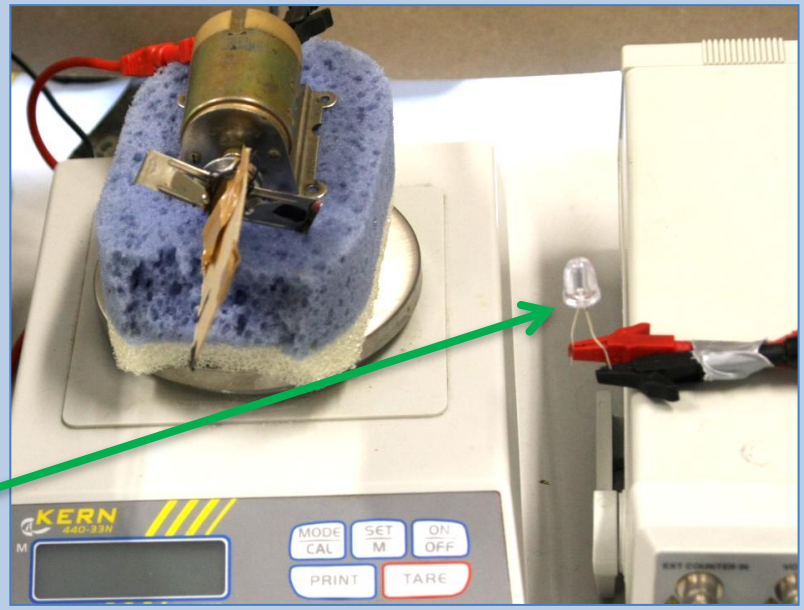
Lift force experimental setup



Scales indication changes were measured versus the voltage and wind generator setting

Lift force experimental setup

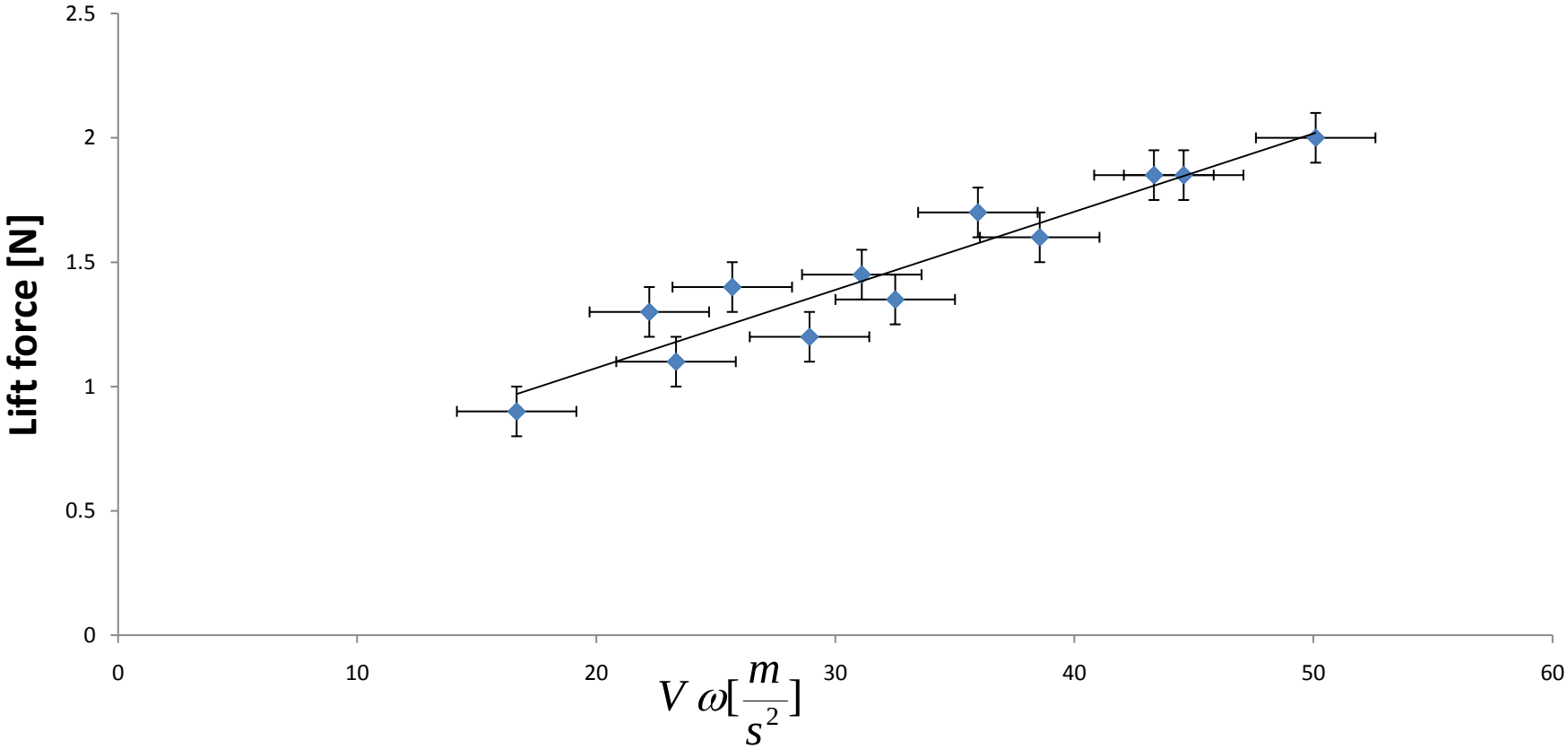
Angular velocity was found as a function of voltage by means of stroboscopic measurement



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 dependend on $V\,\omega$

Flow characteristic

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

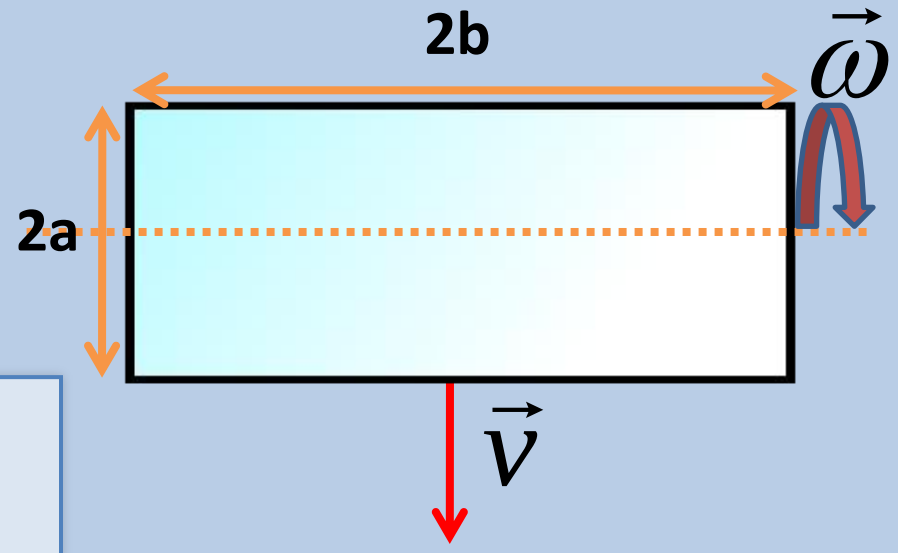
$$\mathrm{Re} = \frac{\text{inertia force}}{\text{viscous force}}$$

Reynolds number describes the flow in given setup.

Flow characteristic

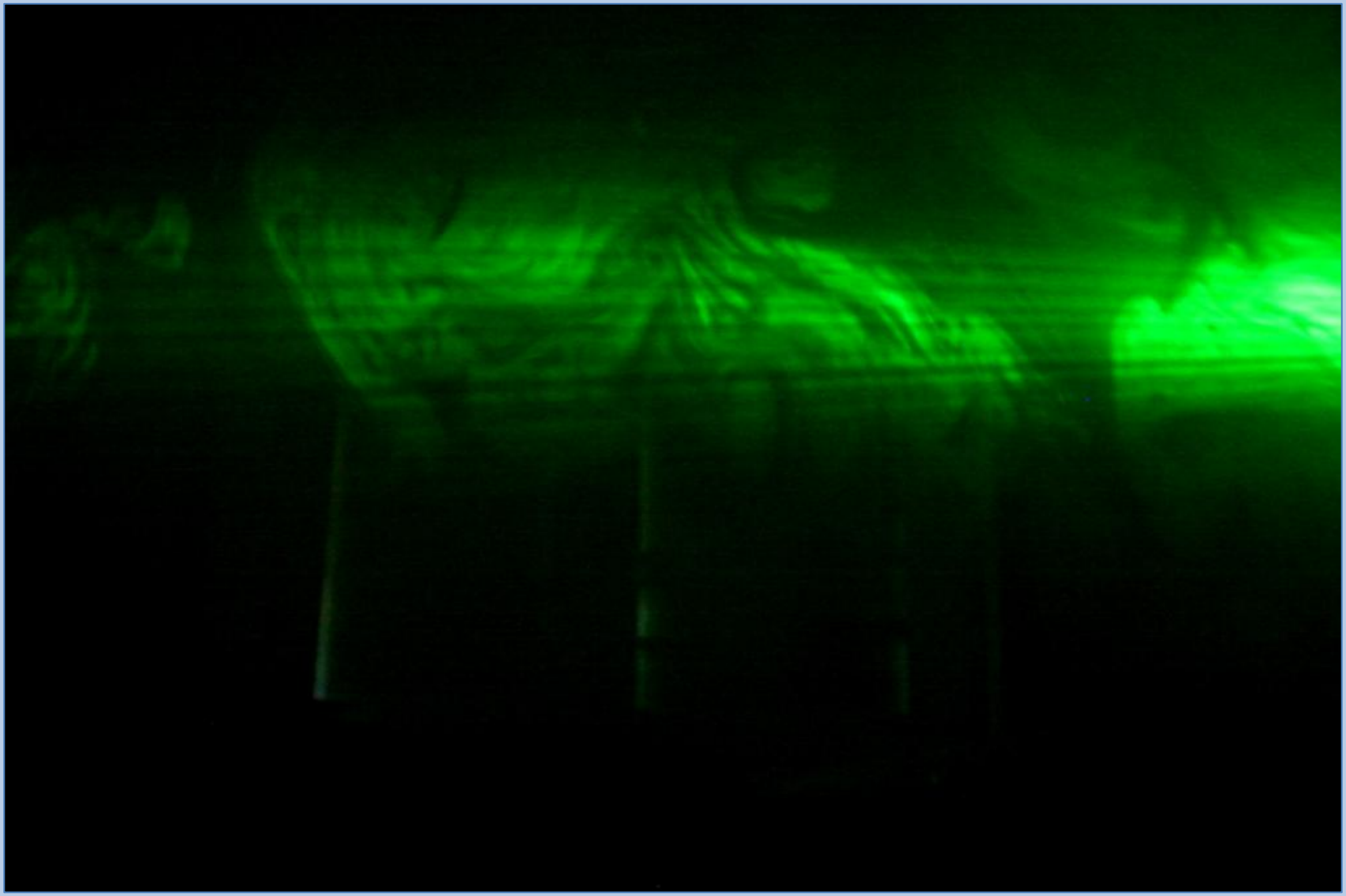
Reynolds number in our case is given by:

$$\mathrm{Re} = \frac{2aV}{\nu}$$



2a – side of the rectangle
V – velocity of the body
ν – 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

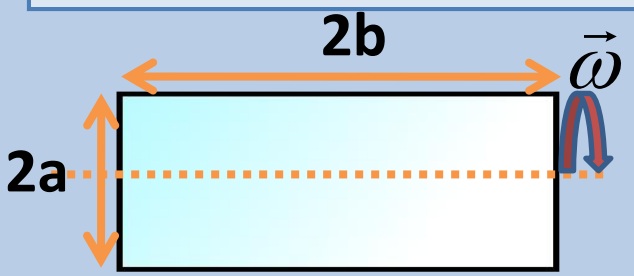
The value of aerodynamic drag for discussed motion can be approximated as (David L. Finn, ”Falling paper and flying business cards”):

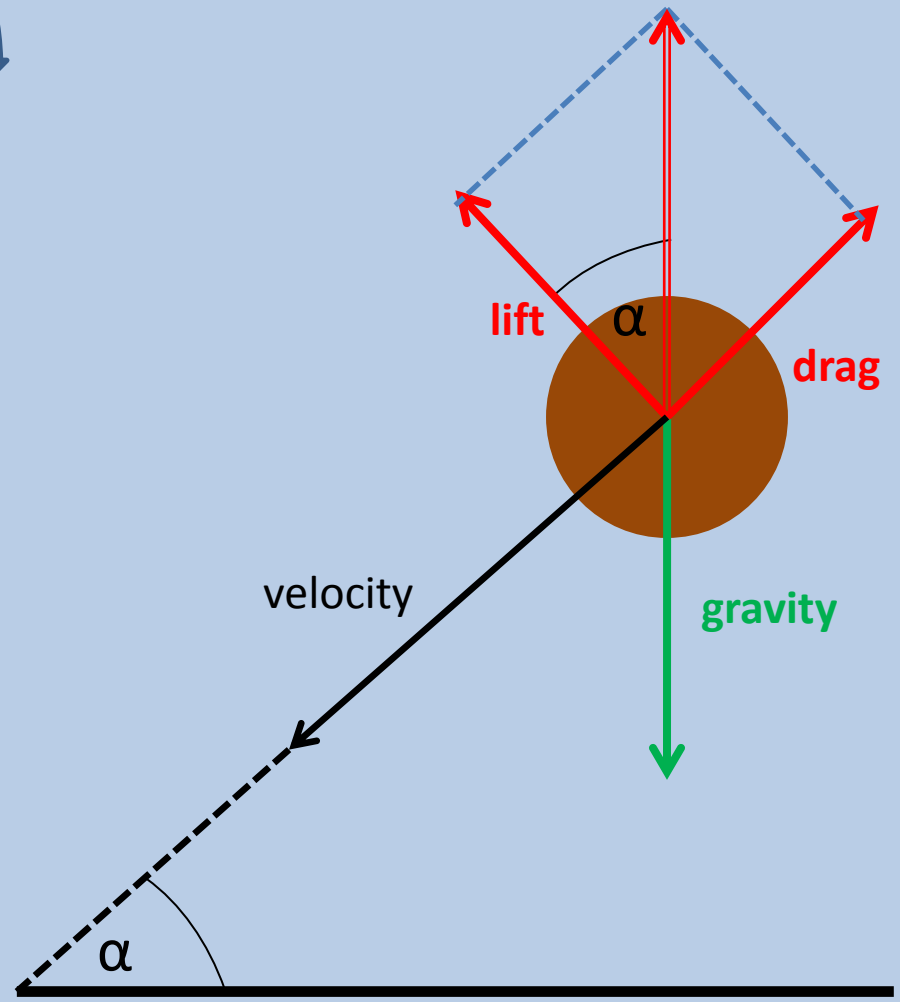
$$F_d = \frac{1}{2} C_d \rho A V^2$$

C_d – dimensionless drag coefficient
ρ – 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

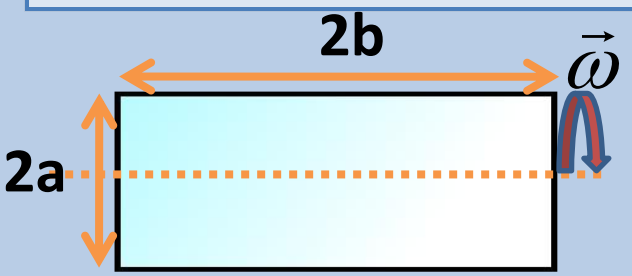




$$drag \propto abV^2$$

$$lift \propto a^2 b\omega V$$

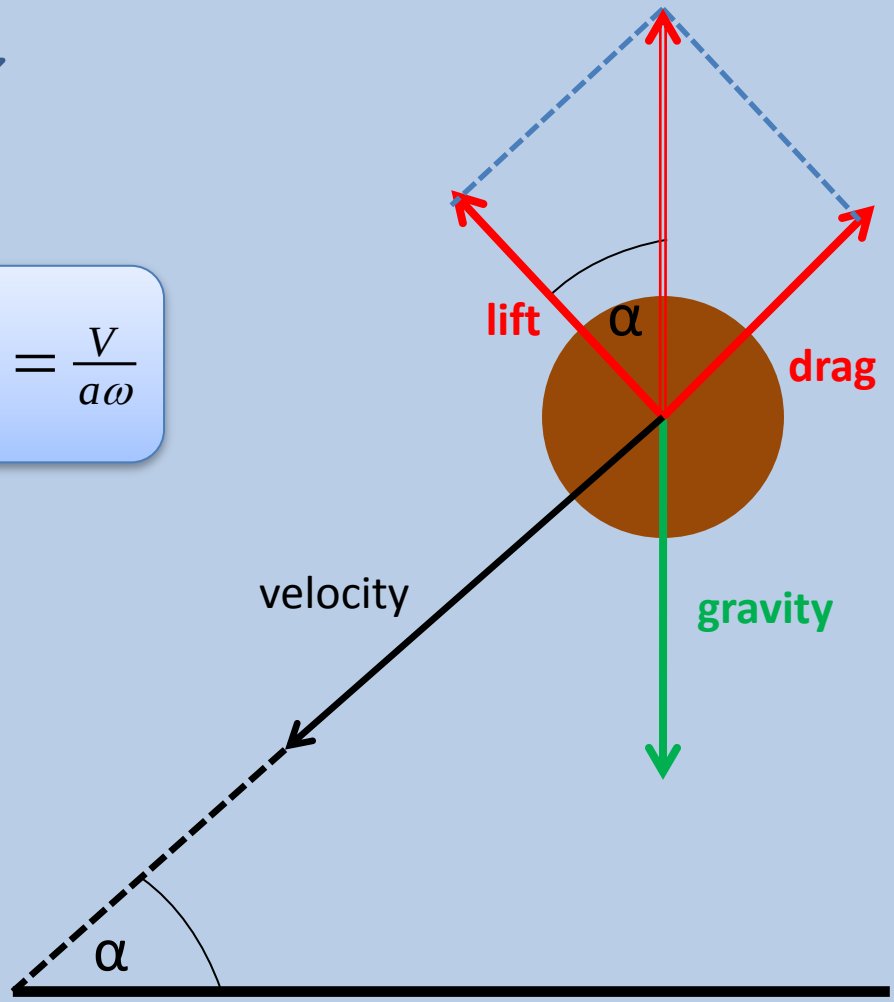
Theoretical parameters of steady motion



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

$$drag \propto abV^2$$

$$lift \propto a^2 b\omega V$$



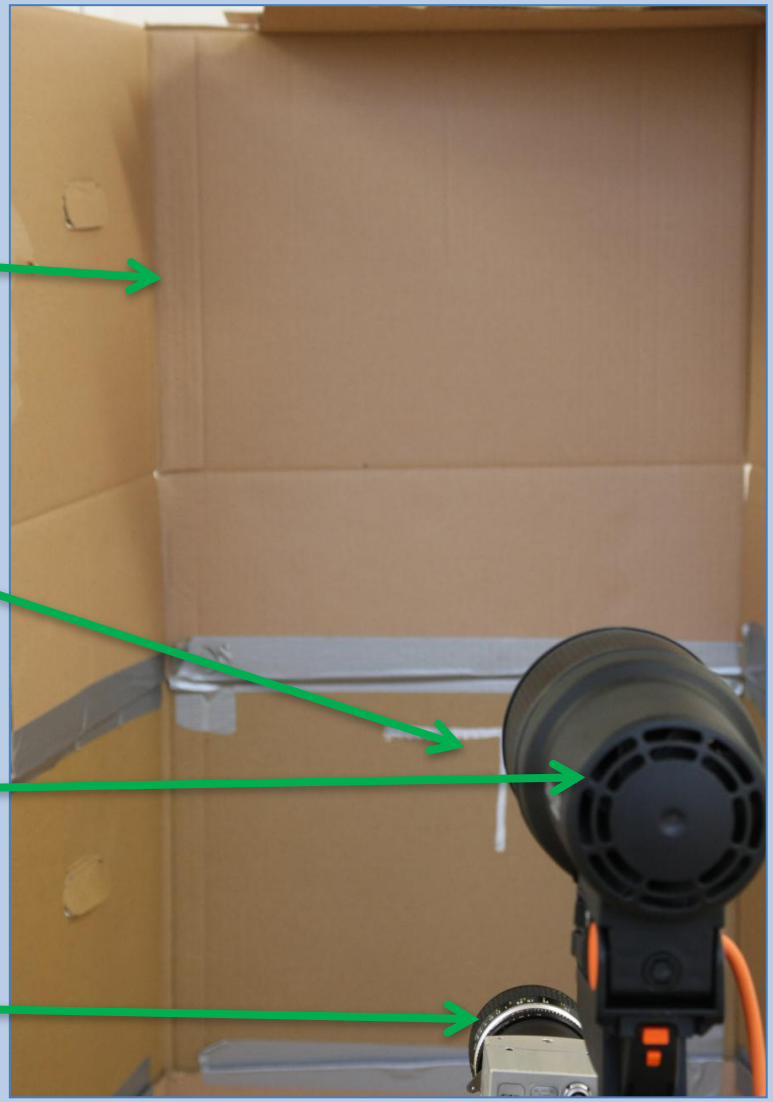
Direct measurements of tumbling bodies

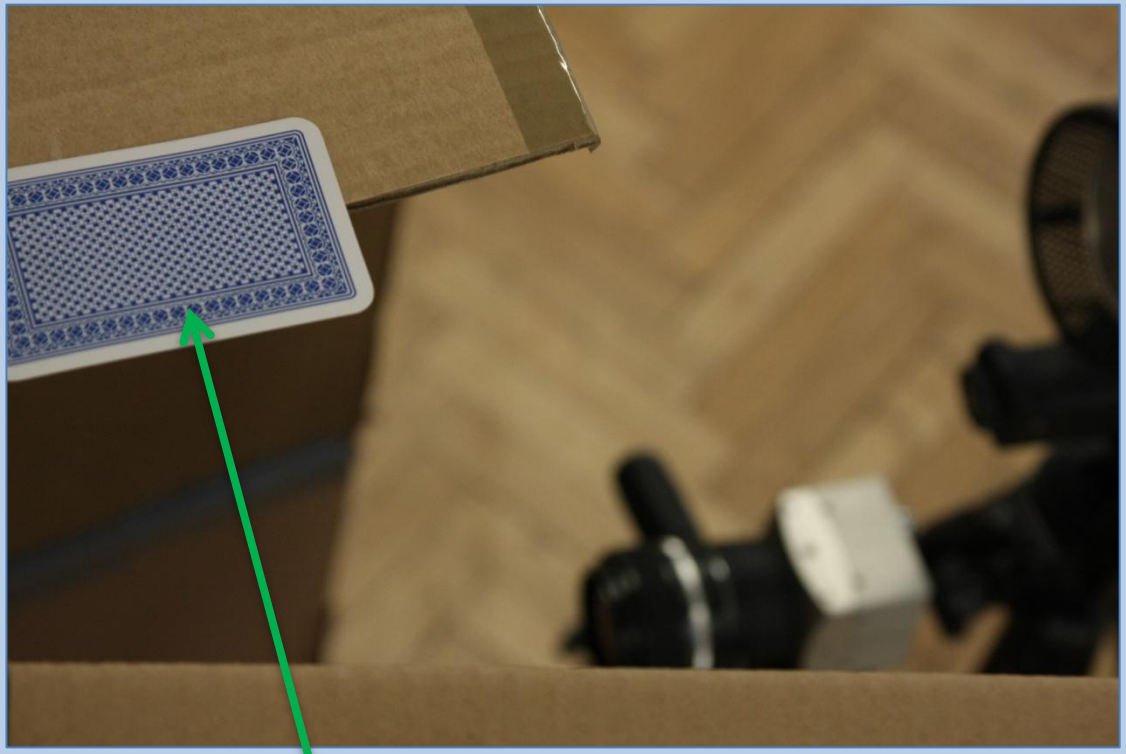
Air motion protection

Distance scale

1000 W lamp

High-speed camera



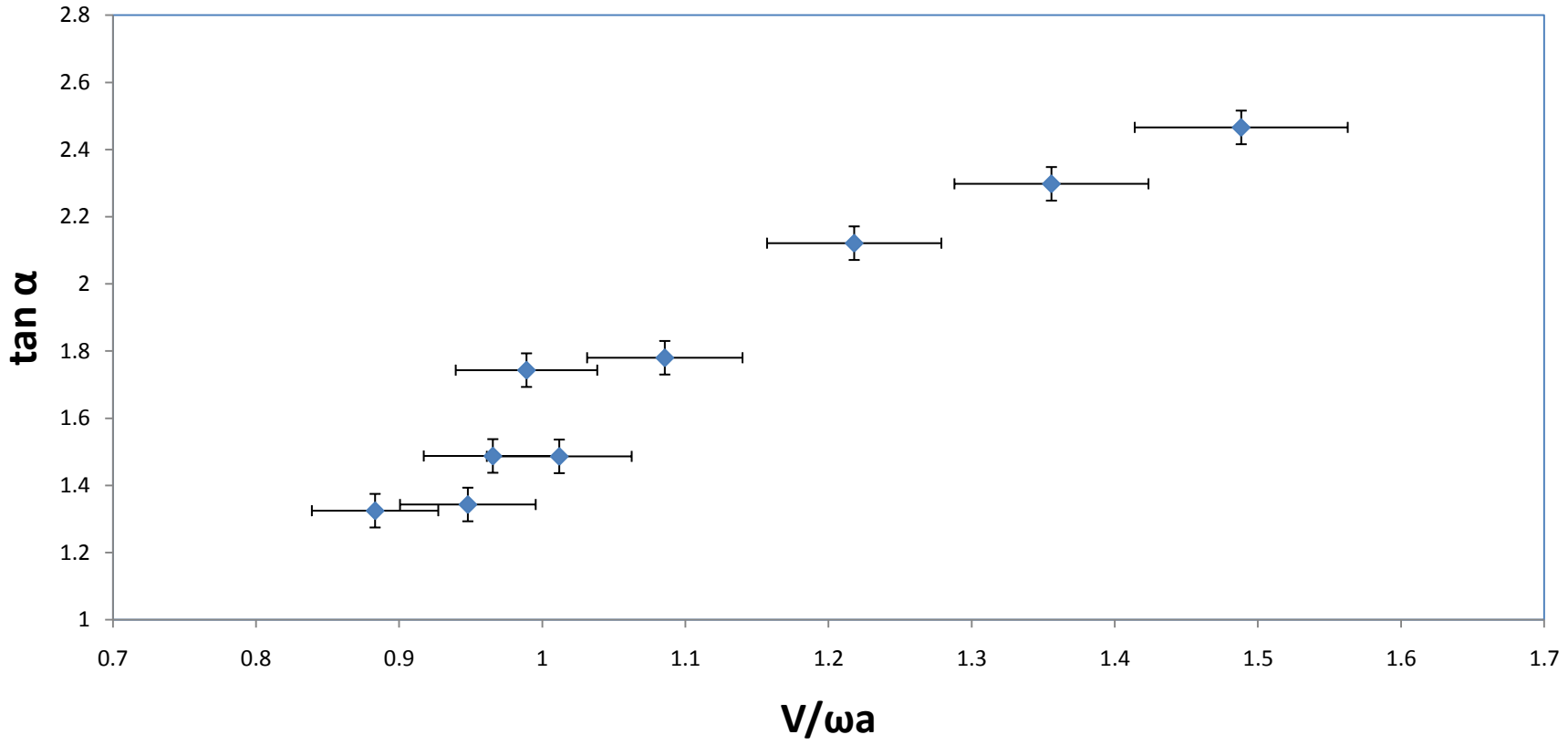


Studied body made of playing card

Measured parameters of motion:

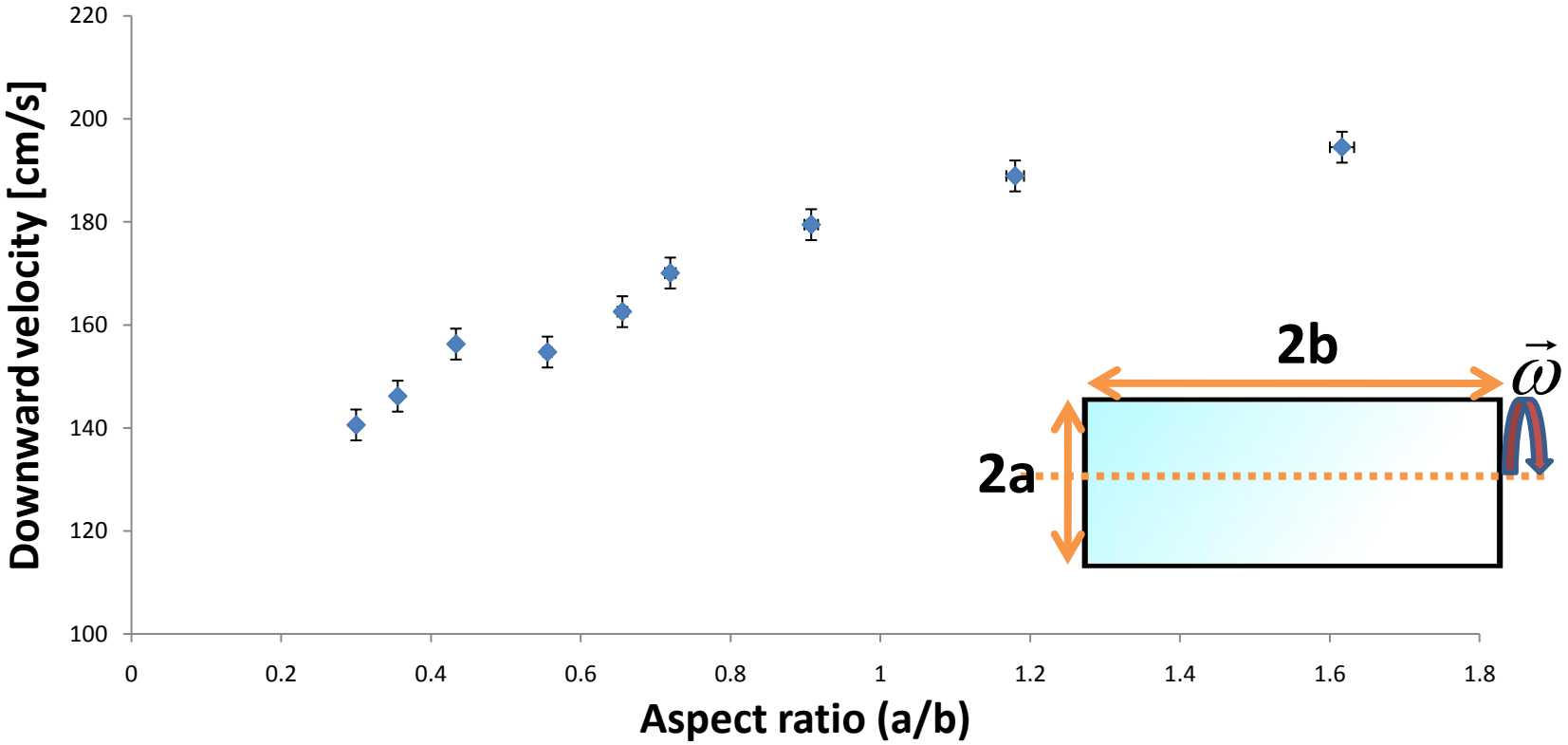
- Linear velocity
- Angular Velocity
- Angle of descent

Comparison with theory



The plot is not linear but it is increasing, so a moderate agreement with the theory was achieved

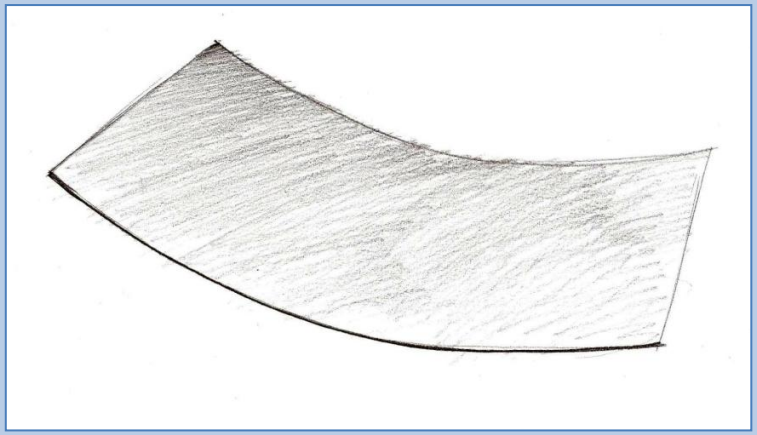
Optimisation of aspect ratio



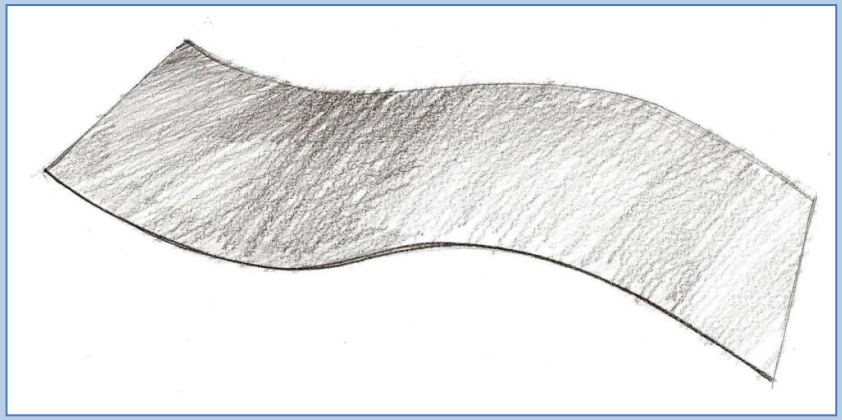
For rigid cards lowest downward velocity are obtained for lowest aspect ratio

Bending of paper

Unlike playing cards, paper strips to bend during the fall



Typical bending

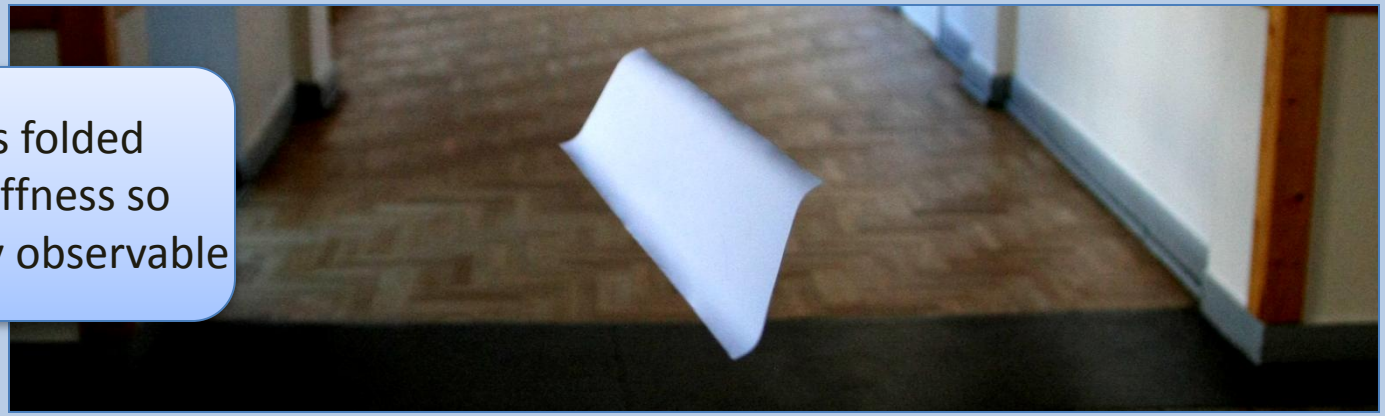


For 3 connected strips bending makes the motion unstable

The core of our device is two glued halves of A4 sheet.

Optimisation – longer edges folded

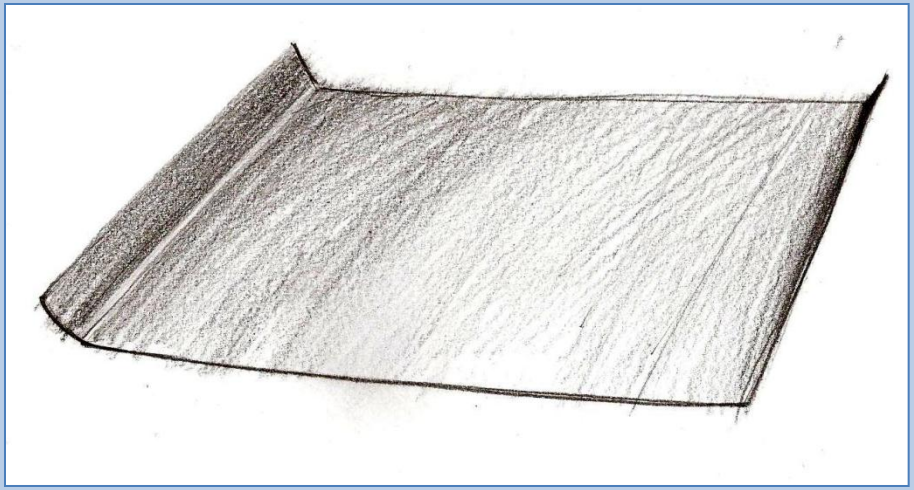
Typical bending during tumbling of paper with a/b=1/6



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

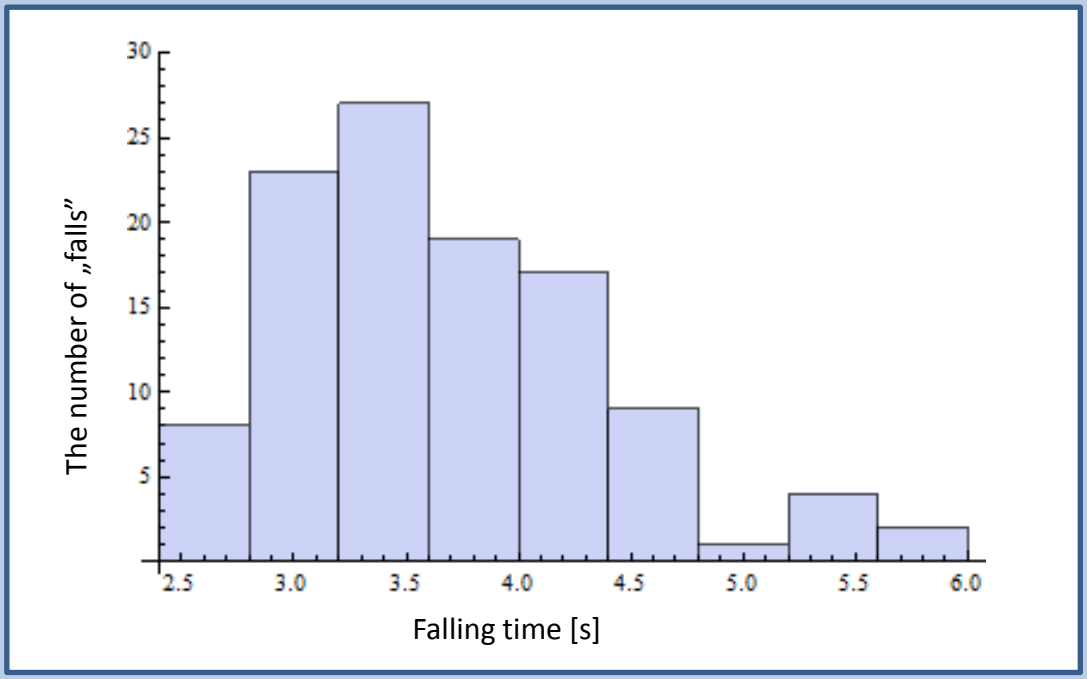


Instabilities (chaotic motion) occur less frequently for paper with shorter edges folded

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

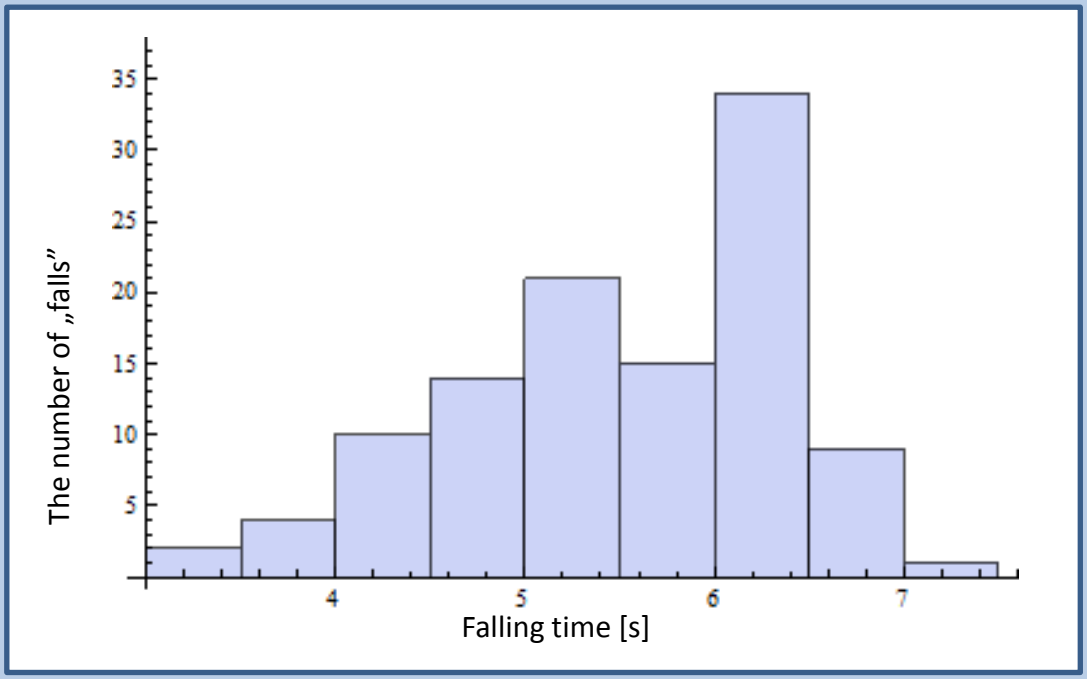
Standard deviation – 0.52s

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 treatement 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.

Literature

•P. Dupleich, *Rotation in free fall of rectangular wings of elongated shape*, NACA Technical Memo No. 1201 (1941)

•J. C. Maxwell, *Scientific Papers of J. C. Maxwell* , New York, 1940, Vol. 1, p. 115.

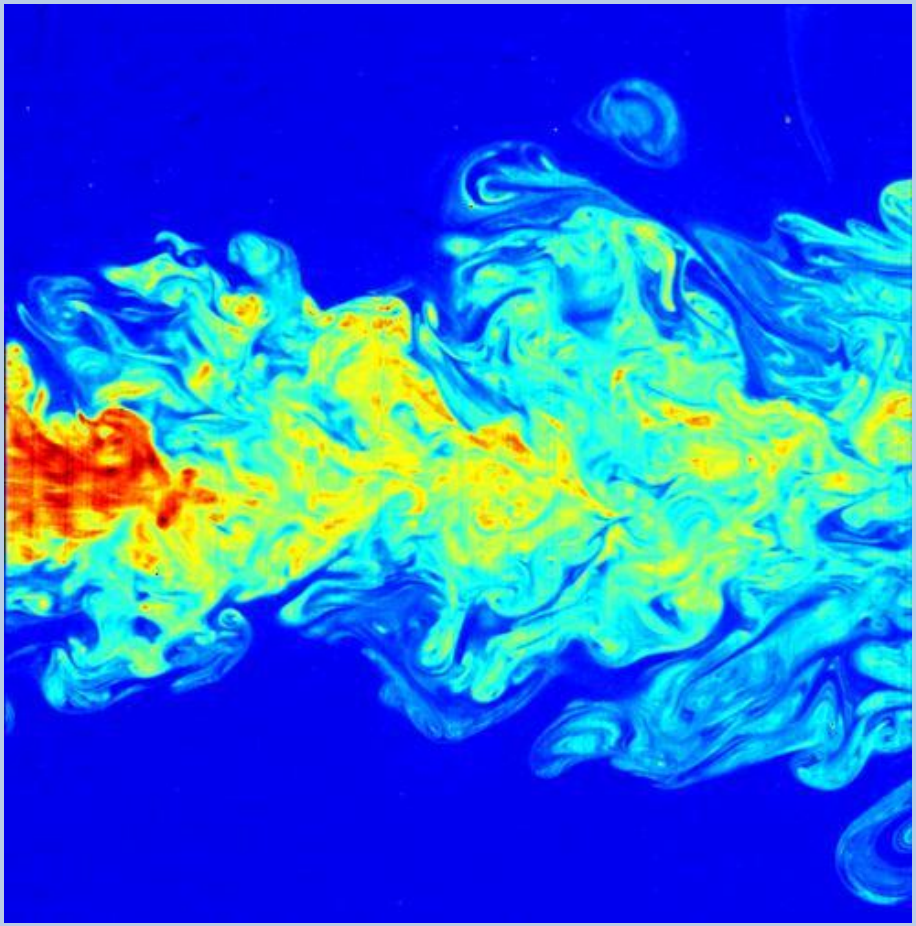
•D.L. Finn, *Falling paper and flying business cards*, SIAM News, 4, 40 (2007)

•A. Belmonte *et al.*, *From flutter to tumble: Inertial Drag and Froude Similarity in Falling Paper*, Phys. Rev. Lett. 2, 81 (1998)

•L. Mehadevan *et al.*, *Tumbling cards*, Phys. Fluids 1, 11 (1999)

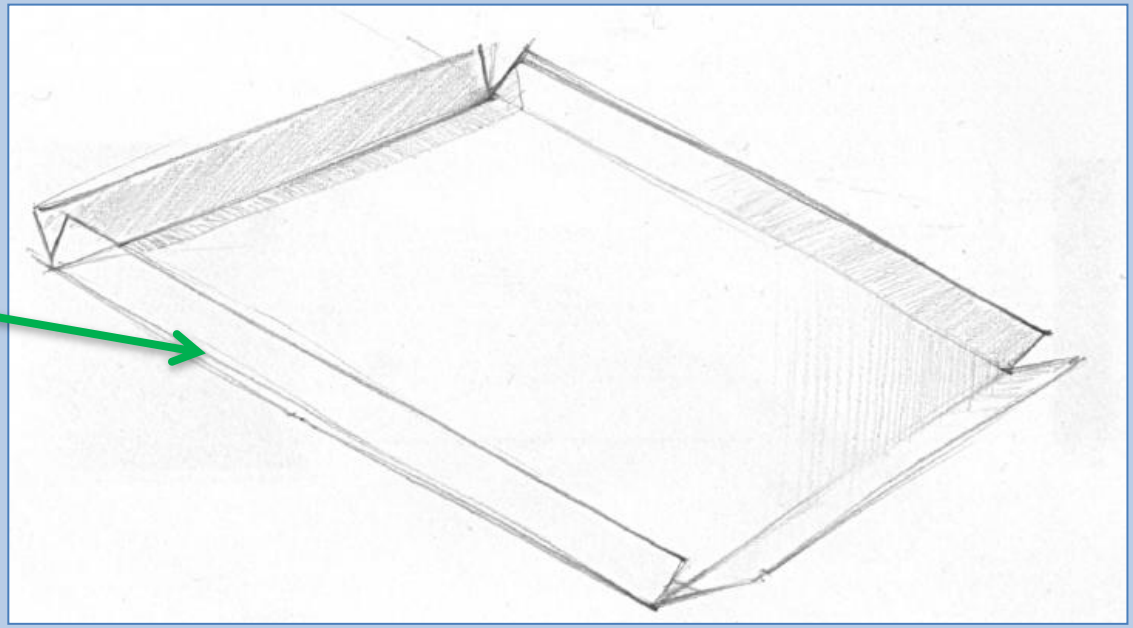
Turbulent flow

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



Aerodynamic drag experiment

A4 sheet with folded edges



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