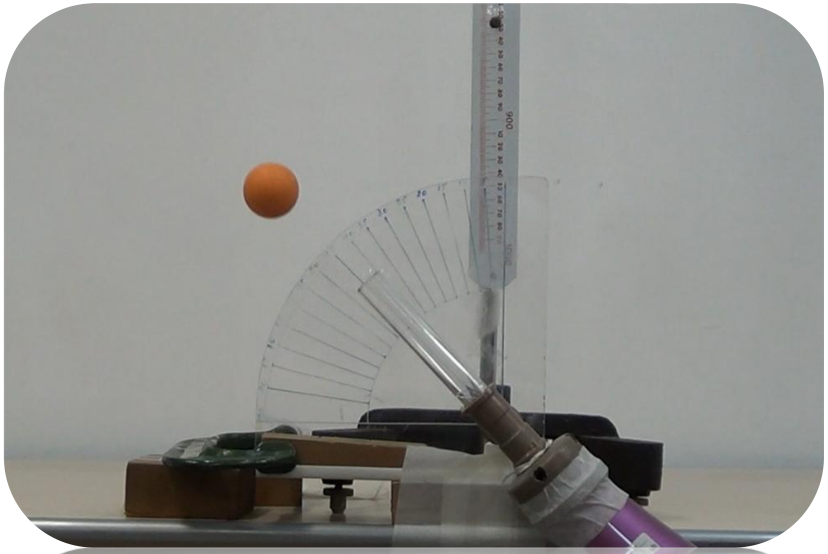
Team of Brazil

Problem 05
Levitation



reporter:

Denise Sacramento Christovam

Problem 05 Levitation

A light ball (e.g. a Ping-Pong ball) can be supported on an upward airstream. The airstream can be tilted yet still support the ball. Investigate the effect and optimize the system to produce the maximum angle of tilt that results in a stable ball position.

Contents

Flow Characteristics

- Reynolds number
  - Molecular behavior

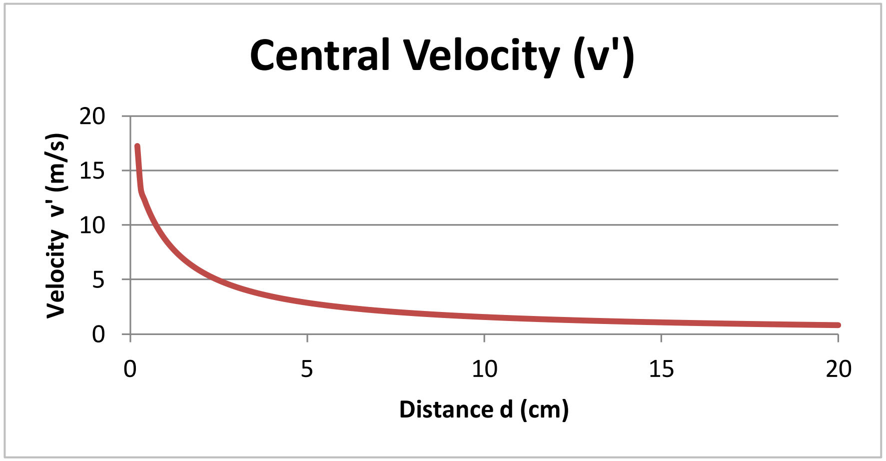
$$Re = \frac{2r \cdot V \cdot \rho}{\eta}$$

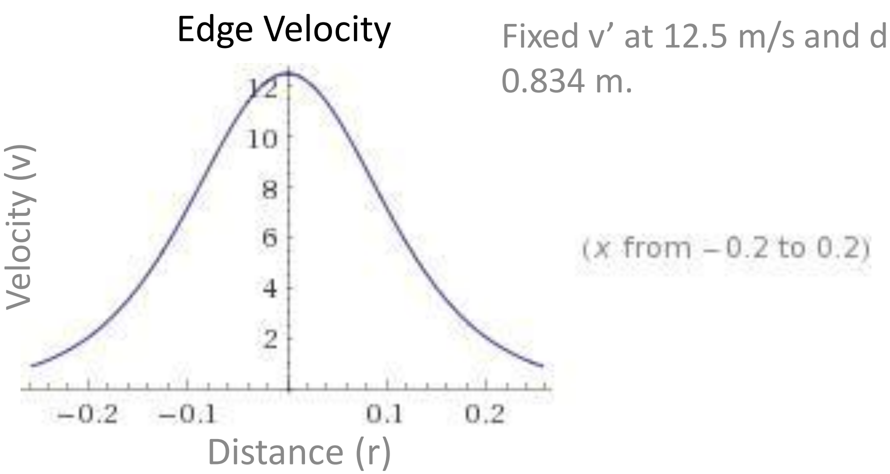
Radius of the ball (r), Velocity (V), Fluid's density (ρ), Dynamic viscosity (η)

  - Re < 2000: laminar flow
  - 2000 < Re < 2400: "transition flow"
  - Re > 2400: turbulent flow
    - Typically over $1.5.10^4$ – turbulent flow

Flow Characteristics

- Flow velocity*
  - Bernoulli's Principle





Fixed v' at 12.5 m/s and d at 0.834 m.

*BECKER, Aaron, SANDHEINRICH, Robert, and BRETL,Timothy. Automated Manipulation of Spherical Objects in Three Dimensions Using A Gimbaled Air Jet.

Aerodynamic Forces

- Drag:
  - Re > 1000:

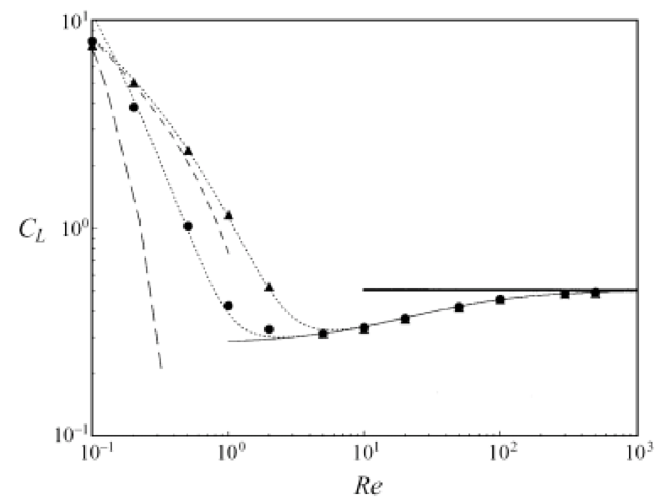
$$D = \frac{C_D}{2}\rho \cdot \pi r^2 \cdot V^2$$

- Surface Forces (lift):

$$L = \frac{C_L}{2}\rho \cdot \pi r^2 \cdot V^2$$

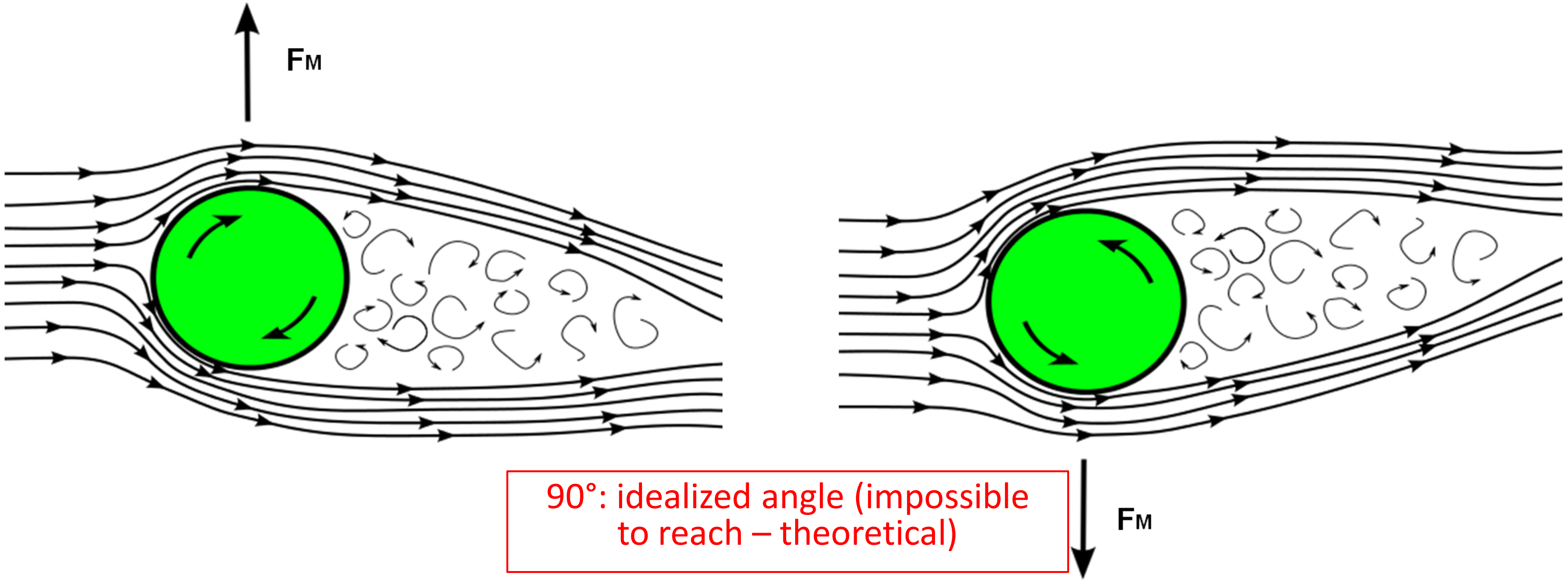
$C_L \approx 0.5$

- Roughness



Aerodynamic Forces

- Magnus-driven force: "rotational lift"



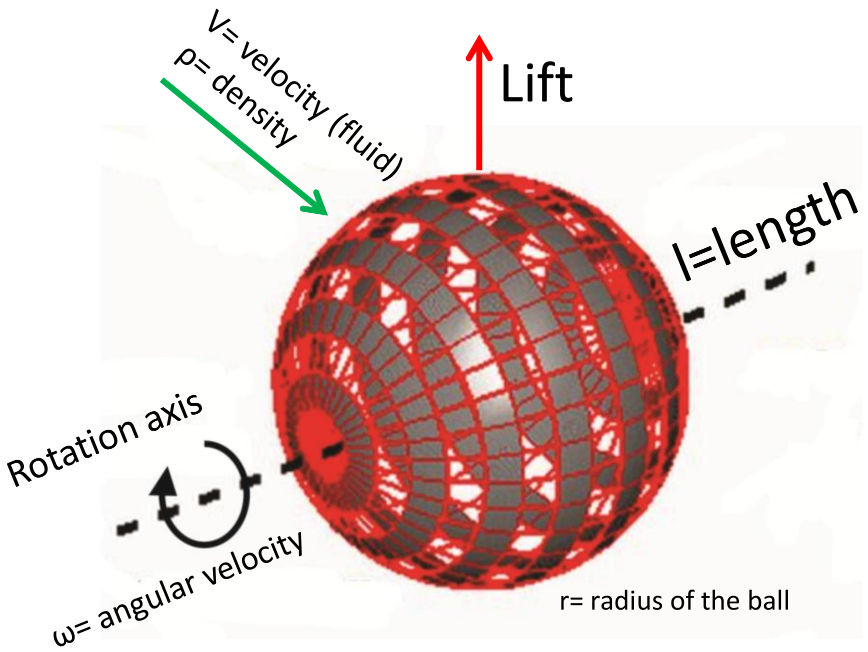
90°: idealized angle (impossible to reach – theoretical)

  - Magnus effect is relevant for rough spheres
  - It can be neglected for highly smooth spheres

  } e.g. Golf Ball

Aerodynamic Forces

- Kutta-Joukowski Lift Theorem for a Cyllinder



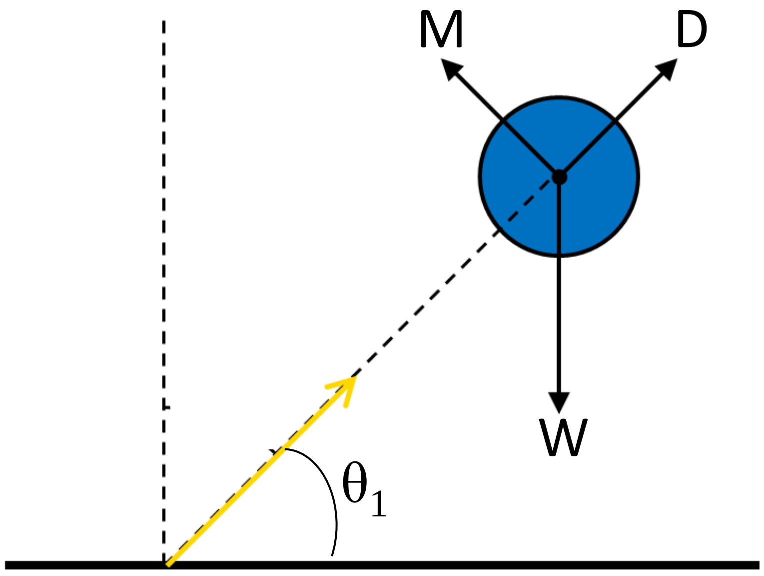
$$M = \rho . \Gamma . V$$

$$M = 4.\pi^2.r'^2.\omega.\rho.V$$

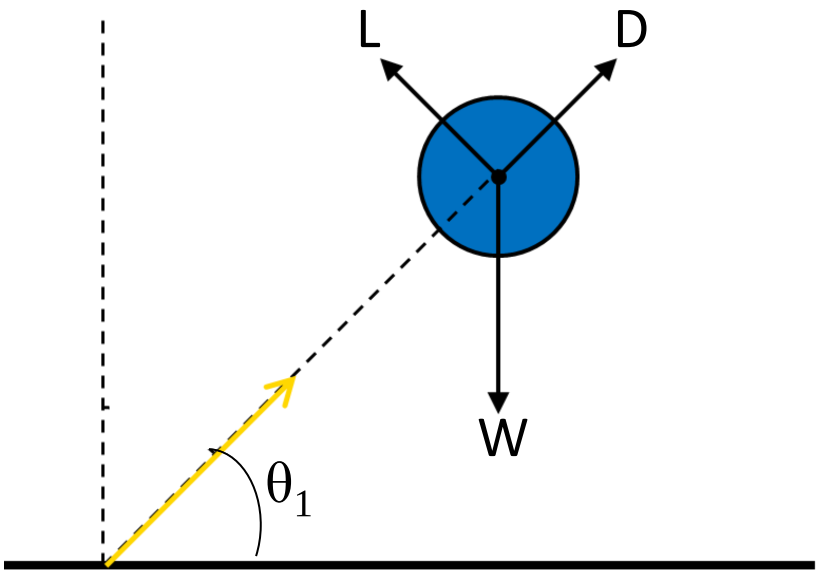
$$\boxed{M = \frac{4}{3}(4.\pi^2.r^3.\omega.\rho.V)}$$

M: “Magnus” force
Γ: strength of rotation
r‘: radius of the cyllinder

Aerodynamic Forces



Rough Sphere

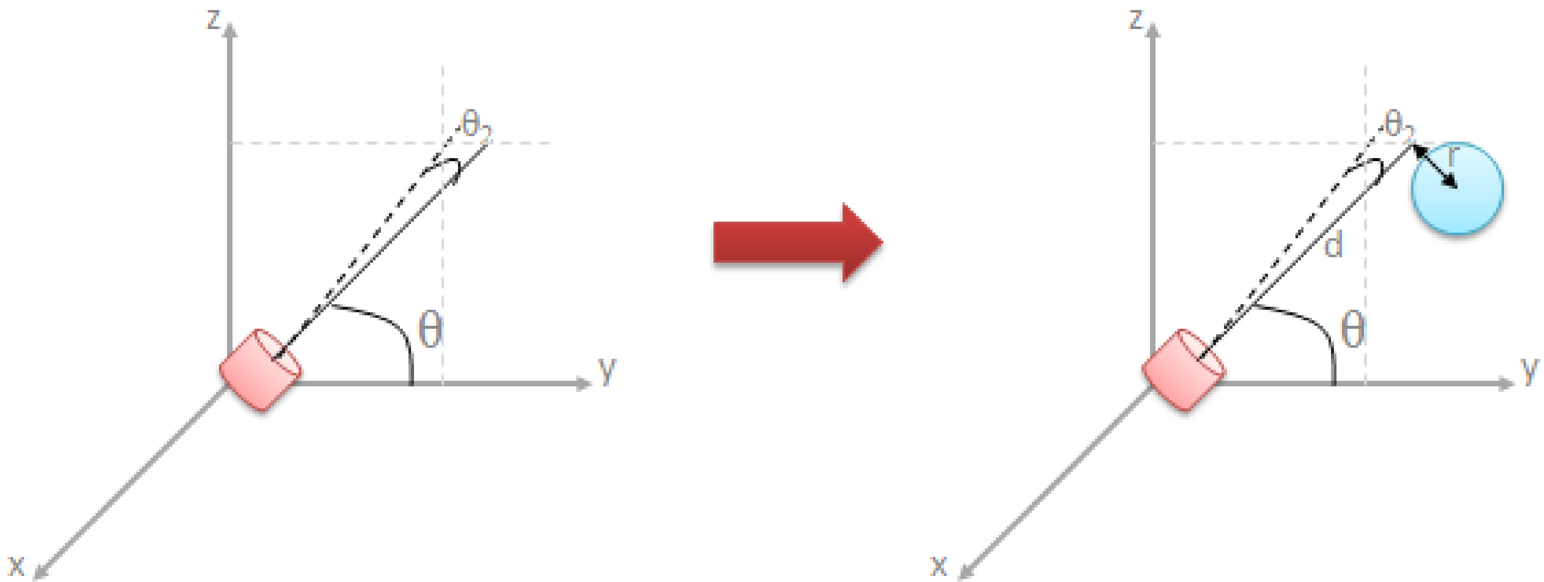


Smooth Sphere

Threshold Angle

θ_2: rotation in the orthogonal plane to the levitation

Fluid's side pressure: stable perpendicular position ($r_{medium}=0$)



θ_2 will be considered 0°, as the object of study is the inclination towards the ground.

Threshold Angle

Ball's weight

$$\tan\theta = \frac{\sqrt{{C_D}^2\rho^2\pi^2R^4V^4 + m^2g^2}}{C_D\rho\pi R^2V^2} - 1$$

Smooth

Drag coefficient

Air density

Ball's radius

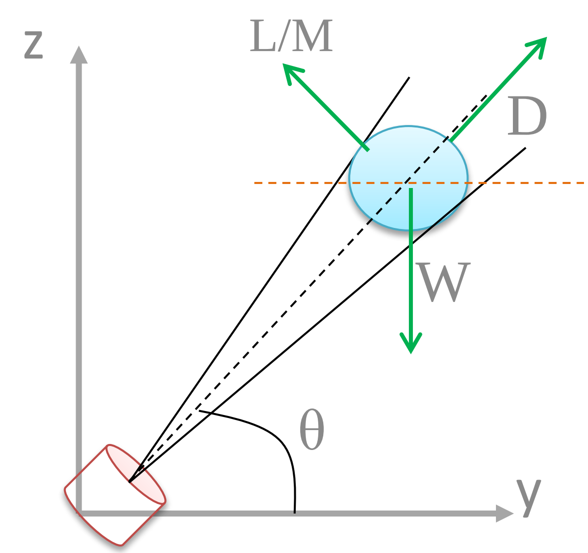
Fluid's central velocity

Lift coefficient

Angular velocity

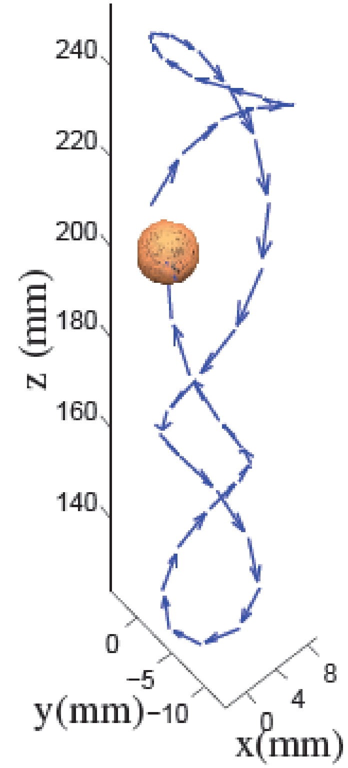
$$\tan\theta = \frac{32}{3}\frac{C_l\pi R\omega}{C_D V}$$

Rough



Oscillations

- Mainly due to small pressure differences inside the jet and turbulence
- Type:
  - Perpendicular (ordinate)
  - Perpendicular (abscissa)
- Perpendicular: slightly similar to simple harmonic oscillations

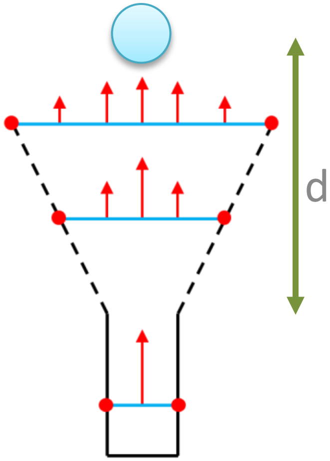


Optimization

- Initial velocity of the jet
  - Minimum height: maximum angle
    - Minimum d initial:

$$W = D \qquad d \rightarrow 0$$

$$v_{0I} = \sqrt{\frac{2mg}{C_d \rho \pi r^2}}$$



  - The greater the pressure difference between center and sides, the greater the stability.
  - Therefore, initial jet velocity must be high.
- Radius and mass of the ball
    - Small mass (smaller weight)
    - Great radius (greater lift and drag)

Optimization

- Nozzle's diameter
  - Fluid cone's formation;
  - Big nozzle: continuity law
  - Small nozzle: viscous fluid in a pipe (lost of pressure leads to lost in lift)
  - Jet nozzle must be of the same magnitude of the ball's radius.
- Ball surface
  - Upward force balancing weight;
  - Magnus-driven force + lift;
  - Rough ball
- Oscillations
  - More oscillations, the ball is more likely to fall
- Flow
  - Must be laminar **before** reaching the ball (directed force), only then the predicted angle is valid

Material

1. Light balls
2. Anemometer (±0.1 m/s)
3. Millimeter Scale (±1 mm)
4. Protractor (±1°)
5. Hair dryer

- Camera (120 FPS)
- Talc
- Scales ($\pm 1.10^{-4}$g)

Experimental Description

- **Experiment 1:** show the cone's formation that helps in stability.
- **Experiment 2:** show that the global equation for flow velocity is applicable.
- **Experiment 3:** verify if our experimental conditions match with the drag crisis'.
- **Experiment 4:** threshold angle.
- **Experiment 5:** variation of balls.
- **Experiment 6:** oscillations analysis

Experiment 1: Flow Format

- Flow Format
- Velocity
- Drag crisis
- Threshold Angle
- Ball Variation
- Oscillations

Experiment 1: Flow Format

- Flow Format
- Velocity
- Drag crisis
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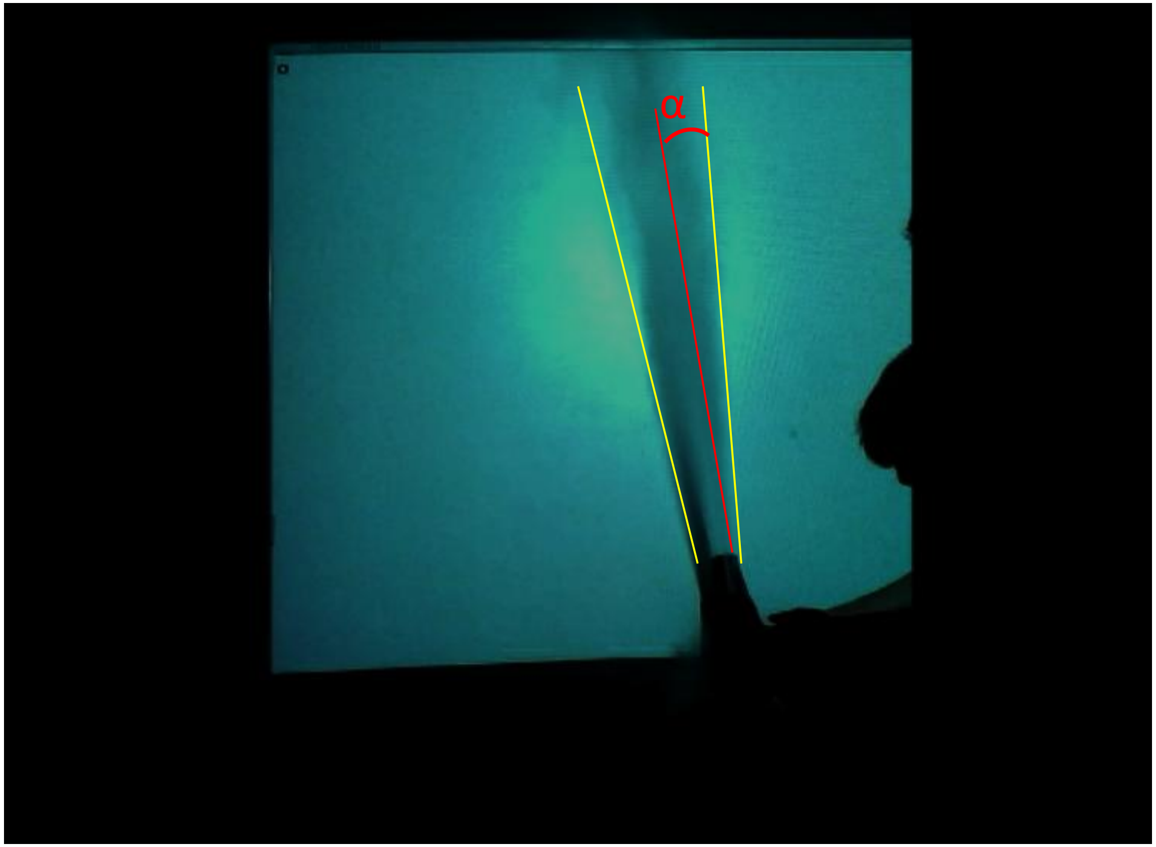
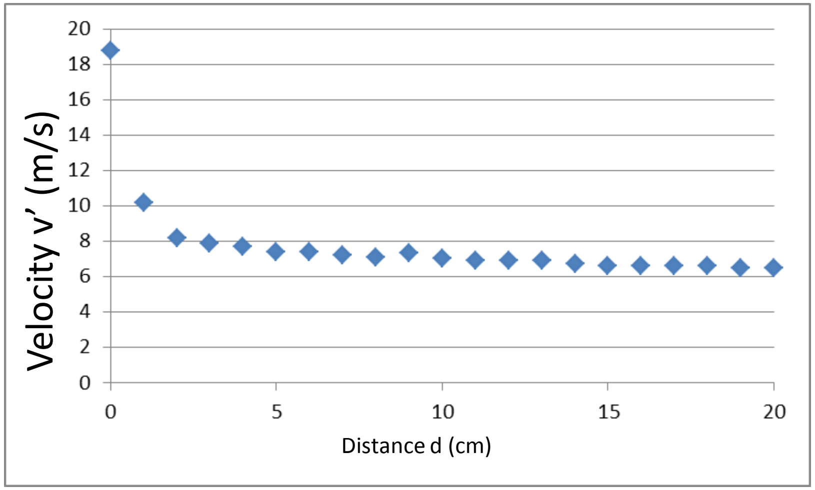
- Oscillations

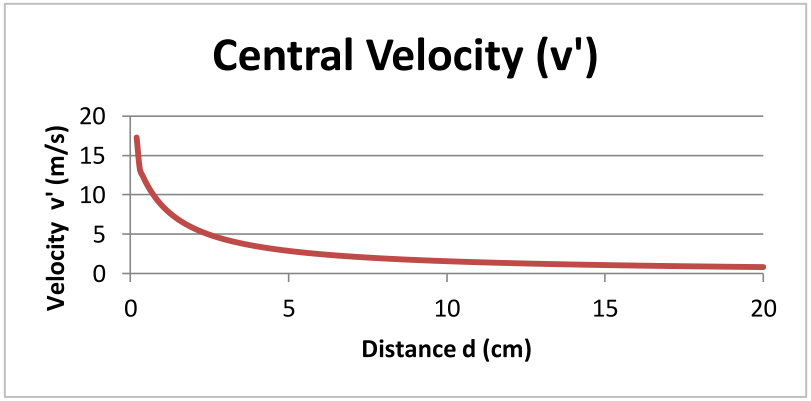


α= 12.3°

Experiment 2: Flow Velocity

- Flow Format
- Velocity
- Drag crisis
- Threshold Angle
- Ball Variation
- Oscillations

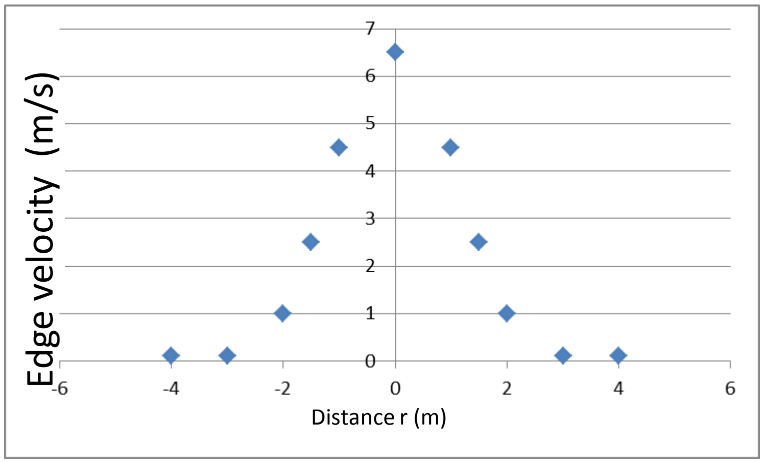


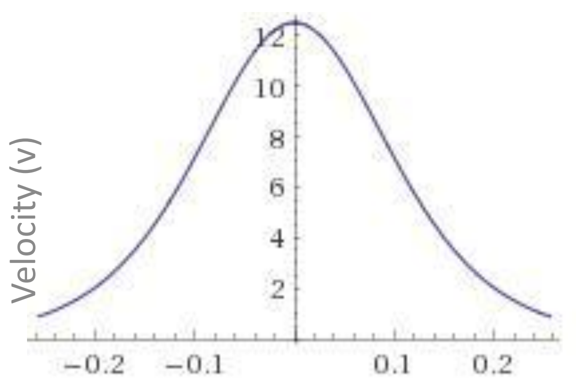


Approximately the same experimental behavior as theoretically predicted (differ by an arbitrary constant)

Experiment 2: Flow Velocity

- Flow Format
- Velocity
- Drag crisis
- Threshold Angle
- Ball Variation
- Oscillations



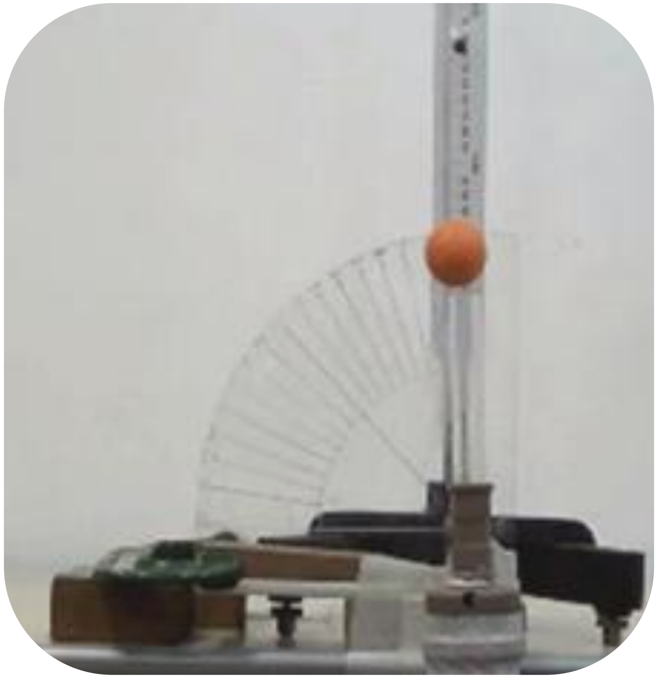


Same experimental behavior as theoretically predicted

Experiment 3: Drag Crisis

- Flow Format
- Velocity
- Drag crisis
- Threshold Angle
- Ball Variation
- Oscillations

- Experimental Setup:



$$D = W$$

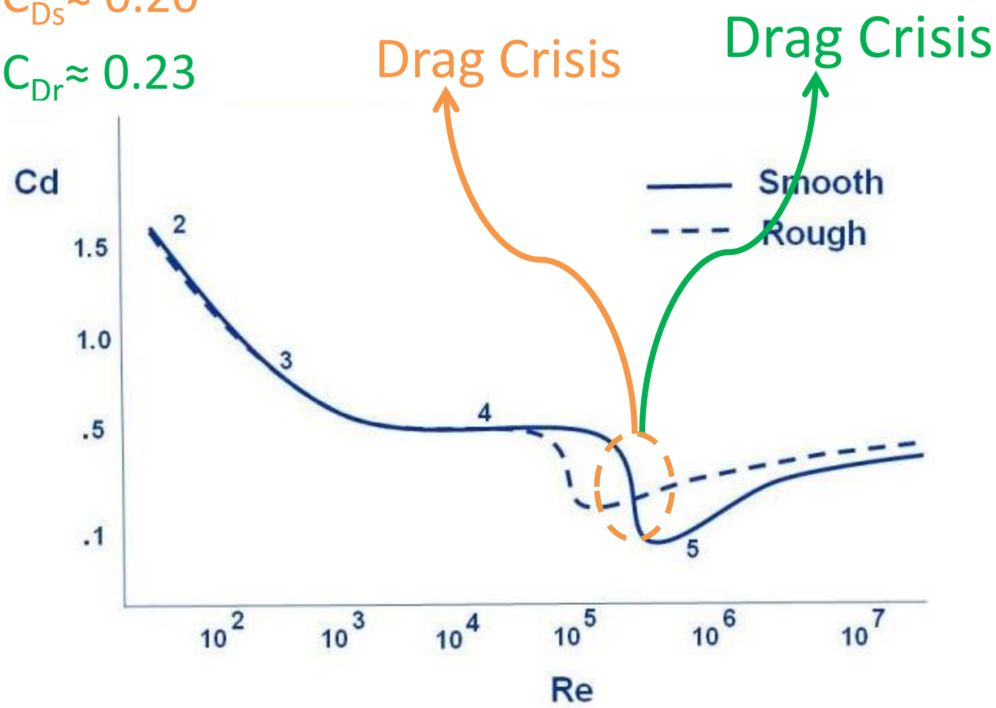
- ρ: 1.2 kg/m^3
- W_s: $2.45.10^{-2}$ N
- W_r: 0.44 N
- R_s: 19 mm
- R_r: 21.5 mm

Experiment 3: Drag Crisis

- Flow Format
- Velocity
- Drag crisis
- Threshold Angle
- Ball Variation
- Oscillations

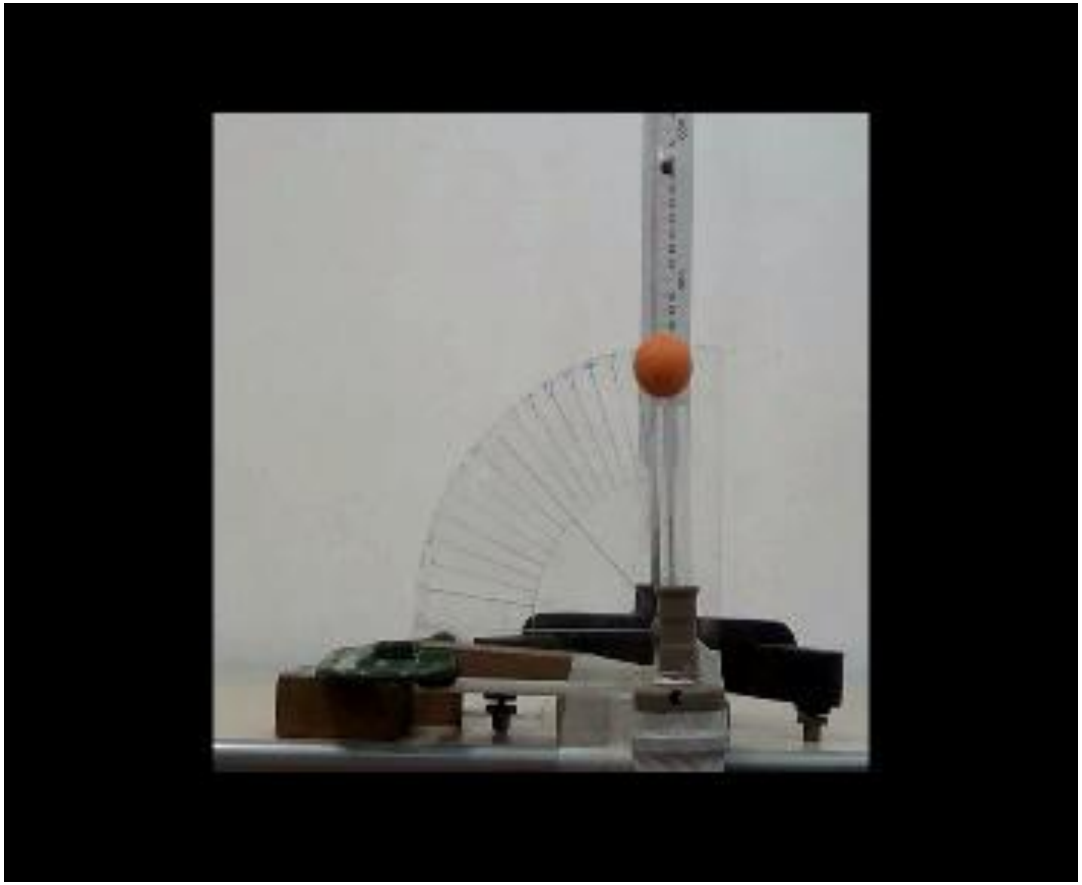
Measured d= 27.5 cm, v'= 12.5 m/s

- Measured $C_{Ds} \approx 0.20$
- Measured $C_{Dr} \approx 0.23$



Experiment 4: Threshold Angle

- Flow Format
- Velocity
- Drag crisis
- Threshold Angle
- Ball Variation
- Oscillations



Experiment 4: Threshold Angle

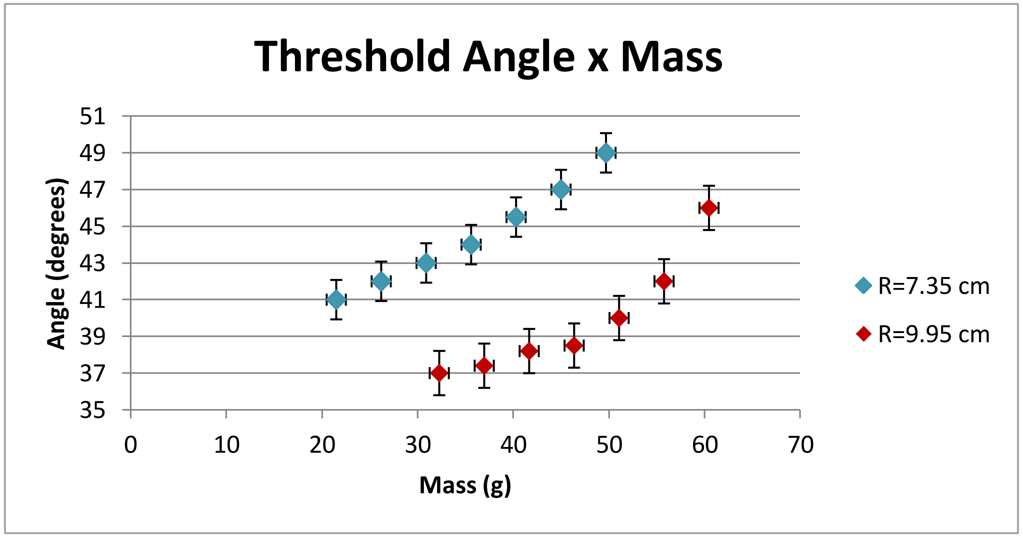
Smooth Ball (in degrees)	
1	39.9
2	39.8
3	39.9
4	38.9
5	41.2
6	46.3
7	46.7
8	42.9
Average	**42.0**
Theoretical	**43.9**
Standard Deviation	3.1

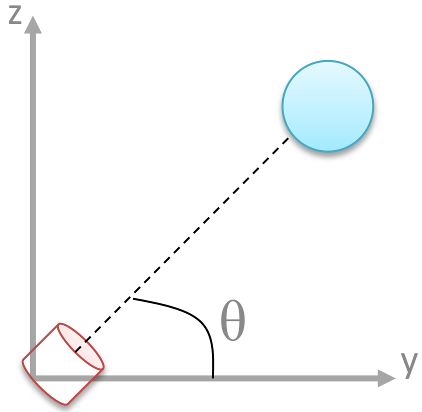
Rough Ball (in degrees)	
1	42.0
2	41.0
3	41.0
4	43.9
5	40.8
6	42.4
7	39.0
8	42.2
Average	**41.5**
Theoretical	**42.7**
Standard Deviation	1.4

Error source: turbulence before ball, number of frames (120 FPS)

Experiment 5 – Ball Variation

- Mass variation



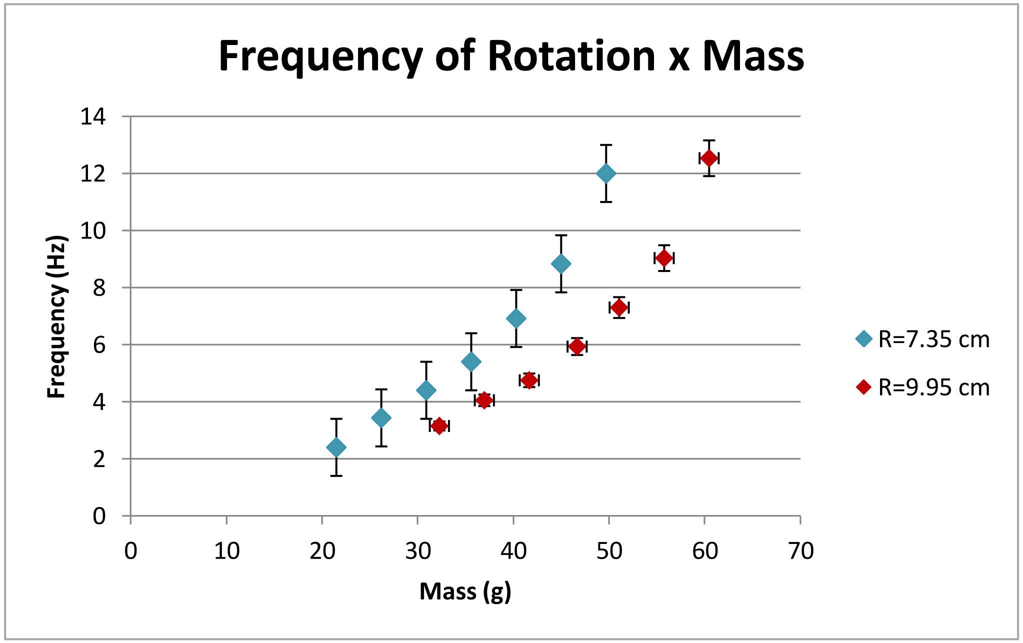


$$\tan\theta = \frac{\sqrt{C_D{}^2\rho^2\pi^2R^4V^4 + m^2g^2}}{C_D\rho\pi R^2V^2} - 1$$

Experiment 5 – Ball Variation

- Flow Format
- Velocity
- Drag crisis
- Threshold Angle
- Ball Variation
- Oscillations

- Frequency of rotation

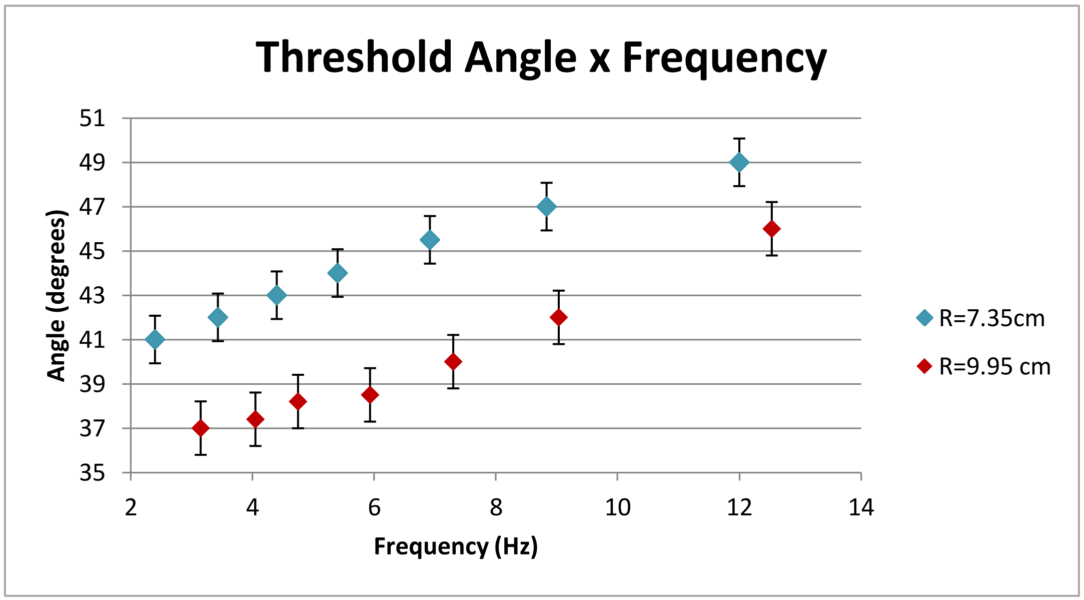


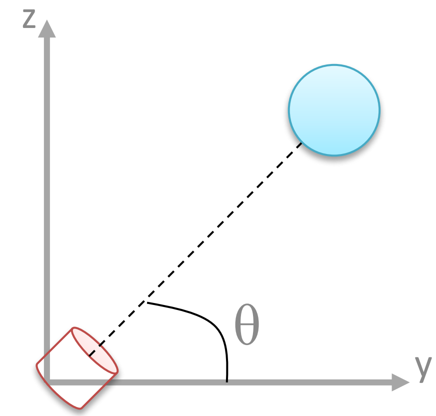
Greater mass → Closer to the nozzle (weight) → Higher velocity → Higher frequency

Experiment 5 – Ball Variation

Flow Format
Velocity
Drag crisis
Threshold Angle
Ball Variation
Oscillations

- Frequency of rotation





$$\tan\theta = \frac{32}{3}\frac{C_l \pi R \omega}{C_D V}$$

Experiment 7: Oscillations

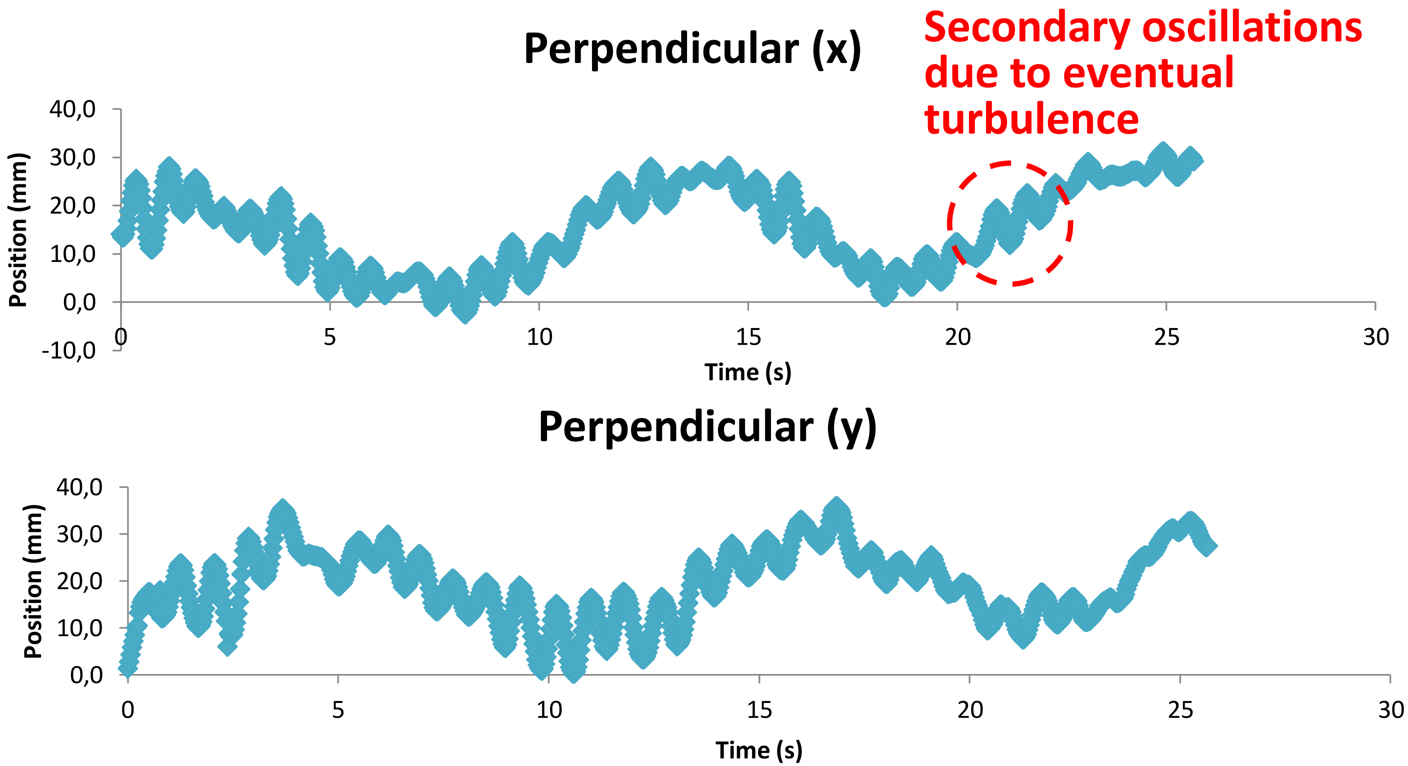
- Flow Format
- Velocity
- Drag crisis
- Threshold Angle
- Ball Variation
- Oscillations

Perpendicular oscillations

(120 FPS)

Experiment 7: Oscillations

- Flow Format
- Velocity
- Drag crisis
- Threshold Angle
- Ball Variation
- Oscillations



Resembles SHO (constant period of oscillation)

Conclusions

- The main cause of the levitation are the pressure differences within the fluid, due to velocity variation, which cause aerodynamic forces;
- The threshold angle in idealized situations is about 90°. As it’s impossible to reach in any experimental condition, the maximum is dependent on the sphere and jet used, and is 41,5°.

fluid’s velocity/mass/radius	→	aerodynamic forces and “lift cone”
surface	→	Magnus effect
nozzle	→	“lift cone”

References

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Thank you!