Team of Russia

Problem No.12

Resonating glasses

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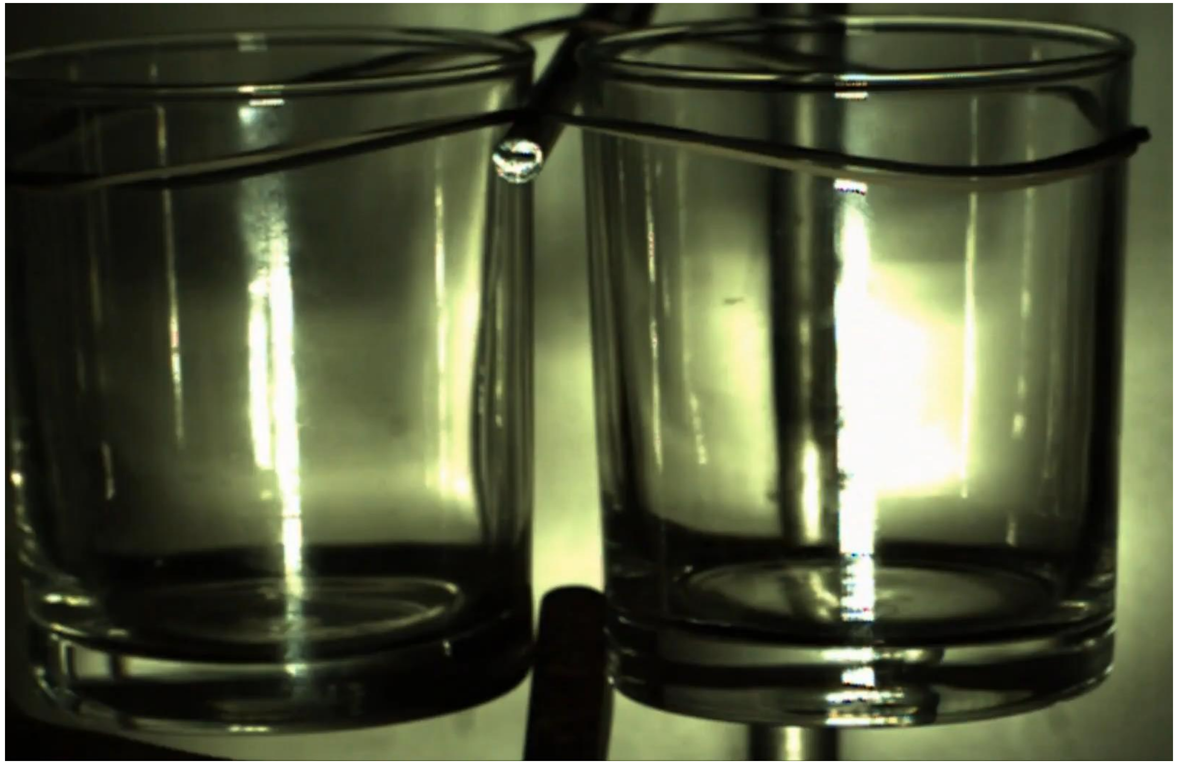
MOSCOW INSTITUTE OF PHYSICS AND TECHNOLOGY

International Physicists' Tournament 2020

When you take **two glasses between your fingers**, they sometimes emit a particular **sound** containing a ***frequency sweep***. Investigate the phenomenon.



Video from 6000 fps camera

1 Introduction

- First observations
- Fingers role
- Frequency sweep
- Experimental setup

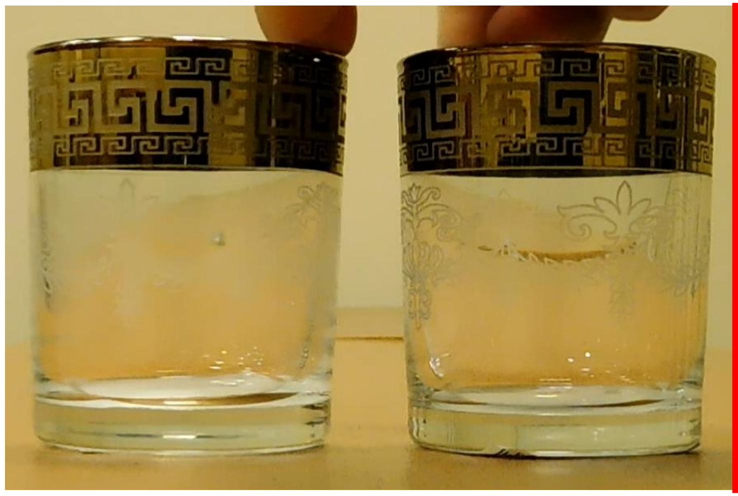
Mechanics problem

Effect occurs with finger between glasses

1 Multi collision is observed

2 Frequency sweep is heard

3 Finger between glasses affect the sound sweeping



Effect is not observed without finger between glasses

Acoustic problem

Background noise is 0 dB

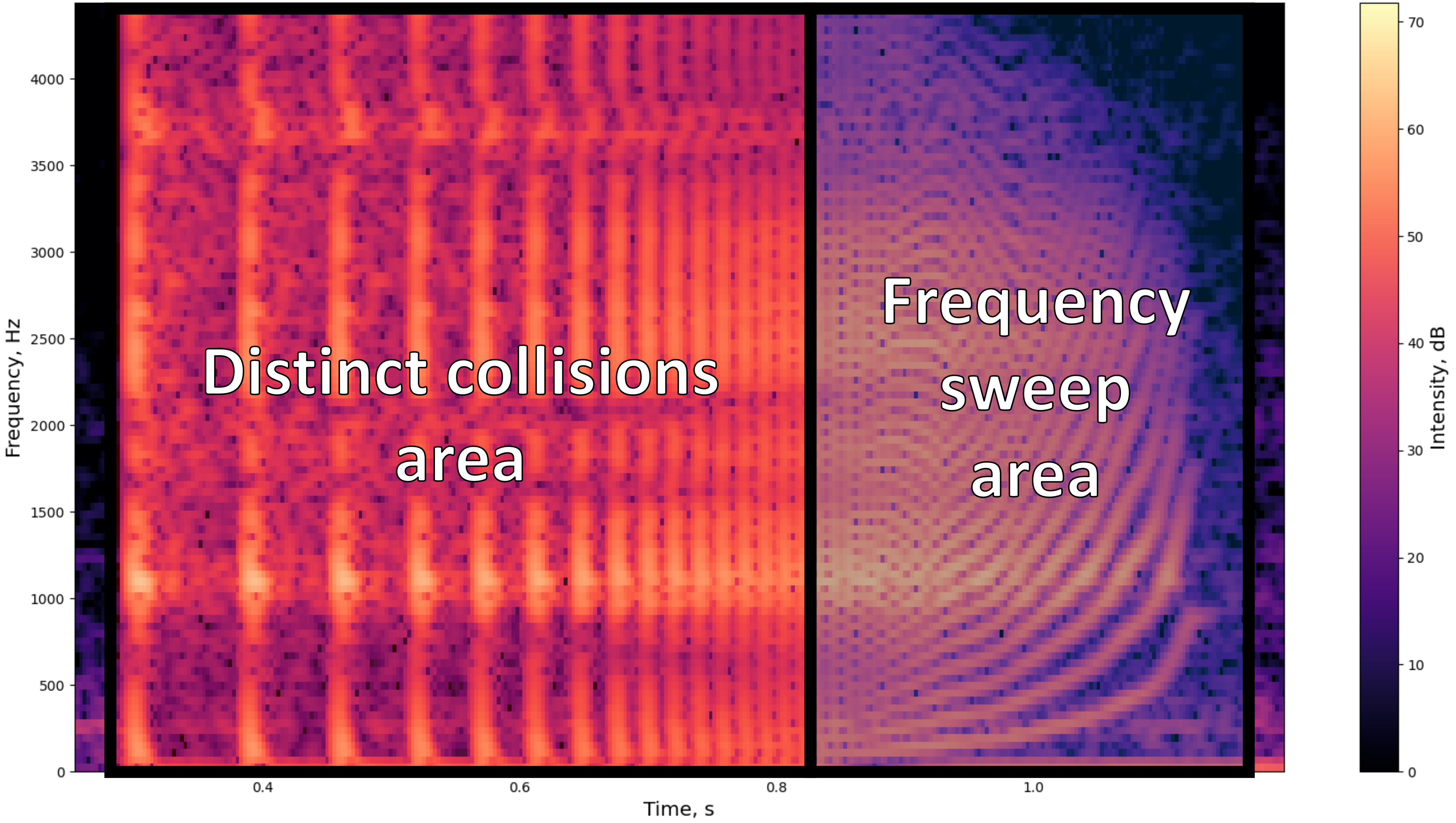
? Main questions

What is the sound of one impact?

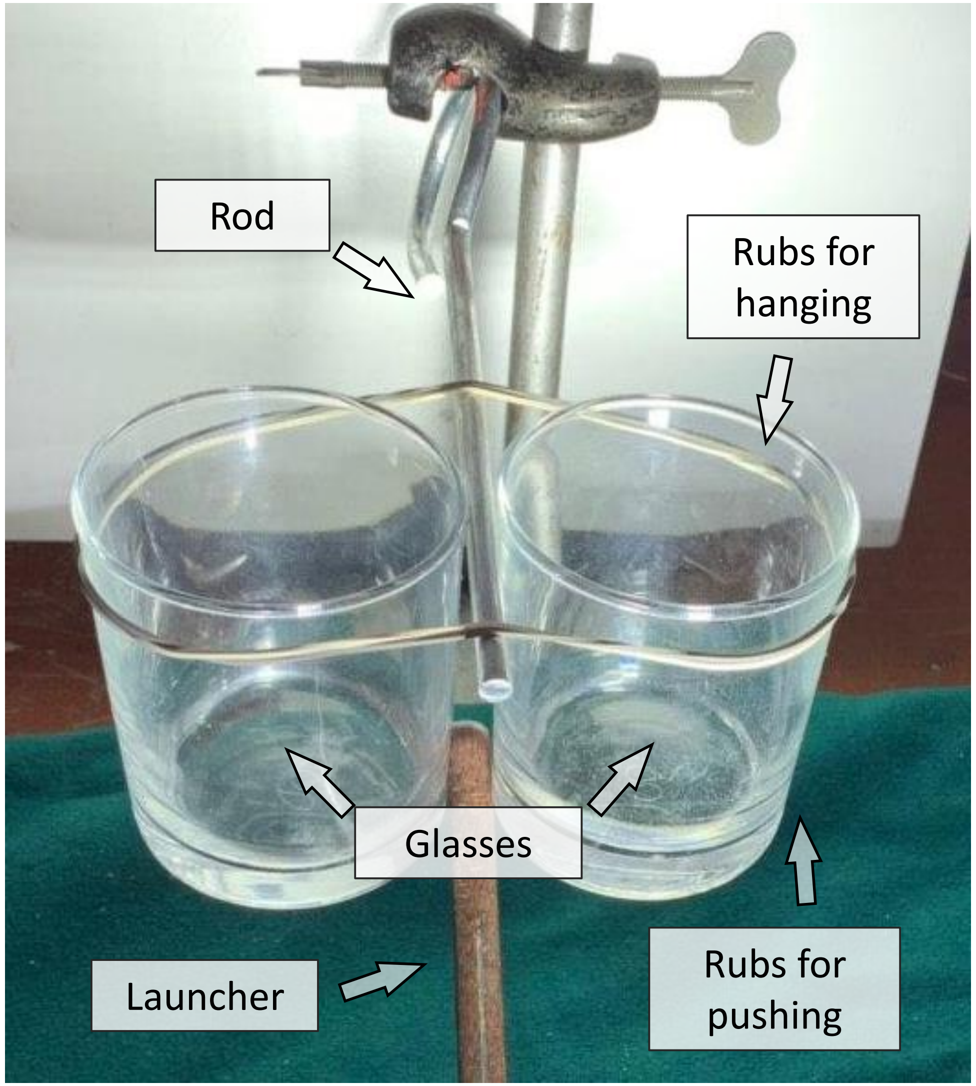
Why are the collisions no longer distinguishable?

How can we determine area changing time?

FFT spectrogram
in Python matplotlib:
Sample rate = 44 100 Hz
Window size = 1024 units
Window step = 128 units
Hamming window

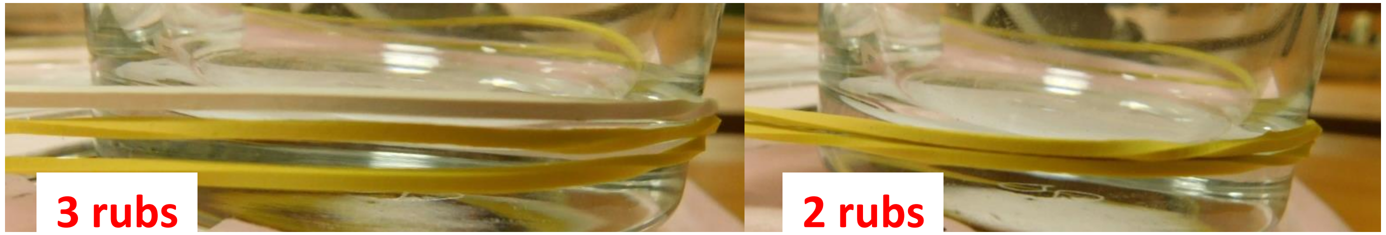


Experimental setup



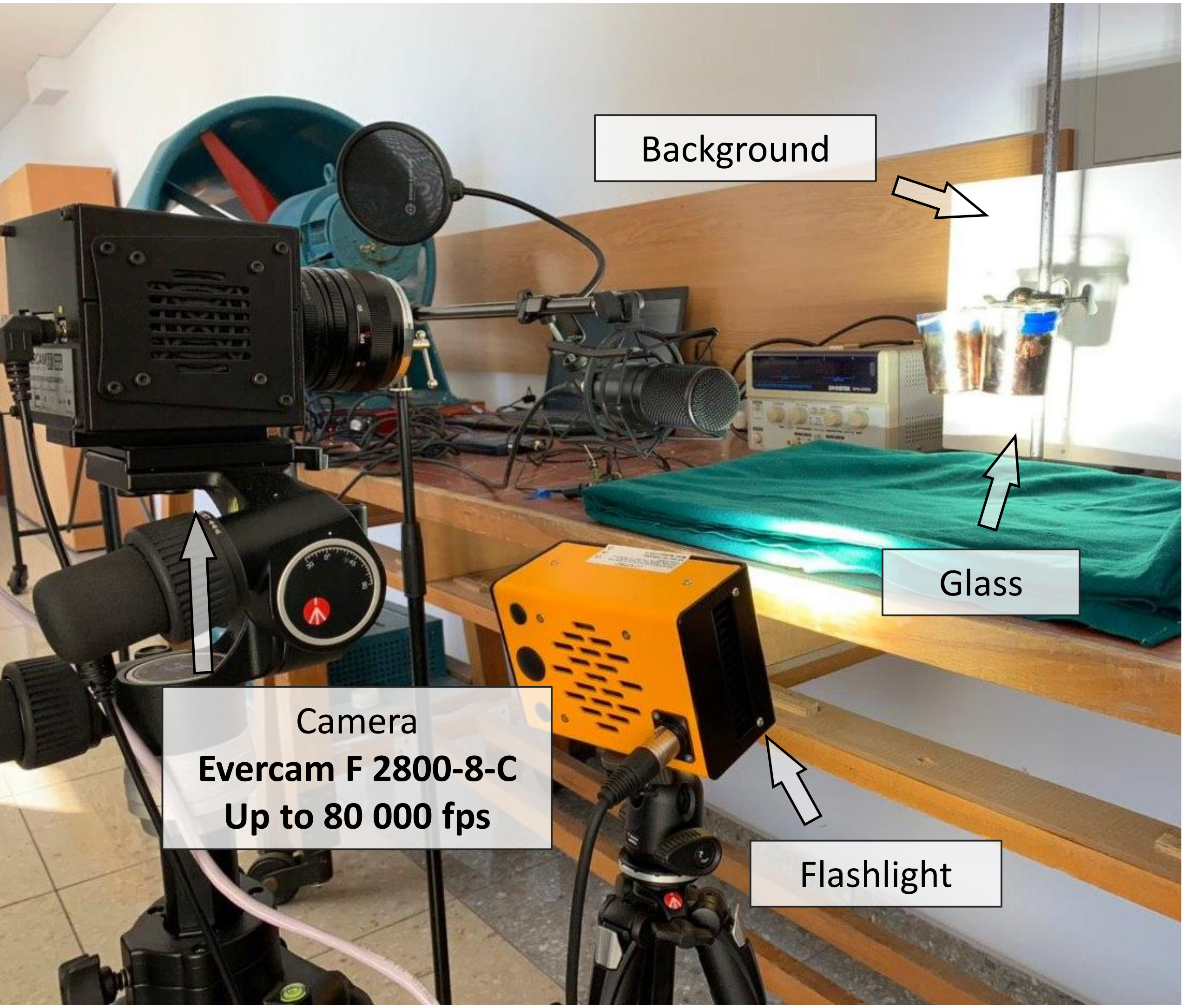
Different rods wit different radiuses

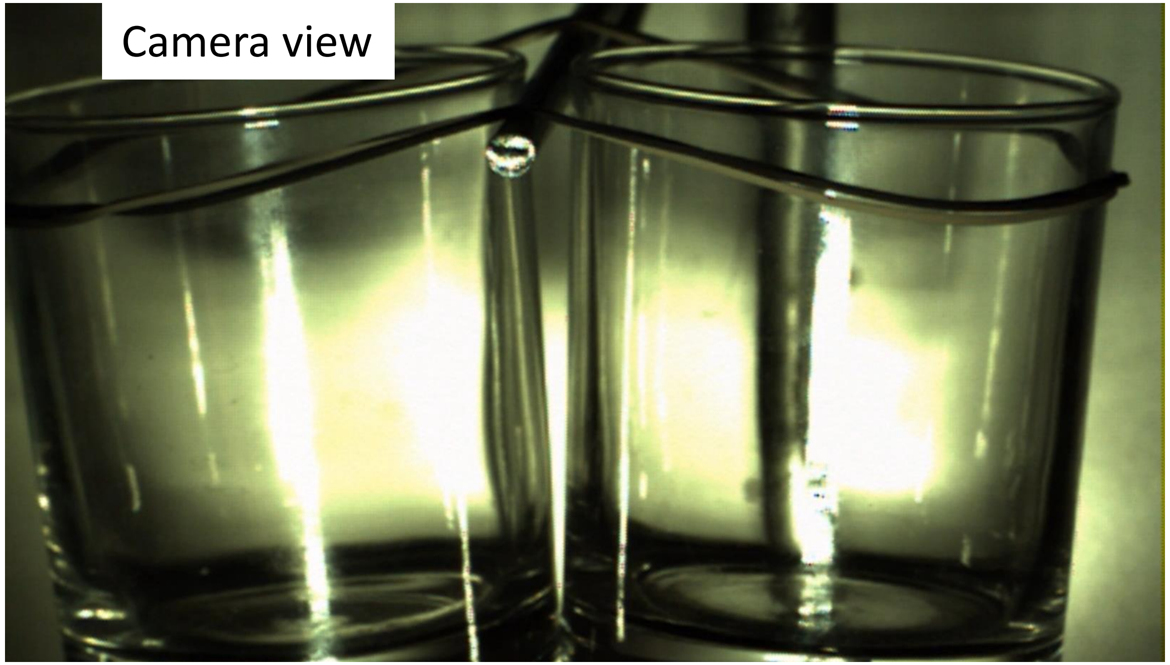
Different forces acting on the system



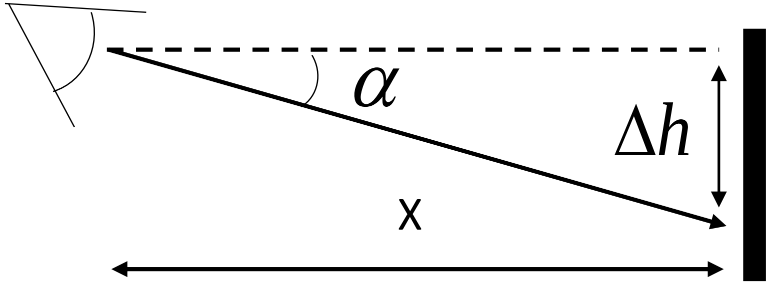
Setup provides symmetry launch

Camera parameters





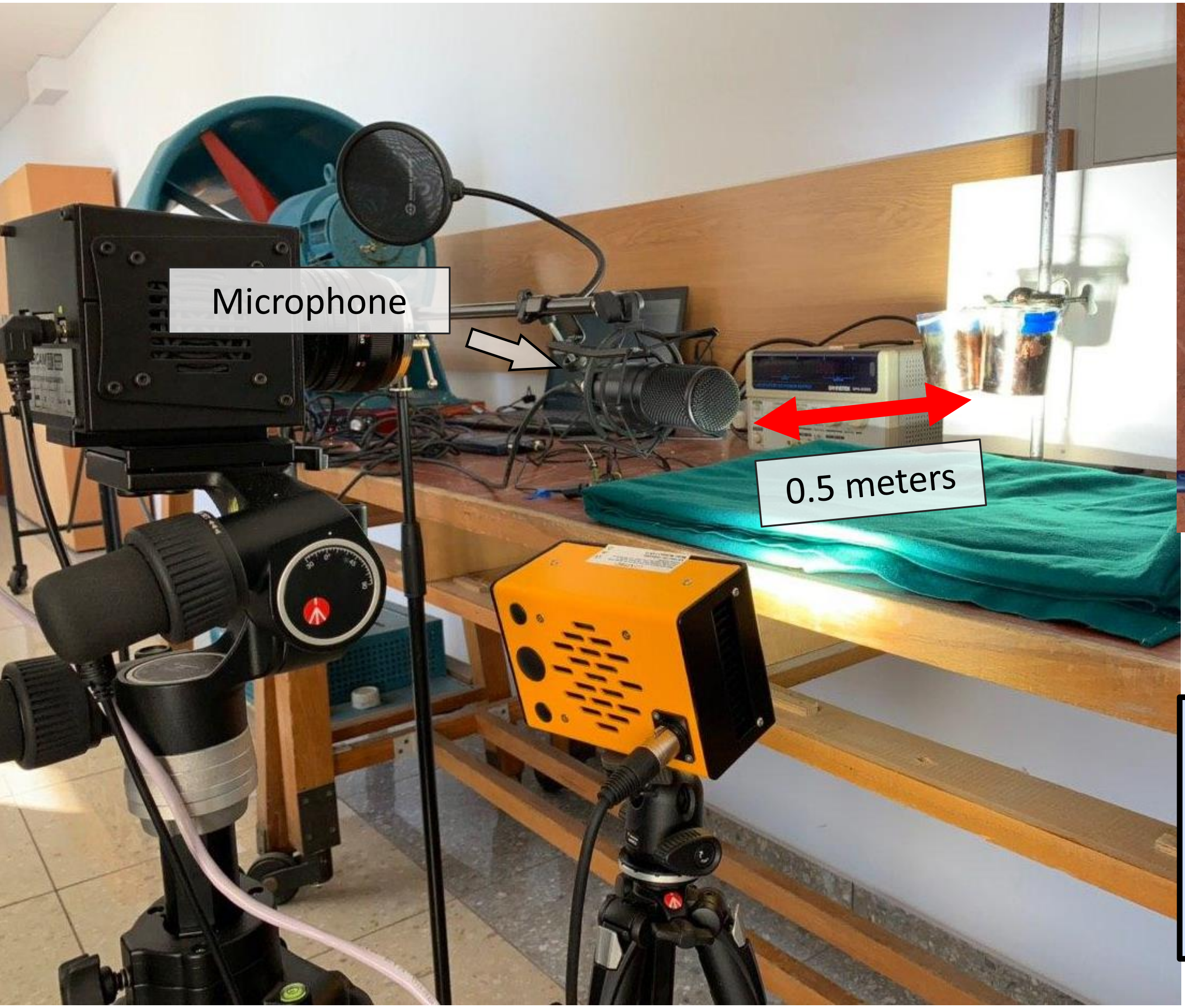
6000 fps, 1624x1080 px, angle of view ~5 degrees



$$\Delta h = x \sin\alpha$$

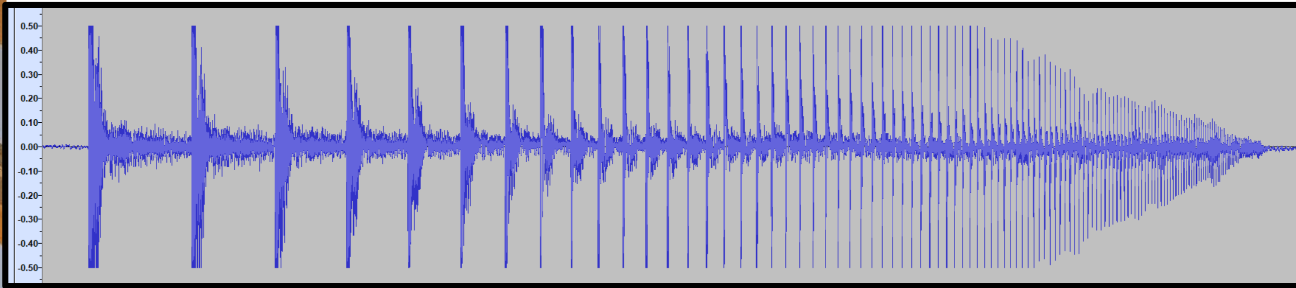
$$\frac{\Delta h}{h} \approx 4\%$$

Microphone parameters



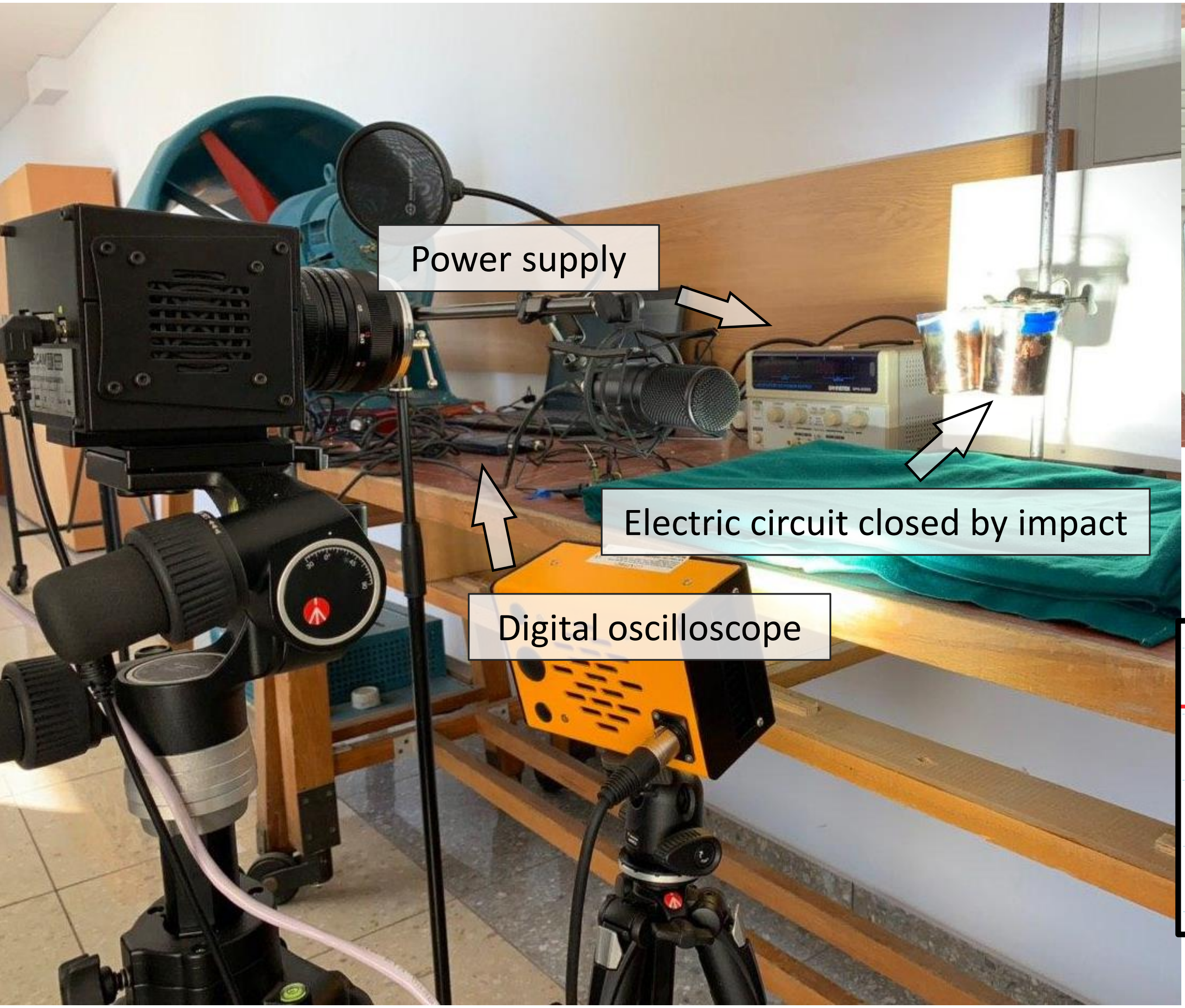
External sound card
Focusrite Scarlett 2nd gen solo
44 100 Hz discretization

Condenser microphone
AKG P120 (cardioid pattern)
20 Hz to 20 kHz response



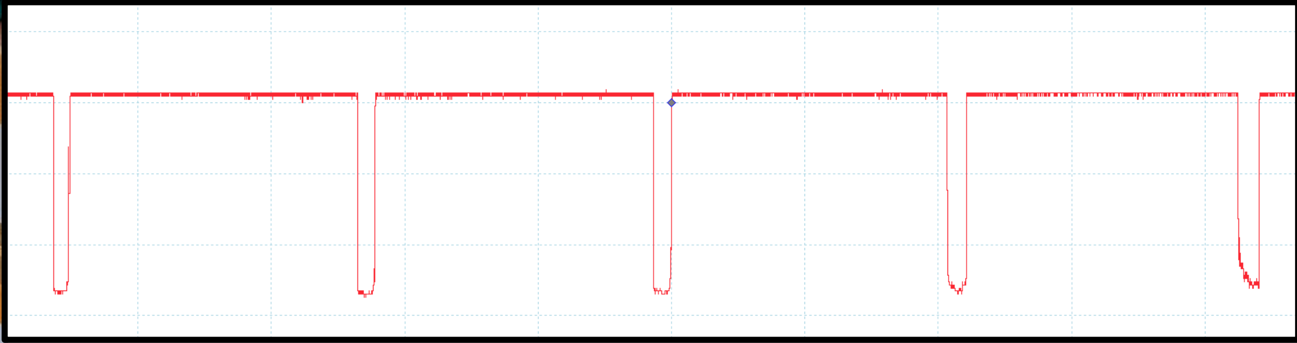
Signal from sound card VS. Time

Electrical parameters



Power supply
GPS-2303 GW INSTEK
Output voltage resolution 100mV

Digital oscilloscope
AKIP-72204A
Discretization up to 100 MHz

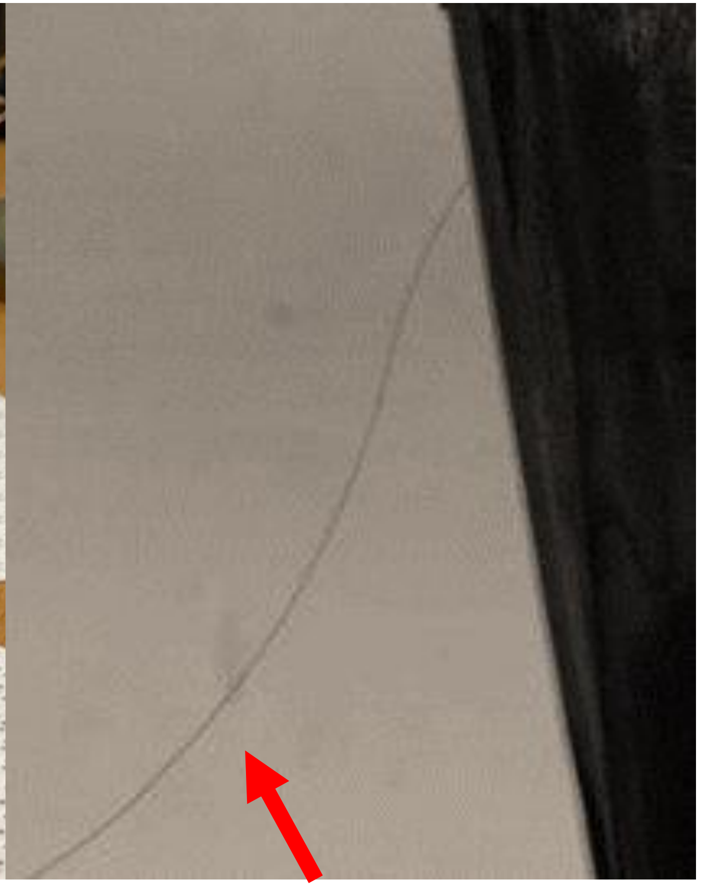


Signal from oscilloscope VS. Time

Sputtering conductor onto glasses

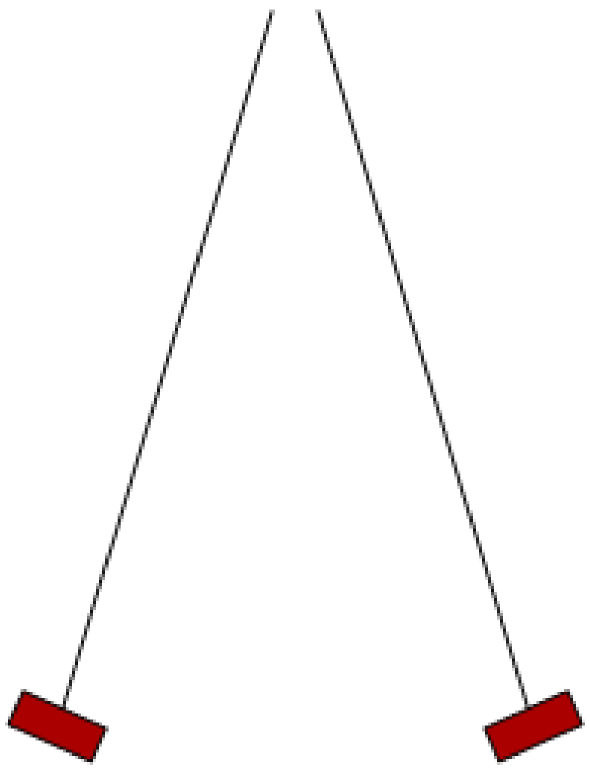
Sputtering setup

Sputtered glasses
Aluminum 2μm$\pm$30nm



Wires **(cold soldered with gold)**
Copper 100μm$\pm$5μm

Investigation plan

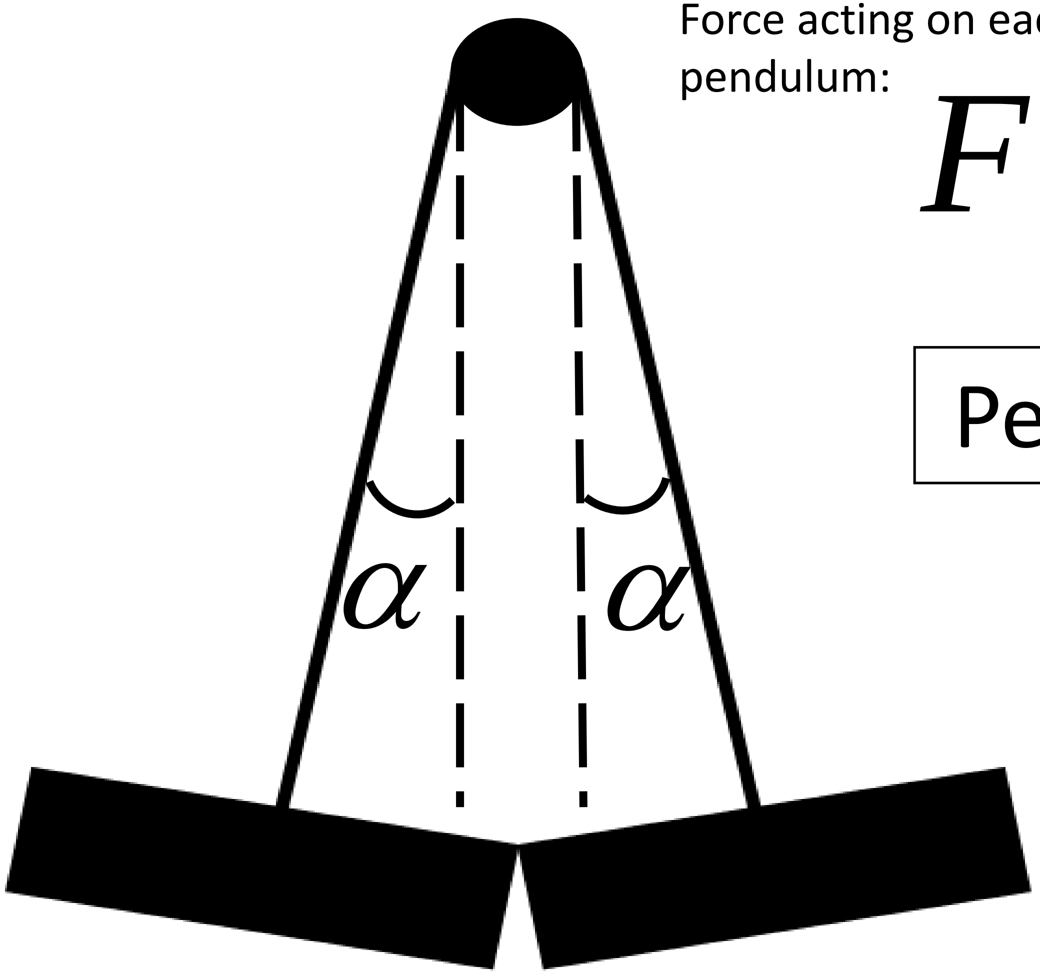


Pendulum analogy simulation

1	Introduction ✓	• Fingers role problem • Collisions distinction problem • Experimental setup
2	Multi collision	• Pendulum analogy • Finger force \ diameter role • Restitution coefficient
3	Contact moment	• Palmgren's contact model • Time of contact • FEM impact modelling
4	System frequencies	• Eigenfrequencies • FEM frequency modelling • Oscillator frequency
5	System acoustics	• Oscillations frequency • FFT window size • Psychoacoustic experiment

Also we have appendix slides for different questions

Qualitative pendulum model



Force acting on each pendulum:

$$F = -kx - f$$

Oscillation strain (kx) · Initial strain (f)

Rubs in Hooke's law application area

Simple harmonic motion

Pendulums collide before equilibrium

Time between collisions:

$$2\cdot\left(\frac{T}{4} - t_{equlibrium-impact}\right) = \frac{1}{\omega}\left(\pi - 2\arcsin\left(\frac{x}{x_m}\right)\right)$$

Collision coordinate (x)

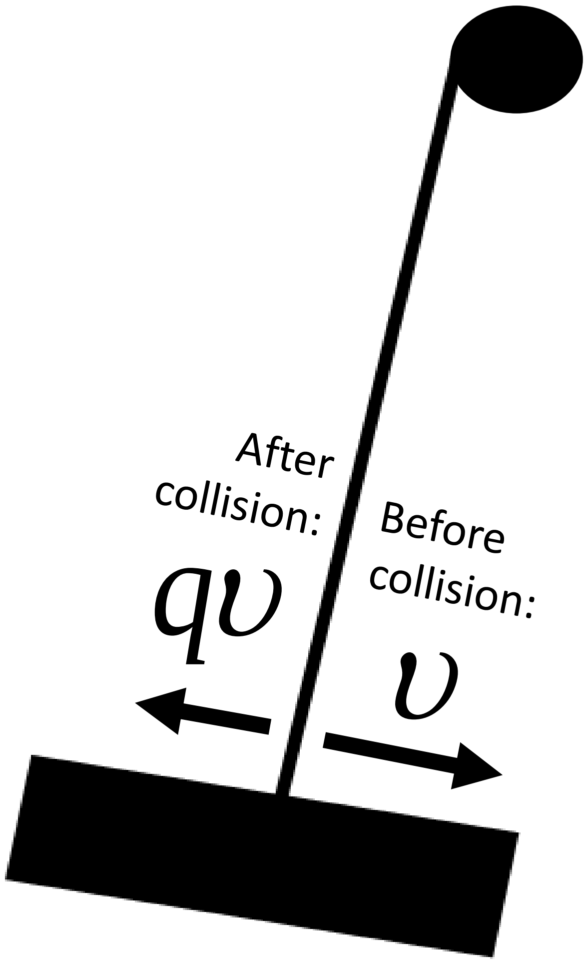
Constant angular frequency (ω)

Current amplitude (x_m)

Amplitude changing

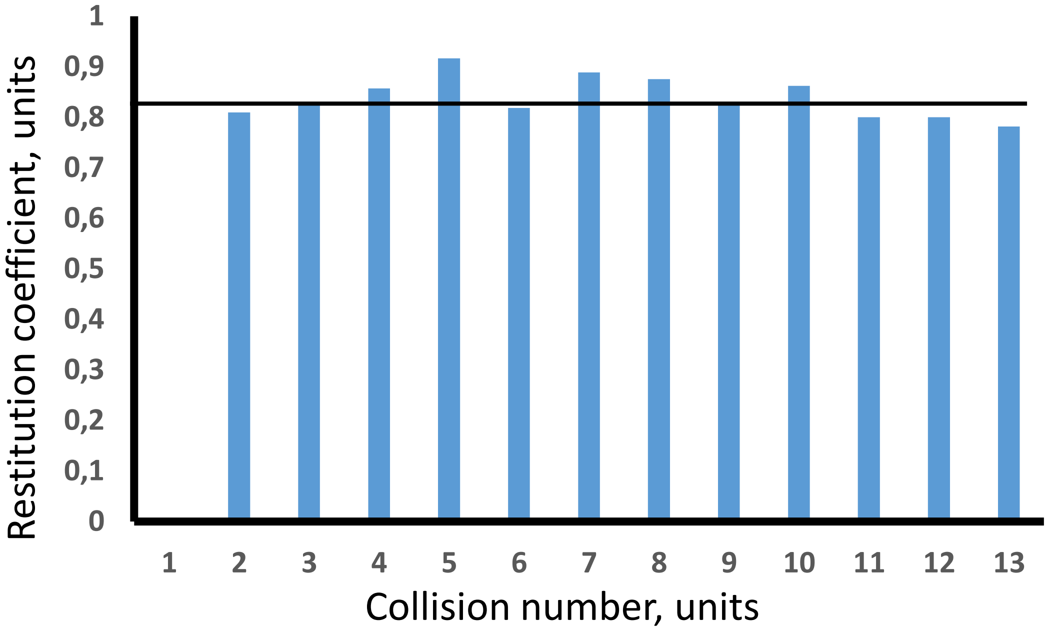
Time between collisions:

$$2\cdot\left(\frac{T}{4}-t_{equlibrium-impact}\right)=\frac{1}{\omega}\left(\pi-2\arcsin\left(\frac{x}{x_m}\right)\right)$$



$$q=\frac{\upsilon_{i+1}}{\upsilon_i}=const$$

$$q=0,82\pm0,02$$



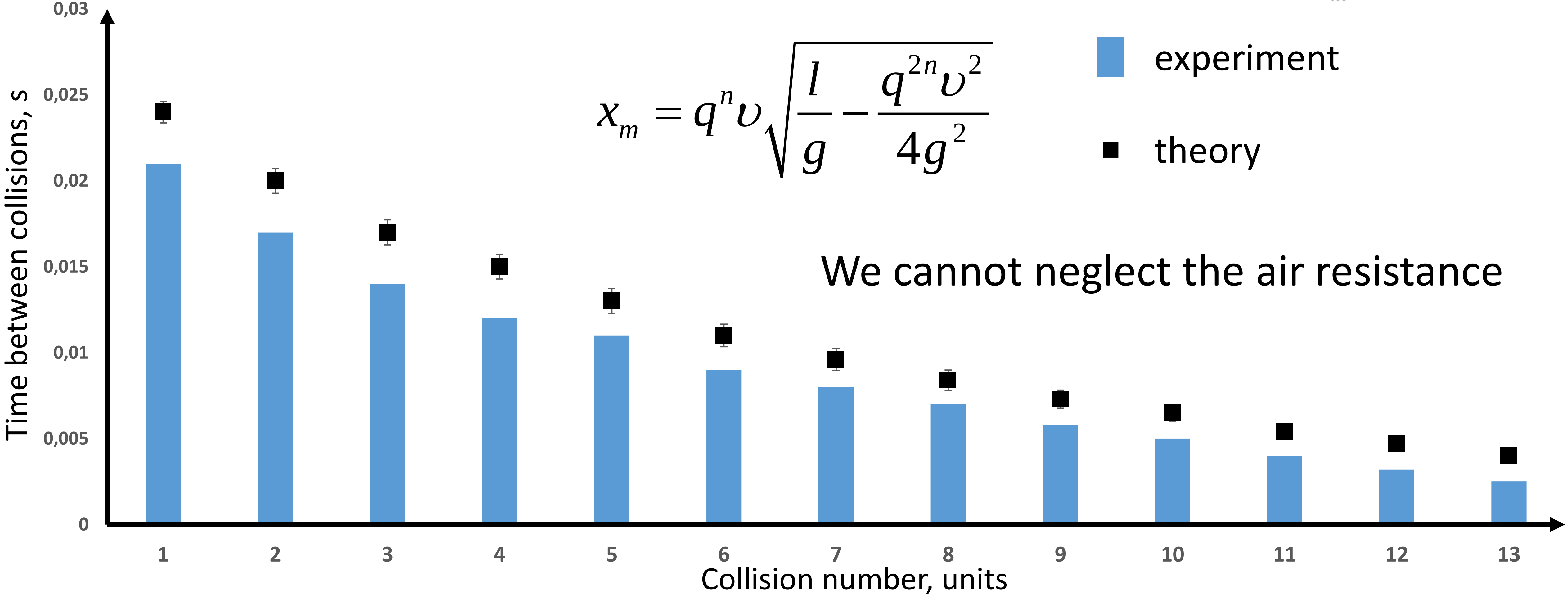
Restitution coefficient is constant for different collisions.

Time between collisions changing

Time between collisions:

$$2\cdot\left(\frac{T}{4}-t_{equlibrium-impact}\right)=\frac{1}{\omega}\left(\pi-2\arcsin\left(\frac{x}{x_m}\right)\right)$$

$$x_m = q^n \upsilon \sqrt{\frac{l}{g}-\frac{q^{2n}\upsilon^2}{4g^2}}$$



We cannot neglect the air resistance

Non-harmonic motion

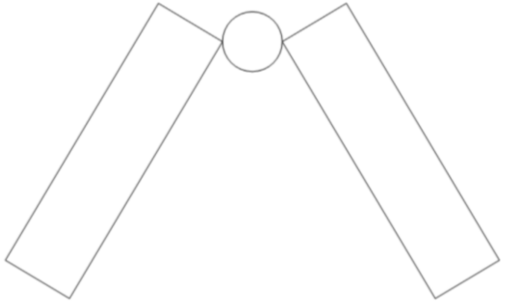
Elasticity coefficient

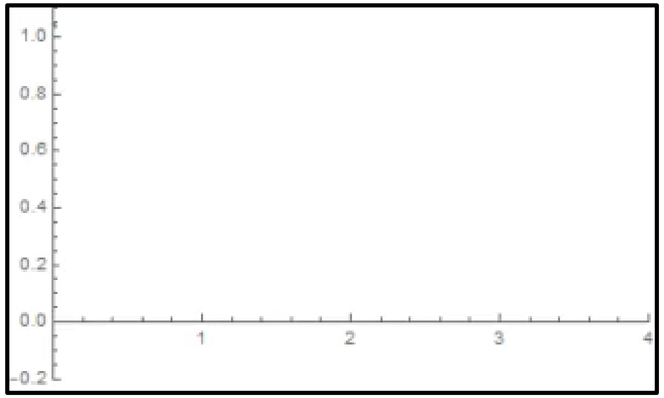
Air resistance coefficient
Re >> 1

Small-angles
model

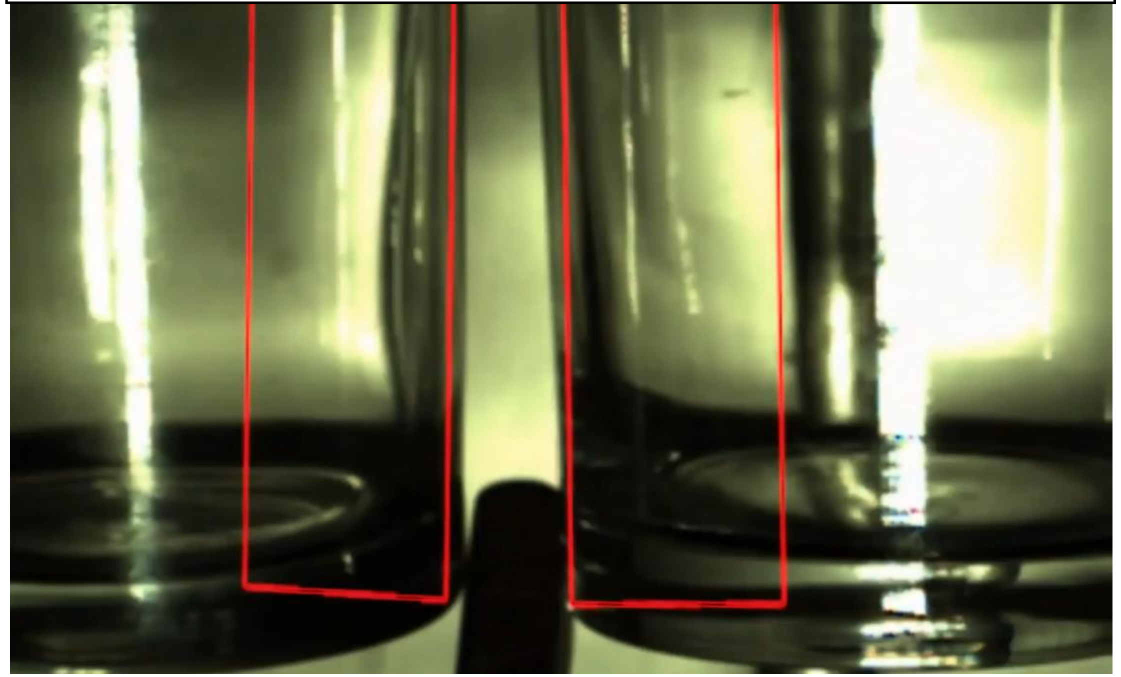
$$\begin{cases} I\ddot{\alpha} = -M - k_{Hooke's}\alpha + k_{\mathrm{Re}}\dot{\alpha}^2 - mgl\sin\alpha \\ \upsilon_{i+1} = -q\upsilon_i, \text{ after collision} \end{cases}$$

Solve the system by Wolfram Mathematica
NDSolve with Runge-Kutta:





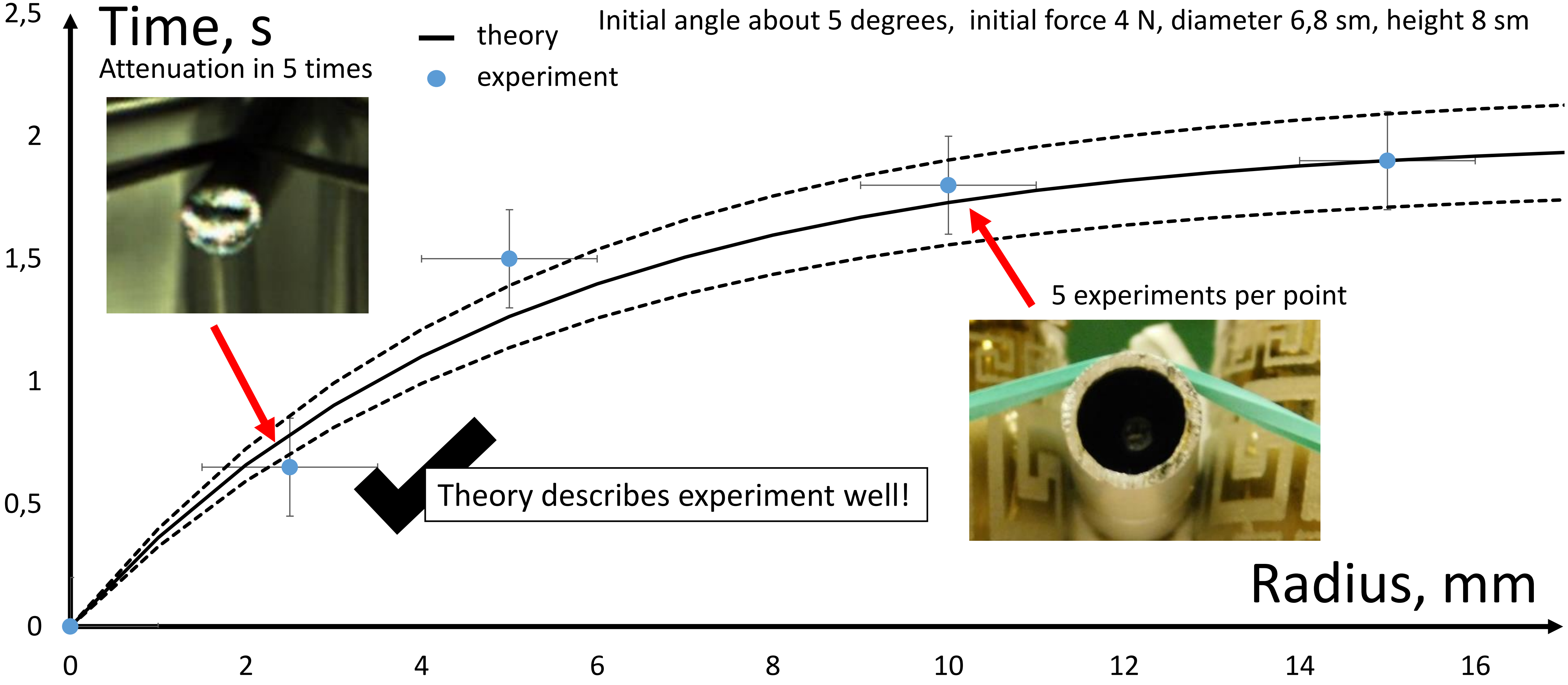
Comparison with the real experiment:



2 **Multi collision**:

- Qualitative pendulum model
- 2nd Newton's law model
- Time between collisions
- Restitution coefficient measurement

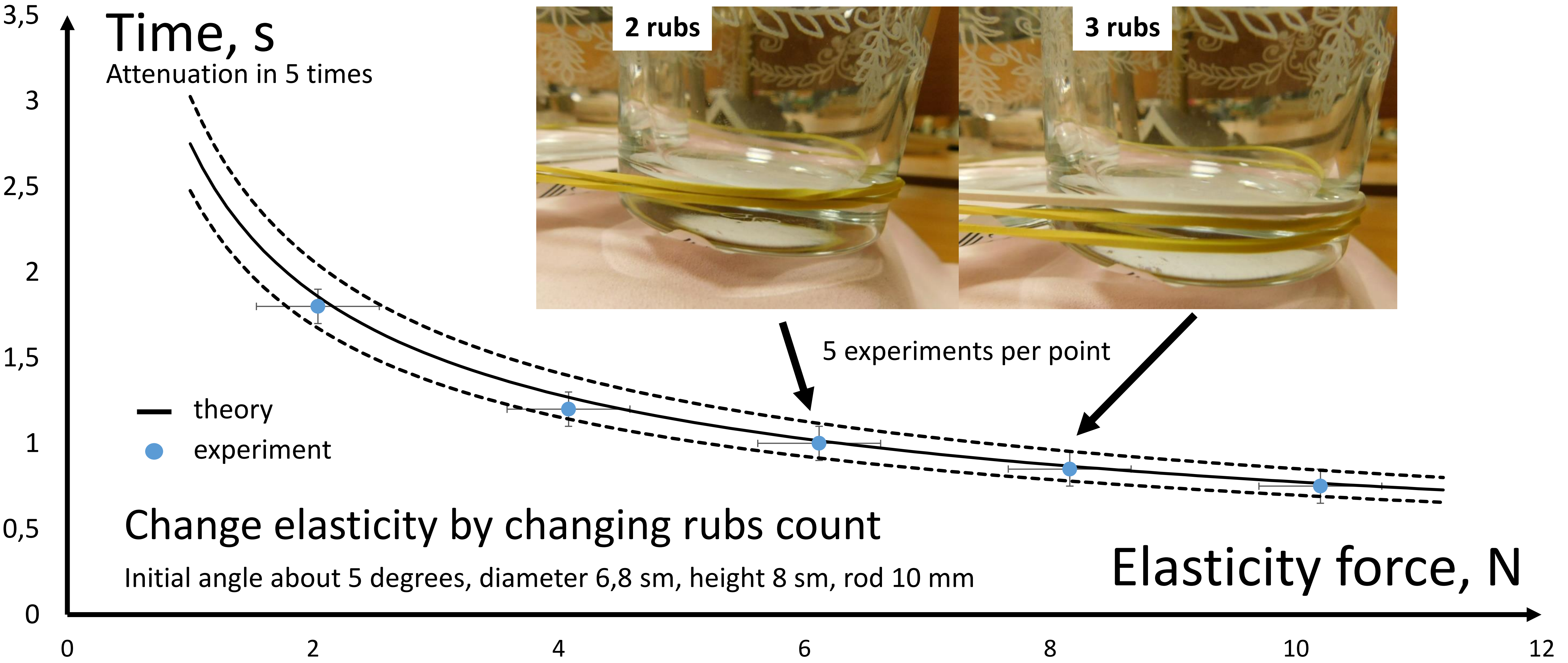
Time of collisions VS. Rod radius



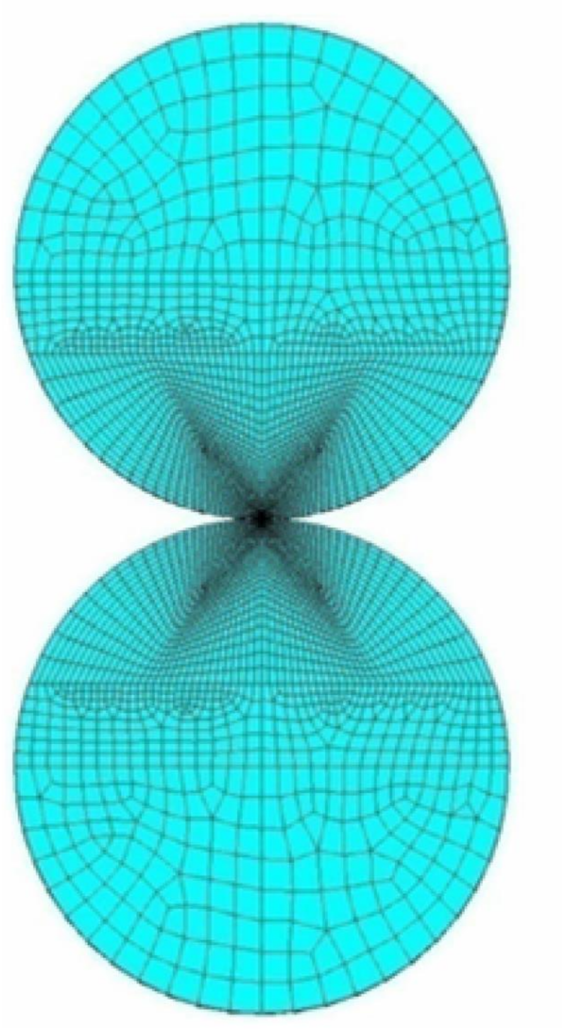
② **Multi collision**

- Qualitative pendulum model
- 2nd Newton's law model
- Time between collisions
- Restitution coefficient measurement

Time of collisions VS. Initial elasticity force



Investigation plan



FEM mesh

1	Introduction ✓	• Fingers role problem • Collisions distinction problem • Experimental setup
2	Multi collision ✓	• Pendulum analogy • Finger force \ diameter role • Restitution coefficient
➡ 3	Contact moment	• Palmgren's contact model • Time of contact • FEM impact modelling
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Also we have appendix slides for different questions

Palmgren's cylinder contact model

T A Harris and M N Kotzalas,. Rolling bearing analysis, New York, NY: Wiley (2001).

Stiffness parameter

Nonlinear power exponent

$$F = K\delta^{n}$$

$$n = \frac{10}{9}$$

Contact force

Relative indentation

Poisson coefficients

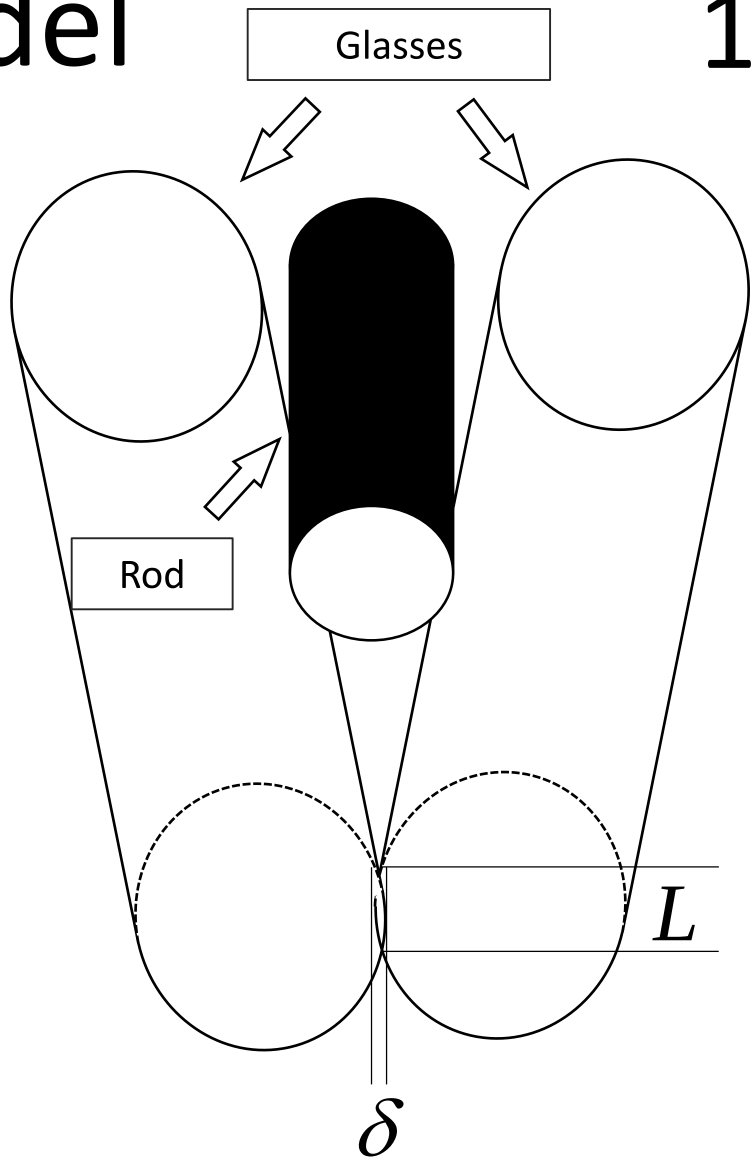
$$\frac{1}{E^{*}} = \frac{1-\nu_i^{2}}{E_i} + \frac{1-\nu_j^{2}}{E_j}$$

Elastic modules

Contact length

$$K = \frac{1}{1.36^{n}} E^{*} L^{\frac{8}{9}}$$

Modulus composition



Palmgren's cylinder contact model

*W. Yufang and T. Zhongfang. Sound radiated from the impact of two cylinders, Journal of Sound and Vibration, **159** (2) (1992) 295-303.*

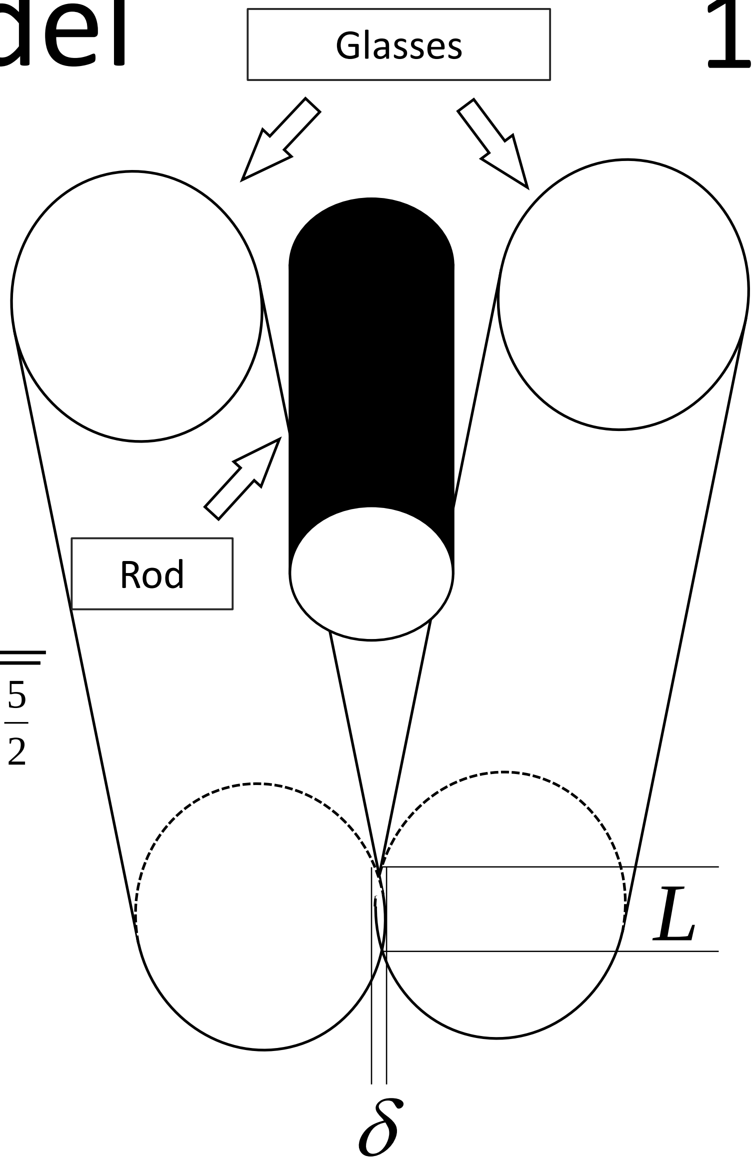
By Newton's law application with Yufang and Zhongfang corrections:

$$\delta_{\max} = \left(\frac{5}{8}\frac{m_{glass}}{K}{v_0}^2\right)^{\frac{2}{5}}$$,where $v_0 = \frac{v_i}{v_j}$

$$F_{\max} = K\left(\frac{5}{8}\frac{m_{glass}}{K}{v_0}^2\right)^{\frac{3}{5}}$$ $$t_{contact} = \frac{2\delta_{\max}}{v_0}\int_0^1 \frac{d\left(\delta/\delta_{\max}\right)}{\sqrt{1-\left(\delta/\delta_{\max}\right)^{\frac{5}{2}}}}$$

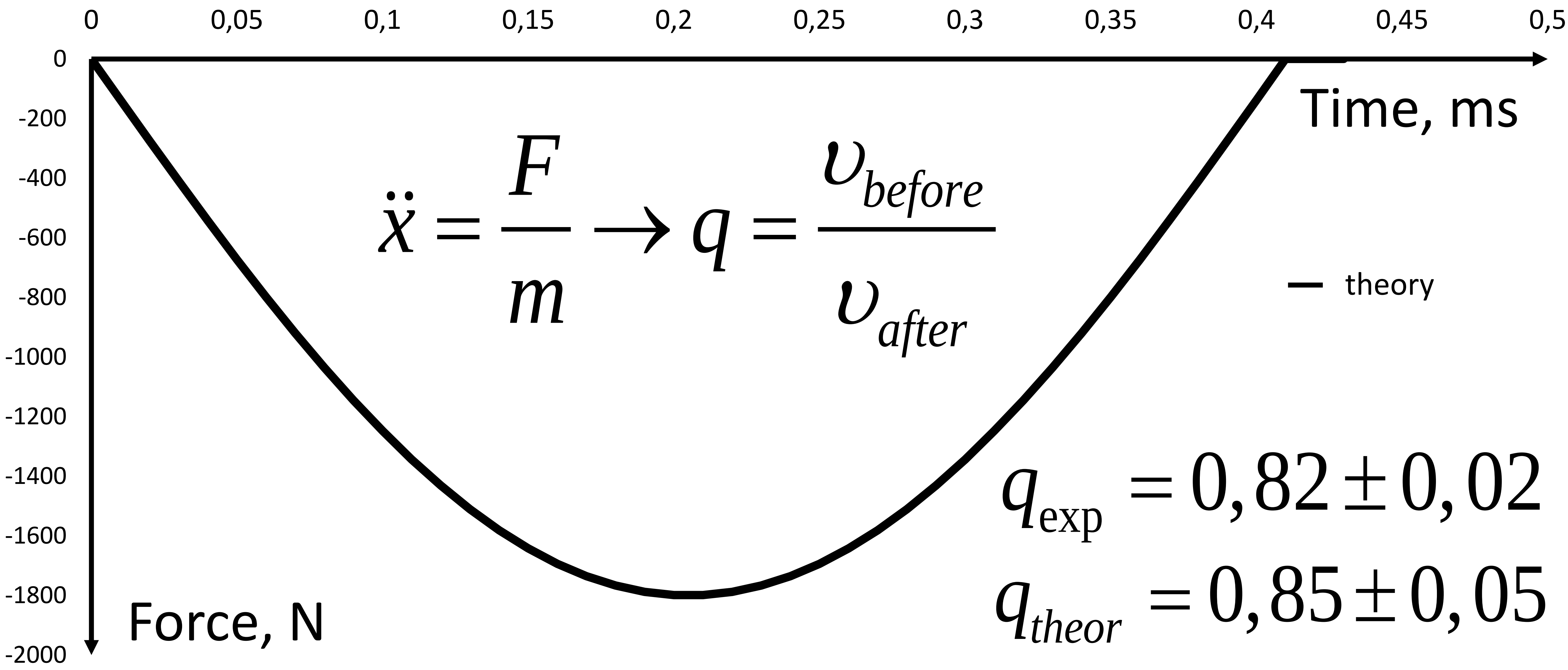
We can assume:

$$F = F_{\max}\sin\omega_c t$$,where $\omega_c = \frac{\pi}{t_{contact}}$



3 Contact moment:
- Palmgren's model
- Time of contact
- FEM contact modelling
- Restitution coefficient calculation

Contact force VS. Time



$$\ddot{x} = \frac{F}{m} \rightarrow q = \frac{\upsilon_{before}}{\upsilon_{after}}$$

$$q_{\exp} = 0,82 \pm 0,02$$

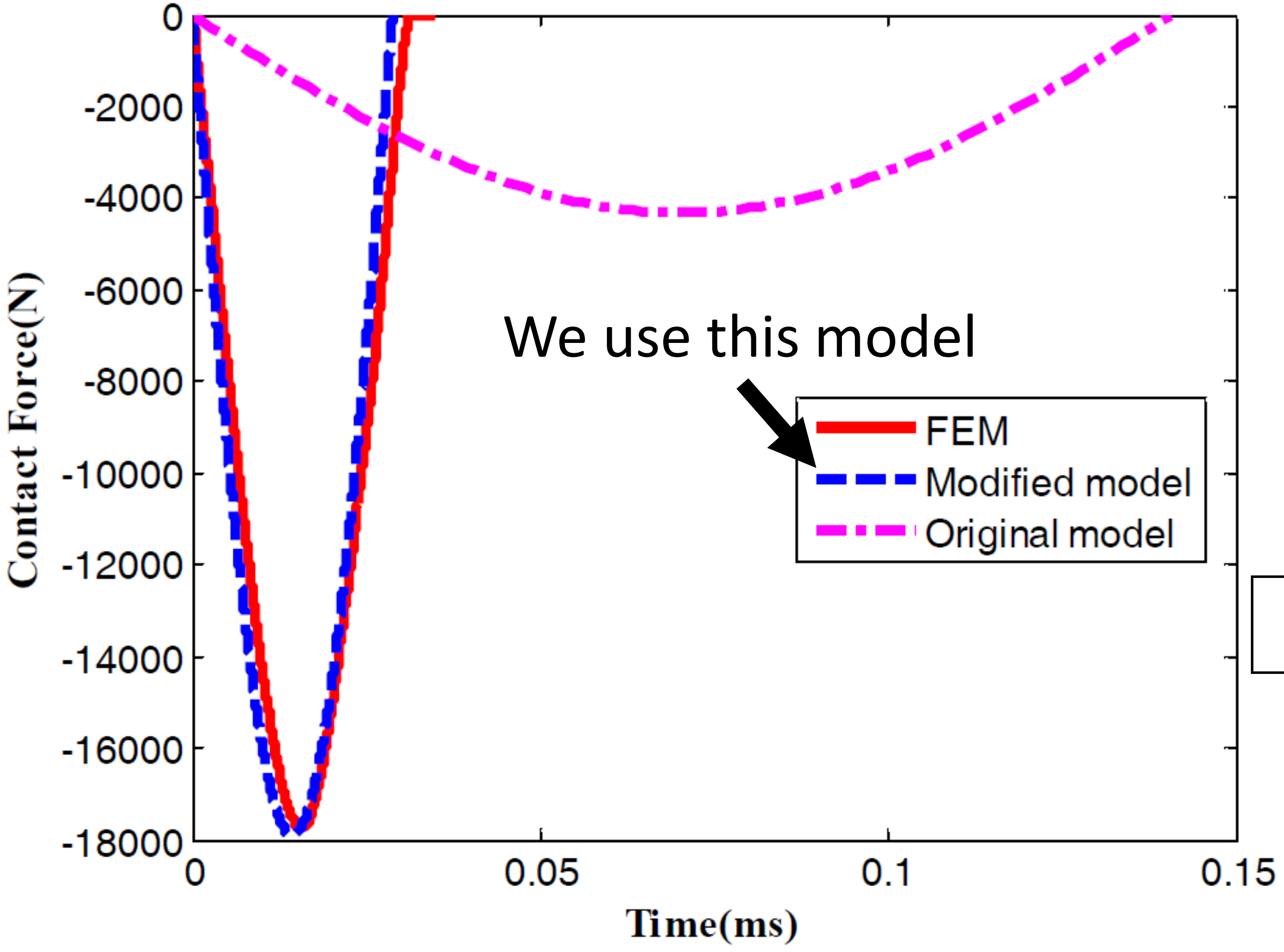
$$q_{theor} = 0,85 \pm 0,05$$

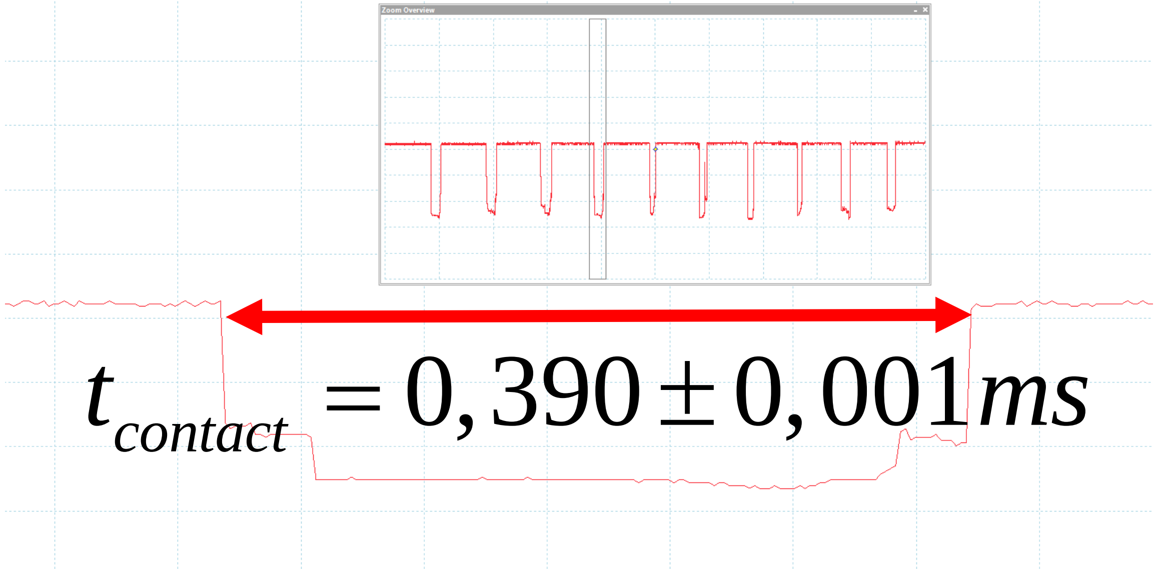
3 <u>Contact moment</u>:

- Palmgren’s model
- Time of contact
- FEM contact modelling
- Restitution coefficient calculation

FEM modelling comparison

Yinggang Li, Tianning Chen, Xiaopeng Wang, Kunpeng Yu and Chao Zhang, Theoretical and numerical investigation on impact noise radiated by collision of two cylinders, Journal of Mechanical Science and Technology* ***28*** *(6) (2014) 2017~2024*





$$t_{contact} = 0,390 \pm 0,001 ms$$

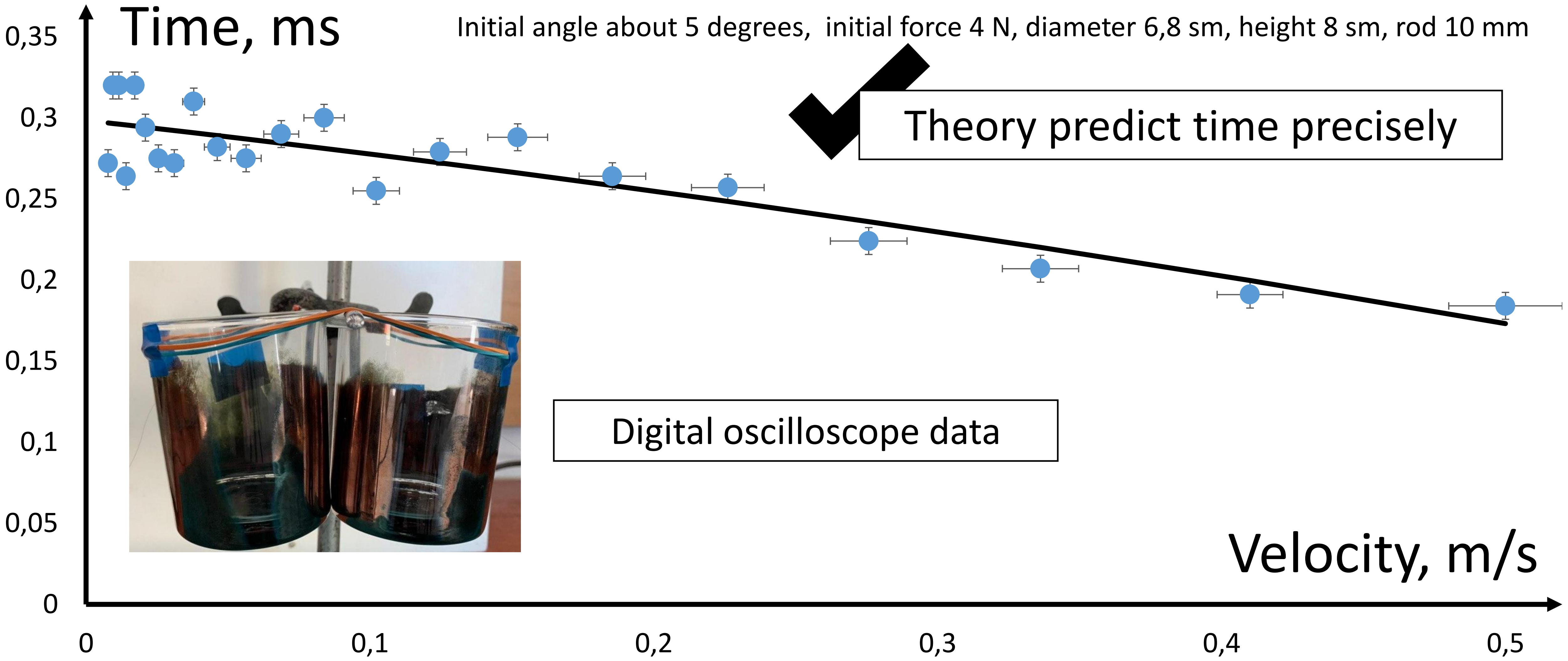
Digital oscilloscope data

$$t_{contact\ theory} = 0,41 \pm 0,1 ms$$

③ <u>Contact moment</u>

- Palmgren's model
- Time of contact
- FEM contact modelling
- Restitution coefficient calculation

Time of contact VS. Velocity



3 Contact moment

- Palmgren's model
- Time of contact
- FEM contact modelling
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Investigation plan

Eigenfrequncies simulation

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Also we have appendix slides for different questions

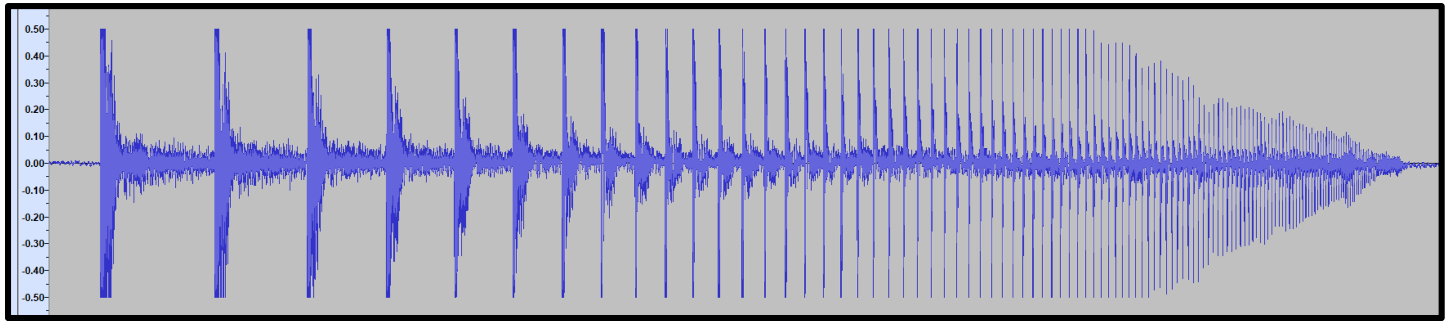
FEM eigenfrequencies modelling

Flexural waves system, eigenfrequencies model:

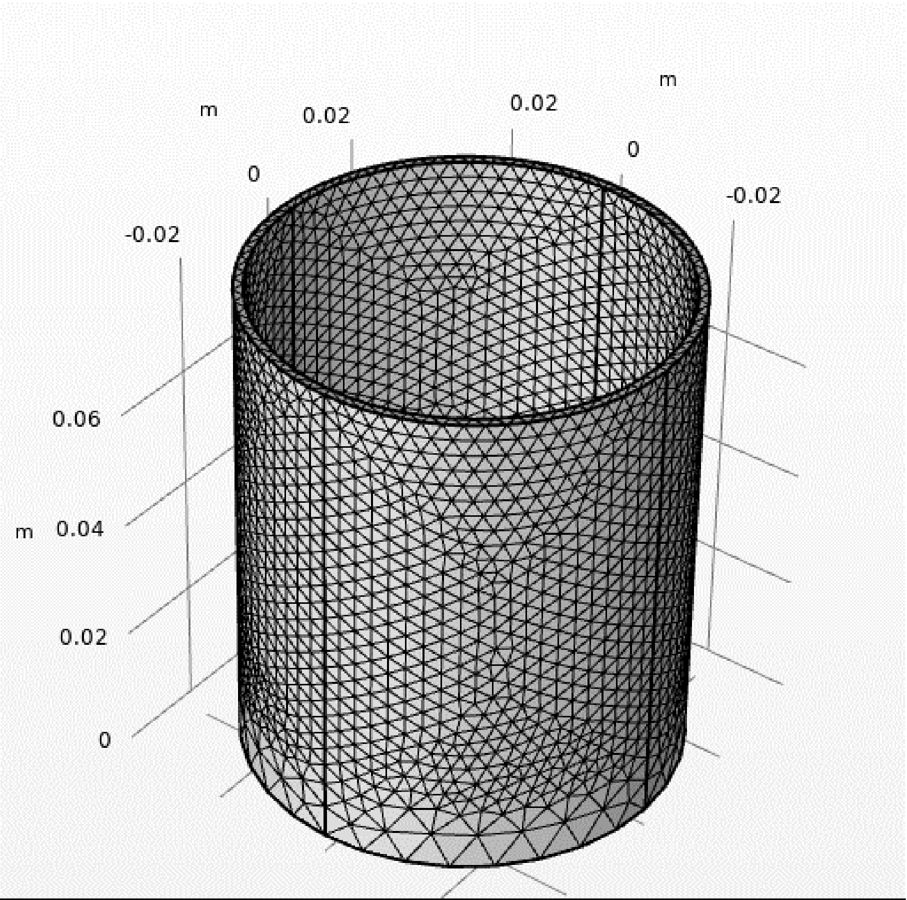
Displacement field **Volume energy density**

$$\begin{cases} -\rho\omega^2 u = \nabla \cdot S & \text{Vibration part} \\ -i\omega = \lambda & \text{Attenuation part} \end{cases}$$

Eigenfrequency Analysis, COMSOL Multiphysics



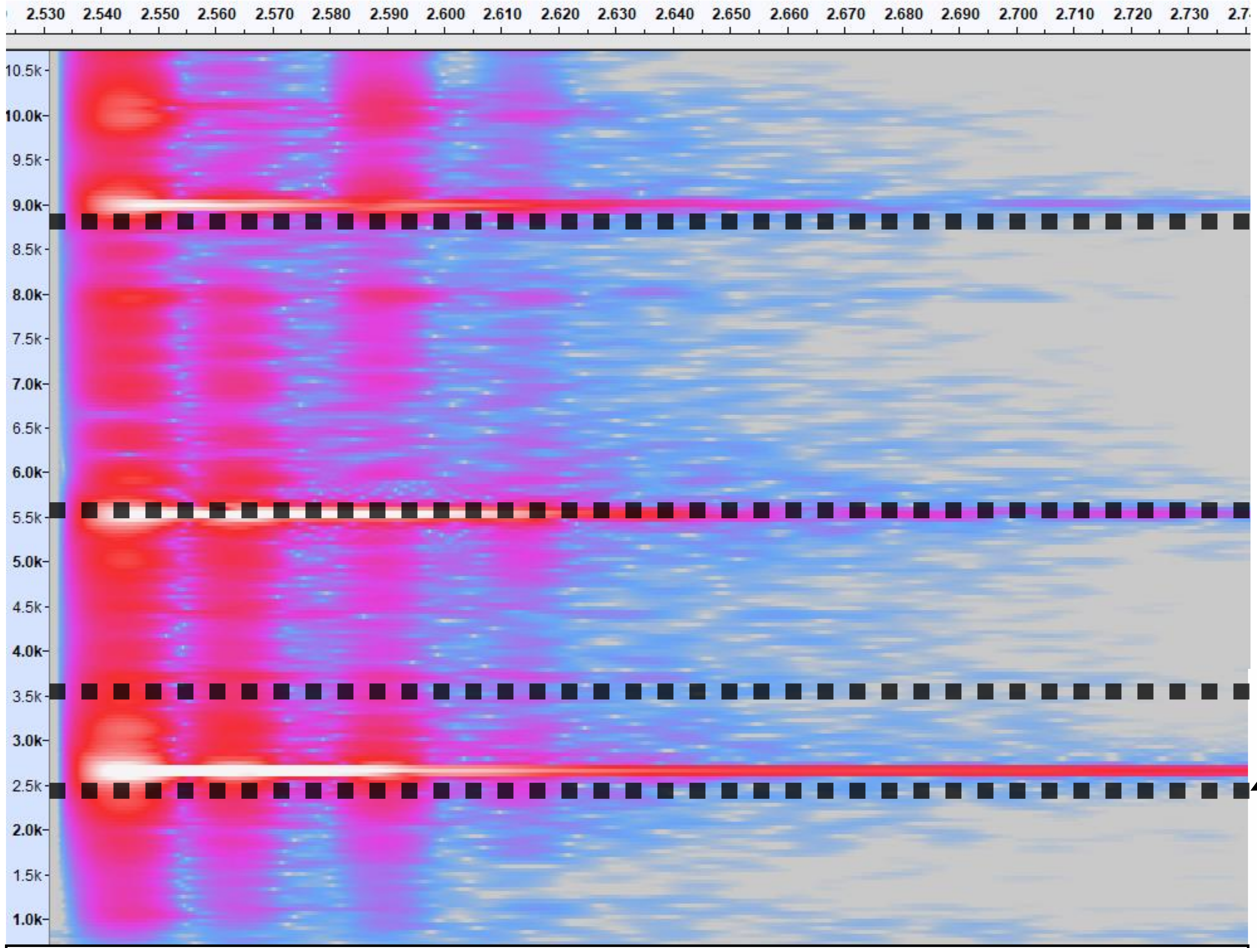
Check our model by Fast Fourier Transform



COMSOL meshing

physics-controlled mesh

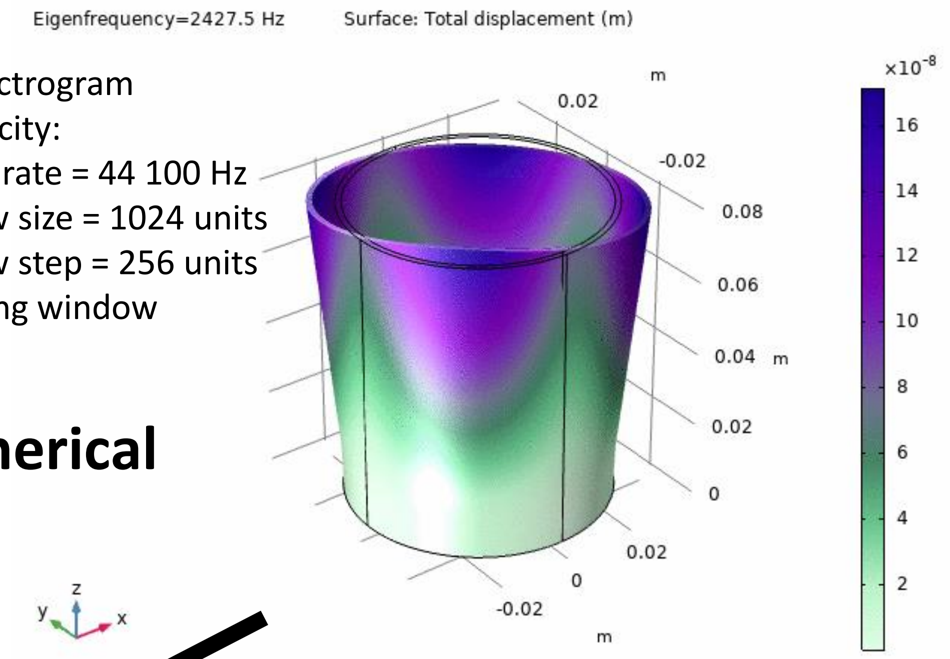
Eigenfrequencies comparison

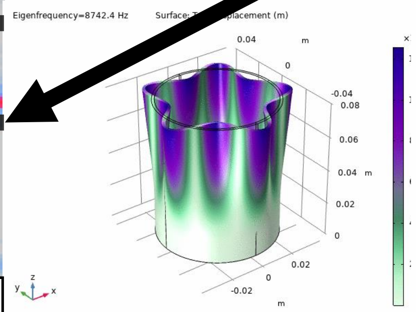


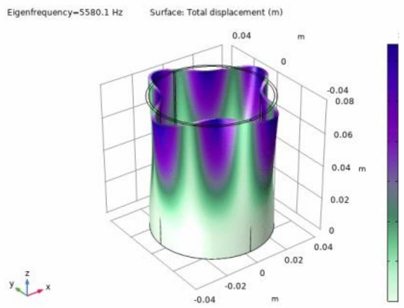
Comparison with single glass impact

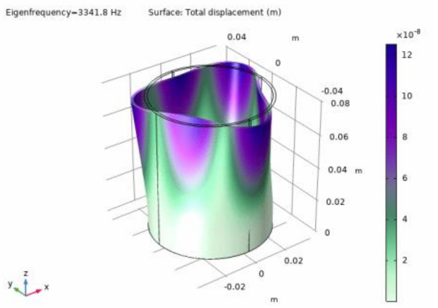
FFT spectrogram
in Audacity:
Sample rate = 44 100 Hz
Window size = 1024 units
Window step = 256 units
Hamming window

Numerical









4 System frequencies

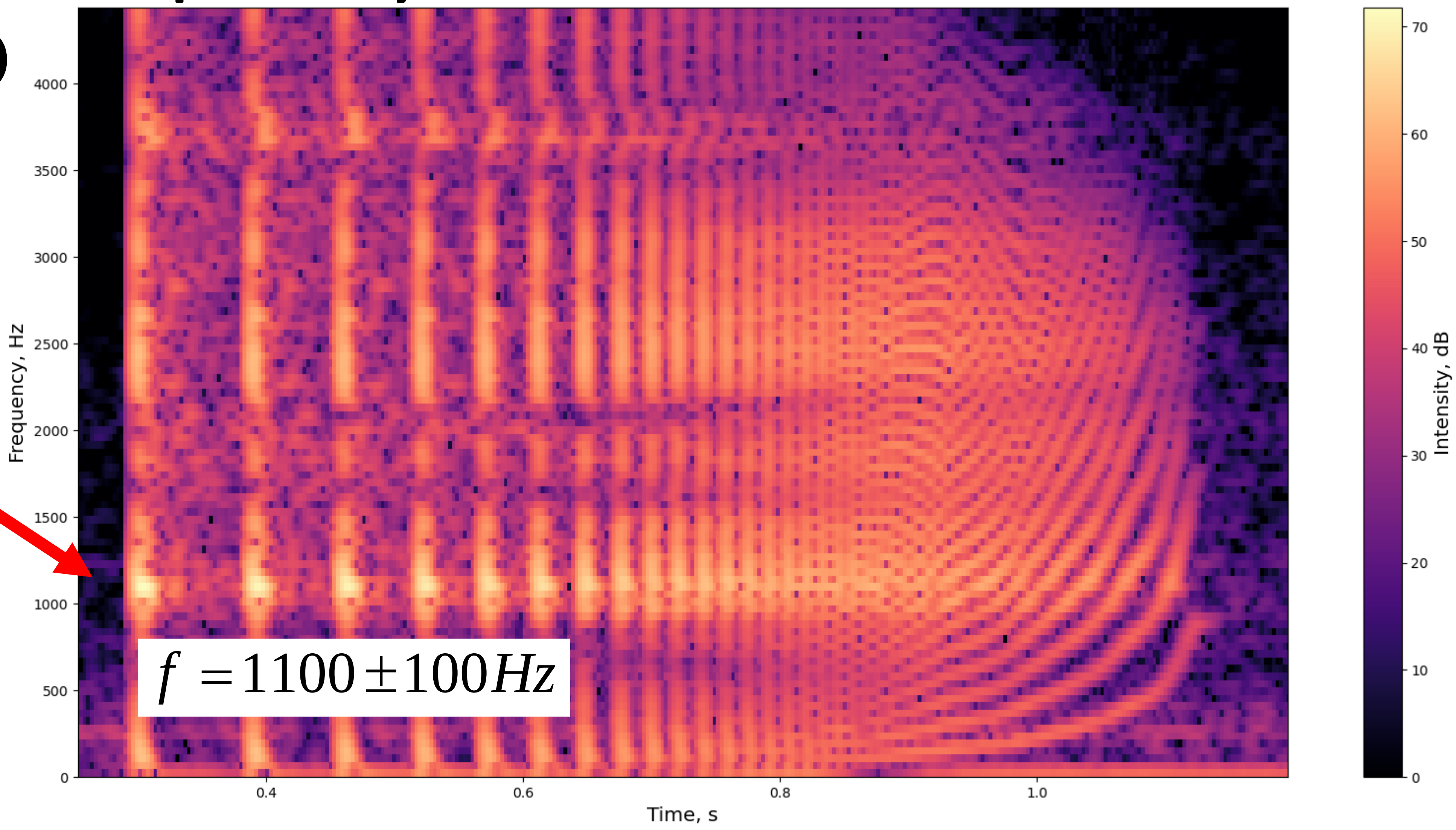
- Eigenfrequencies
- Oscillator frequency
- FEM frequency modelling
- Experimental prove

Our system frequency

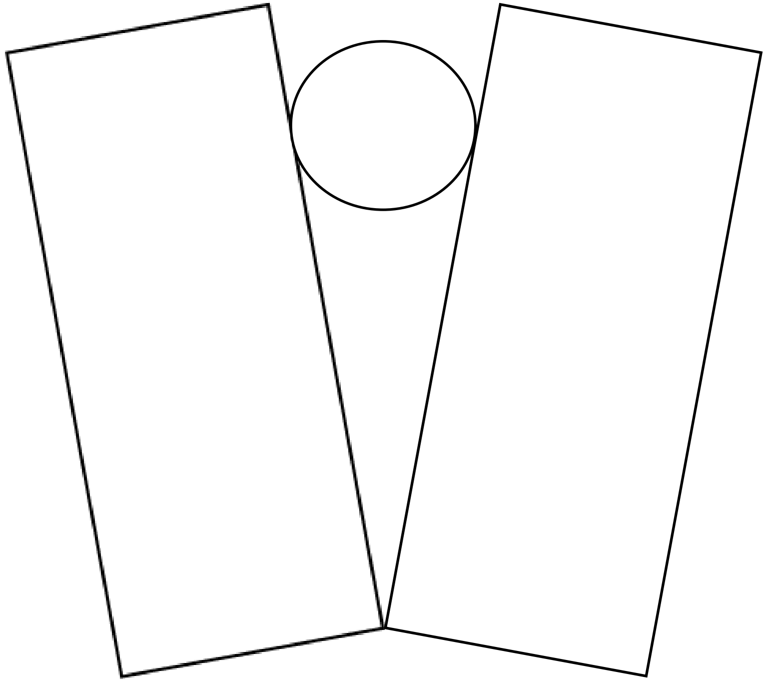
What is the frequency around 1kHz? ?

It's not eigenfrequency of glass!

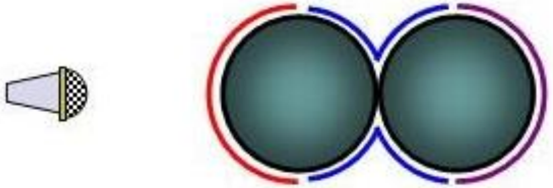
FFT spectrogram
in Python matplotlib:
Sample rate = 44 100 Hz
Window size = 1024 units
Window step = 128 units
Hamming window

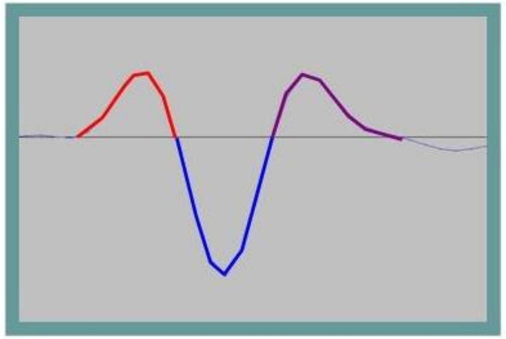


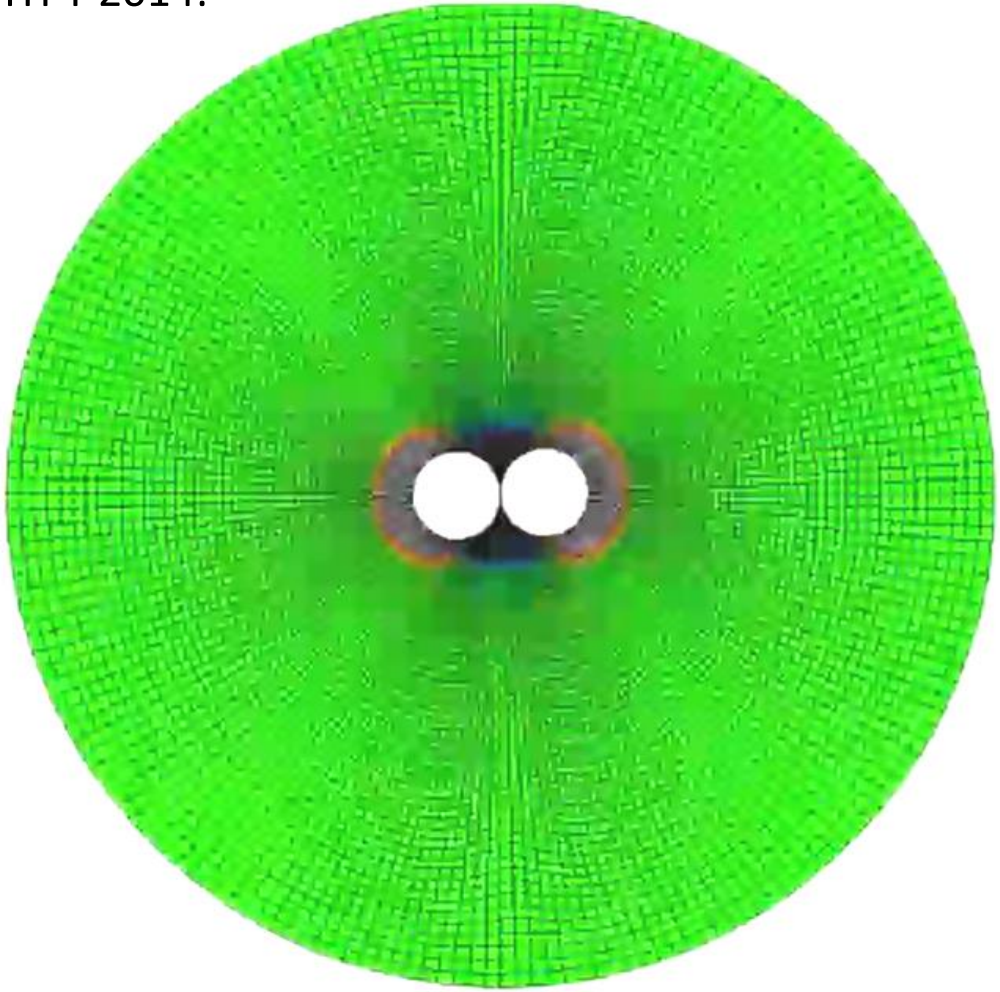
Specific frequency



Ball sound team of Russia solution IYPT 2014:







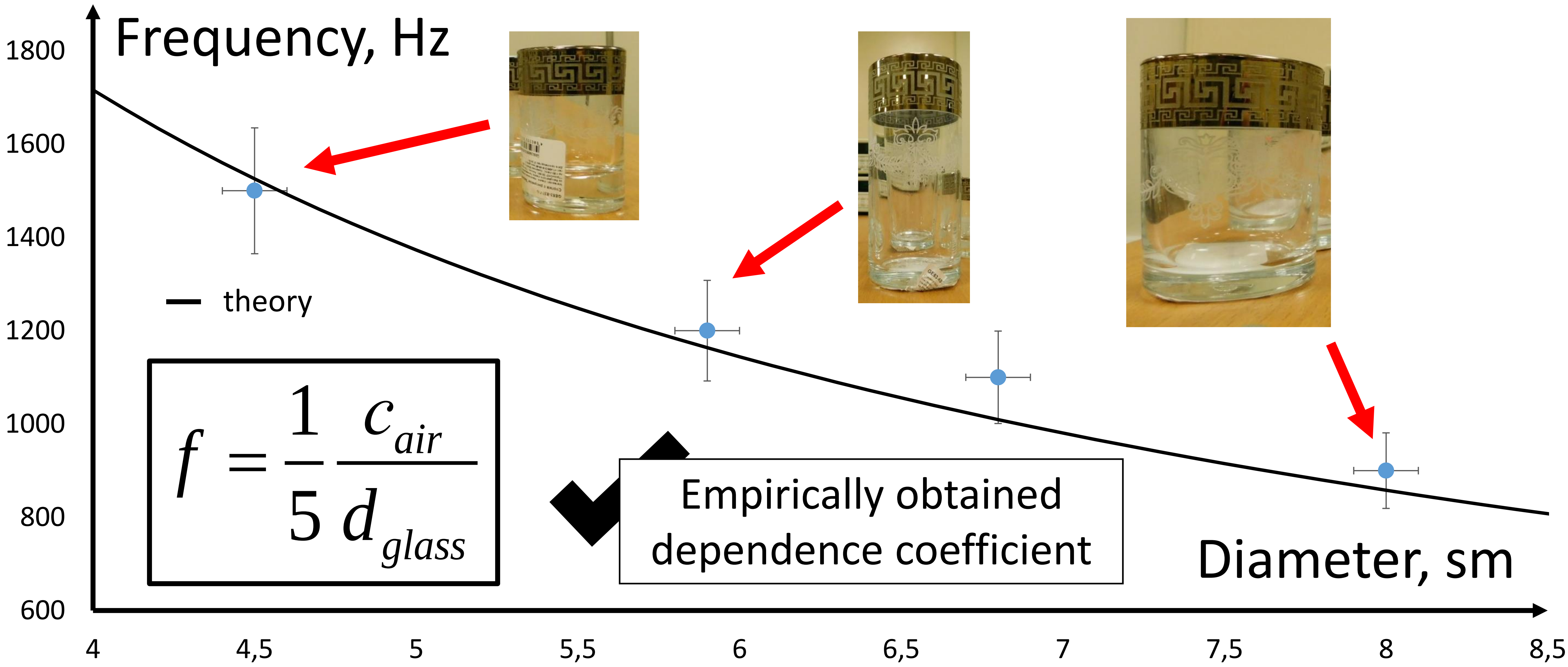
$$f \sim \frac{c_{air}}{d_{glass}}$$

K. Mehraby, H. Khademhosseini Beheshti, and M. Poursina, Impact noise radiated by collision of two spheres: Comparison between numerical simulations, experiments and analytical results, Journal of Mechanical Science and Technology* ***25*** *(7) (2011) 1675~1685*

4 System frequencies

- Eigenfrequencies
- Oscillator frequency
- FEM frequency modelling
- Experimental prove

Frequency VS. Diameter of glasses

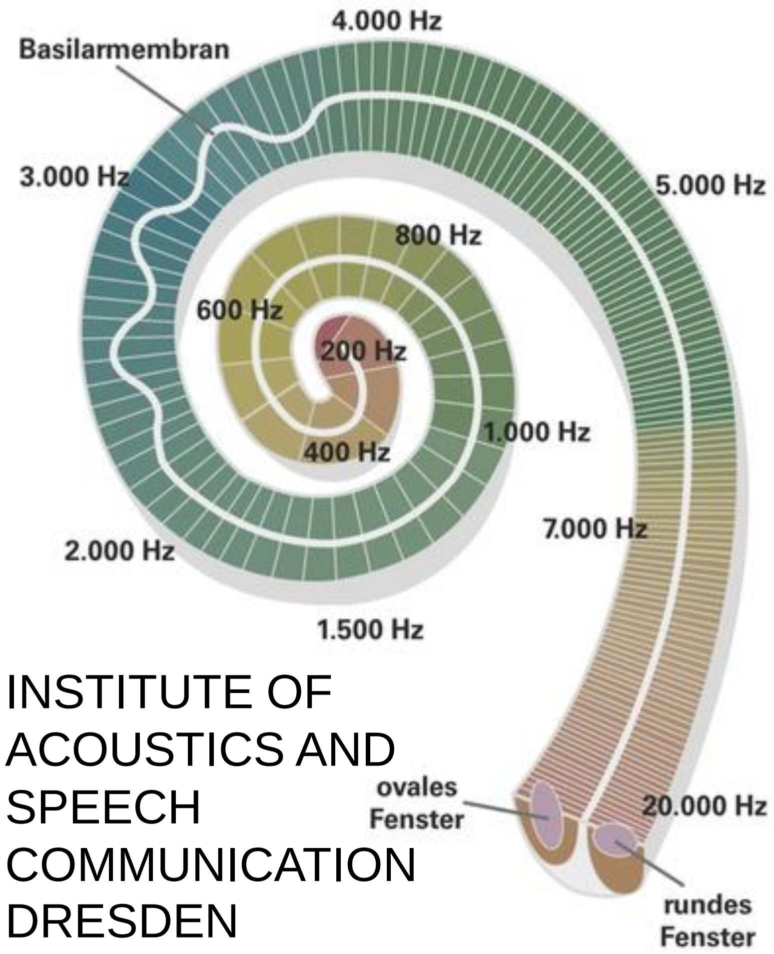


$$f = \frac{1}{5}\frac{c_{air}}{d_{glass}}$$

4 System frequencies

- Eigenfrequencies
- Oscillator frequency
- FEM frequency modelling
- Experimental prove

Investigation plan



INSTITUTE OF ACOUSTICS AND SPEECH COMMUNICATION DRESDEN

1. **Introduction** ✓
   - Fingers role problem
   - Collisions distinction problem
   - Experimental setup
2. **Multi collision** ✓
   - Pendulum analogy
   - Finger force \ diameter role
   - Restitution coefficient
3. **Contact moment** ✓
   - Palmgren's contact model
   - Time of contact
   - FEM impact modelling
4. **System frequencies** ✓
   - Eigenfrequencies
   - FEM frequency modelling
   - Oscillator frequency
5. **System acoustics** ←
   - Oscillations frequency
   - FFT window size
   - Psychoacoustic experiment

Also we have appendix slides for different questions

Area changing time

We describe all of the impact mechanics

Time between oscillations

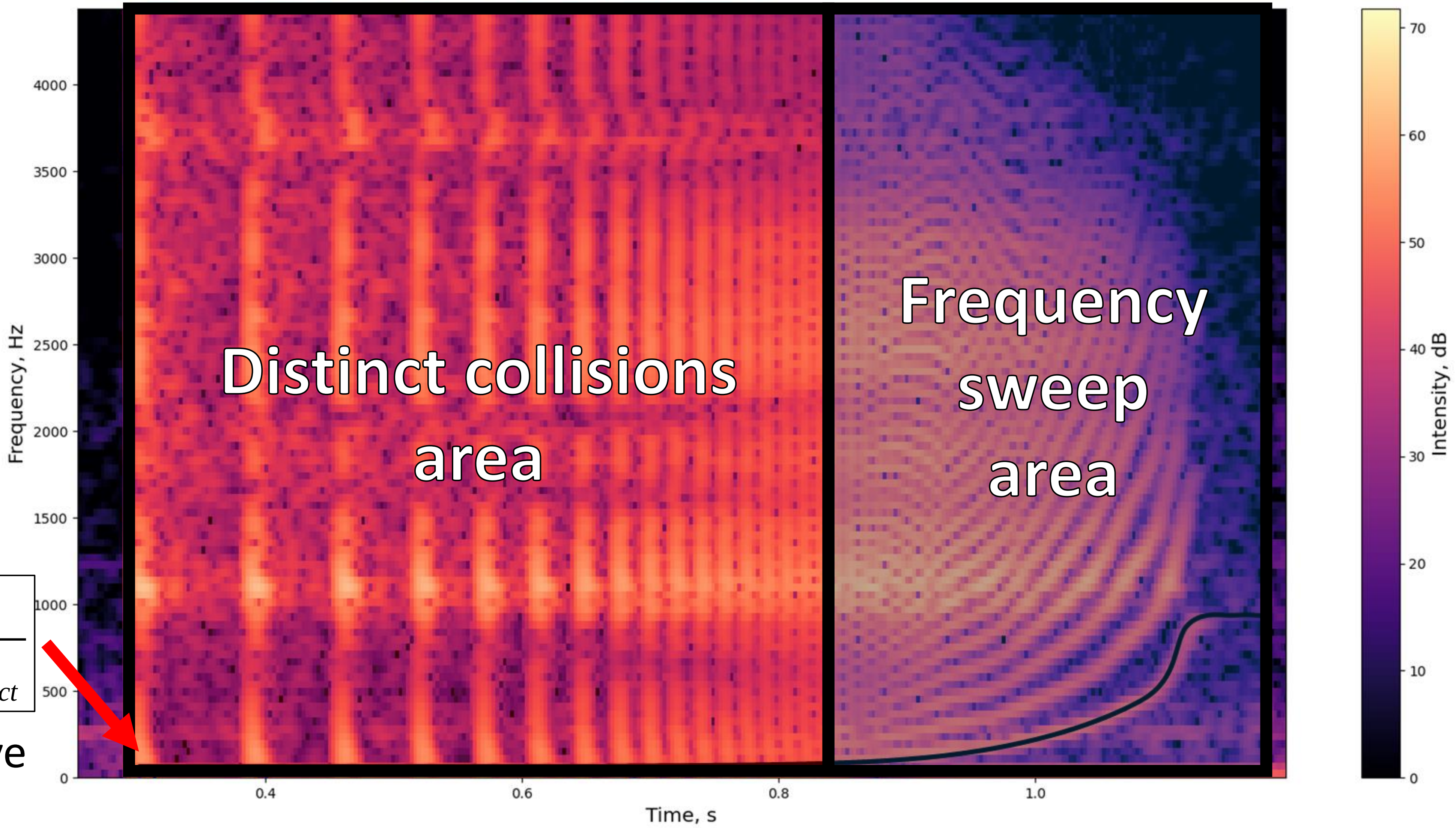
Contact time

System frequencies

We also can describe final sweep sound:

$$f = \frac{1}{t_{between-collision} + t_{contact}}$$

Python modeled curve



5 System acoustics

- Fast Fourier Transform
- Signal model
- Oscillations sound
- Psychoacoustic experiment

Area changing time depends on the window size of Fast Fourier Transform

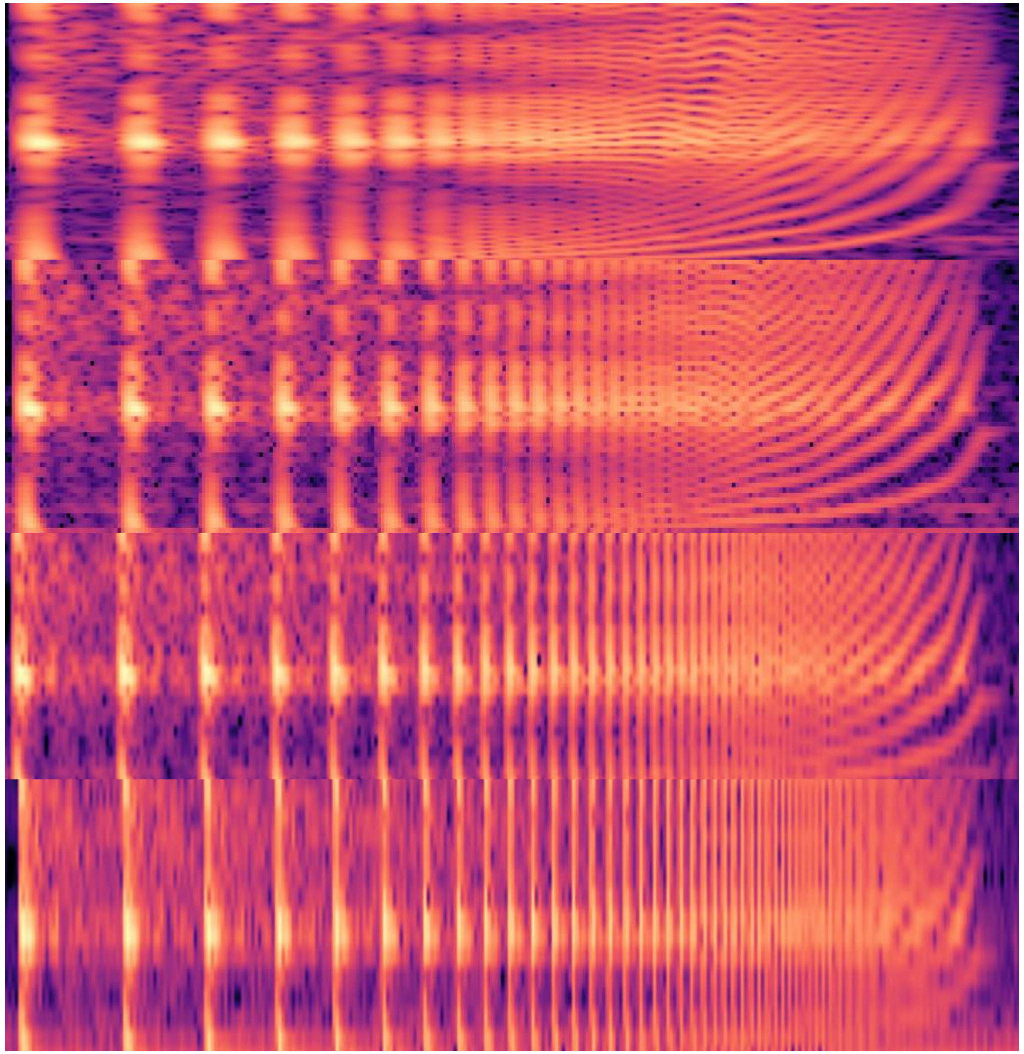
FFT spectrogram in Python matplotlib:
Sample rate = 44 100 Hz
Window step = 128 units
Hamming window

2048 units

1024 units

512 units

256 units



Higher window size earlier frequency sweep!

Fourier transform – Dirac comb

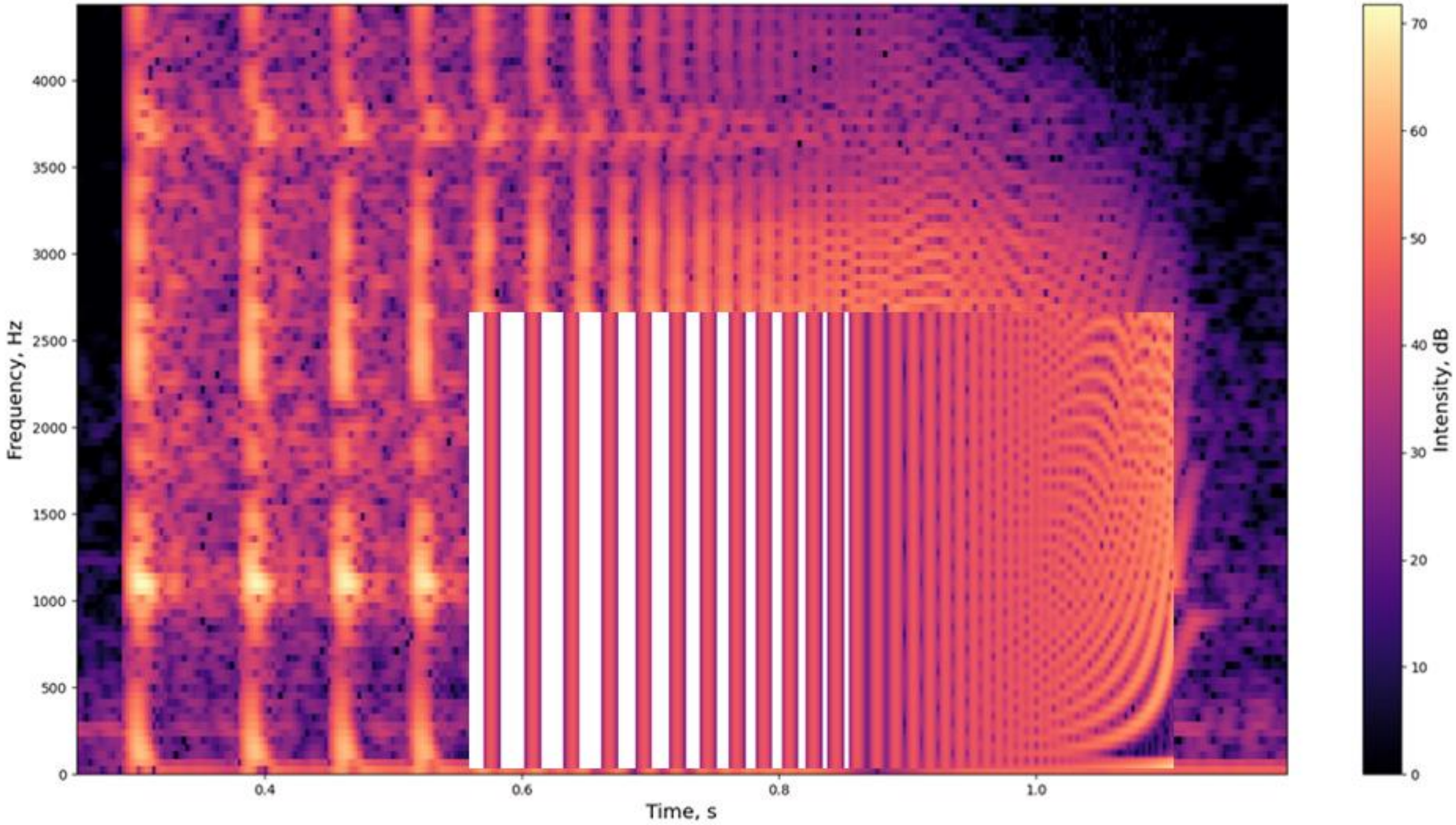
Each collision is delta function

One delta function per window - Rectangle

Periodic delta function structure per window – ***Dirac comb*** (frequency of periodic structure and overtones)

Window time affect the spectrogram view!

✔ Model describes experiment well



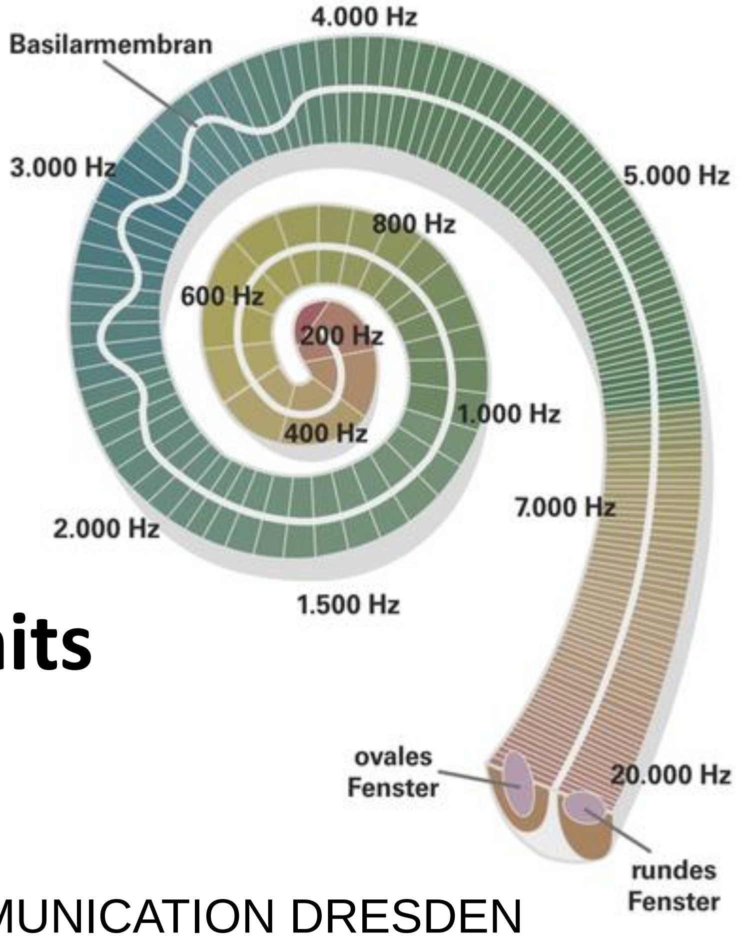
Psychoacoustic experiment

Interesting model: Our ears – Fourier Transform Filter (wavelet)

We ask: What is the time where sound frequency increases?

211 participants, 13 – 40 years old

Control group with immediately frequency changing (20 participants)



Results: **Window size of human ear about 512 units**

(if we assume 44100 Hz discretization)

Musician = Man = Woman

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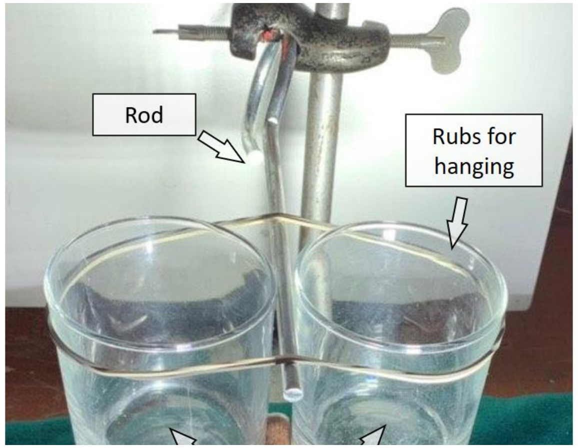
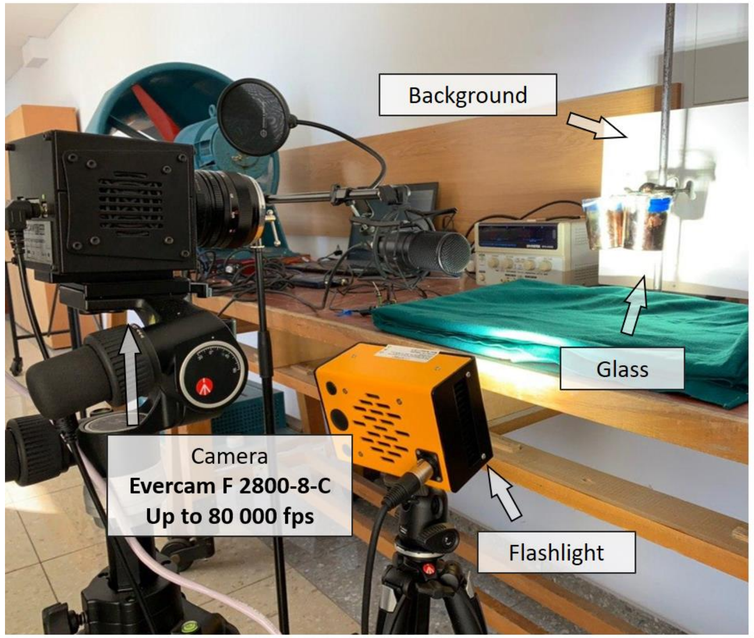
Conclusions

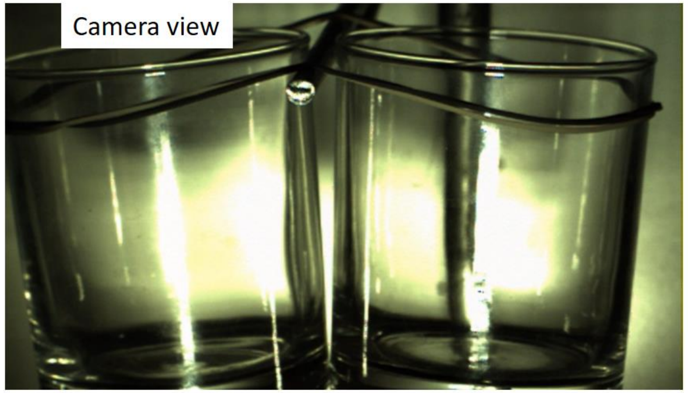
Experimental setup is constructed.

It consists of:
Video equipment
Audio equipment
Electrical equipment

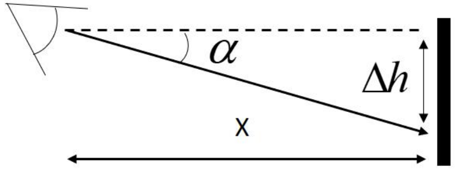


Different forces acting on the system





6000 fps, 1624x1080 px, angle of view ~5 degrees



$$\Delta h = x \sin \alpha$$

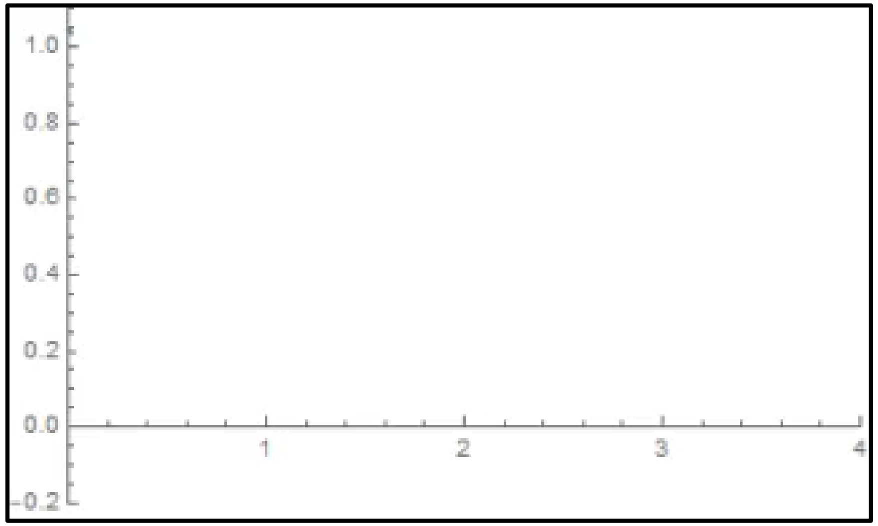
$$\frac{\Delta h}{h} \approx 4\%$$

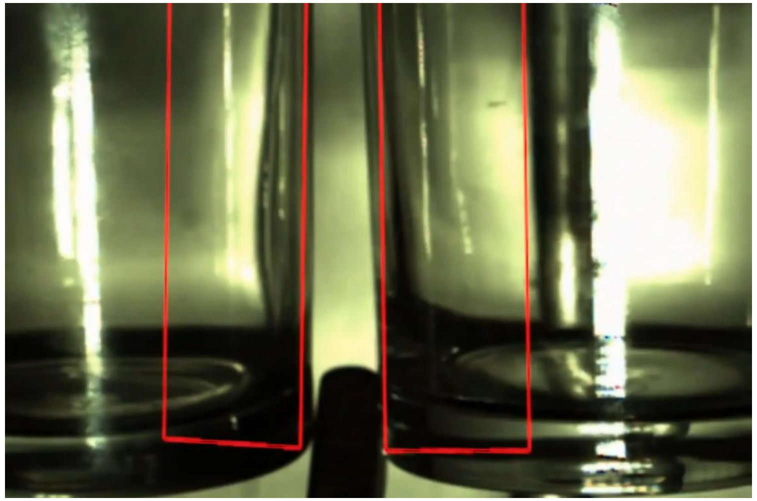
Conclusions

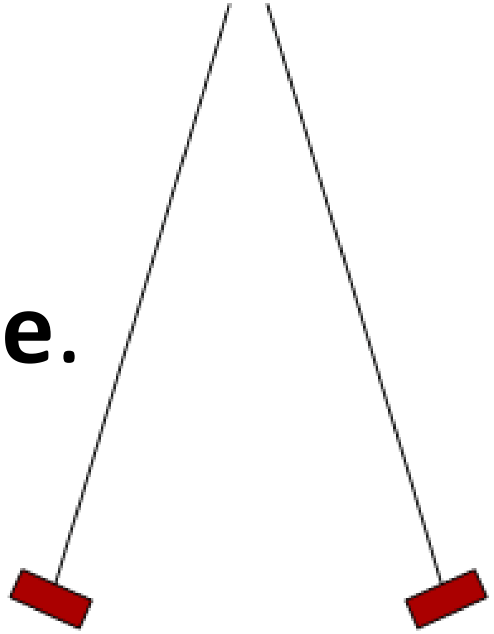
Glasses multi collision is described.

According to pendulum analogy

time between collisions decreases by time.







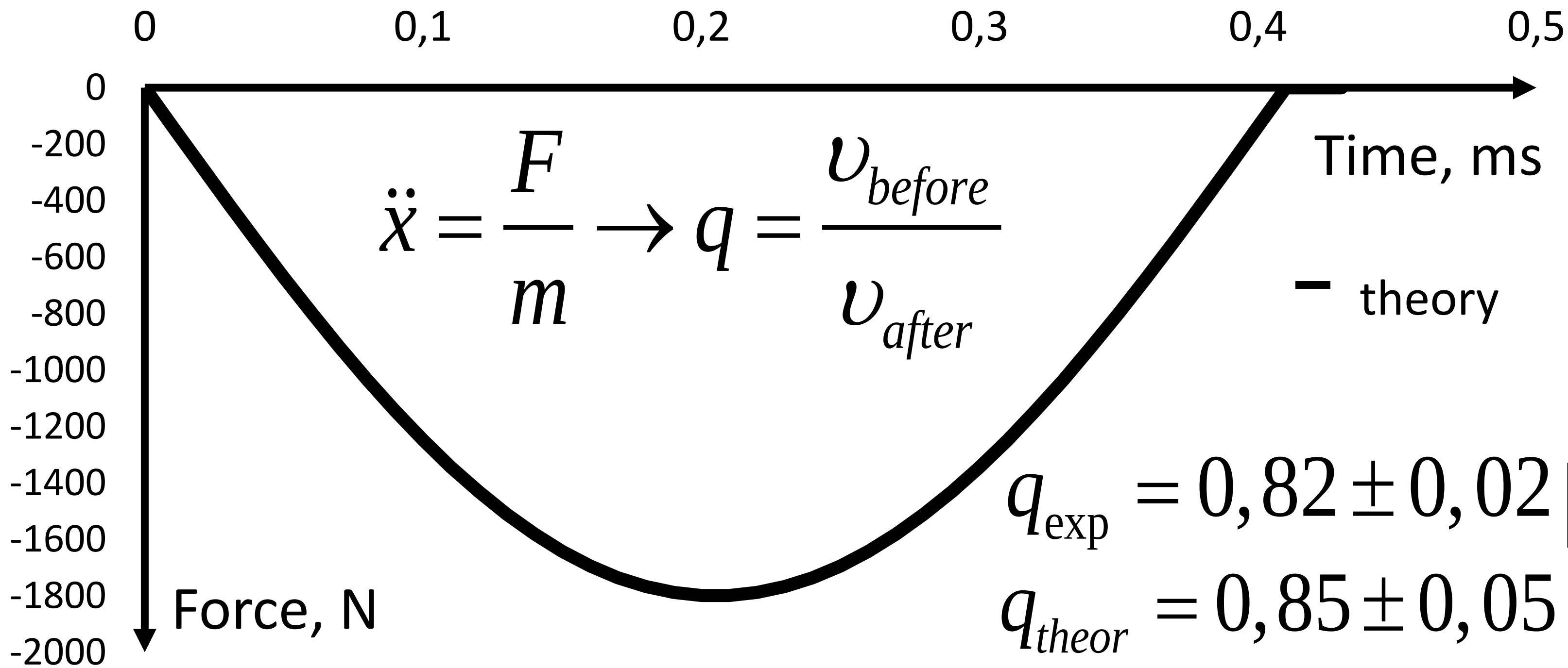
Pendulum analogy simulation

2 <u>Multi collision</u>:

- Qualitative pendulum model
- 2nd Newton's law model
- Time between collisions
- Restitution coefficient measurement

Conclusions

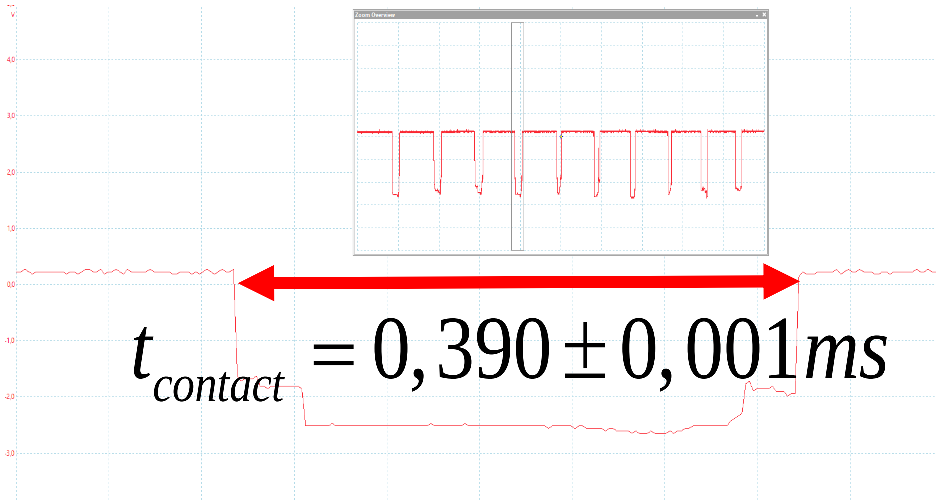
Contact time we can **predict** well by Palmgren's model as well as **restitution coefficient**.



$$\ddot{x} = \frac{F}{m} \rightarrow q = \frac{\upsilon_{before}}{\upsilon_{after}}$$

$$q_{\exp} = 0,82 \pm 0,02$$

$$q_{theor} = 0,85 \pm 0,05$$



$$t_{contact} = 0,390 \pm 0,001 ms$$

Digital oscilloscope data

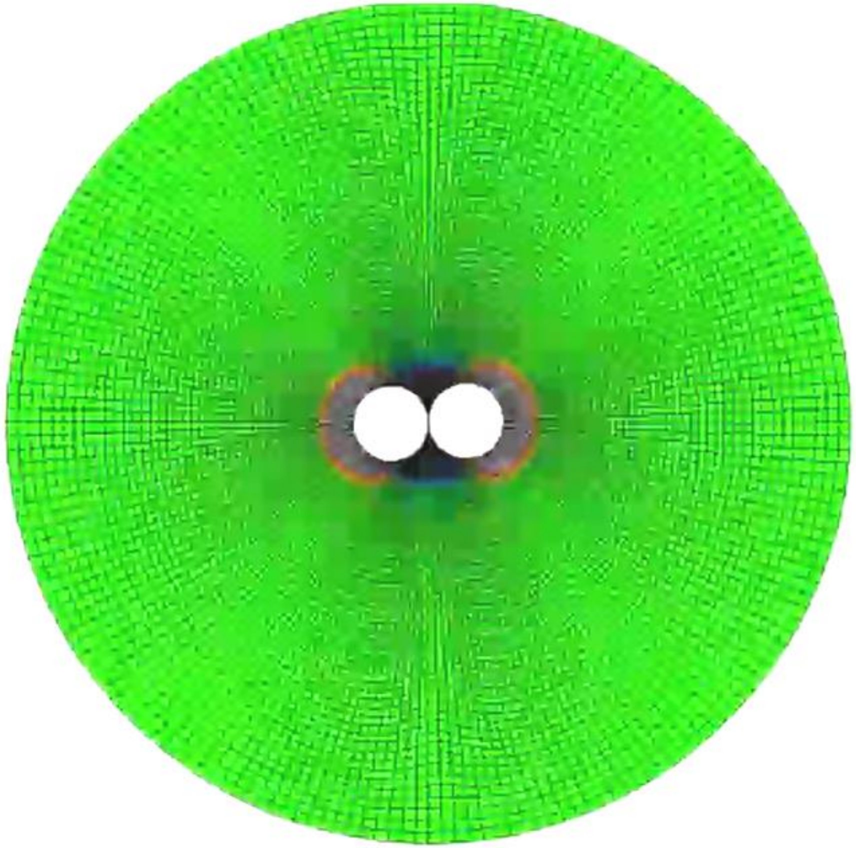
$$t_{contact\ theory} = 0,41 \pm 0,1 ms$$

3 Contact moment

- Palmgren's model
- Time of contact

- FEM contact modelling
- Restitution coefficient calculation

Conclusions



We can hear not only **eigenfrequencies**, but also **specific system frequency.**

4 System frequencies

- Eigenfrequencies
- Oscillator frequency
- FEM frequency modelling
- Experimental prove

Conclusions

GENERATED SOUND

✔ Frequency sweep sound is generated

Further research:

- Prediction of oscillator frequency coefficient
- Detailed attenuation investigation
- Detailed material investigation

5 System acoustics

- Fast Fourier Transform
- Signal model
- Oscillations sound
- Psychoacoustic experiment

✔

Bibliography

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K. Mehraby, H. Khademhosseini Beheshti, and M. Poursina, Impact noise radiated by collision of two spheres: Comparison between numerical simulations, experiments and analytical results, Journal of Mechanical Science and Technology* ***25*** *(7) (2011) 1675~1685*

Also we have appendix slides for different questions

Problem No.12

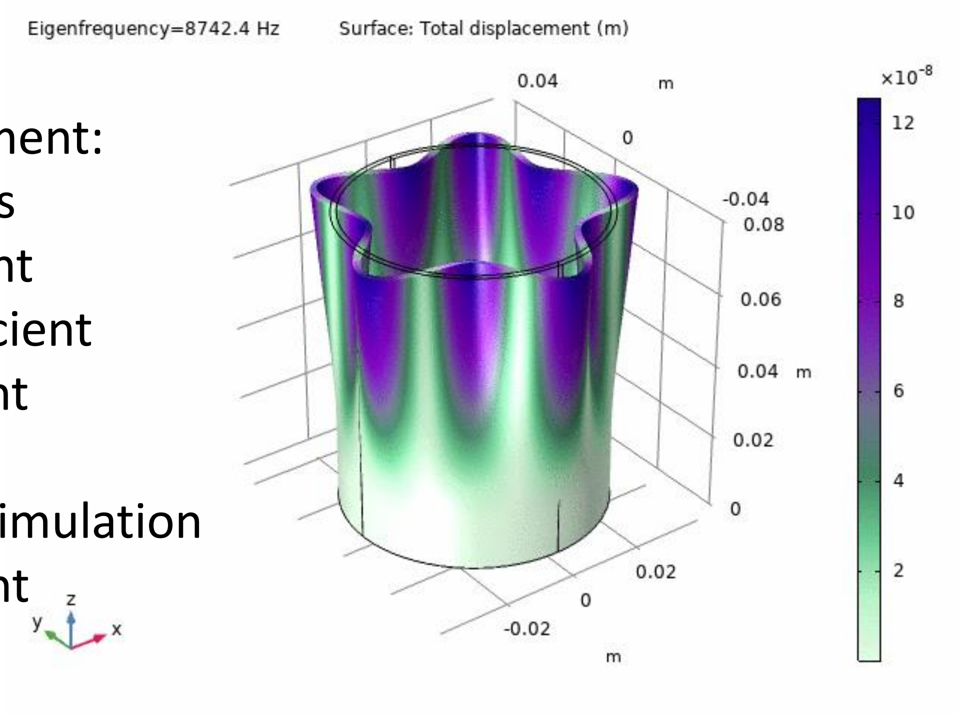
Resonating glasses

Team of Russia

Reporter: Artem Sukhov

Also investigated:

- Parameters measurement:
  - Elasticity modulus
  - Hooke's coefficient
  - Resistance coefficient
  - Poisson coefficient
- Sound attenuation
- Sound propagation simulation
- Restitution coefficient (velocity dependence)



Thank you! Questions?

<u>Also</u> we have appendix slides for different questions