Problem №14

Rising in the bulk

Sophia Kanyukova

Smells like Team Spirit

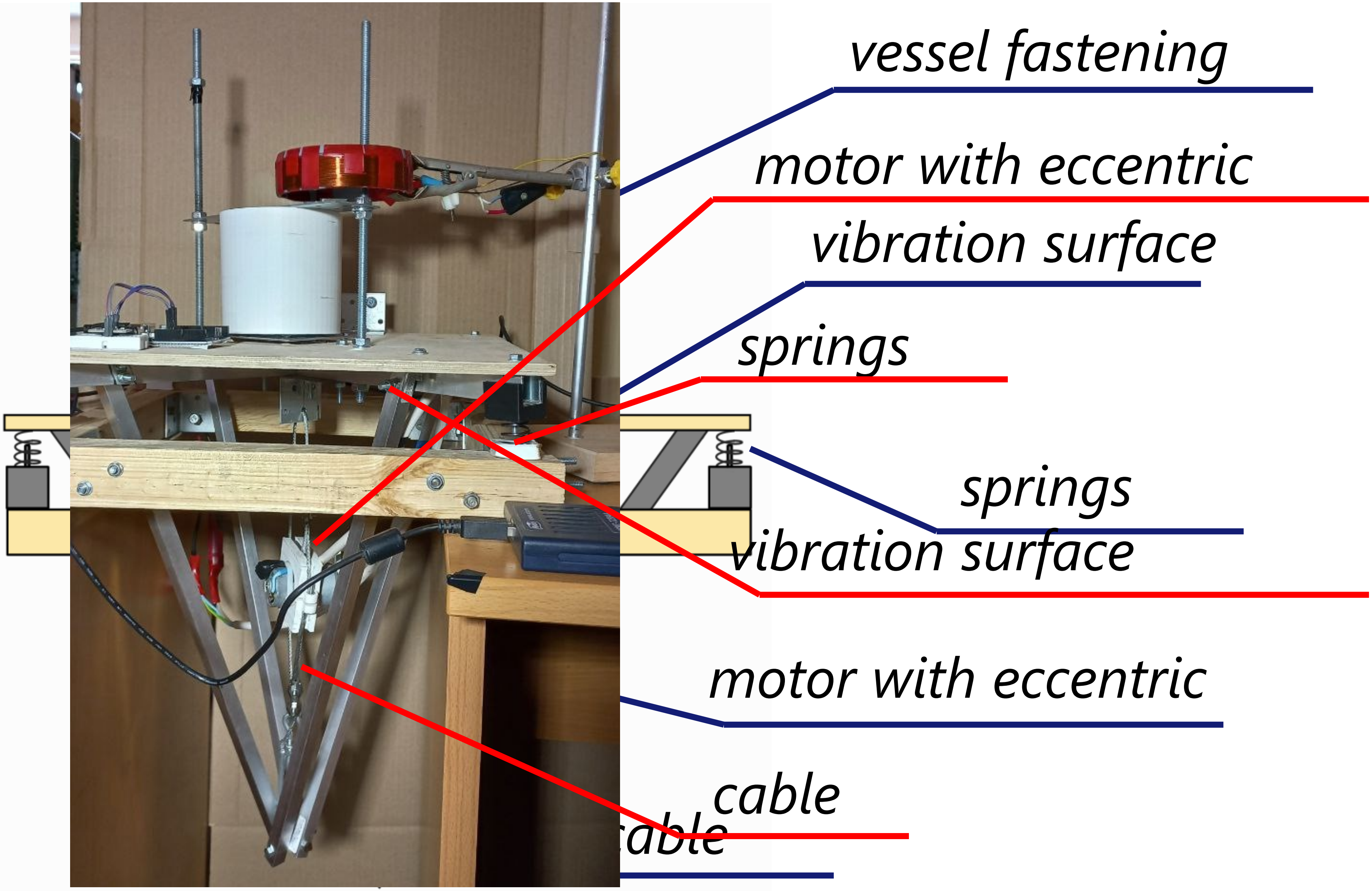
ВСТФ

ВСЕРОССИЙСКИЙ СТУДЕНЧЕСКИЙ ТУРНИР ФИЗИКОВ

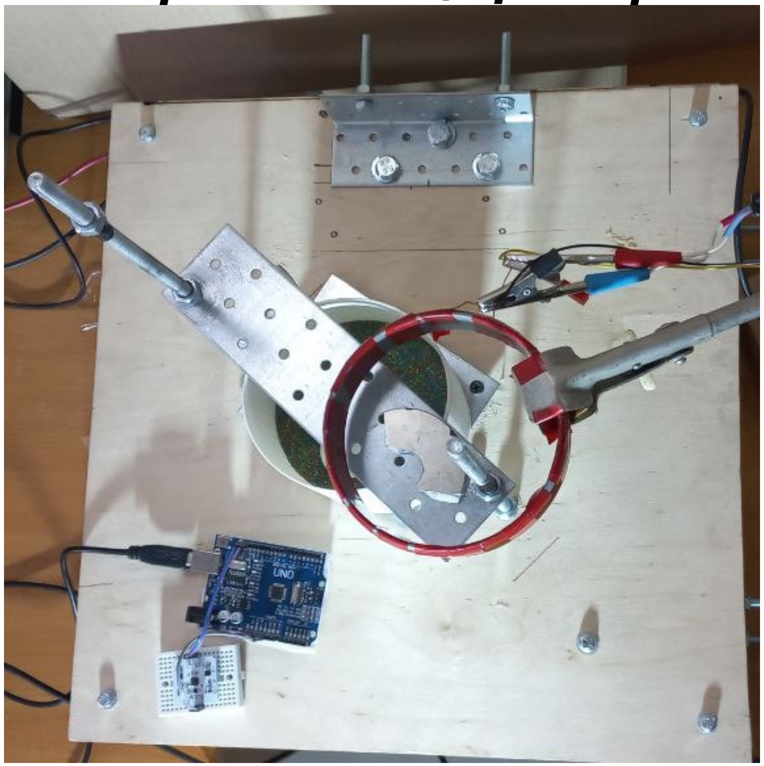
МФТИ

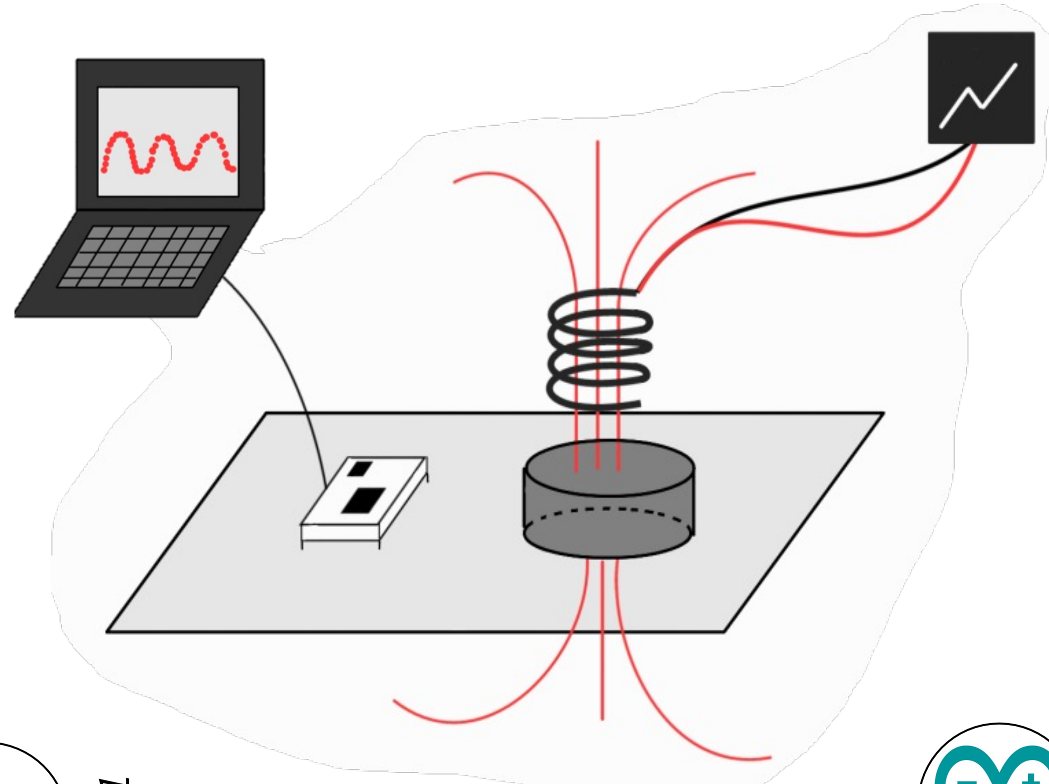
If a vessel containing granular material is shaken appropriately, an item placed at the bottom will ascend upward through the material and emerge at the top. Explain the phenomenon and devise the most energy efficient shaking technique to raise the item up.

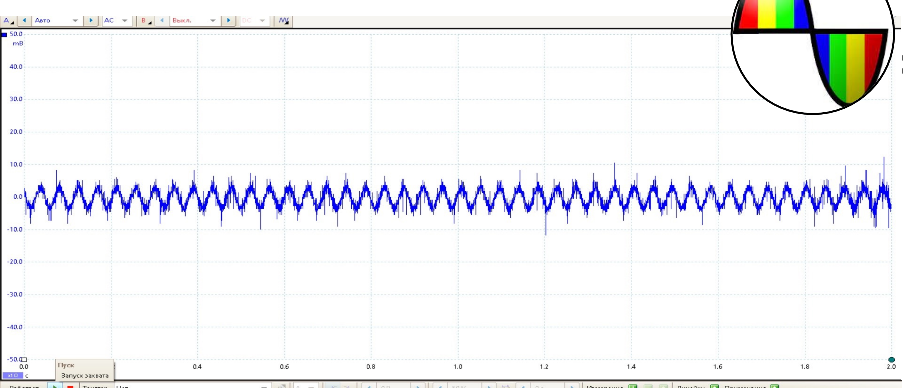
Vibration setup

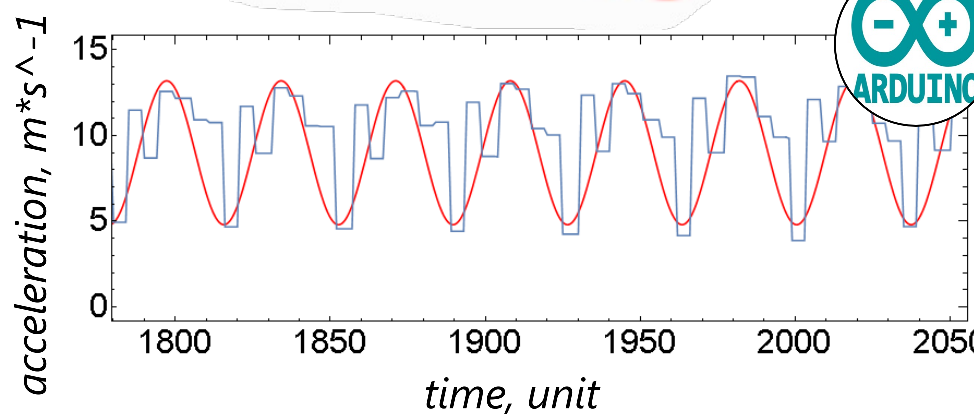


Amplitude, frequency measurements

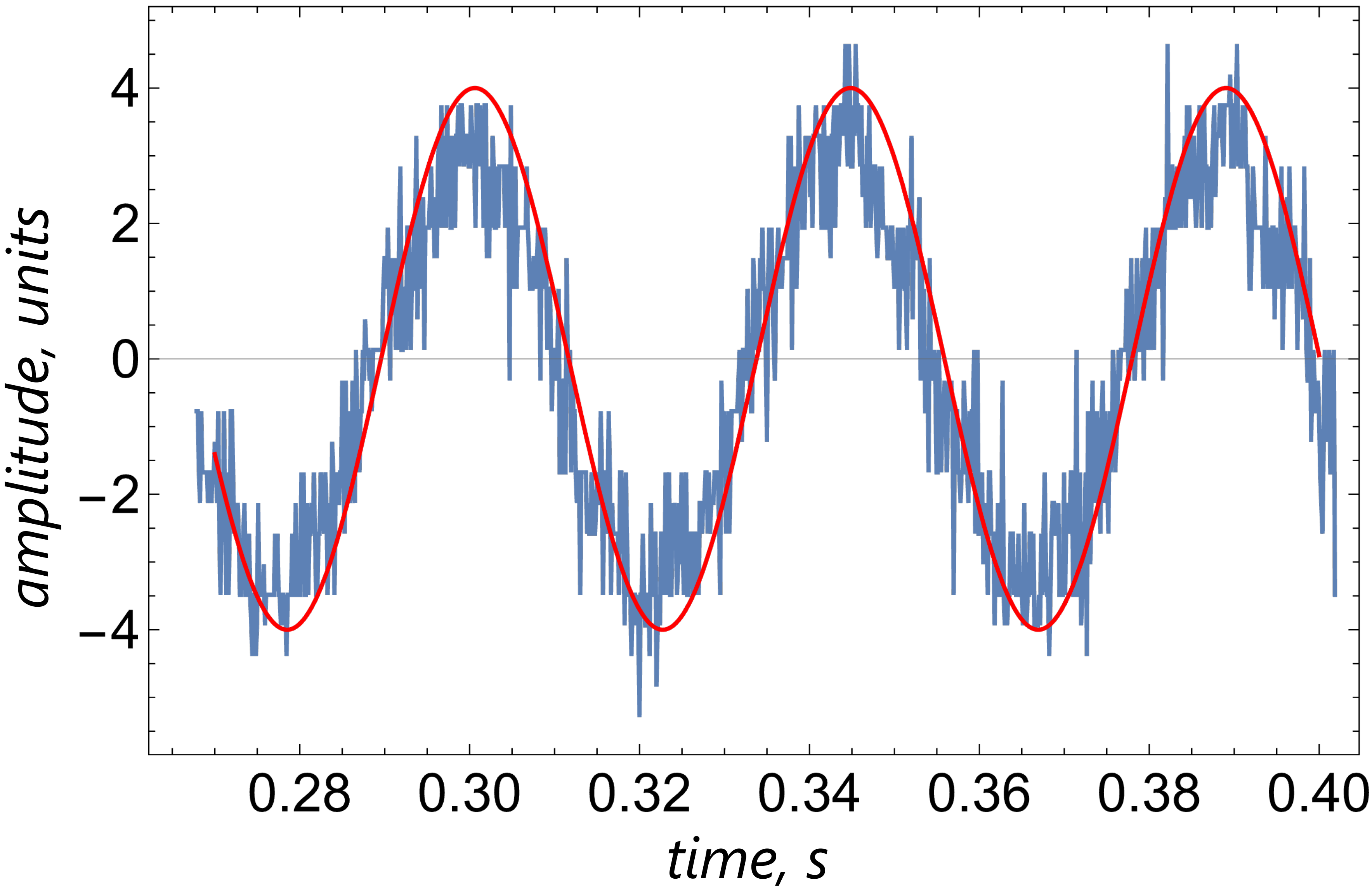




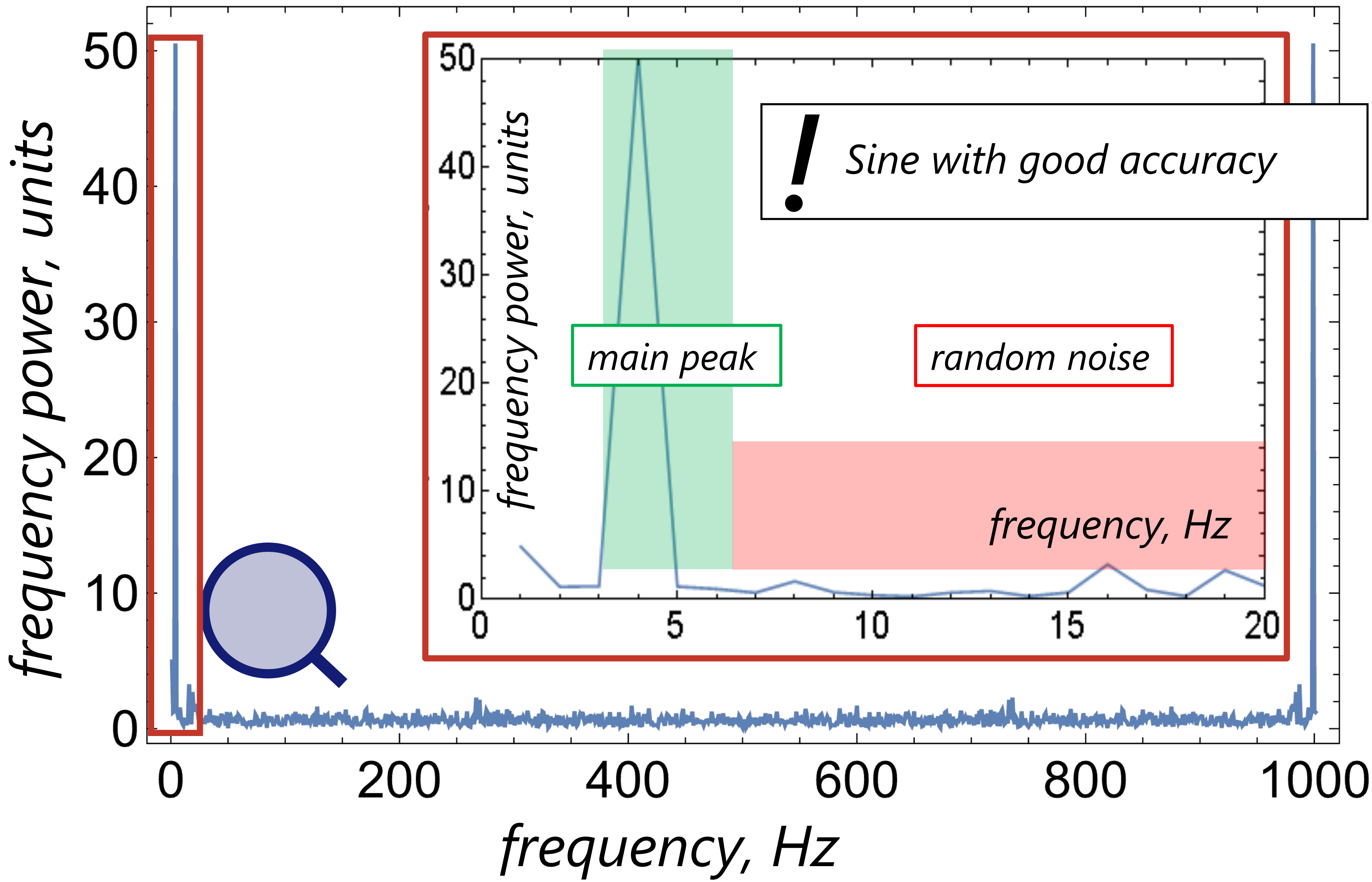




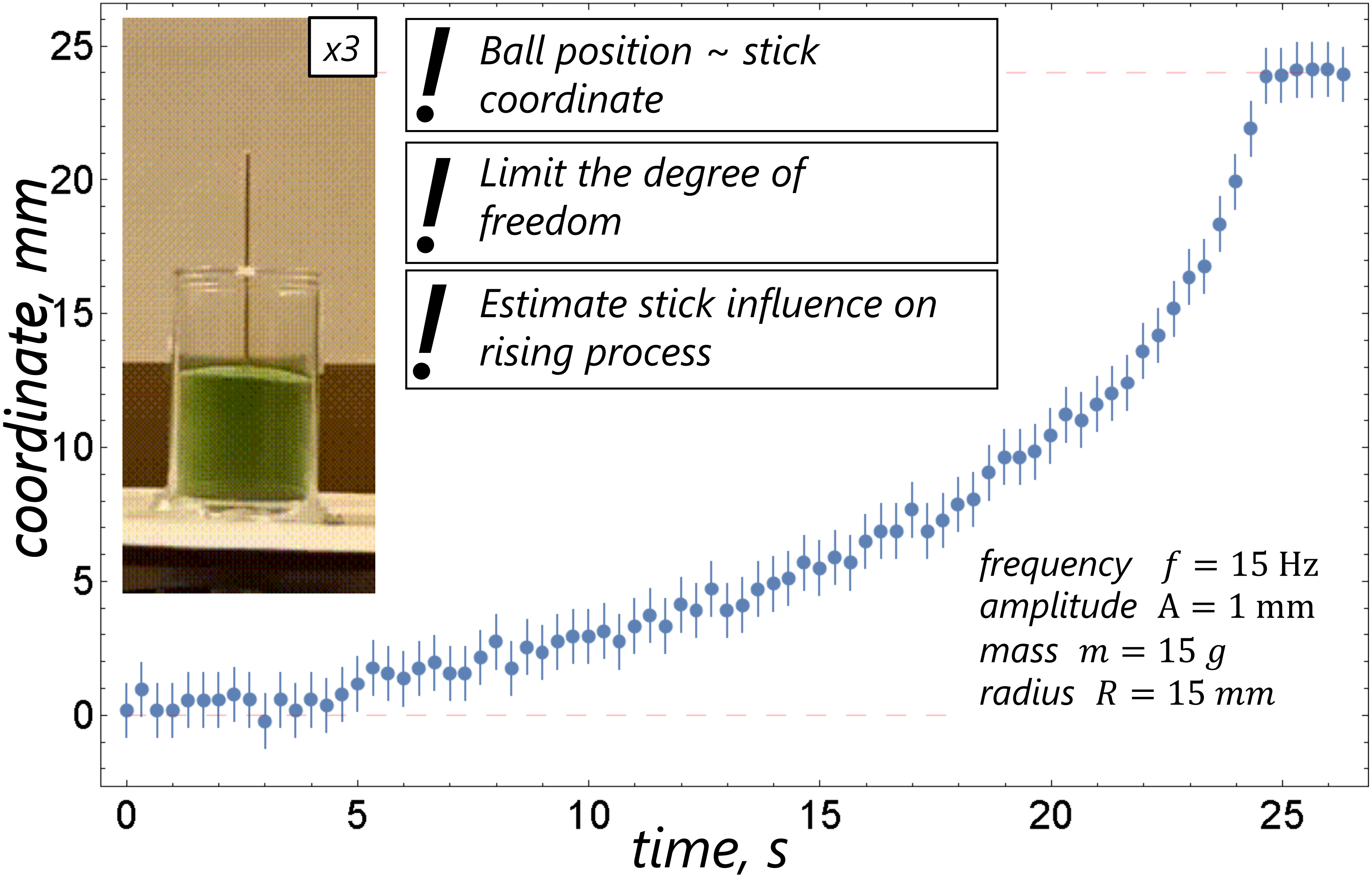
Oscillations type



Oscillations type



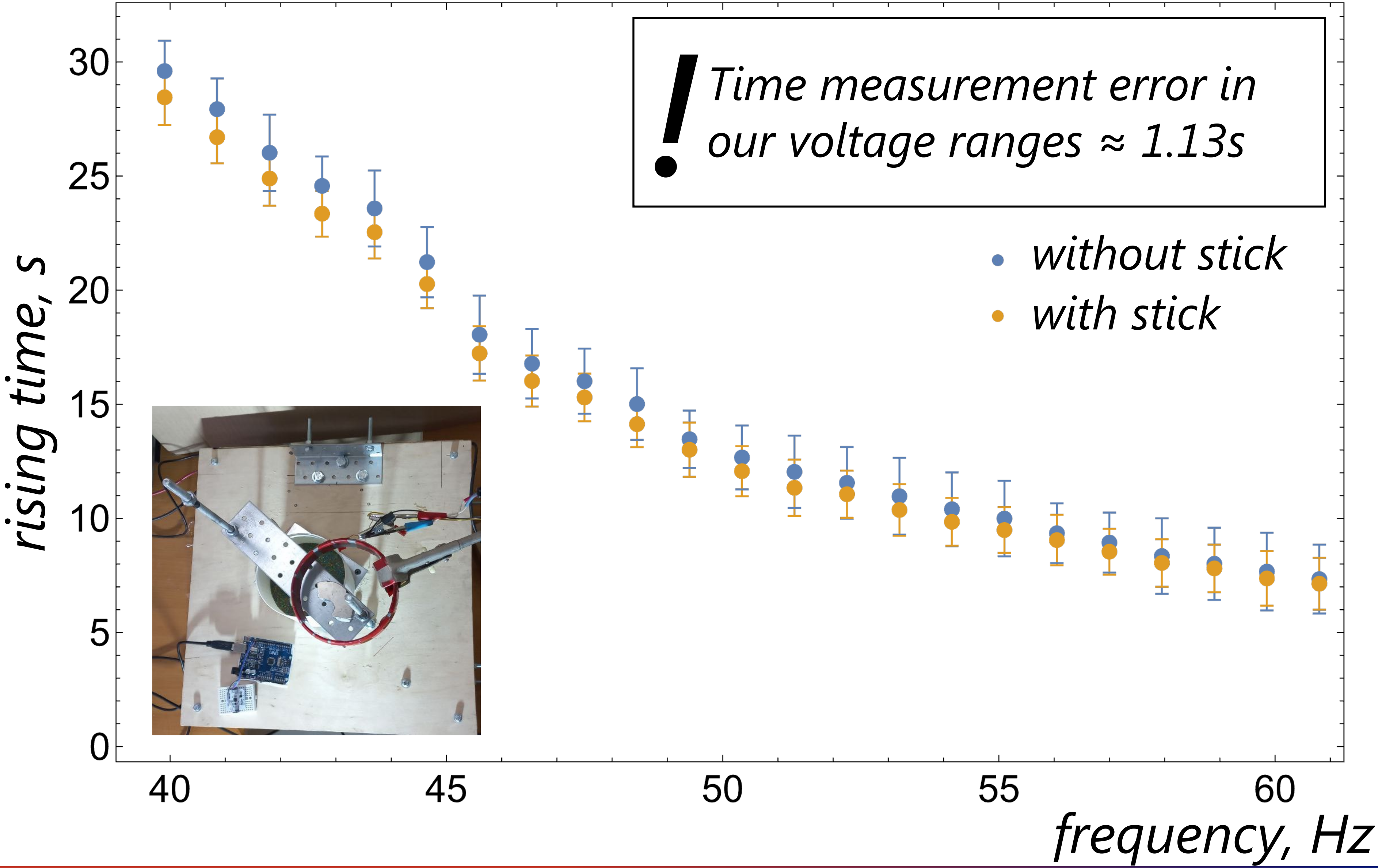
First observations



- Ball position ~ stick coordinate
- Limit the degree of freedom
- Estimate stick influence on rising process

frequency $f = 15\ \mathrm{Hz}$
amplitude $\mathrm{A} = 1\ \mathrm{mm}$
mass $m = 15\ g$
radius $R = 15\ mm$

Method applicability



Outline

1 **Rising mechanism**

One period ball motion

2 **Sand behavior in shaking process**

Janssens effect. Pressure distribution depending on shaking

3 **Quantitative part**

Ball motion equation. Filling cavities equation Their explanation

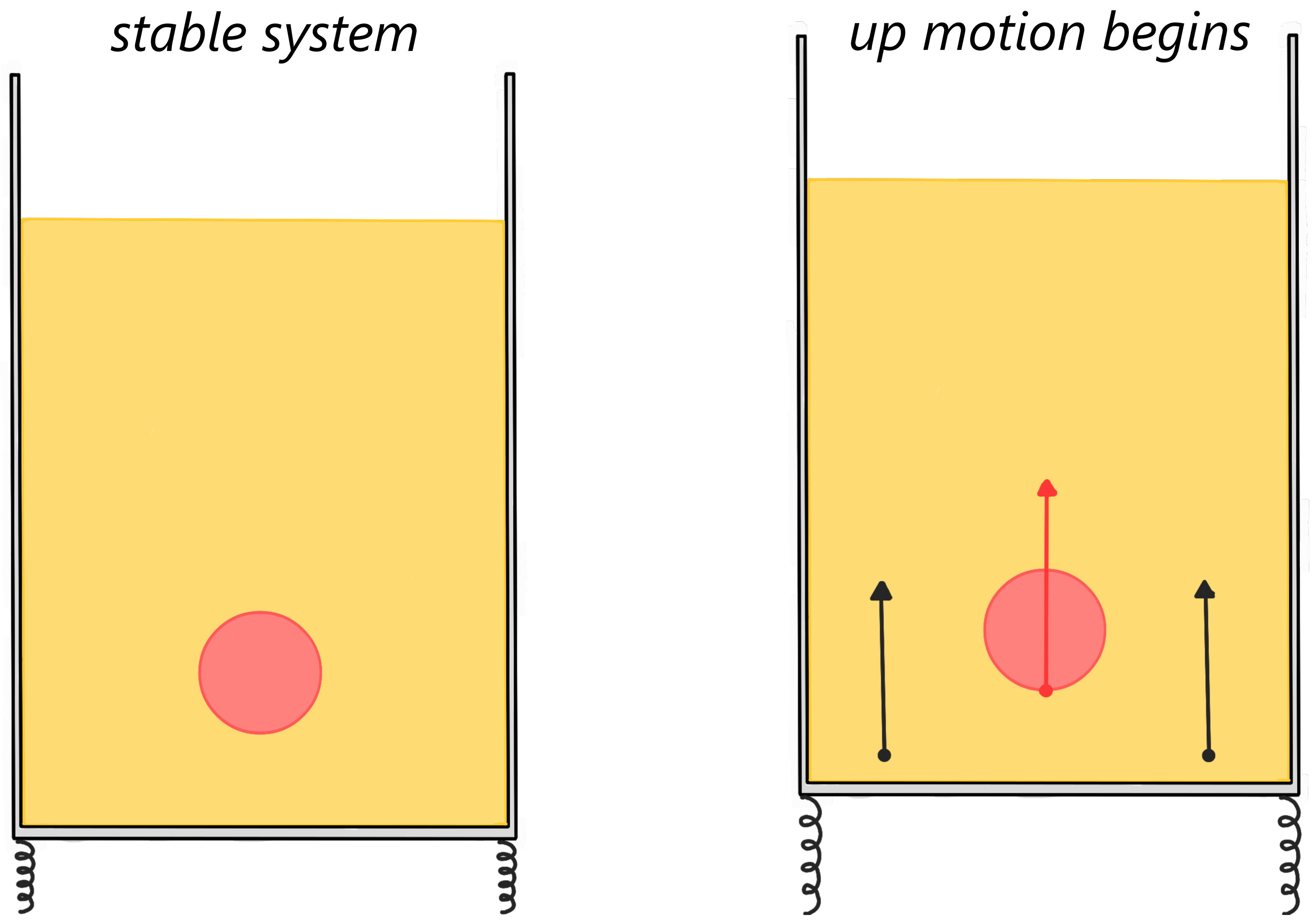
4 **Experimental description**

Rising time vs sand height, density, frequency. Sand flows and pressure distribution

5 **Shaking technique optimization**

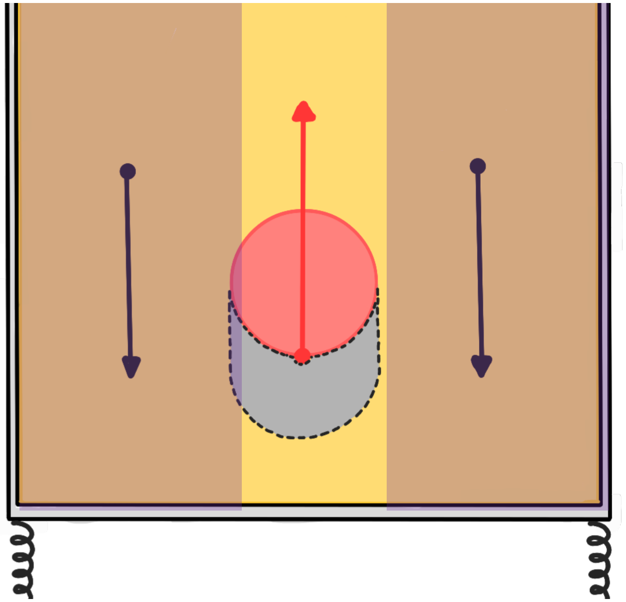
The most energy efficient shaking technique to raise the item up

Period movement



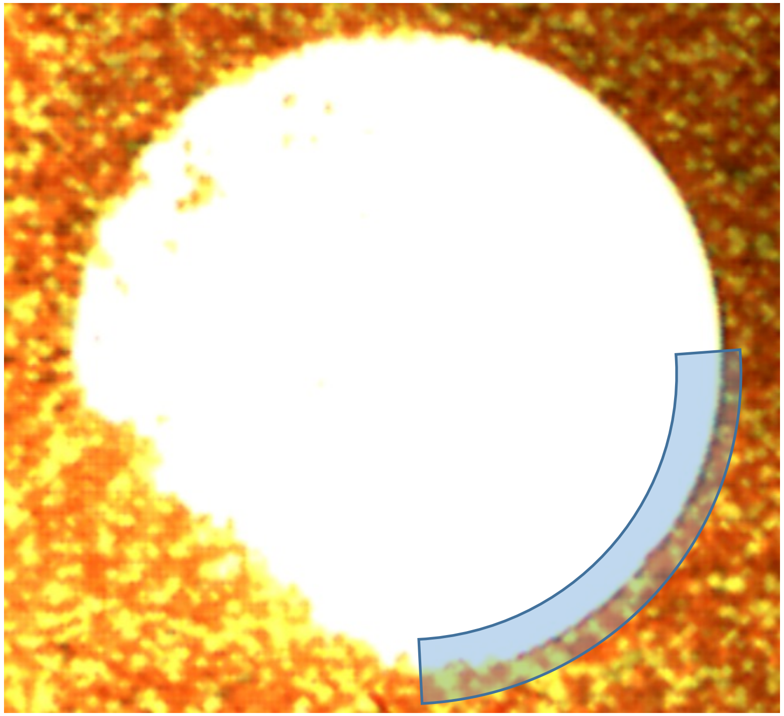
Period movement

sand goes down with the system under the action of friction force



ball moves up by inertia relative to the table

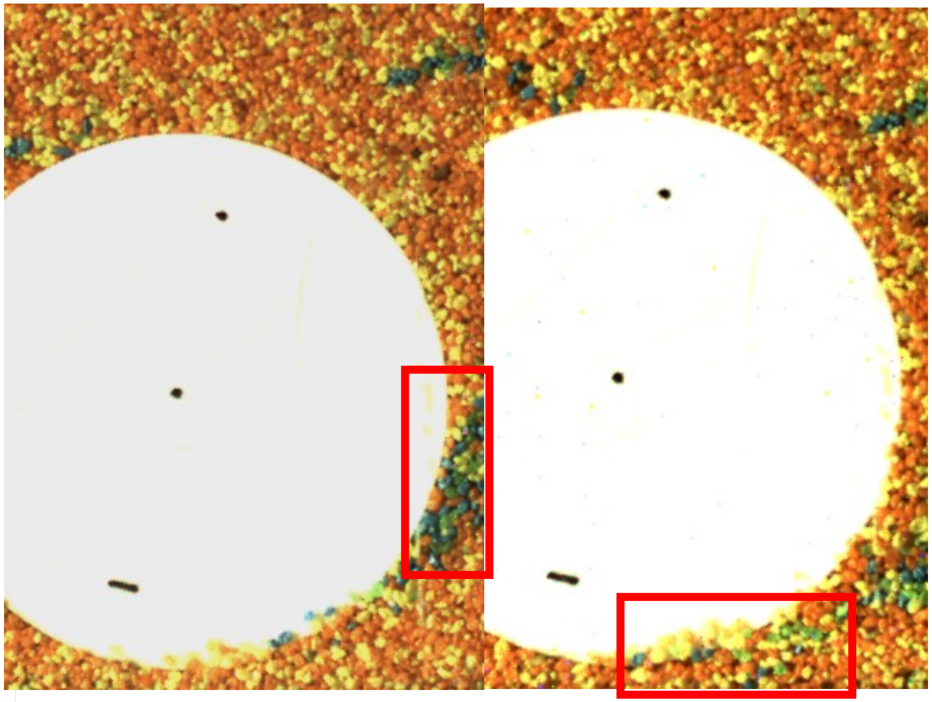
cavity forms



we cant see second part because of 2D condition imperfections

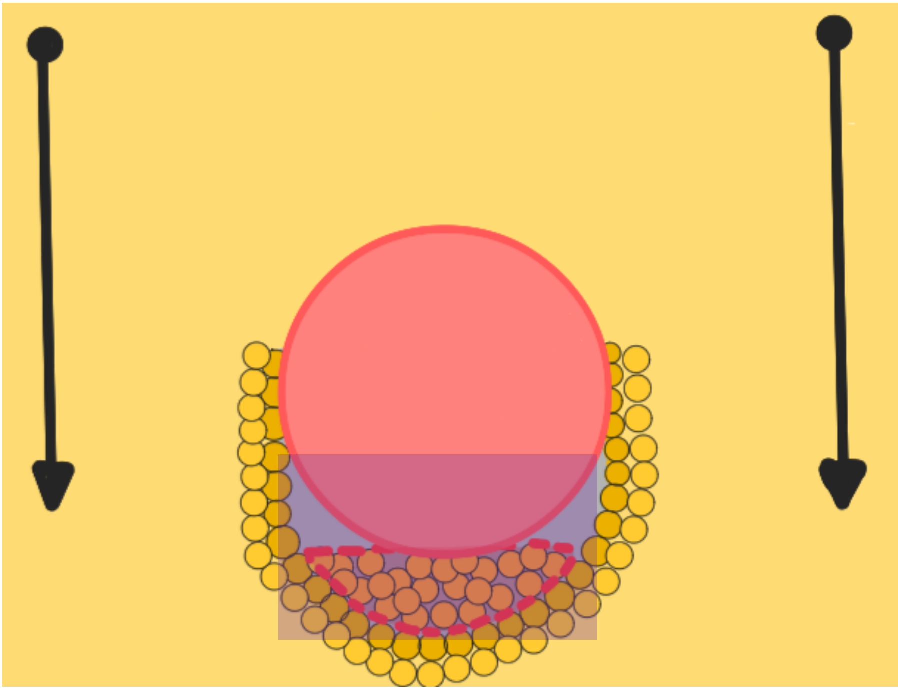
Ball movement in one period

Sand particles start to fill free cavity space



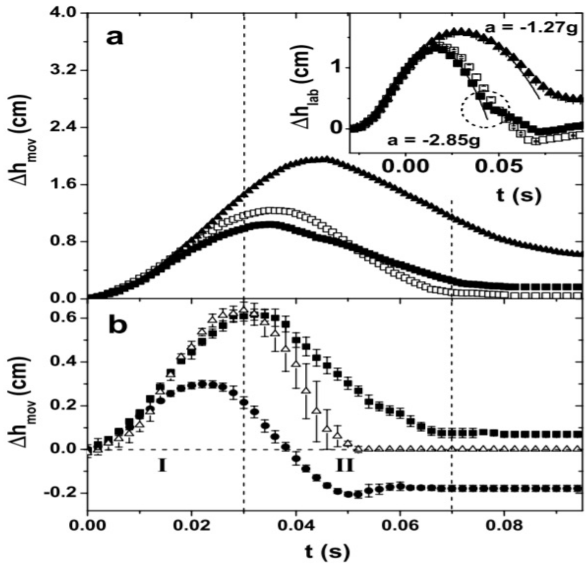
the ball is stopped by the force of resistance and starts to fall

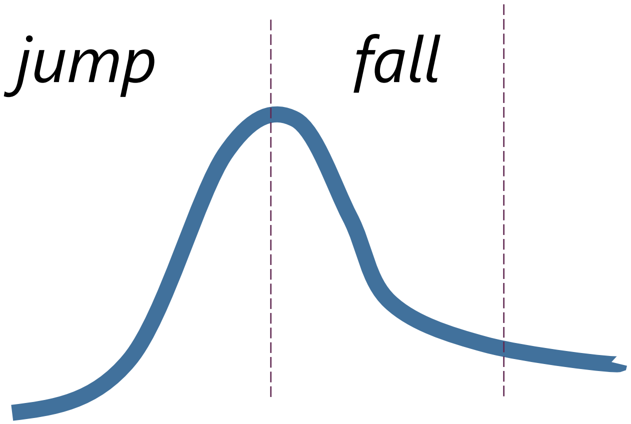
the ball falls on a new surface of sand

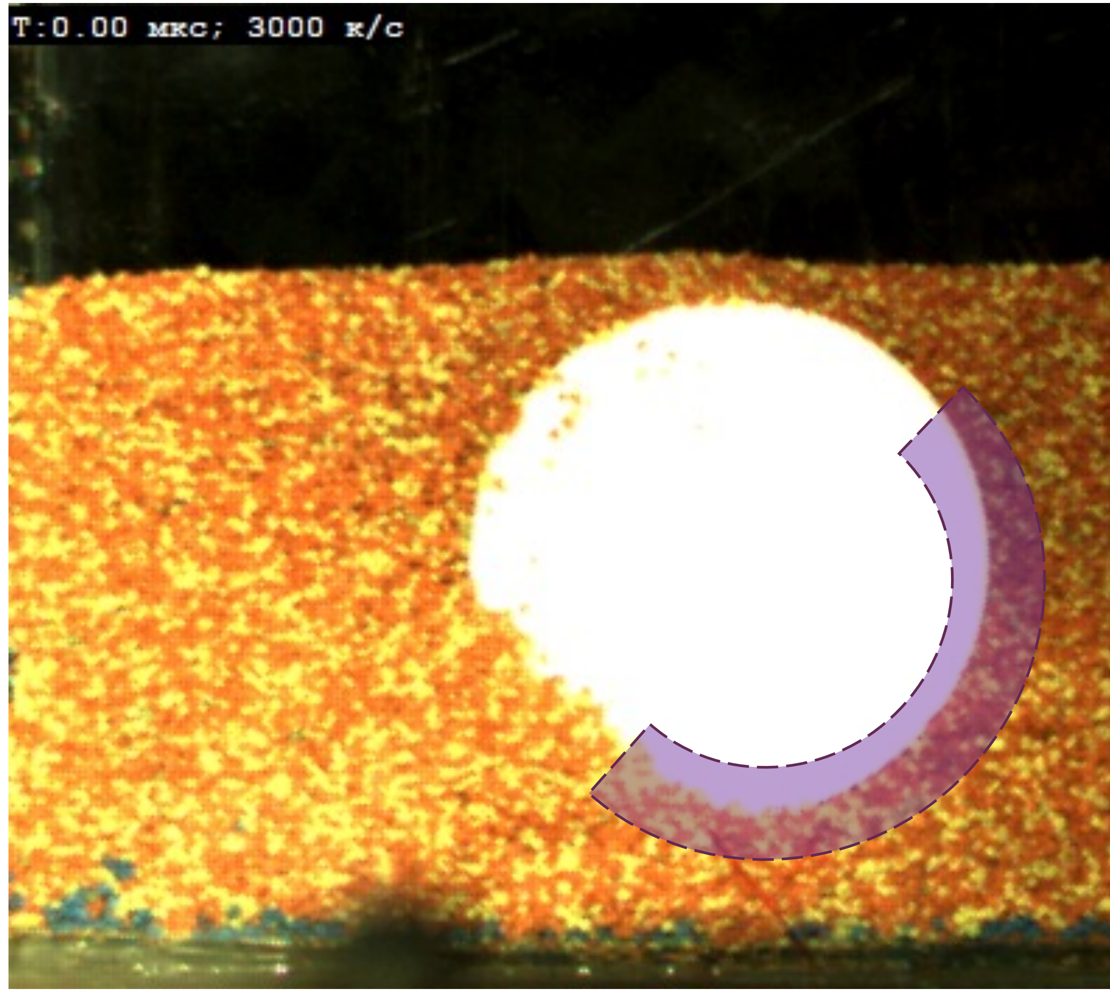


not the entire volume of emptiness managed to be filled

One period movement







Matthias E. Möbius, Xiang Cheng, Greg S. Phys. Rev. Lett. 2004

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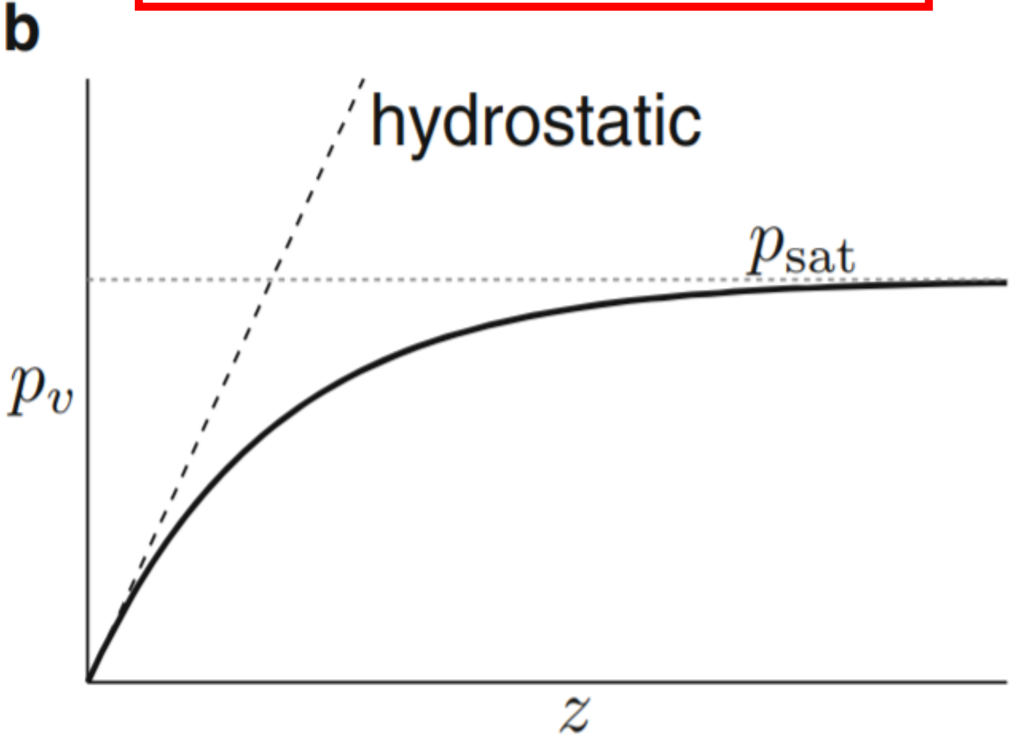
Pressure distribution in sand

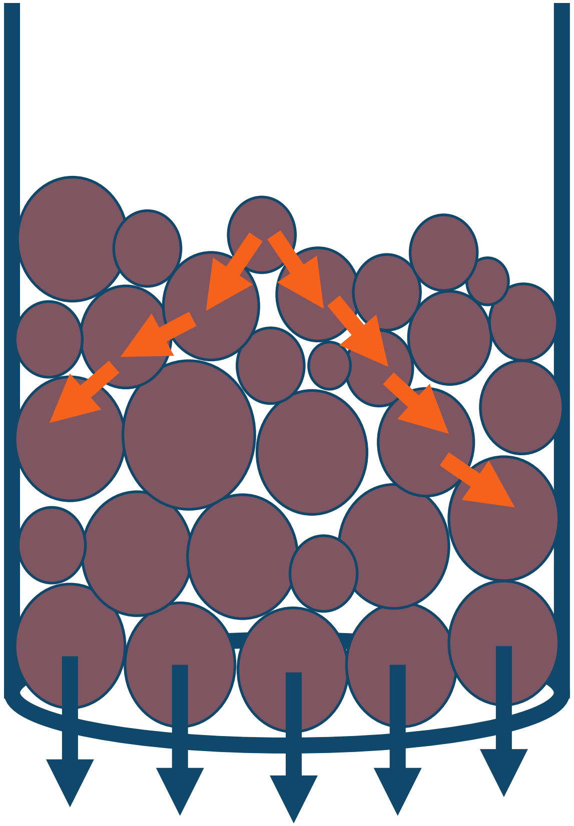
Janssen's equation

$$\boxed{p_h = \kappa \cdot p_v}$$

part of sand particle's weight is distributed to the lower particles

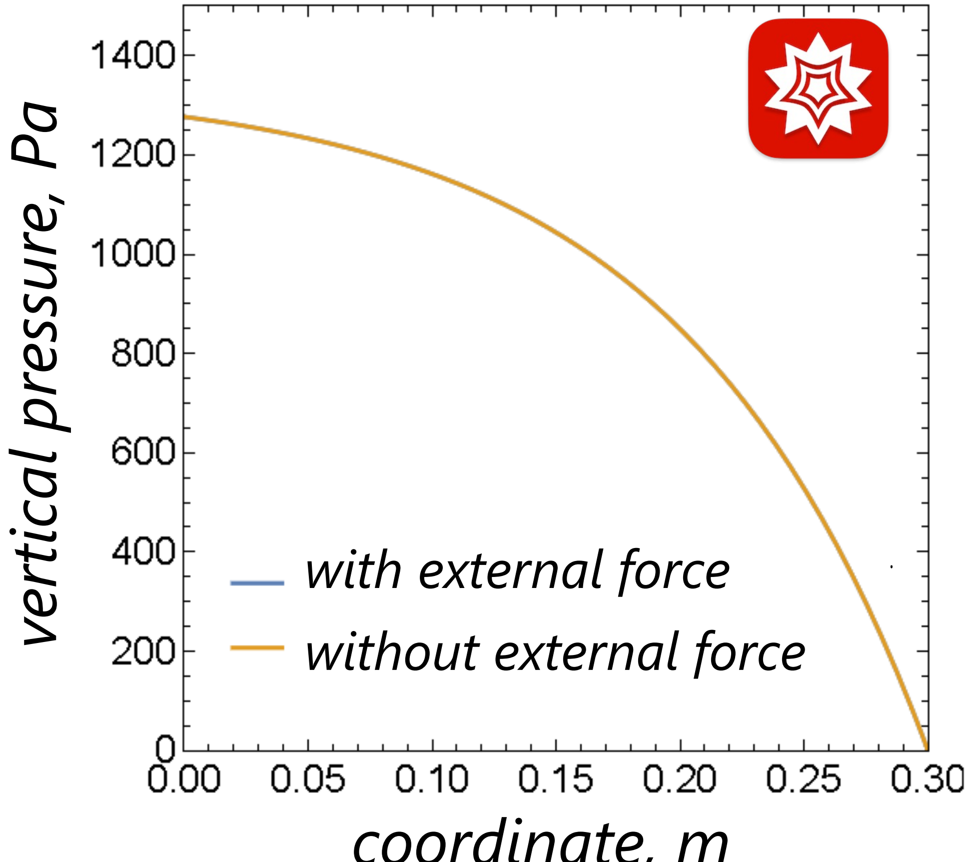


Physics of Soft Impact and Cratering, 2016

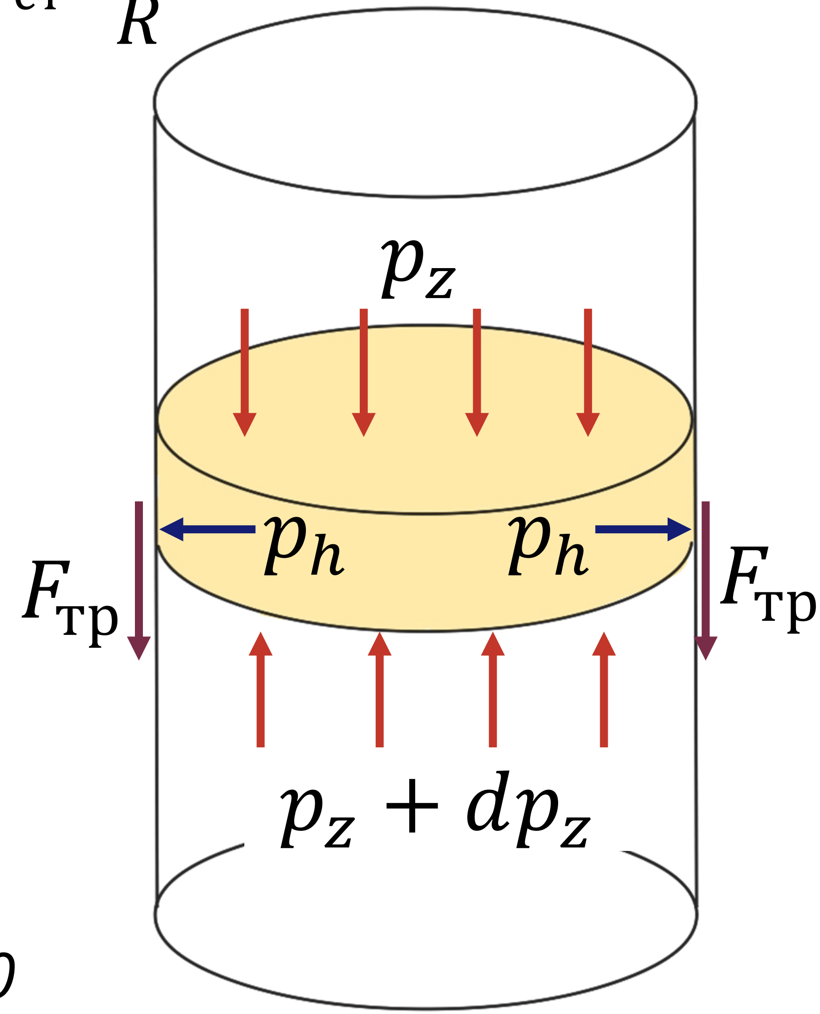


Vertical pressure gradient

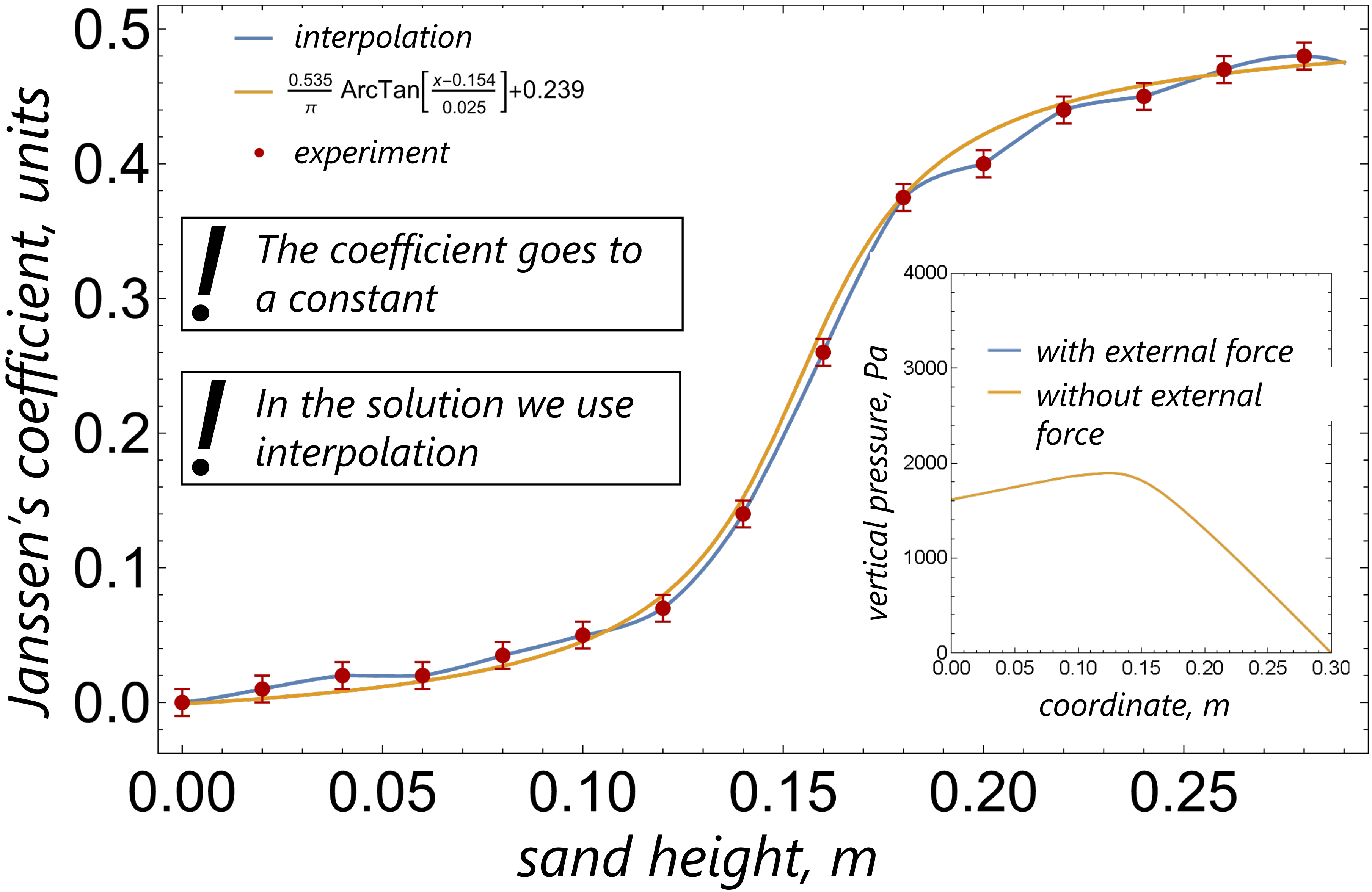
$$\frac{\partial p_z}{\partial z} = \rho\left(A_0\omega^2 \sin\omega t\right) - \rho_{\text{п}} g - \mu_{\text{ст}} \frac{2\overbrace{p_h}^{\kappa p_z}}{R}$$



0s t 10 s



Janssen coefficient



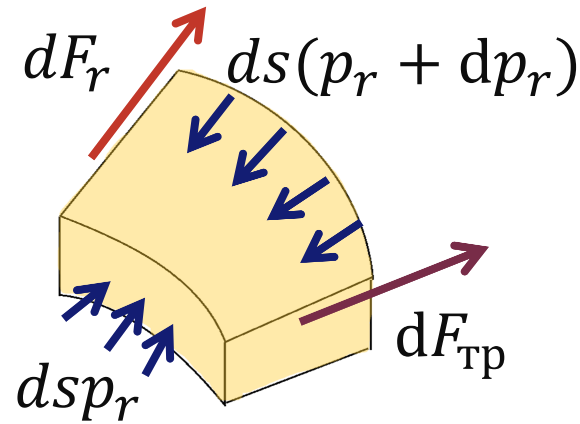
The coefficient goes to a constant

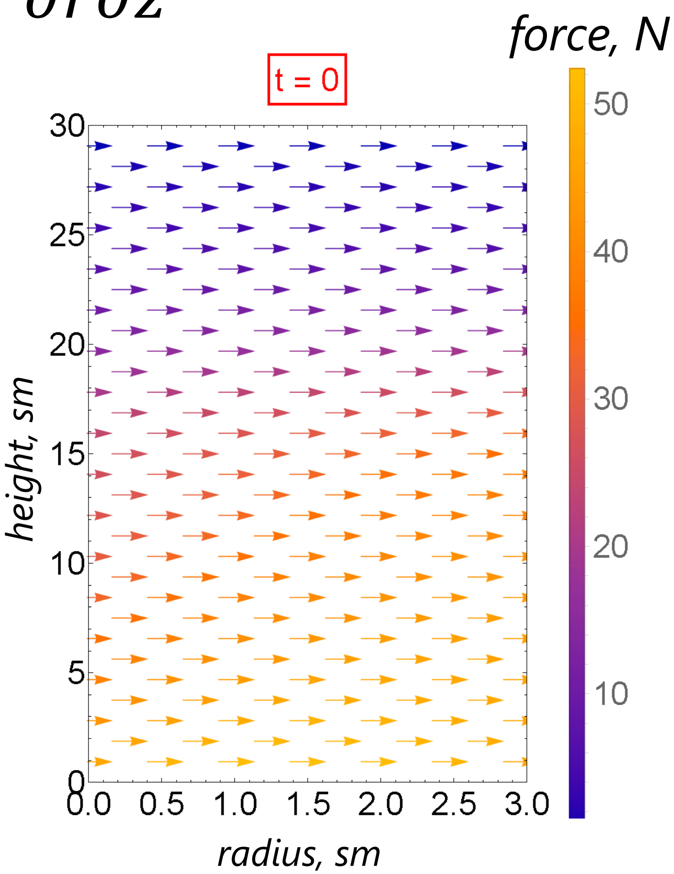
In the solution we use interpolation

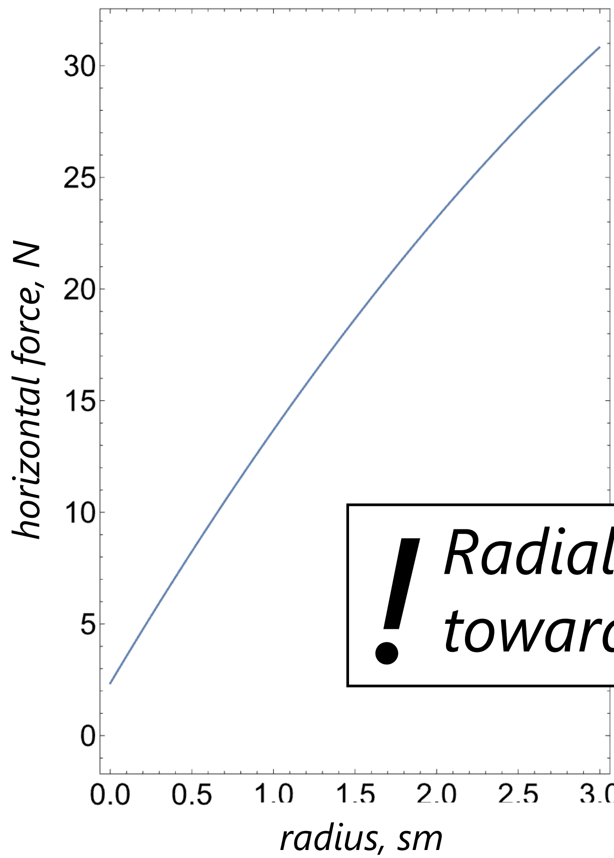
Horizontal pressure

$$dF_r - \big((p_r + dp_r)dzd\varphi(r + dr) - p_r dzd\varphi r\big) + \mu_{sand} dN = 0$$

$$\frac{\partial^2 F_r}{\partial r \partial z} = 2\pi\left[\kappa(z)p_z - \mu_{sand} r \frac{\partial p_z}{\partial z}\right]$$



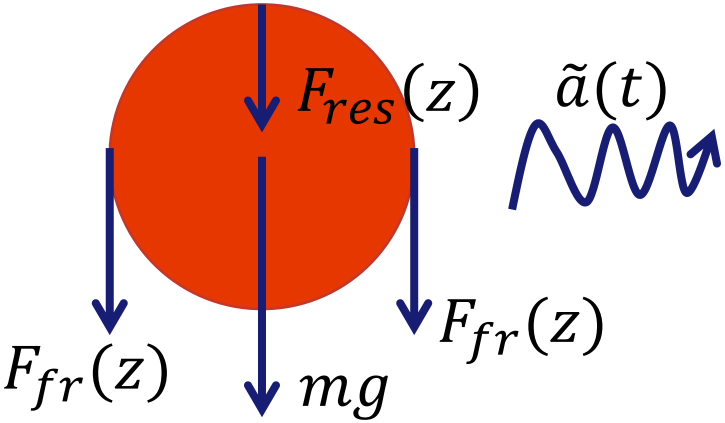




! *Radial force increases towards the wall*

Outline

Ball motion in sand reference frame

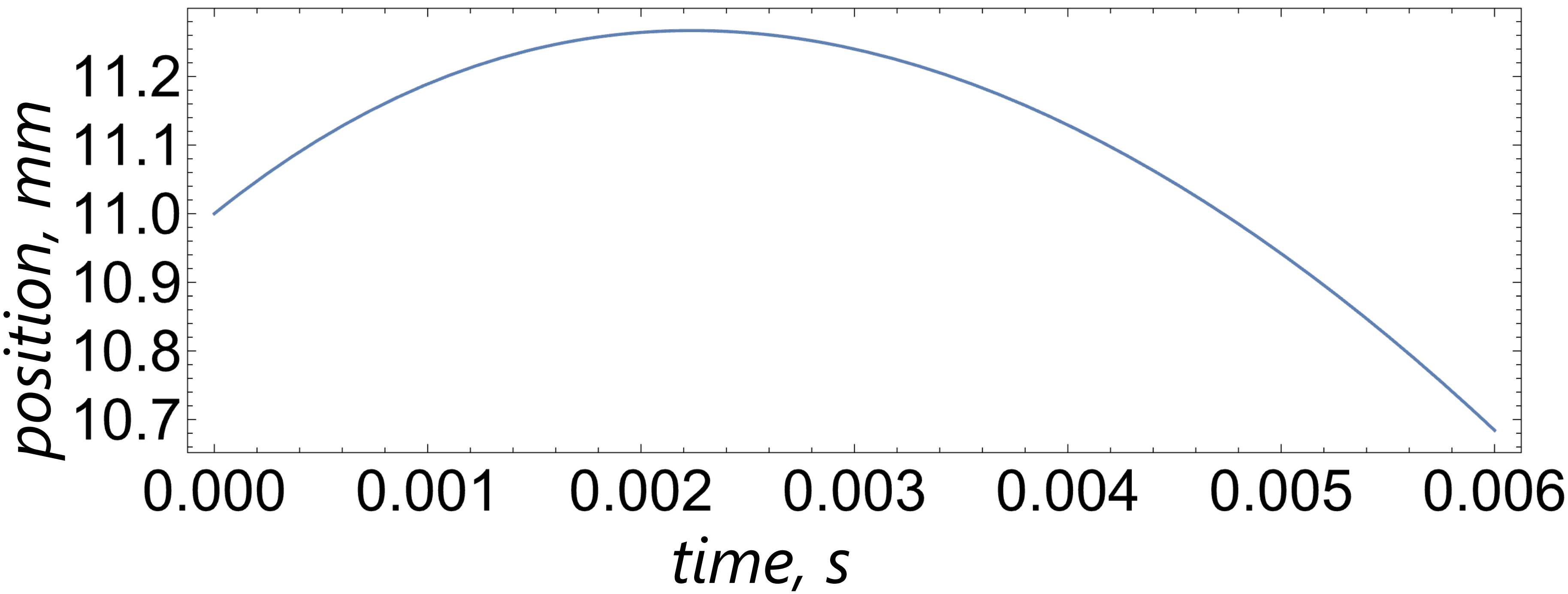


initial coordinate: $z(0) = r_b$

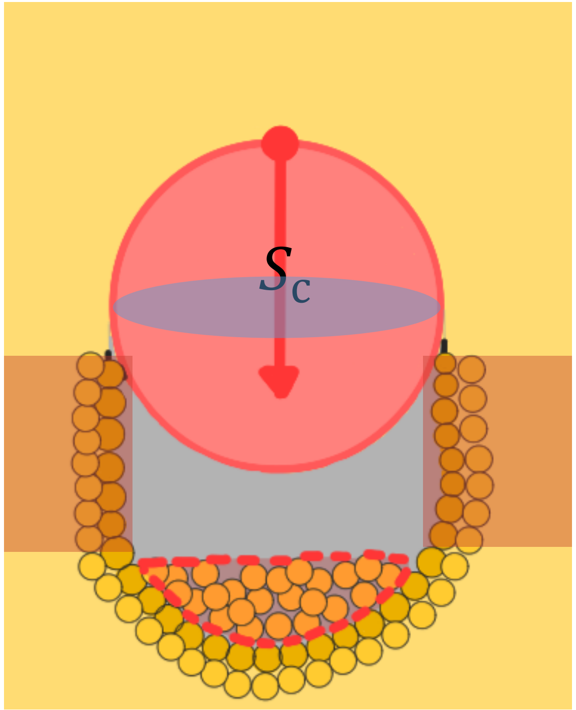
initial velocity: $v(0) = 0$

resistance force: $F_c(z) = \pi R^2 p_z(z)$

II Newton law: $m\ddot{z} = -mg - F_c(z) - F_{\text{тр}}(z) - mA\omega^2 sin(\omega t)$



Cavity filling

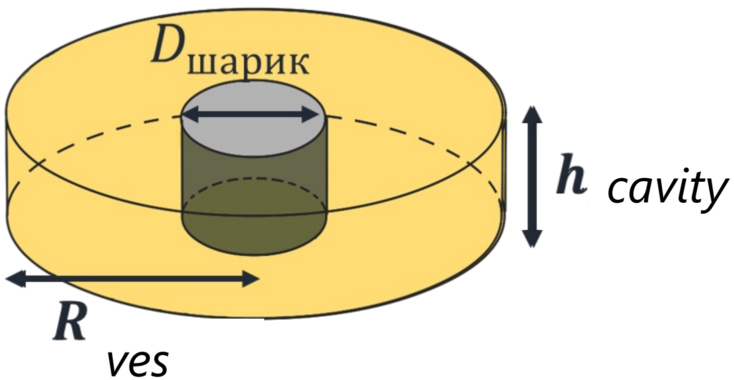


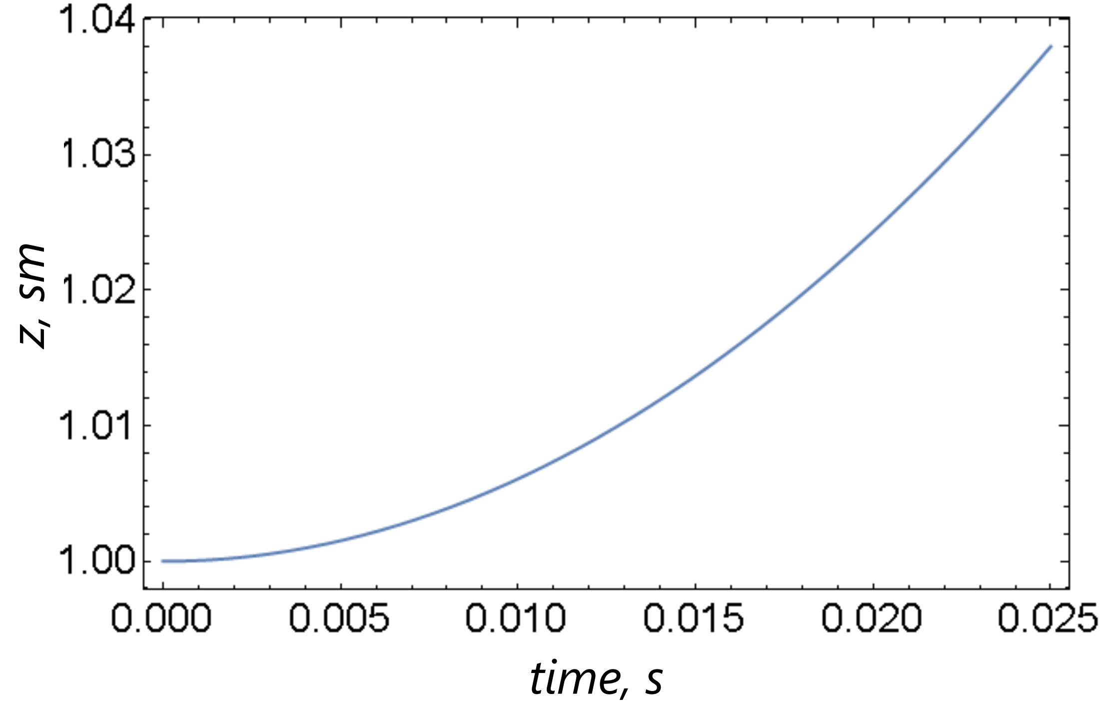
II Newton law: $mk\ddot{z} = F_h(z)$

filling coefficient

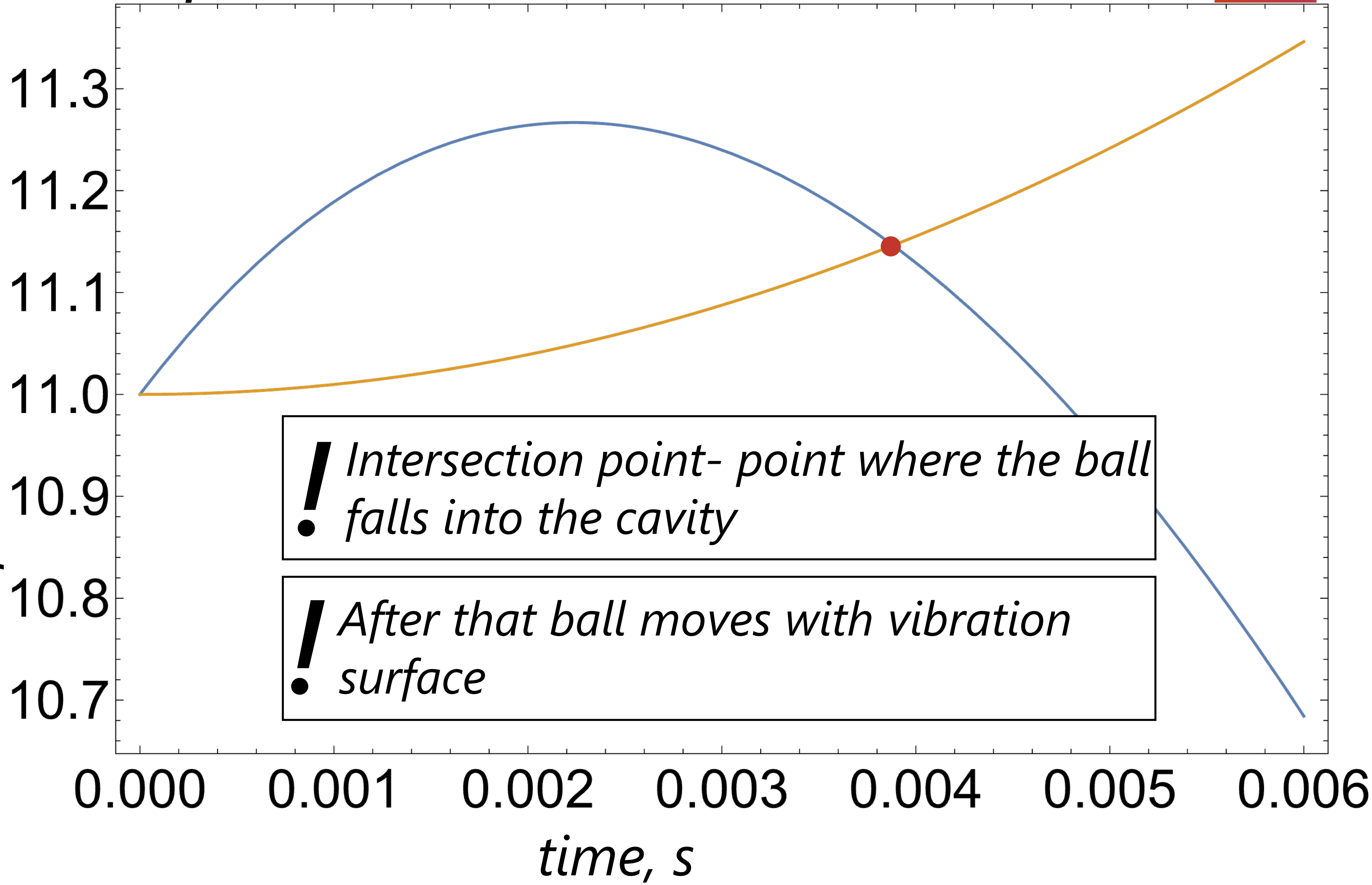
$$S_b \dot{z} = S_{wall} \dot{h}$$

$$k = \frac{S_b}{S_{wall}}$$





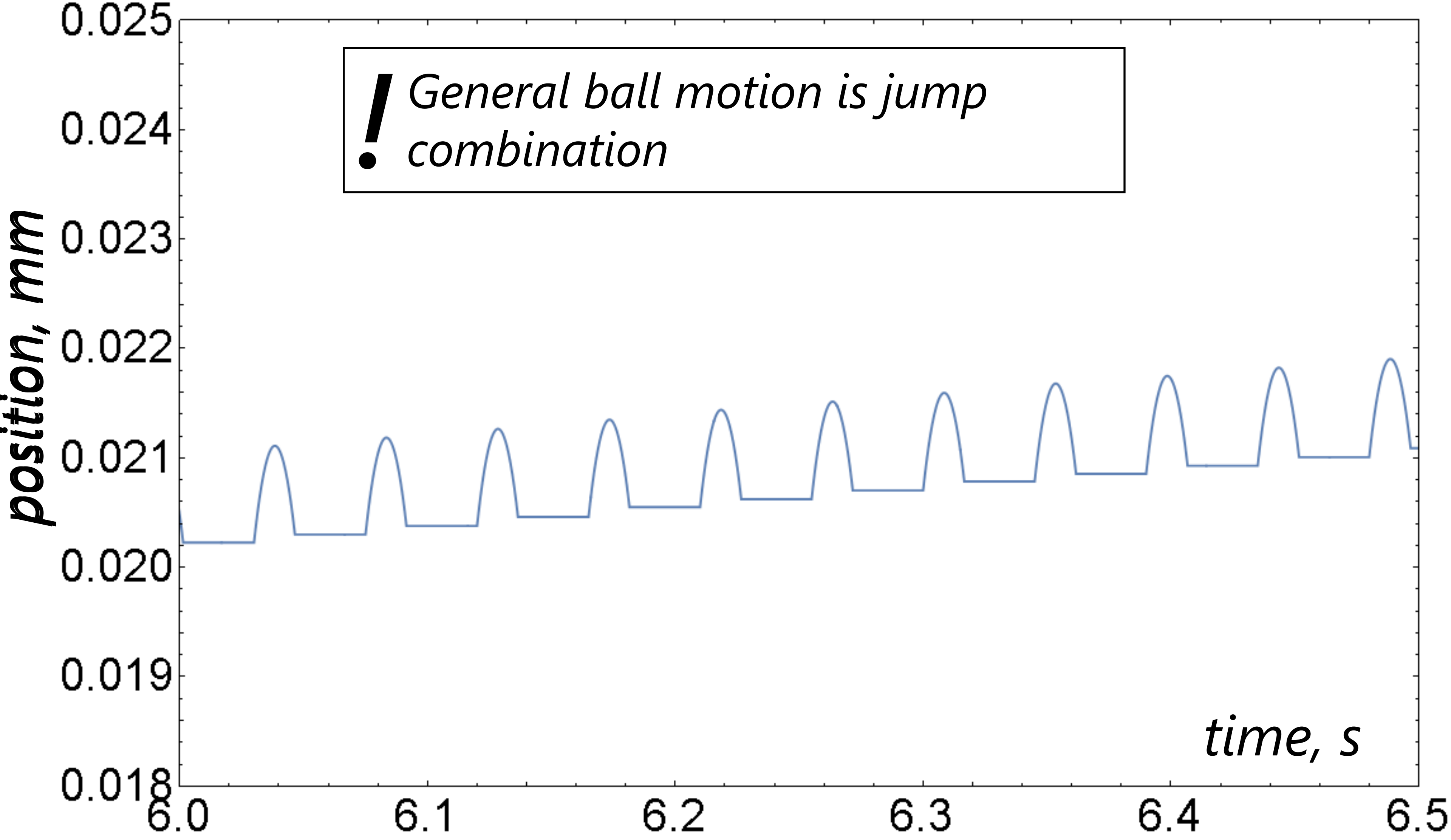
Ball drop



! *Intersection point- point where the ball falls into the cavity*

! *After that ball moves with vibration surface*

Multiple solution



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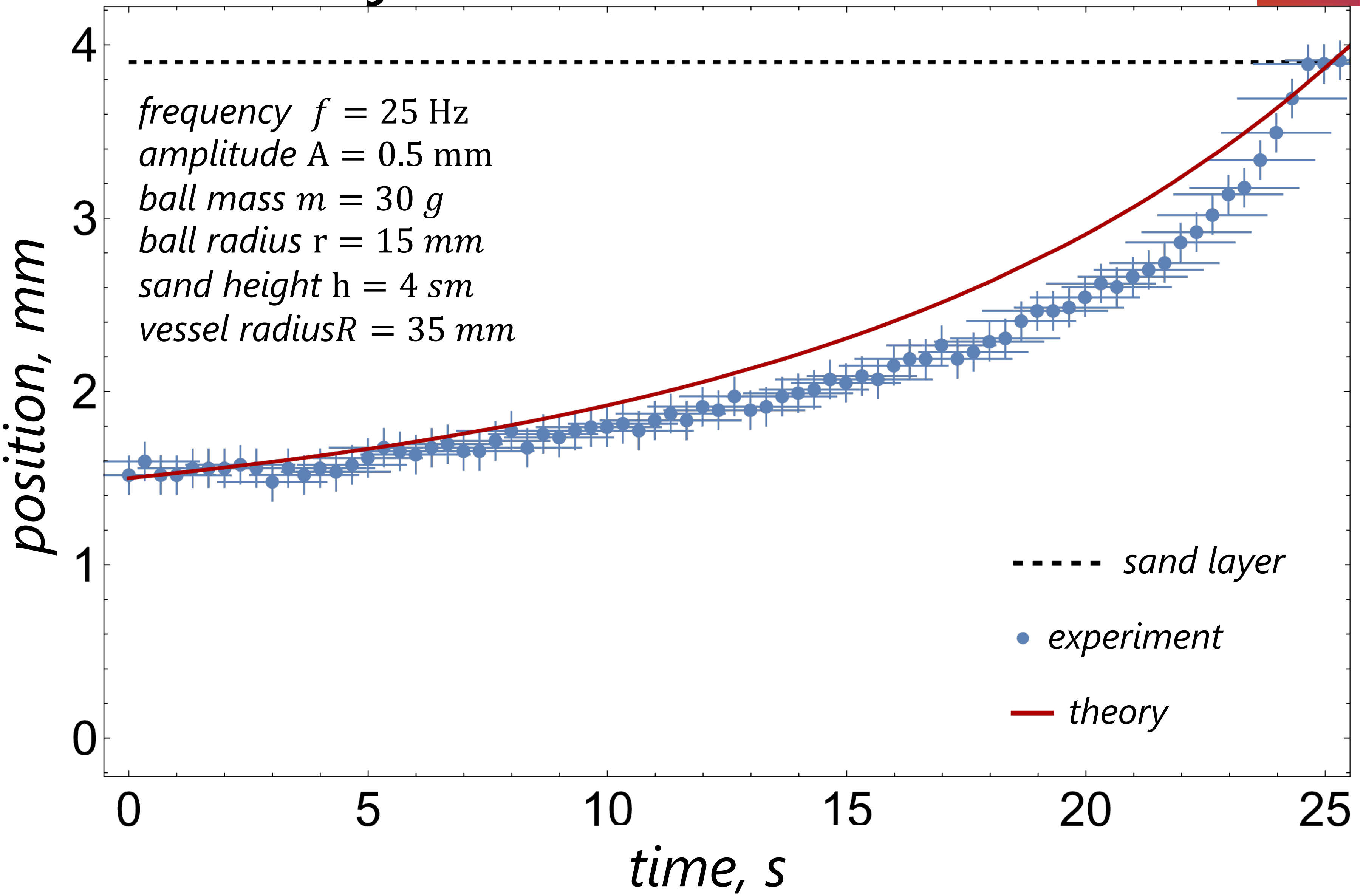
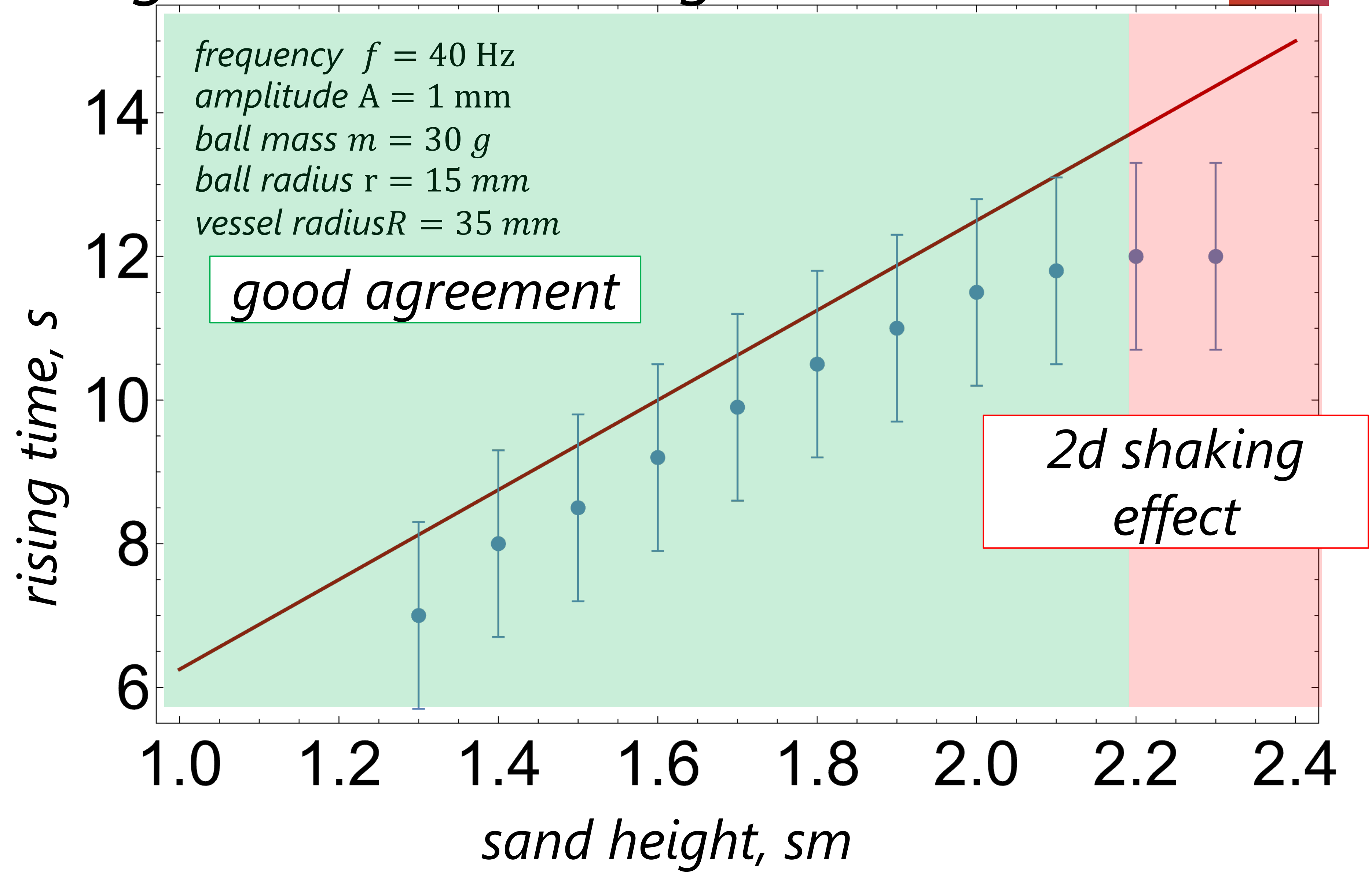
The most energy efficient shaking technique to raise the item up

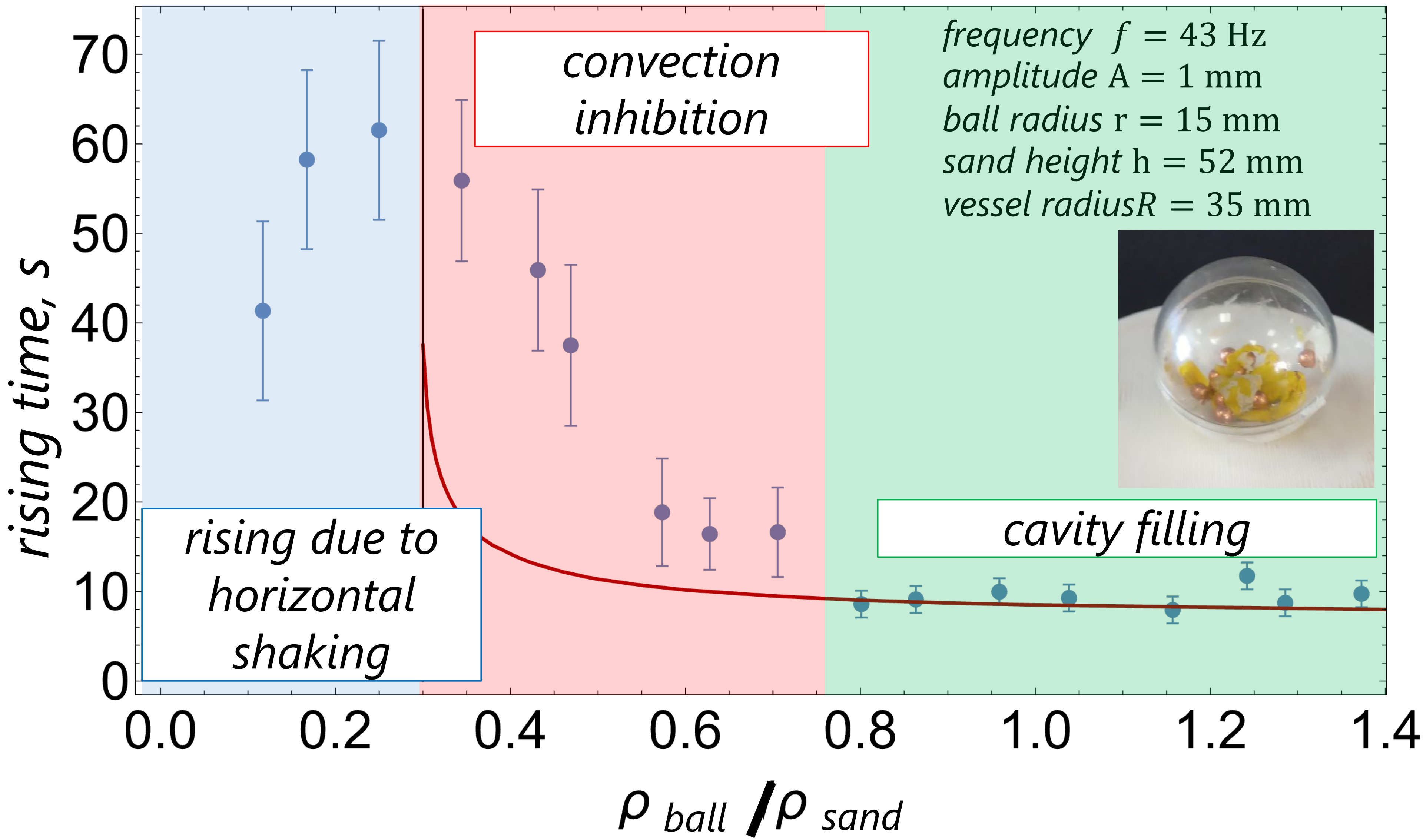
Observed trajectories



Rising time vs sand height



Rising time vs density



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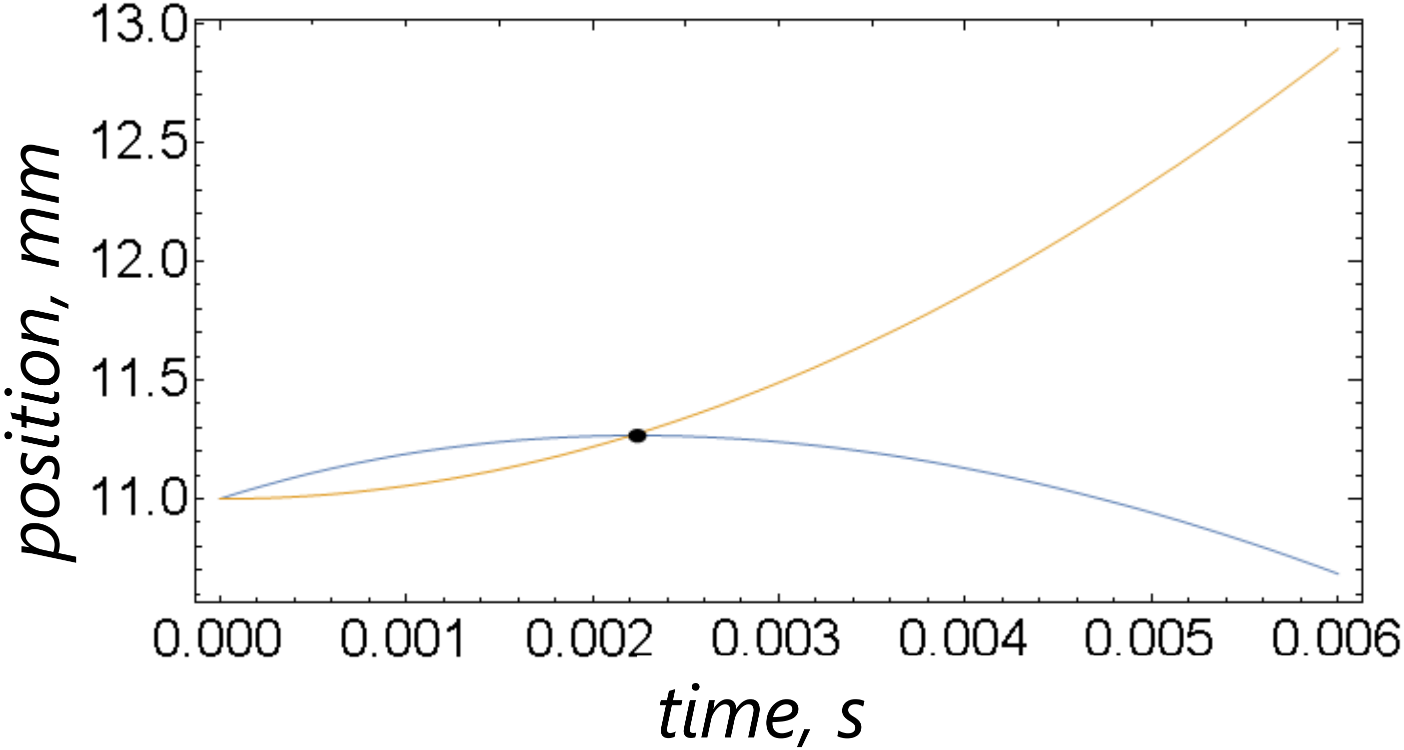
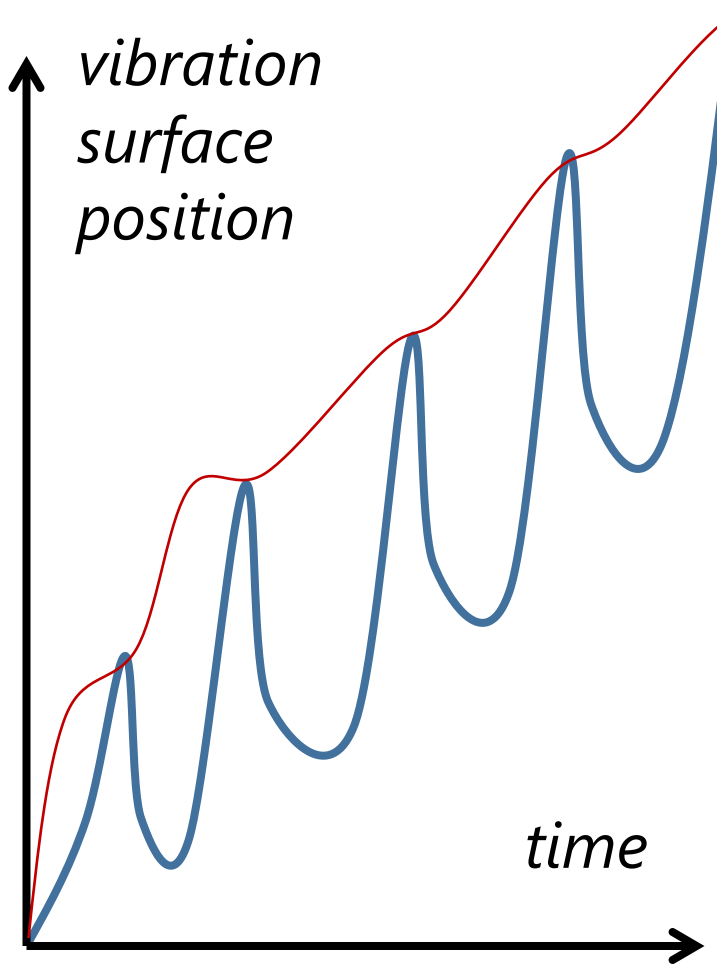
Rising optimization

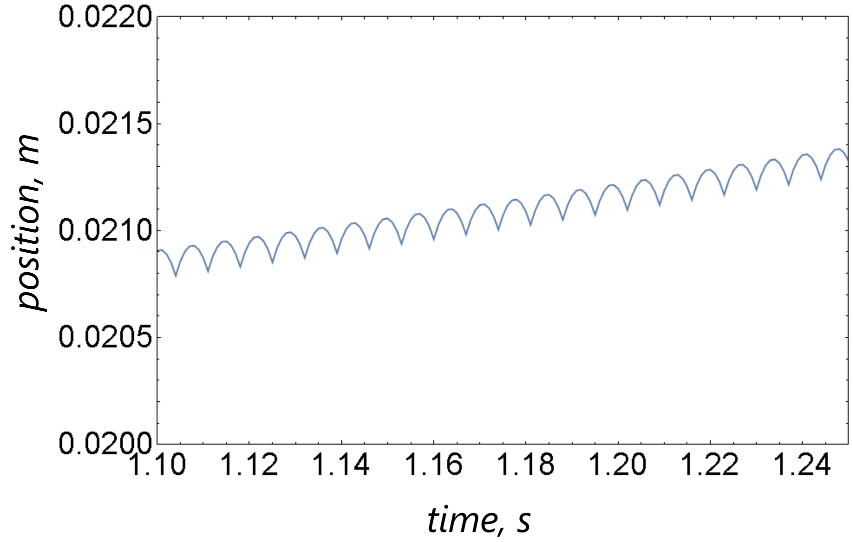
! The surface of the sand should catch up with the ball at the top of the lift.

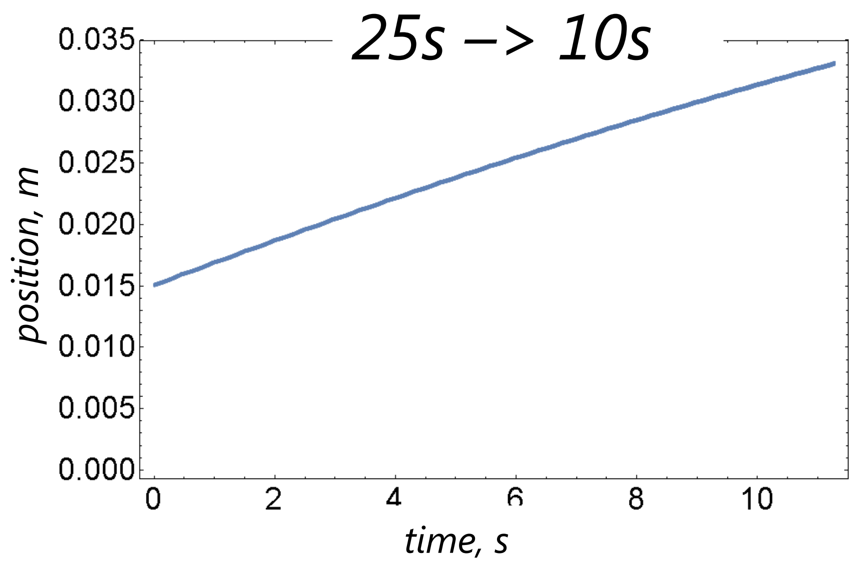
! At the top of the ball's rise, a new impact must occur



Vibration type for most efficient rising time







Conclusions

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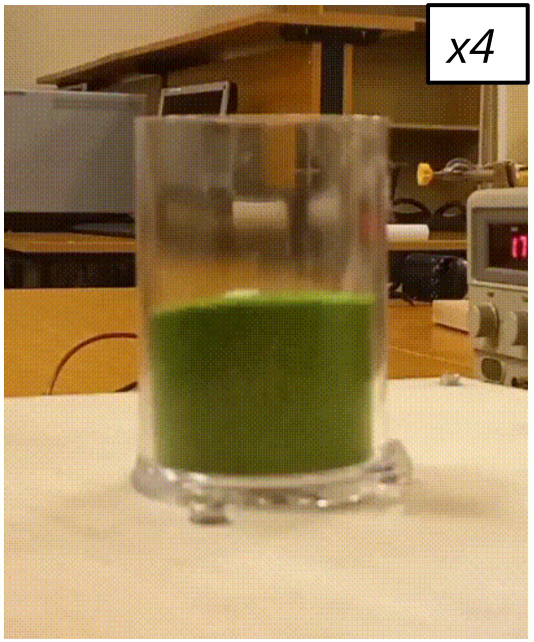
МФТИ

Thanks for attention!

Questions?



Additional slides

Vertical pressure gradient

II з-н Ньютона в со столба

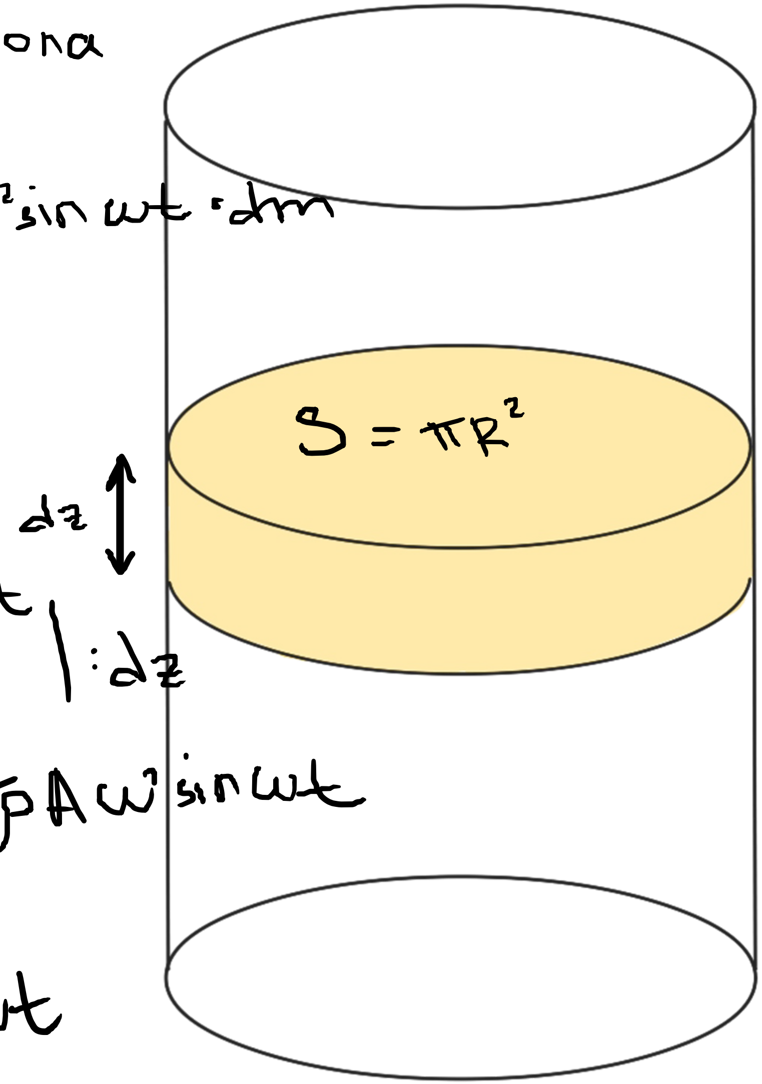
$$\pi R^2\, dp_v = -dm\, g - 2\mu p_n \cdot dz\, \pi R + A\omega^2 \sin\omega t \cdot dm$$

$$dm = dz \cdot \pi R^2 \cdot \rho$$

$$\pi R^2\, dp_v = -dz \cdot \pi R^2 \rho g - 2\mu p_n dz\, \pi R + dz\, \pi R^2 \rho \cdot A\omega^2 \sin\omega t \quad \Big|:dz$$

$$\cancel{\pi R^2} \cdot \frac{dp_v}{dz} = -\cancel{\pi R^2}\rho g - \frac{2\mu p_n \cancel{\pi R}}{R} + \cancel{\pi R^2}\rho A\omega^2 \sin\omega t$$

$$\frac{dp_v}{dz} = -\rho g - \frac{2\mu p_n}{R} + \rho A\omega^2 \sin\omega t$$



Horizontal pressure

$$dF_r - \left((p_r + dp_r)dzd\varphi(r + dr) - p_r dzd\varphi r\right) + \mu_{\text{песок}} dN = 0$$

$$dF_r = (p_r dzd\varphi dr + dp_r dzd\varphi r) - \mu_{\text{песок}} dN$$

$$dF_r = p_r dzd\varphi dr + dp_r dzd\varphi r - \mu_{\text{песок}} dp_z (r + dr) d\varphi dr$$

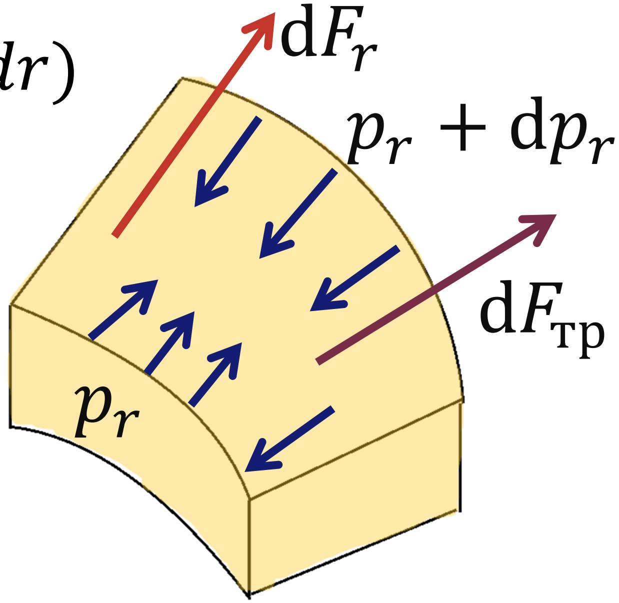
$$dF_r = 2\pi(p_r dzdr + rdp_r dz - \mu_{\text{песок}} rdp_z dr)$$

$$dF_r = 2\pi(p_r dzdr + rdp_r dz - \mu_{\text{песок}} rdp_z dr)$$

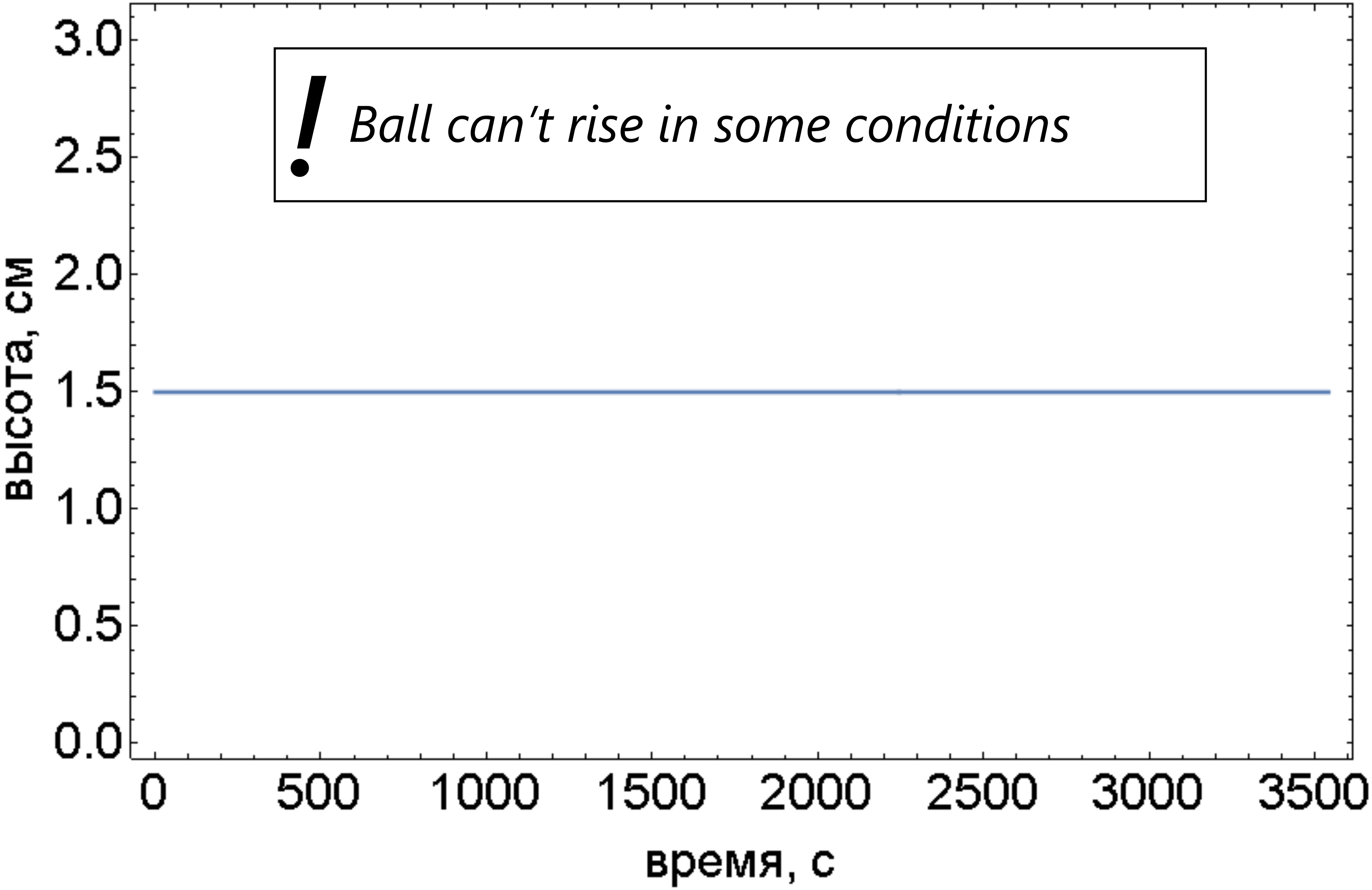
$$\frac{\partial F_r}{\partial r \partial z} = 2\pi(p_r + r\frac{\partial p_r}{\partial r} - \mu_{\text{песок}} r\frac{\partial p_z}{\partial z})$$

$$\frac{\partial F_r}{\partial r \partial z} = 2\pi(\kappa p_z + \cancel{r\kappa\frac{\partial p_z}{\partial r}} - \mu_{\text{песок}} r\frac{\partial p_z}{\partial z})$$

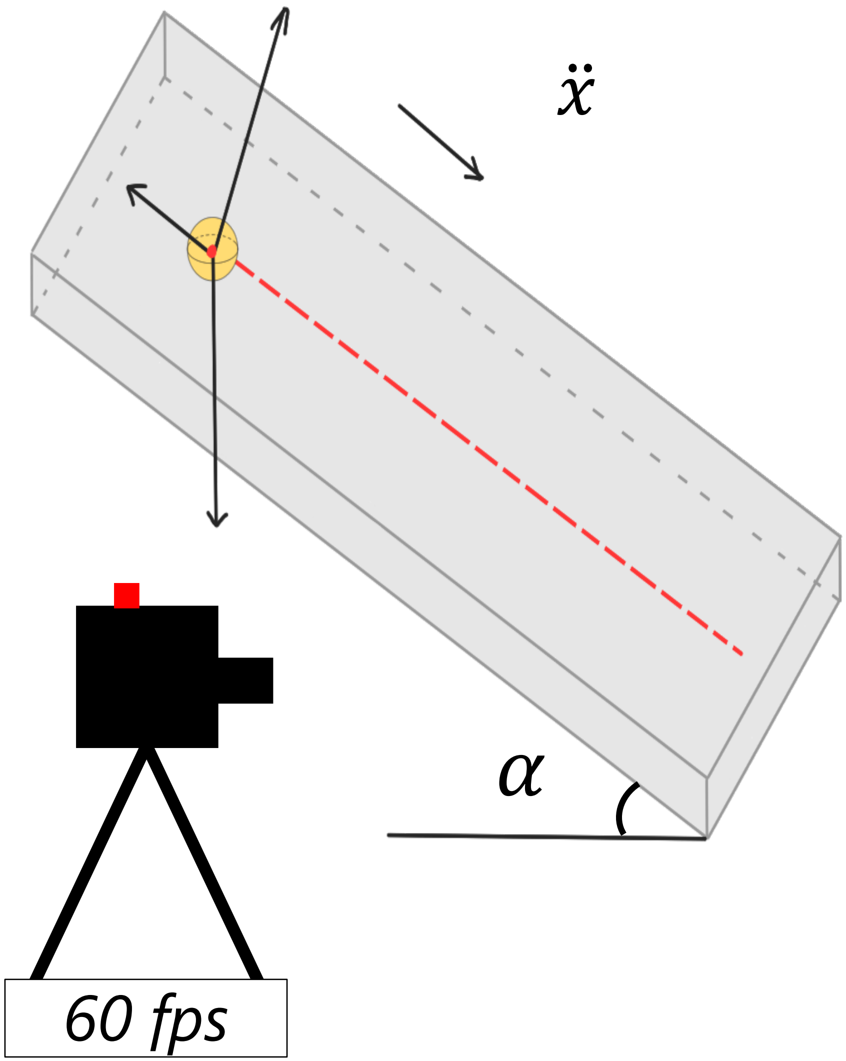
$$\frac{\partial^2 F_r}{\partial r \partial z} = 2\pi(\kappa p_z - \mu_{\text{песок}} r\frac{\partial p_z}{\partial z})$$



Some solutions

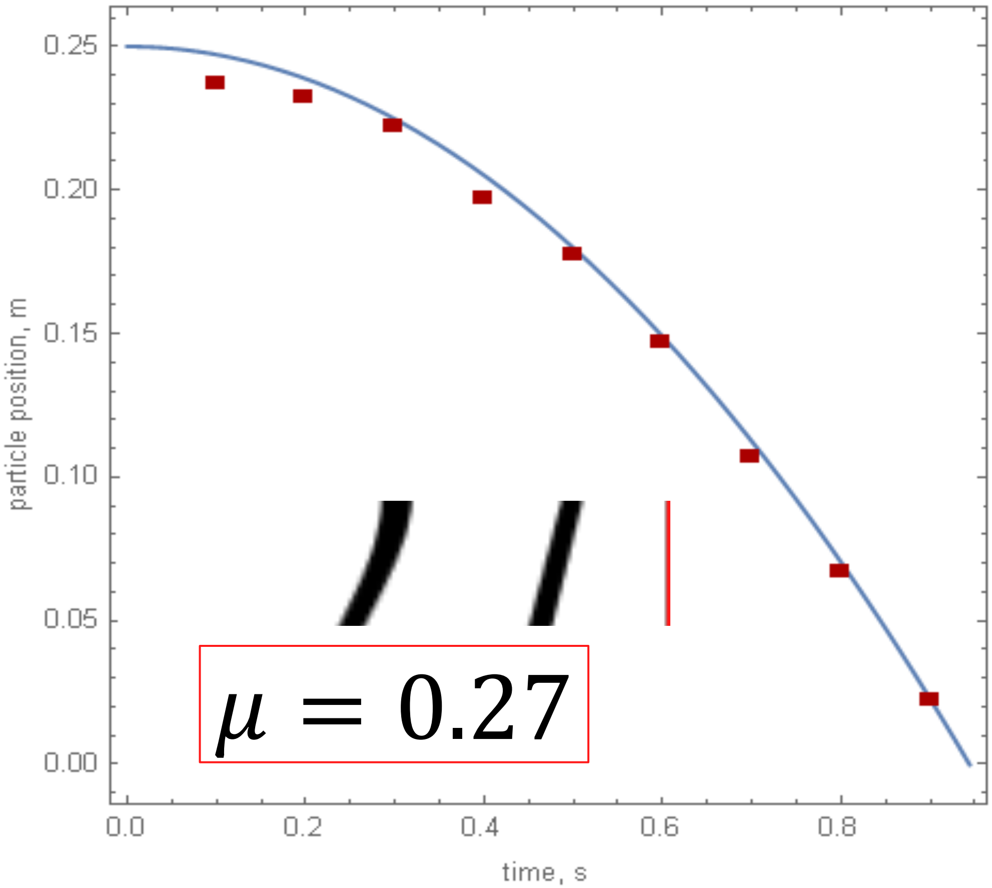


Friction coefficient



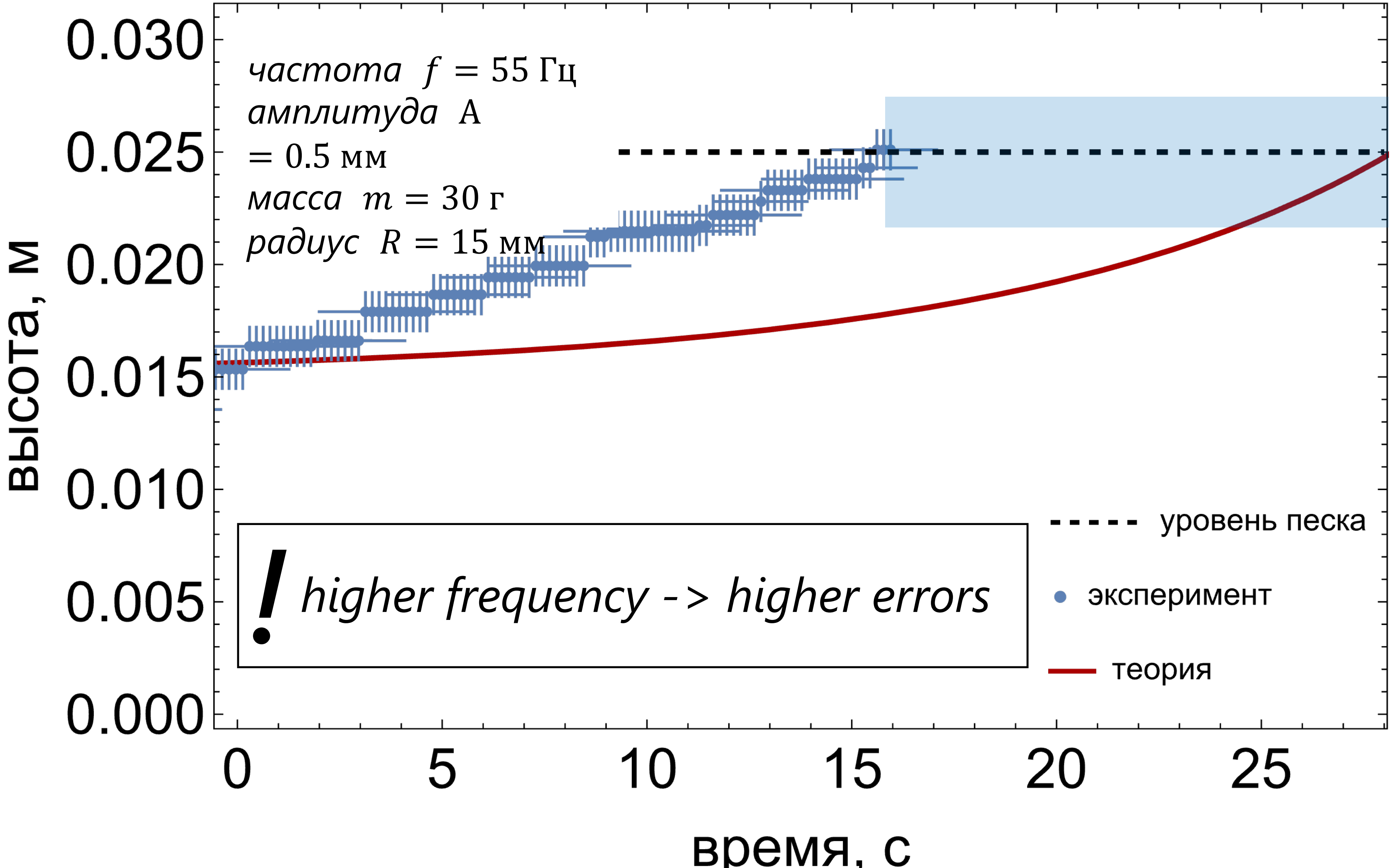
II закон Ньютона:

$$g(\sin\alpha - \mu\cos\alpha) = \ddot{x}$$



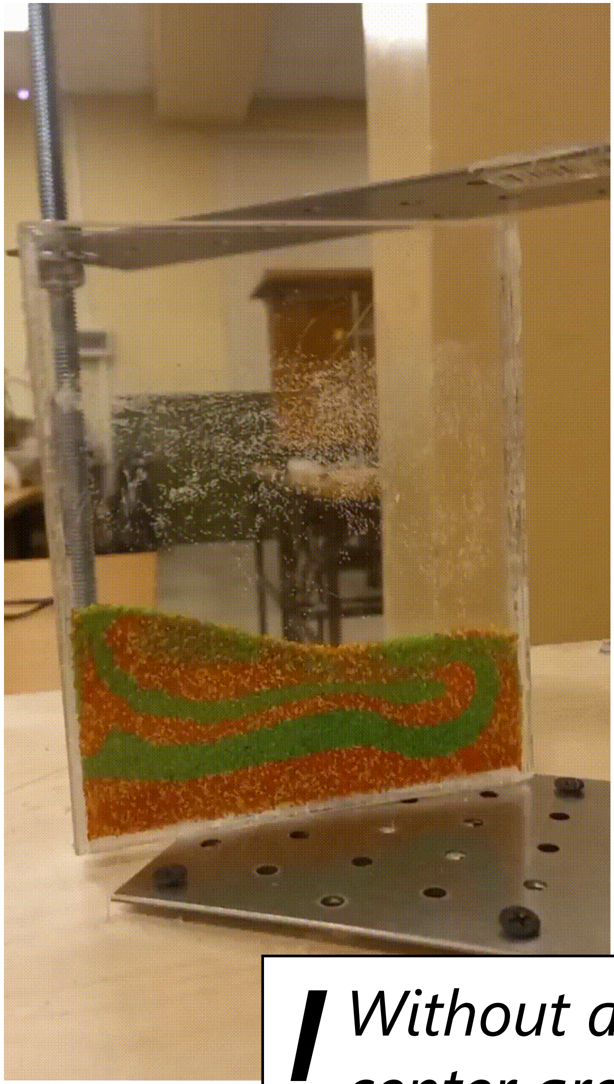
$$\boxed{\mu = 0.27}$$

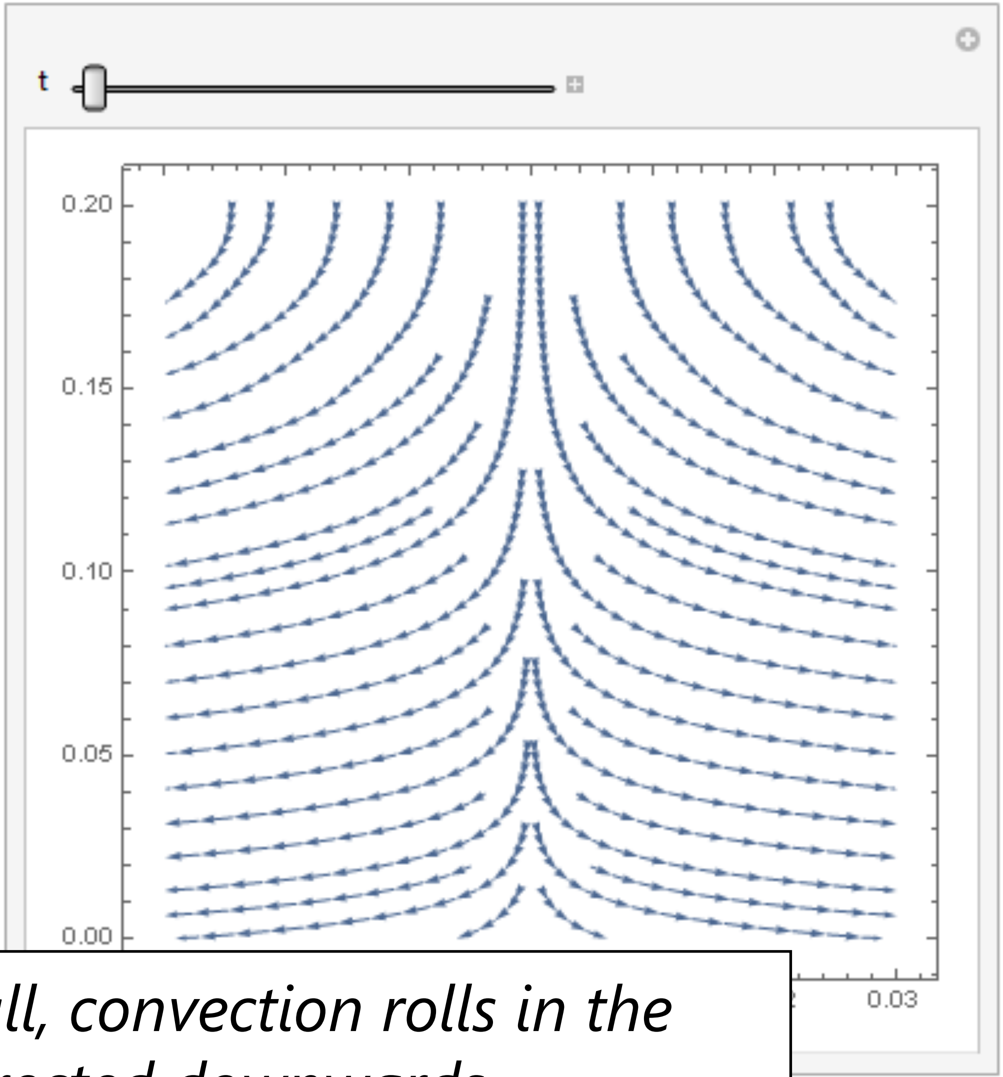
Observed trajectories



! *higher frequency -> higher errors*

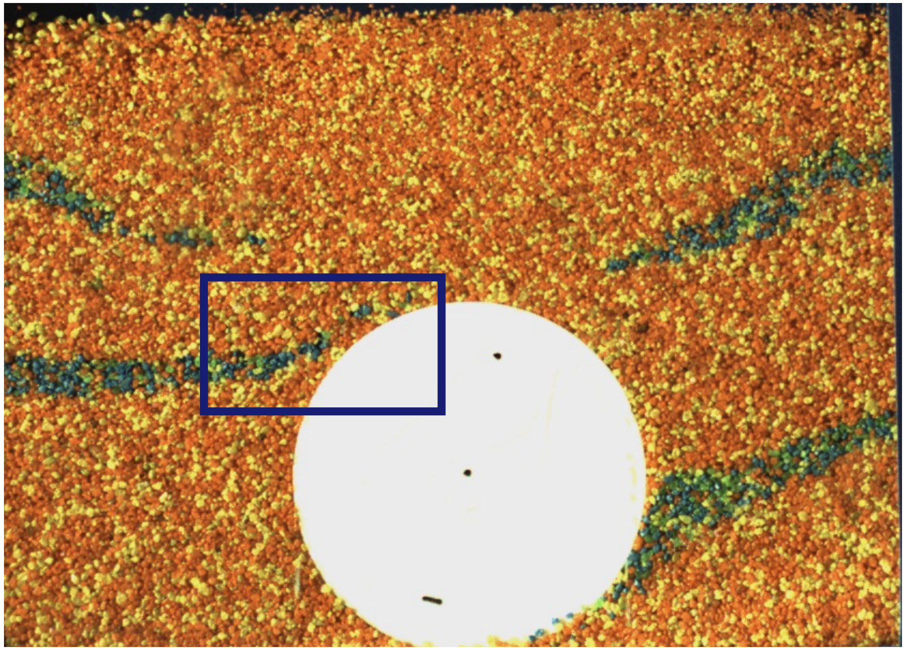
Convection rolls

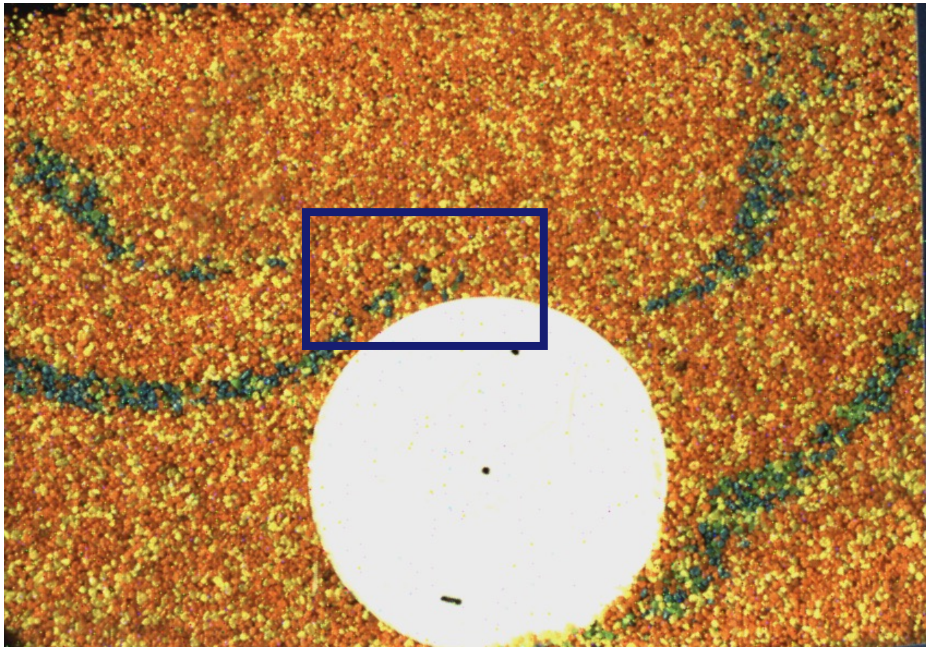




! *Without a ball, convection rolls in the center are directed downwards*

Convection rolls





! Convection is directed upwards in the center only due to the ball

! Convection increases rising time

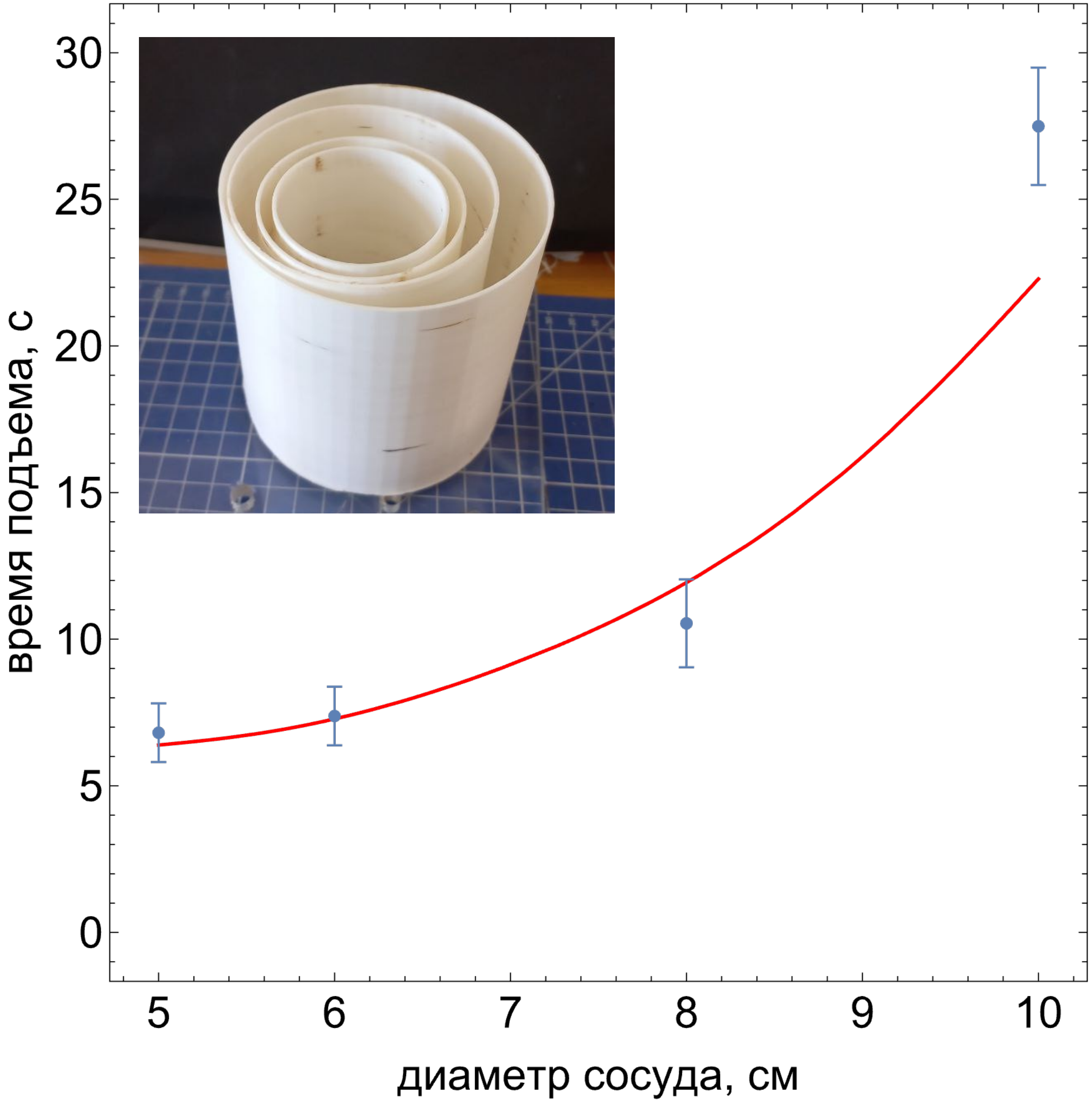
2D vibrations

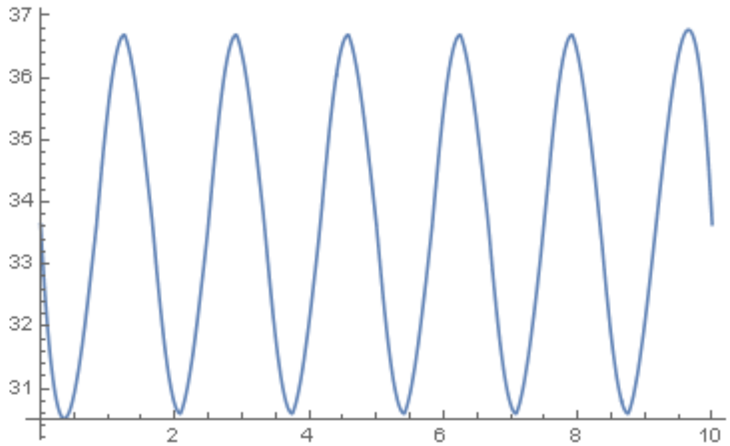
! It is impossible to get rid of horizontal oscillations in the experimental setup

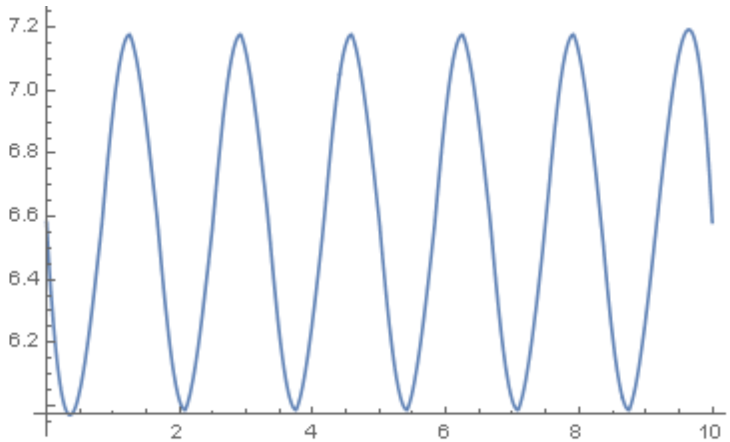
! Horizontal vibrations alone can make the ball float.

! Horizontal vibrations decrease rising time

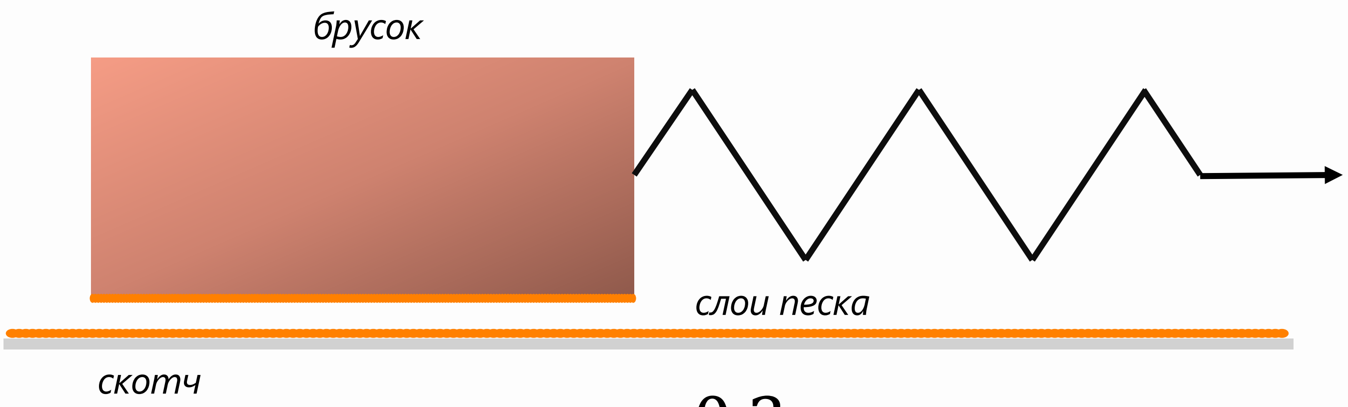
Rising time vs vessel diameter



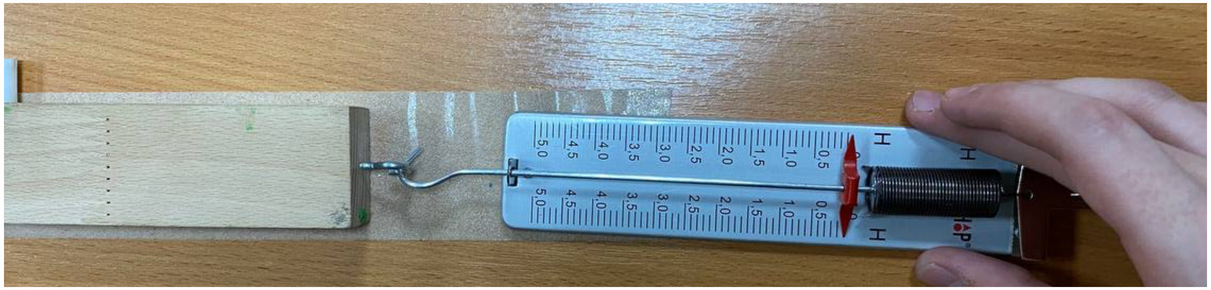


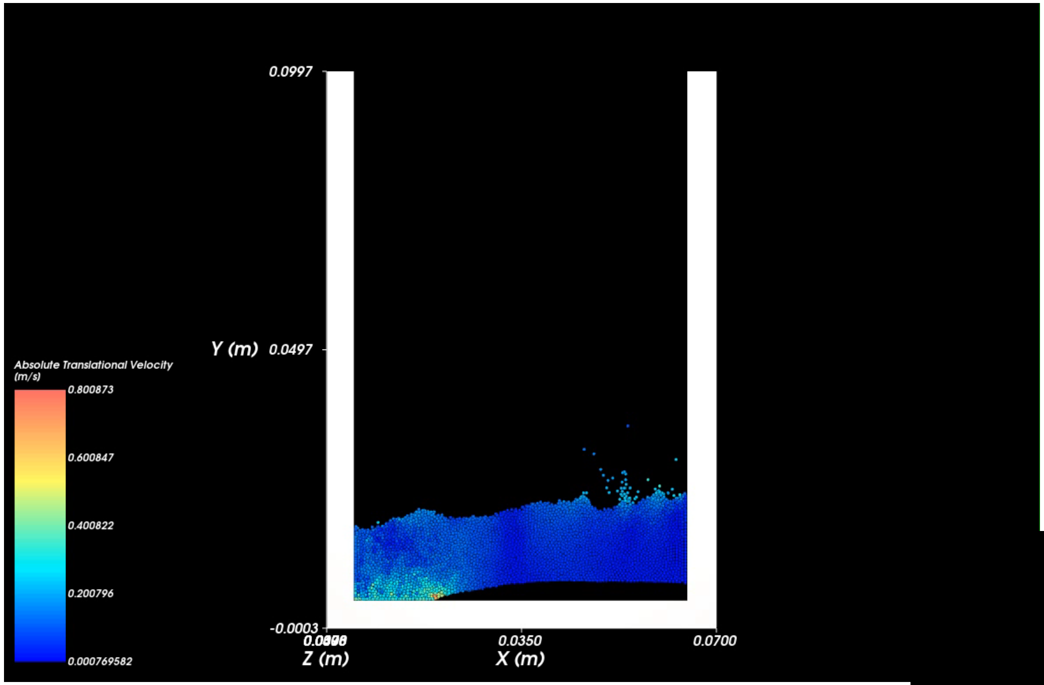


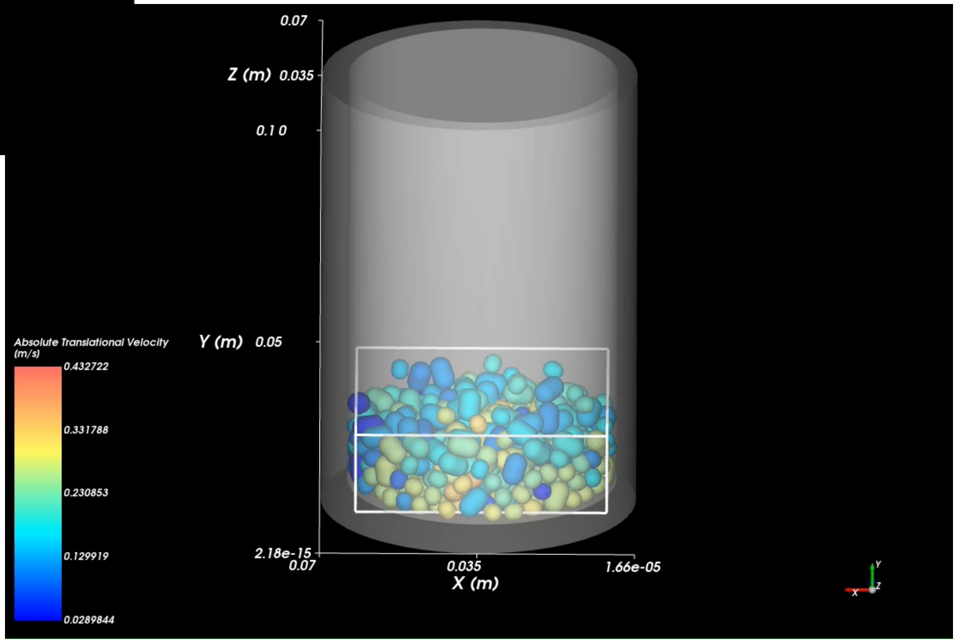
Измерение коэффициента трения

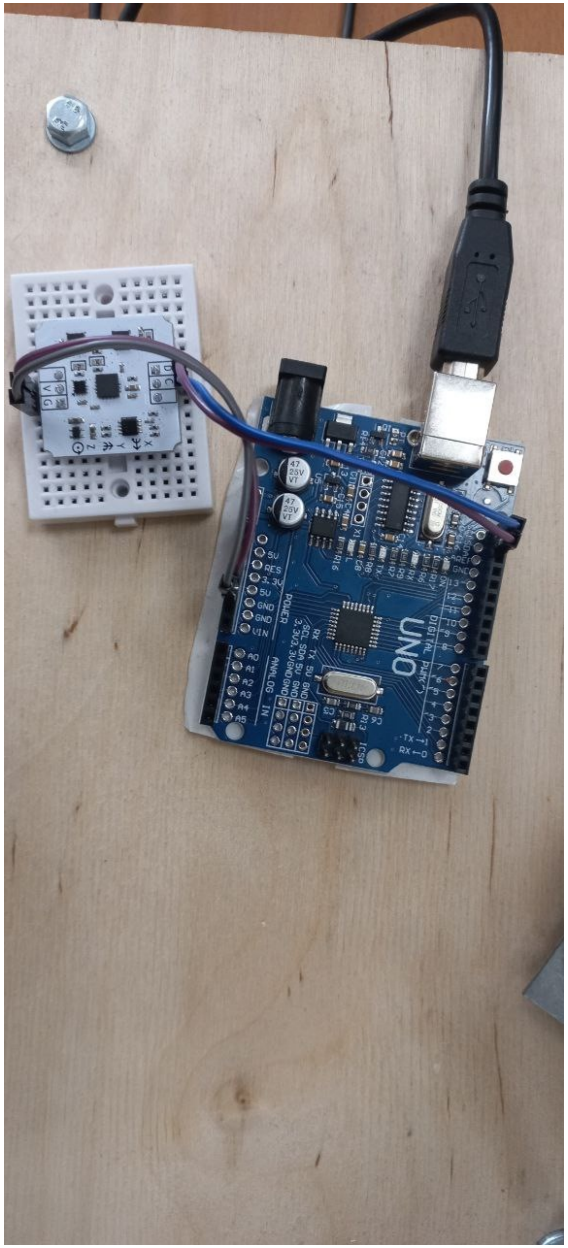


$$\mu = 0.3$$

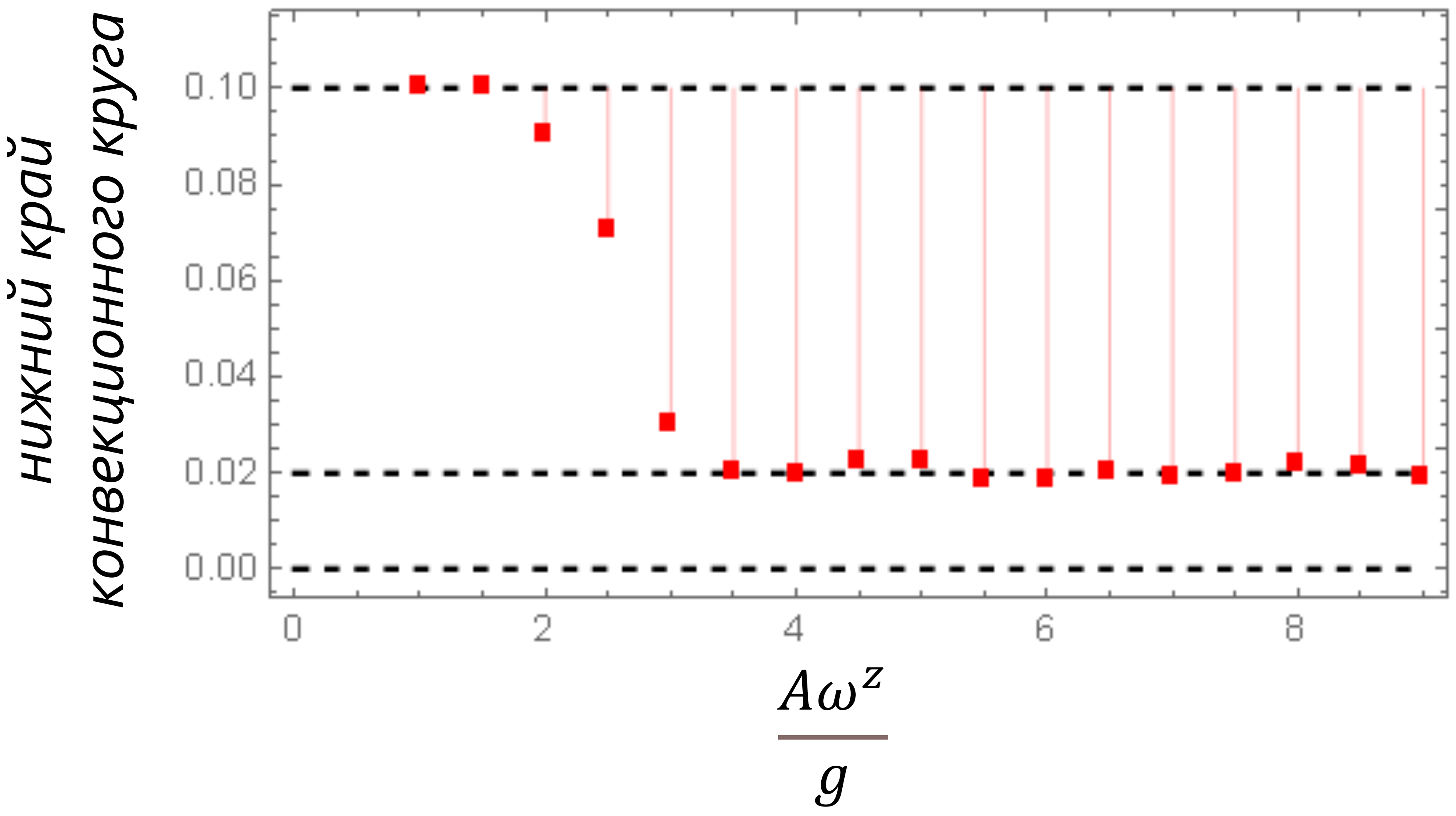


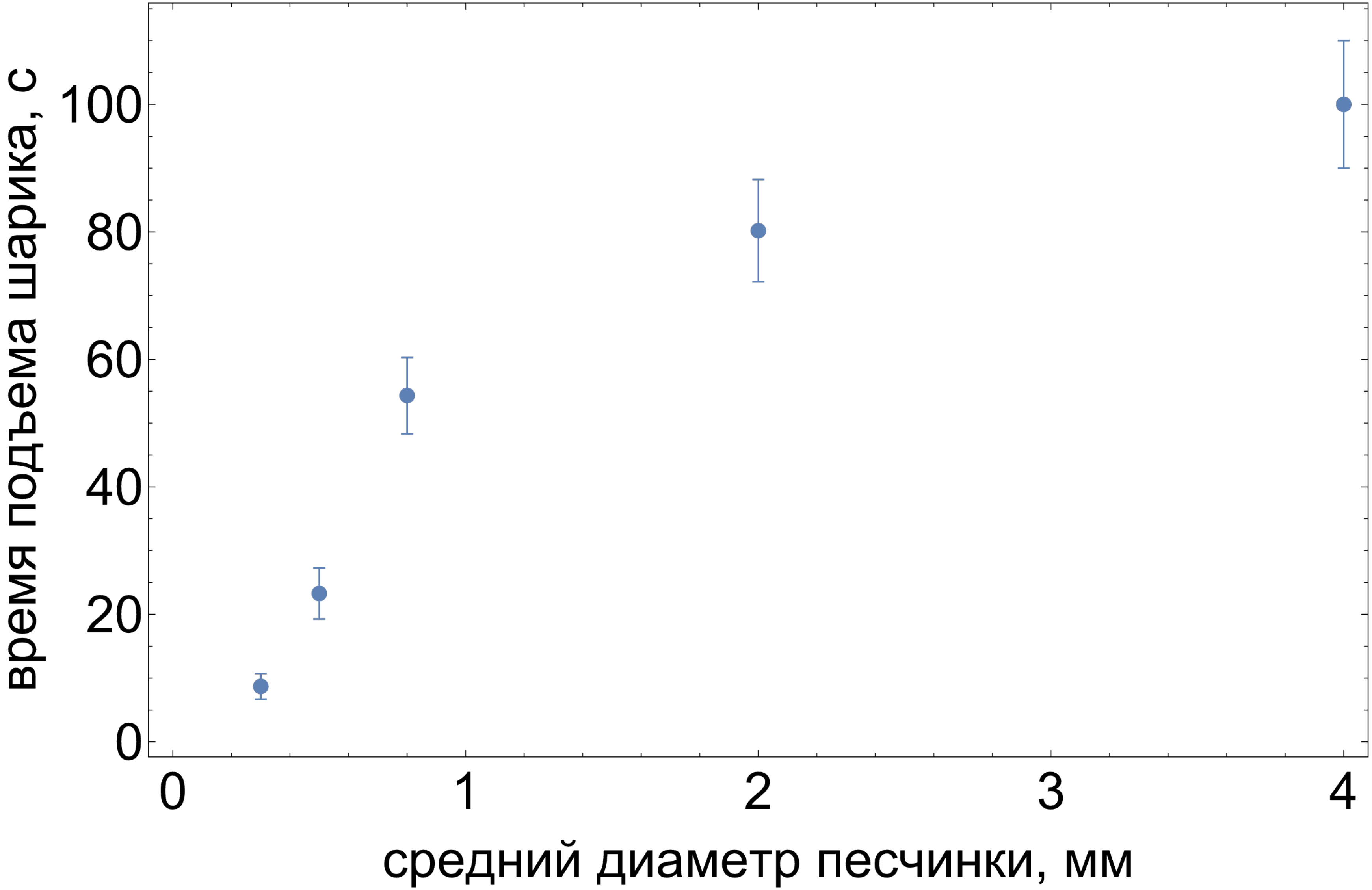

0.0997
Y (m) 0.0497
-0.0003
Absolute Translational Velocity (m/s)
0.800873
0.600847
0.400822
0.200796
0.000769582
0.0350
0.0700
Z (m)
X (m)


0.07
Z (m) 0.035
0.1 0
Y (m) 0.05
2.18e-15
0.07
0.035
1.66e-05
X (m)
Absolute Translational Velocity (m/s)
0.432722
0.331788
0.230853
0.129919
0.0289844

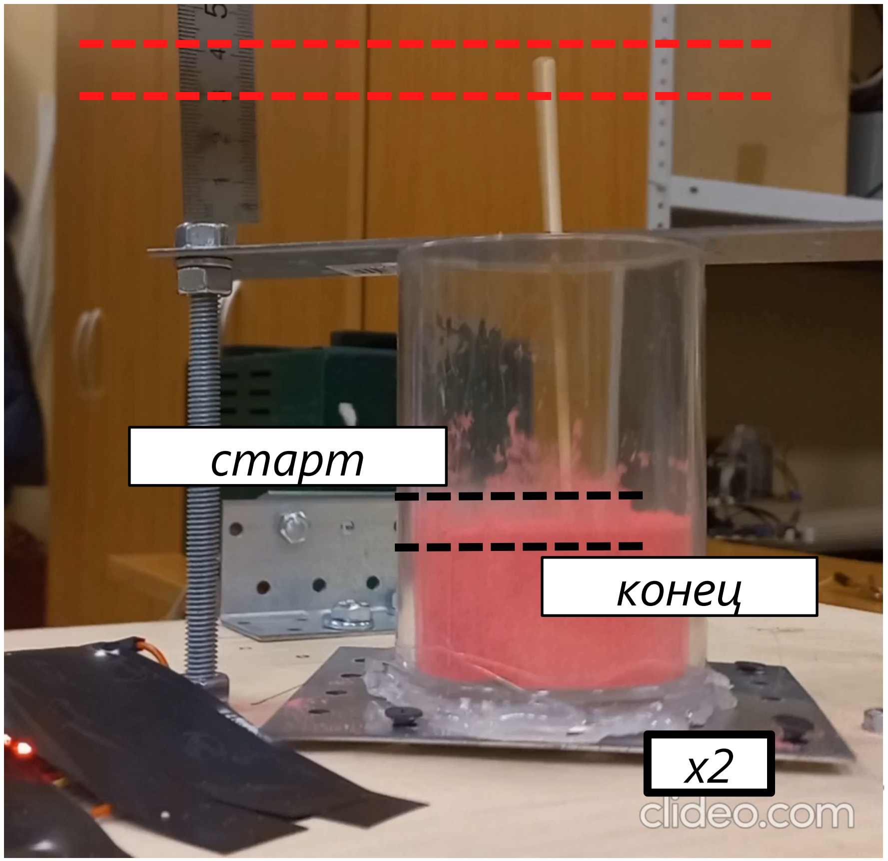


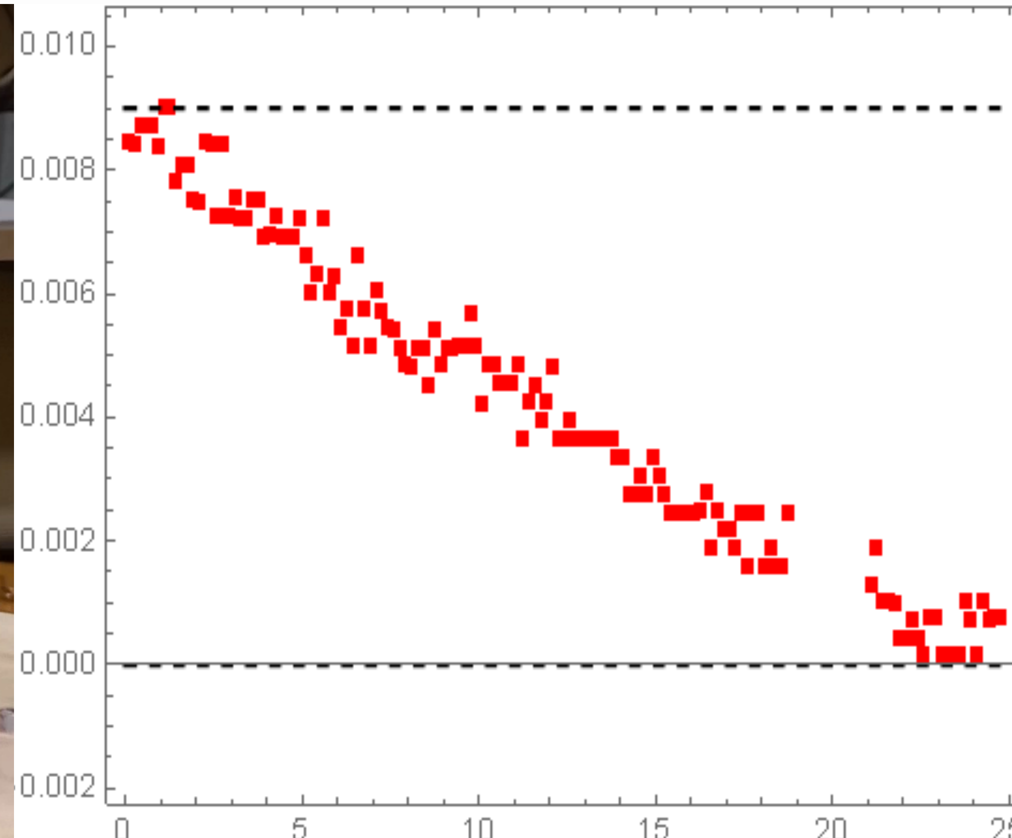
5 Эксперимент • Параметрика


нижний край
конвекционного круга
0.10
0.08
0.06
0.04
0.02
0.00
0
2
4
6
8
$\frac{A\omega^z}{g}$


время подъема шарика, с
0
20
40
60
80
100
0
1
2
3
4
средний диаметр песчинки, мм

высота, м





время, с