Screaming balloon

Problem №9

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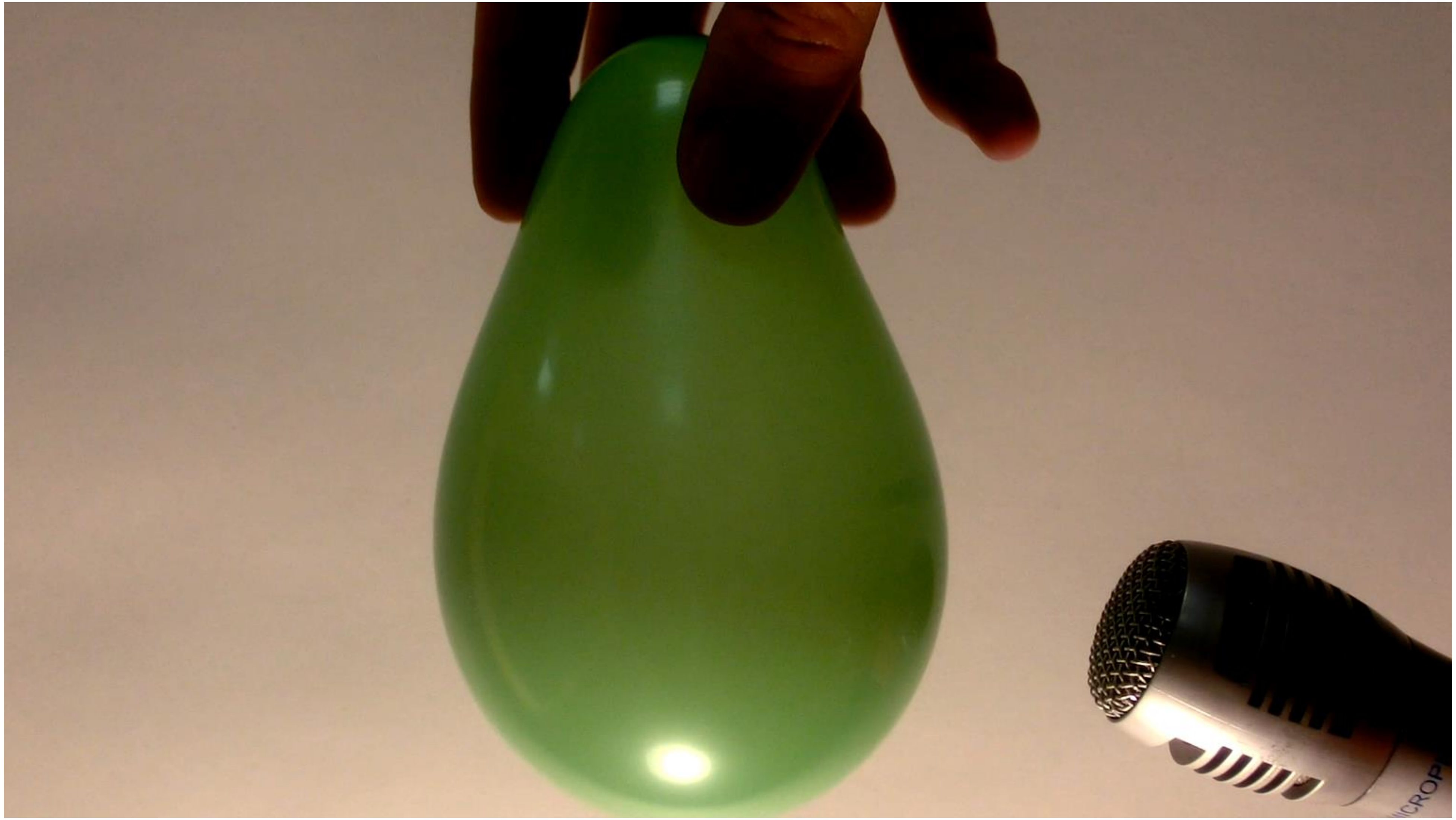
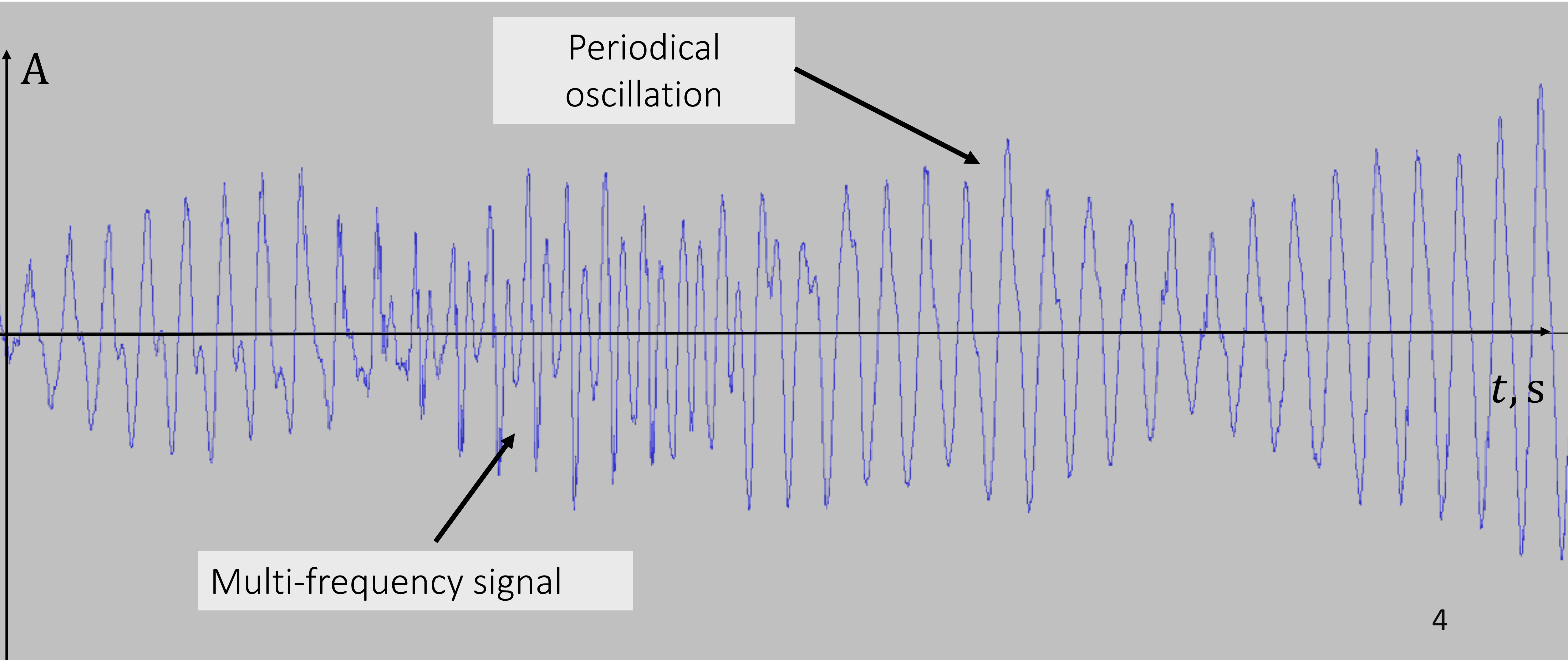
The problem

If you put a hex nut in a balloon it is possible to make it «scream» by giving a certain rotational movement to the balloon (see video). How do the characteristics of the sound produced depend on the important parameters of the system?

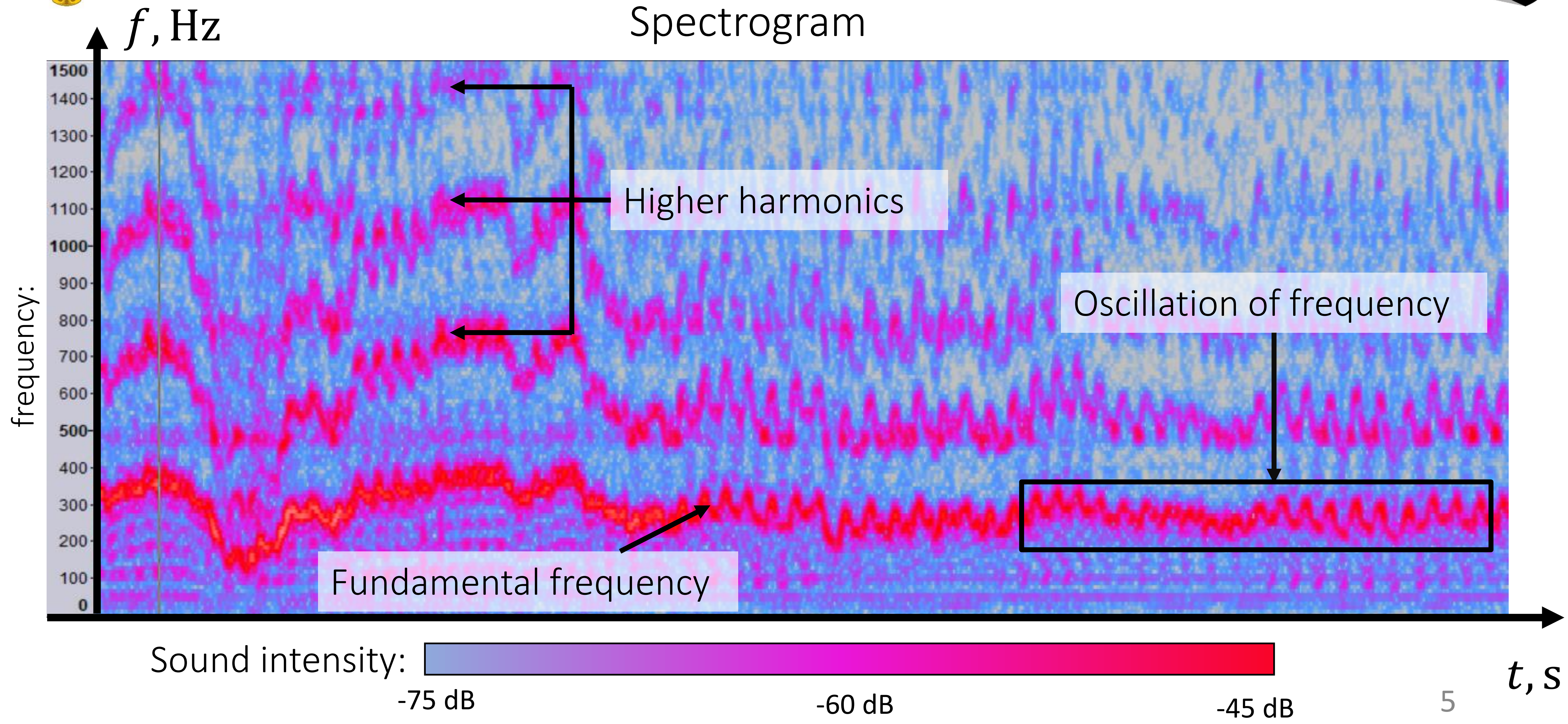
Observation



Sound wave form

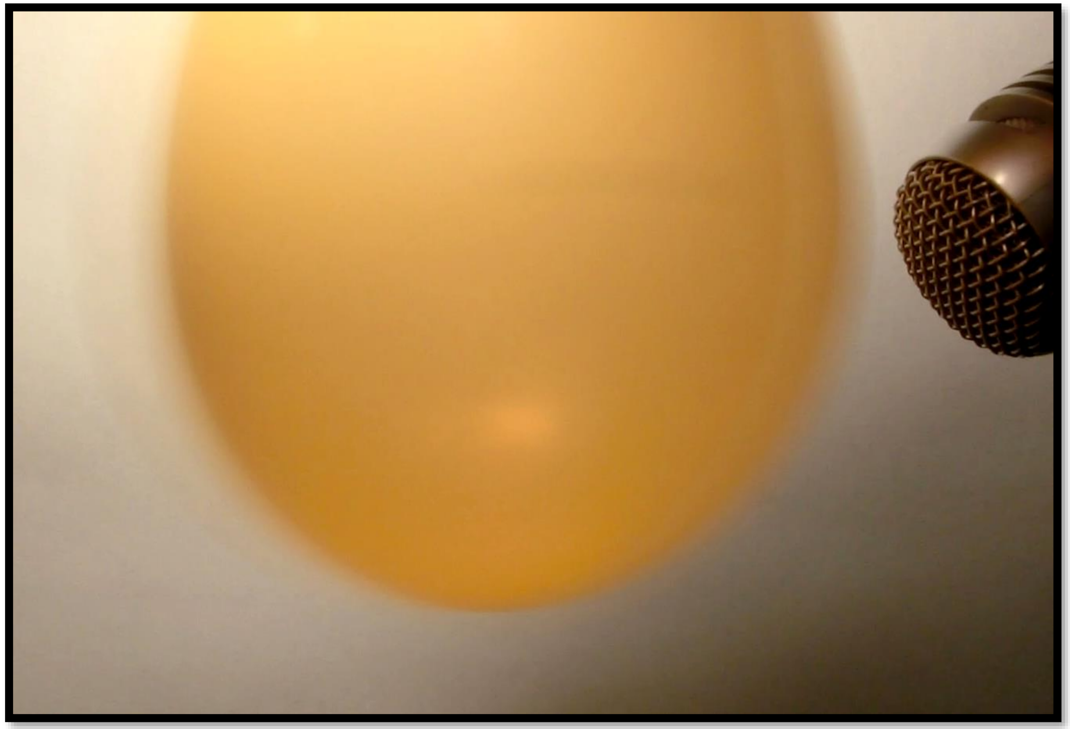


Sound processing

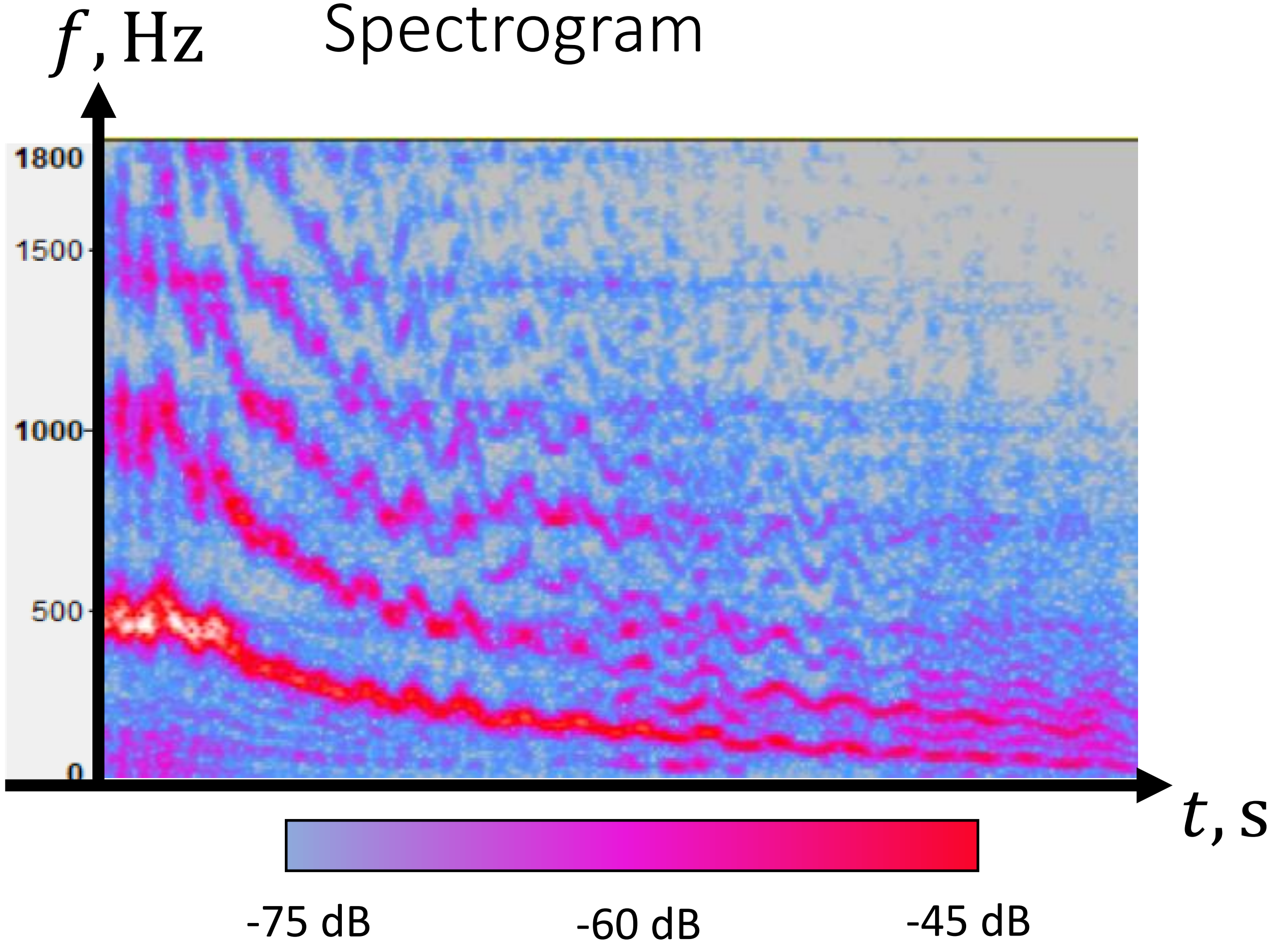


Decelerating nut

System dynamics



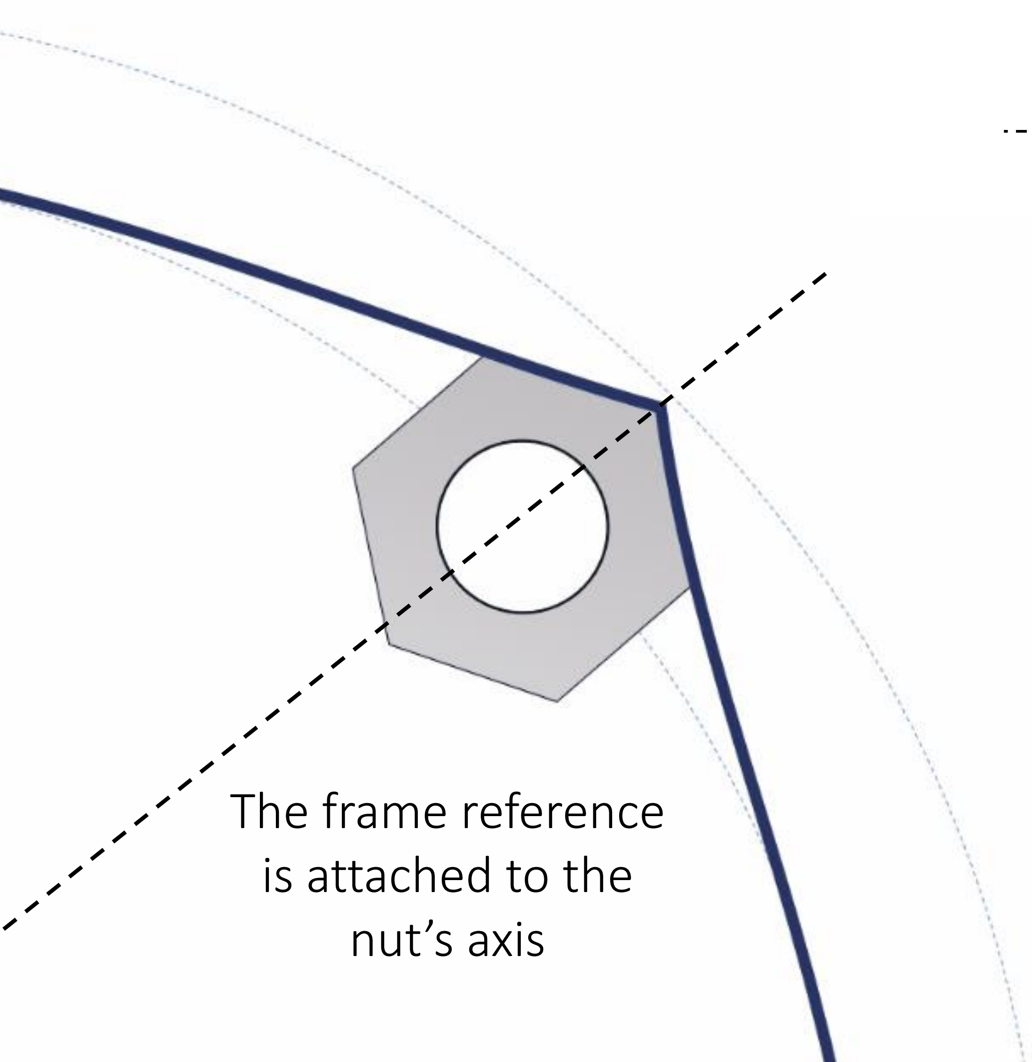
Spectrogram



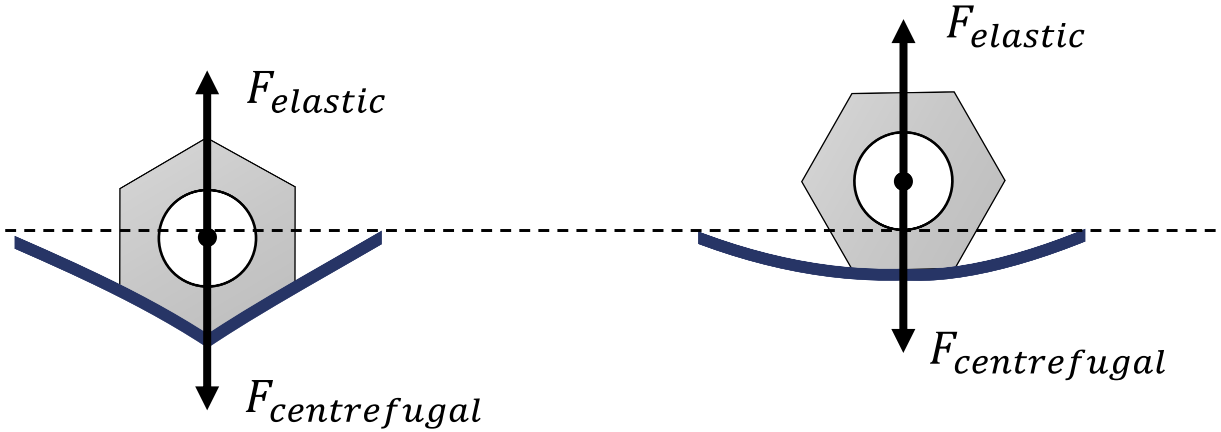
The frequency decreases while the nut slows down

System dynamics (1000 fps)

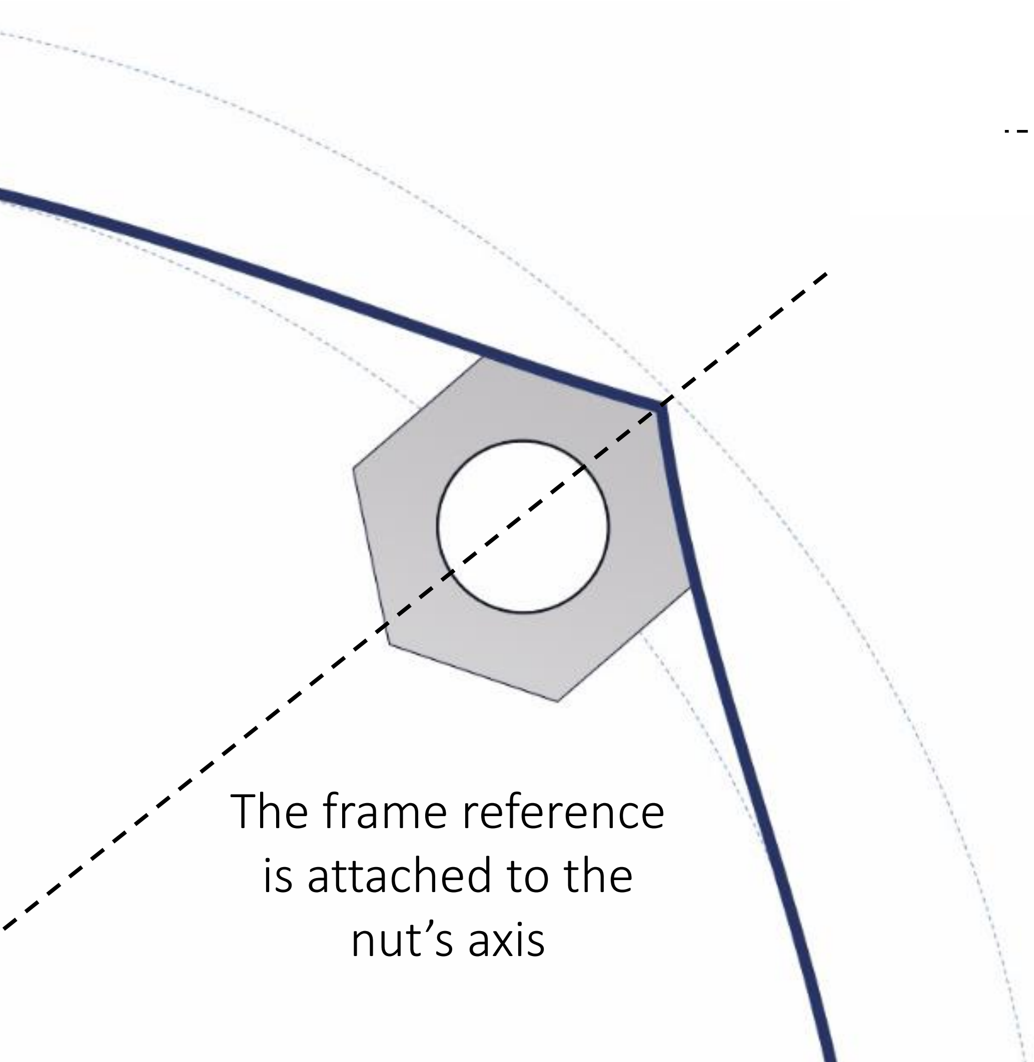
System dynamics



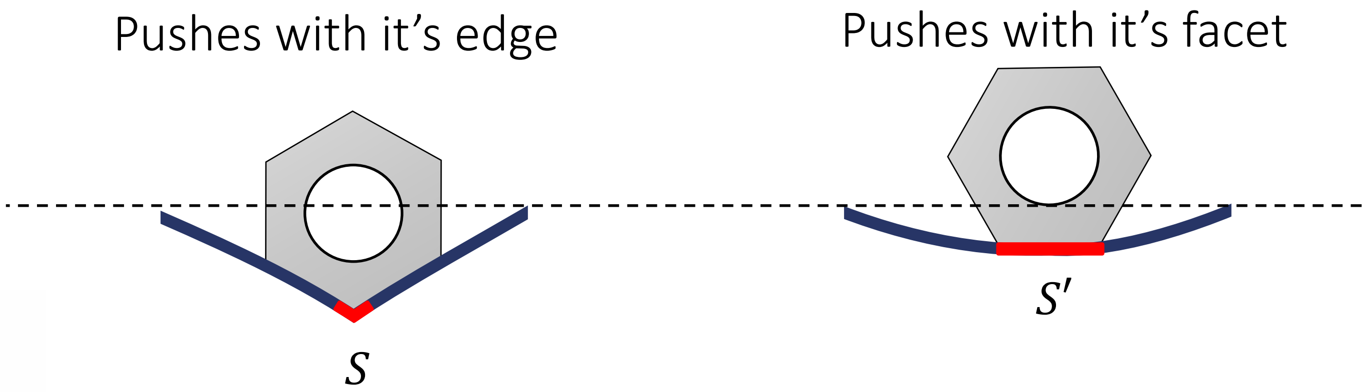
The frame reference is attached to the nut's axis



System dynamics

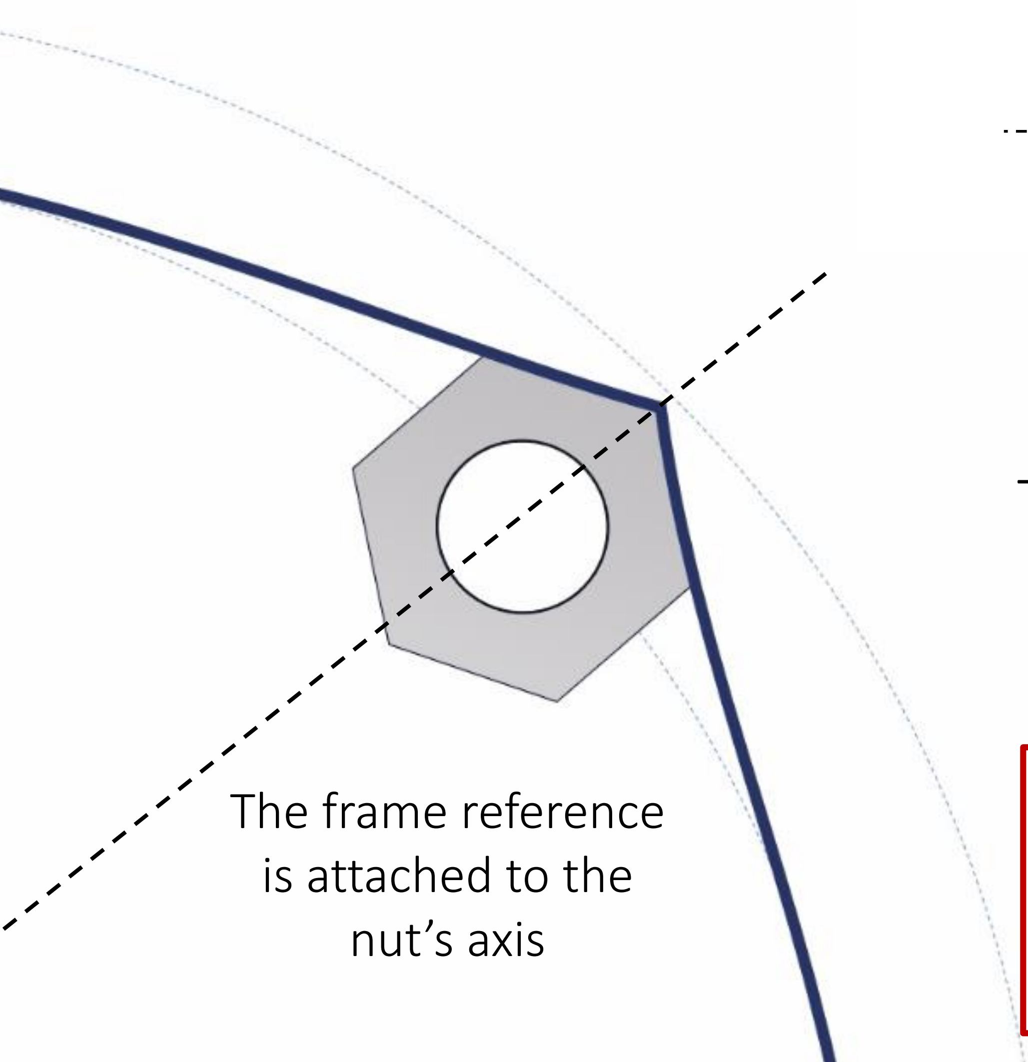


The frame reference is attached to the nut's axis

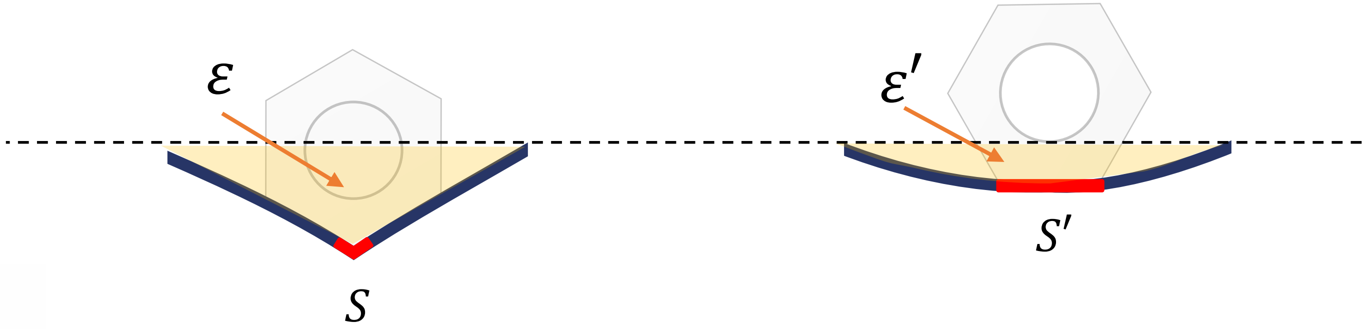


$$S < S'$$

System dynamics



Pushes with it's edge | Pushes with it's facet



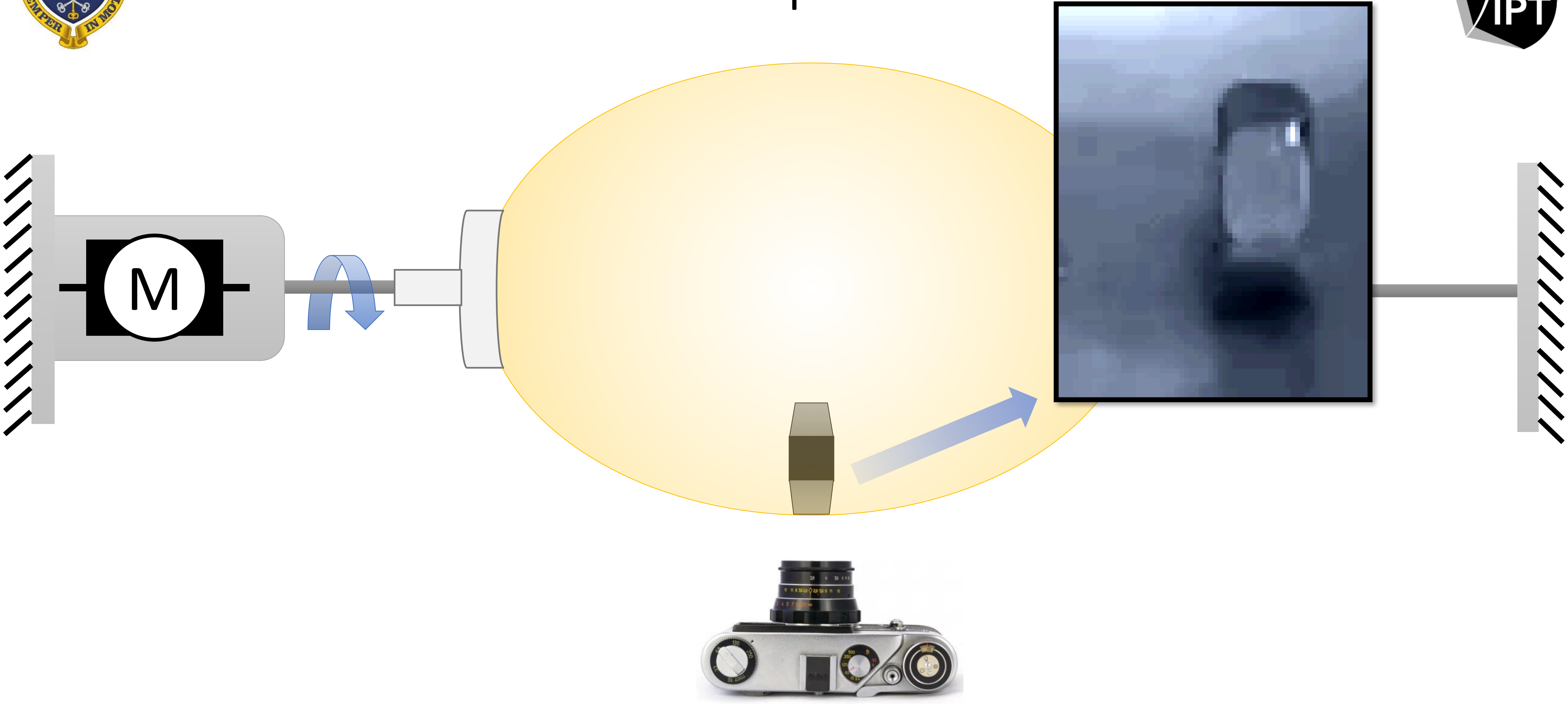
$$S < S' \Rightarrow \varepsilon > \varepsilon'$$

The motion of the nut causes forced oscillation of the balloon

⇓

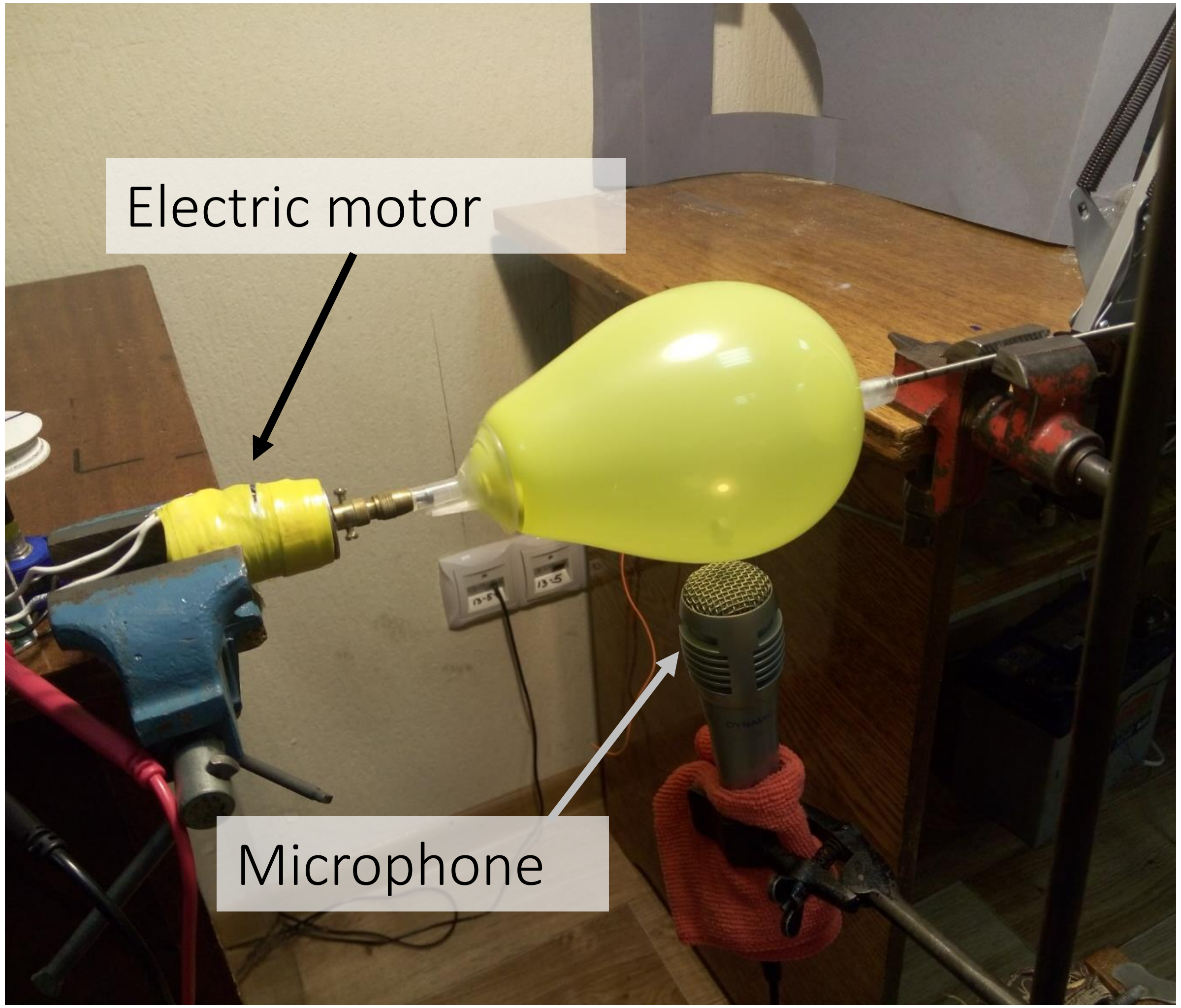
Fundamental frequency of the sound → $f_\varepsilon = 6\Omega$ ← Angular velocity of the nut

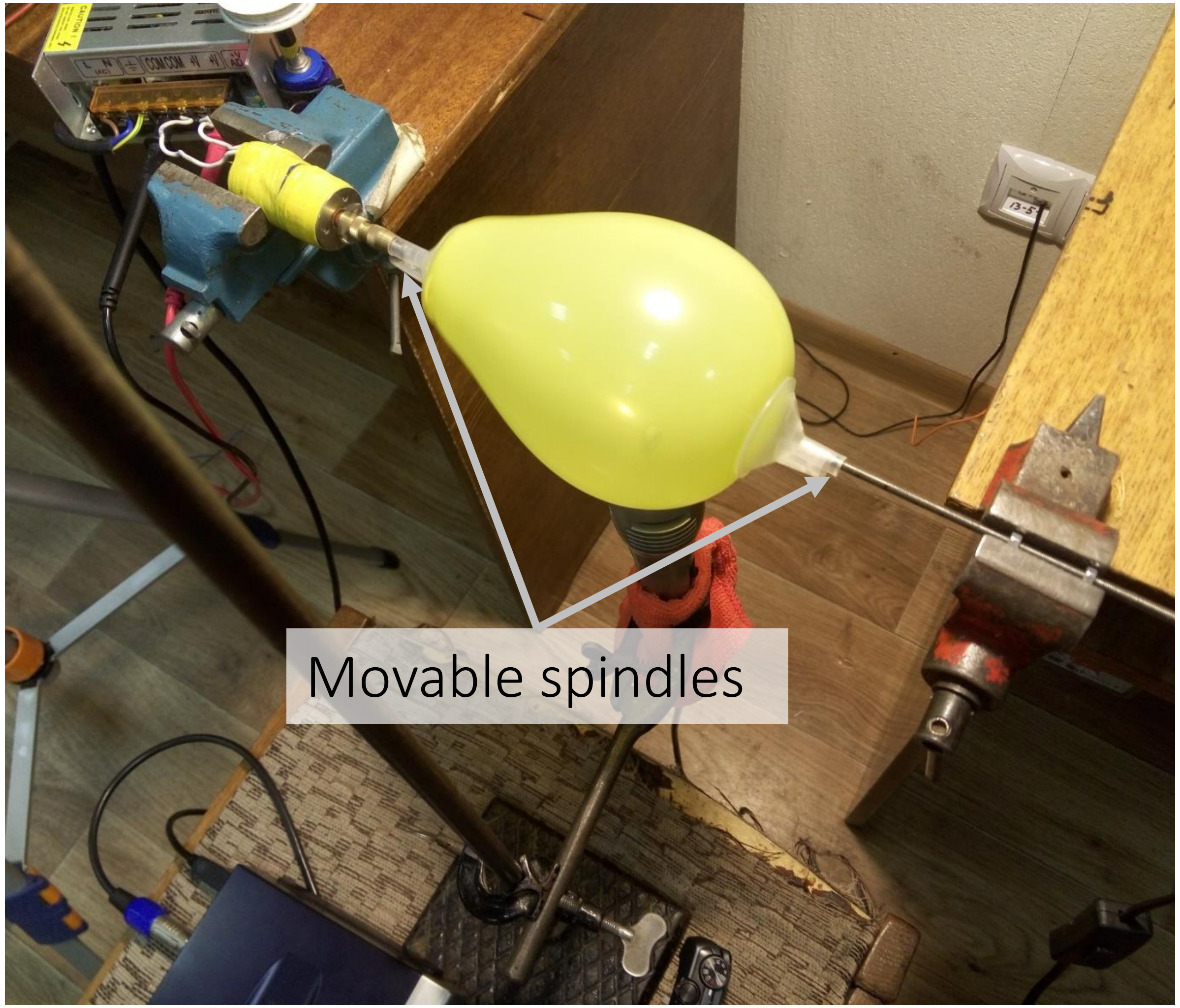
Model experiment



1000 FPS

The setup

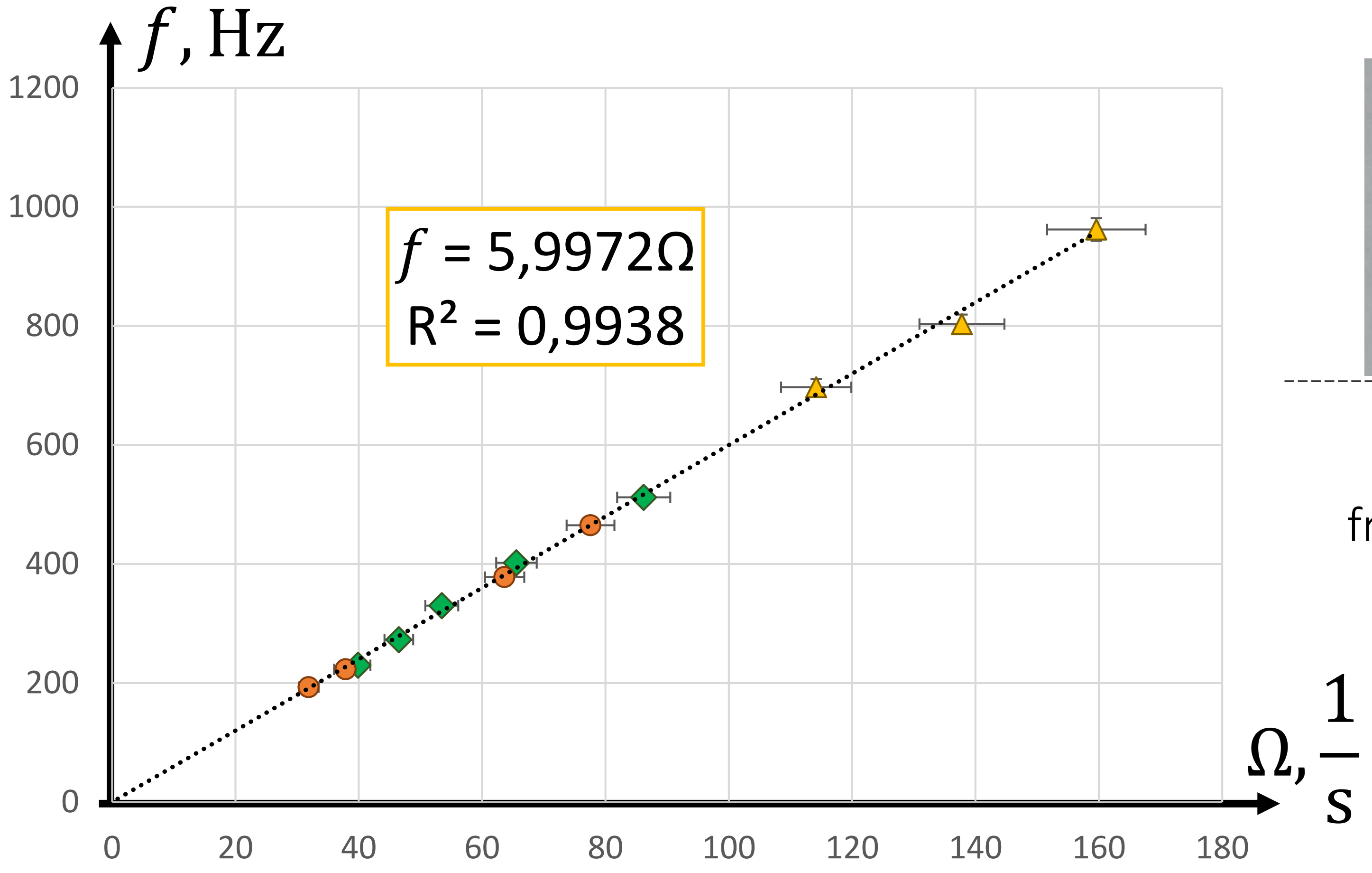


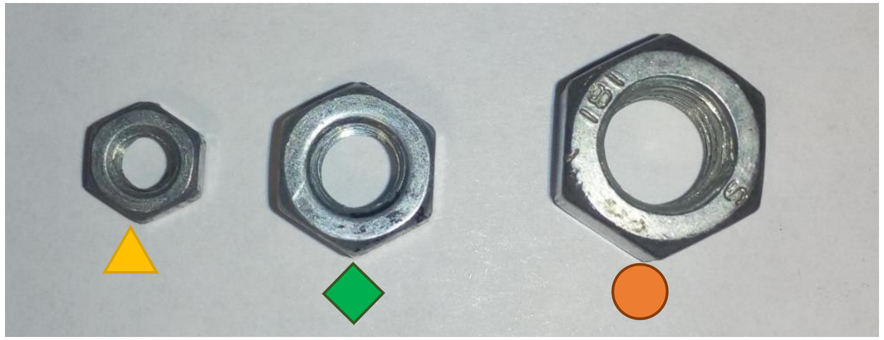


Running setup

Oscillations of the balloon surface(1000 fps)

Experimental results





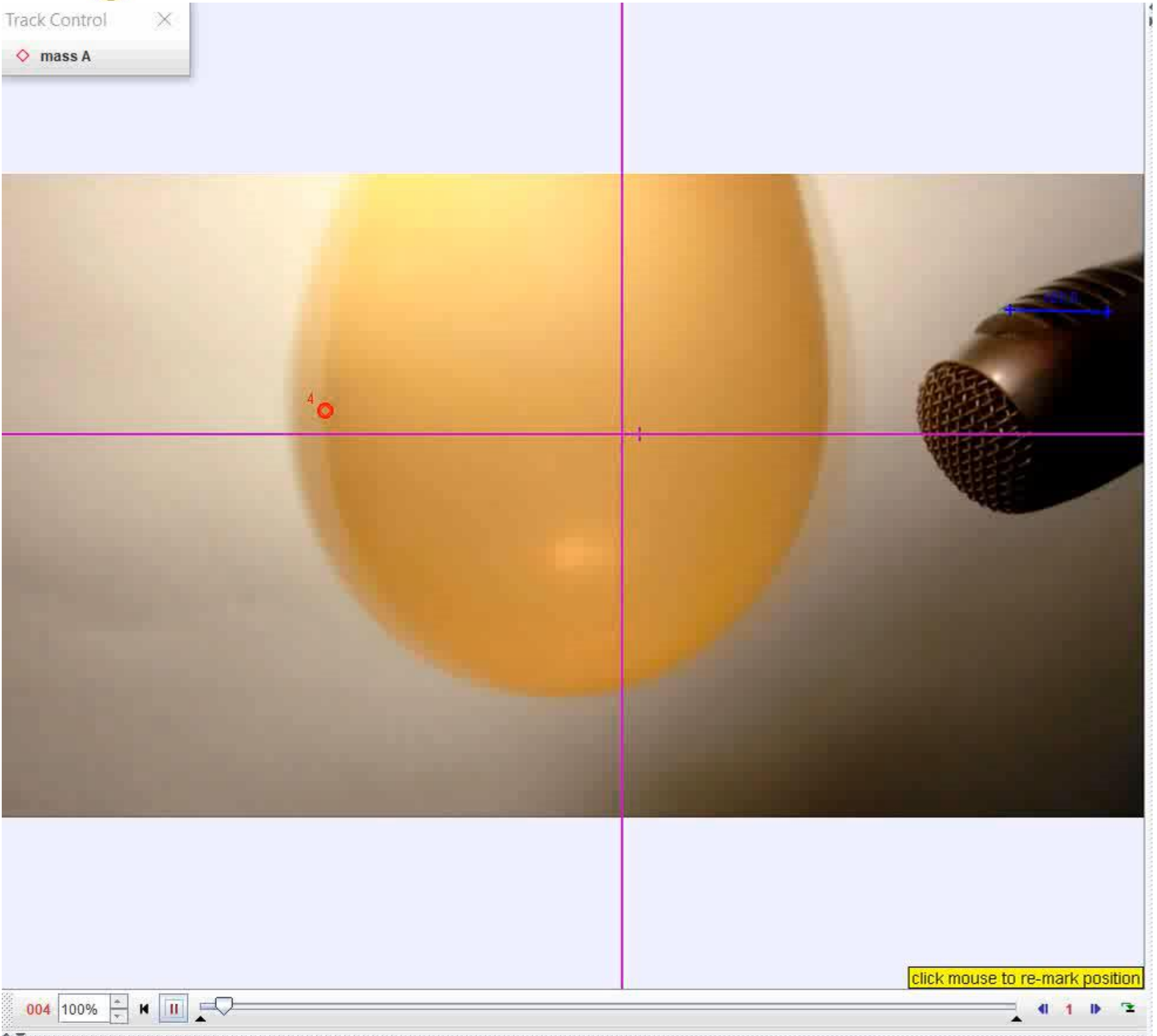
Fundamental frequency of the sound

Angular velocity of the nut

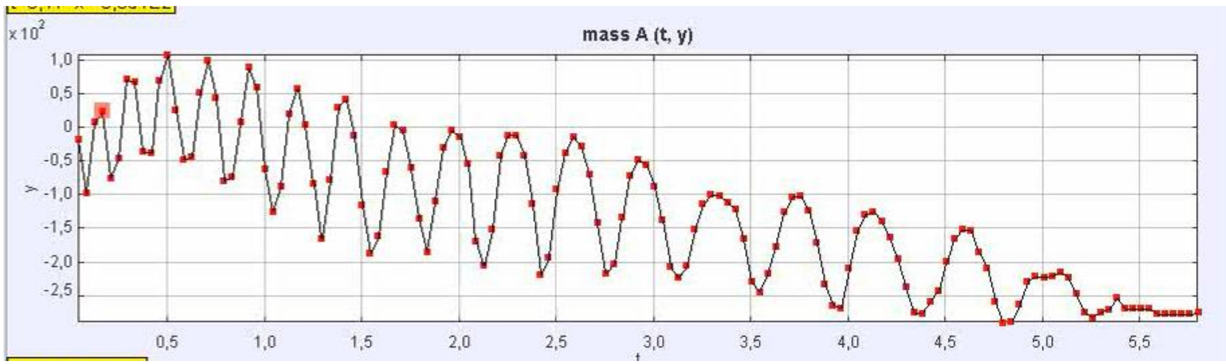
$$f = 6\Omega$$

The frequency of the sound is determined by the angular velocity

«Screaming»



Vertical coordinate (h)

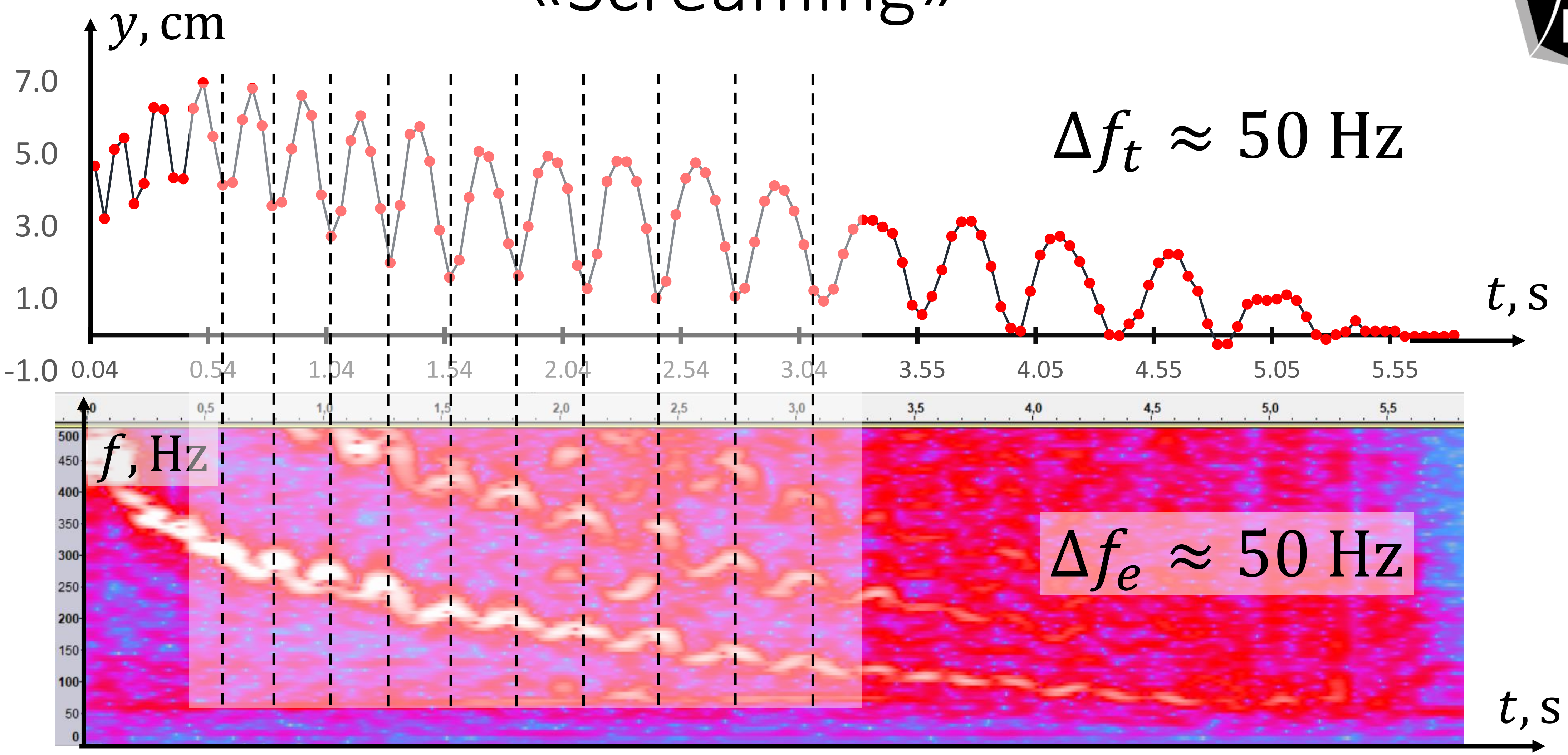


Energy conservation law

$$\frac{mv^2}{2} = E - mgh$$

v is the hex velocity

«Screaming»

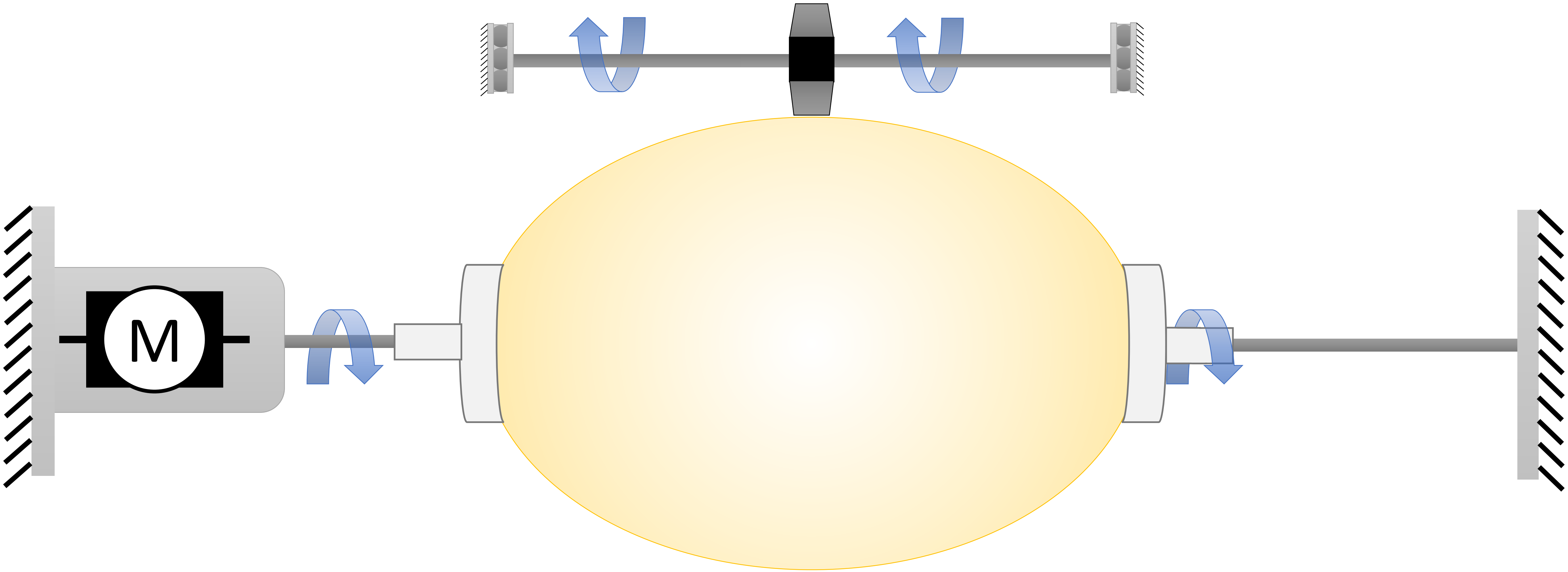


The «screaming» is caused by the gravitational acceleration of the nut

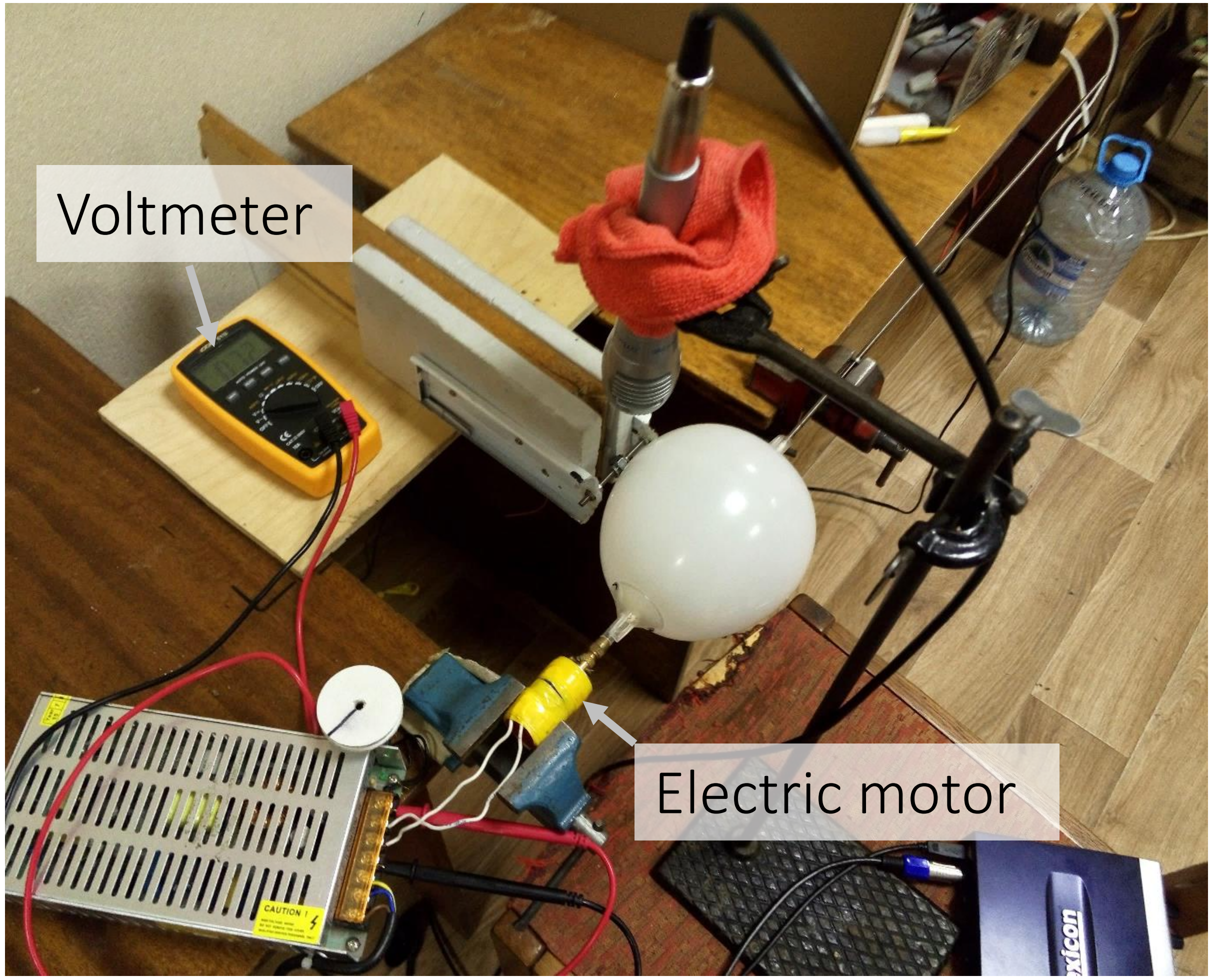
How do characteristics of the sound depend on angular velocity of the nut?

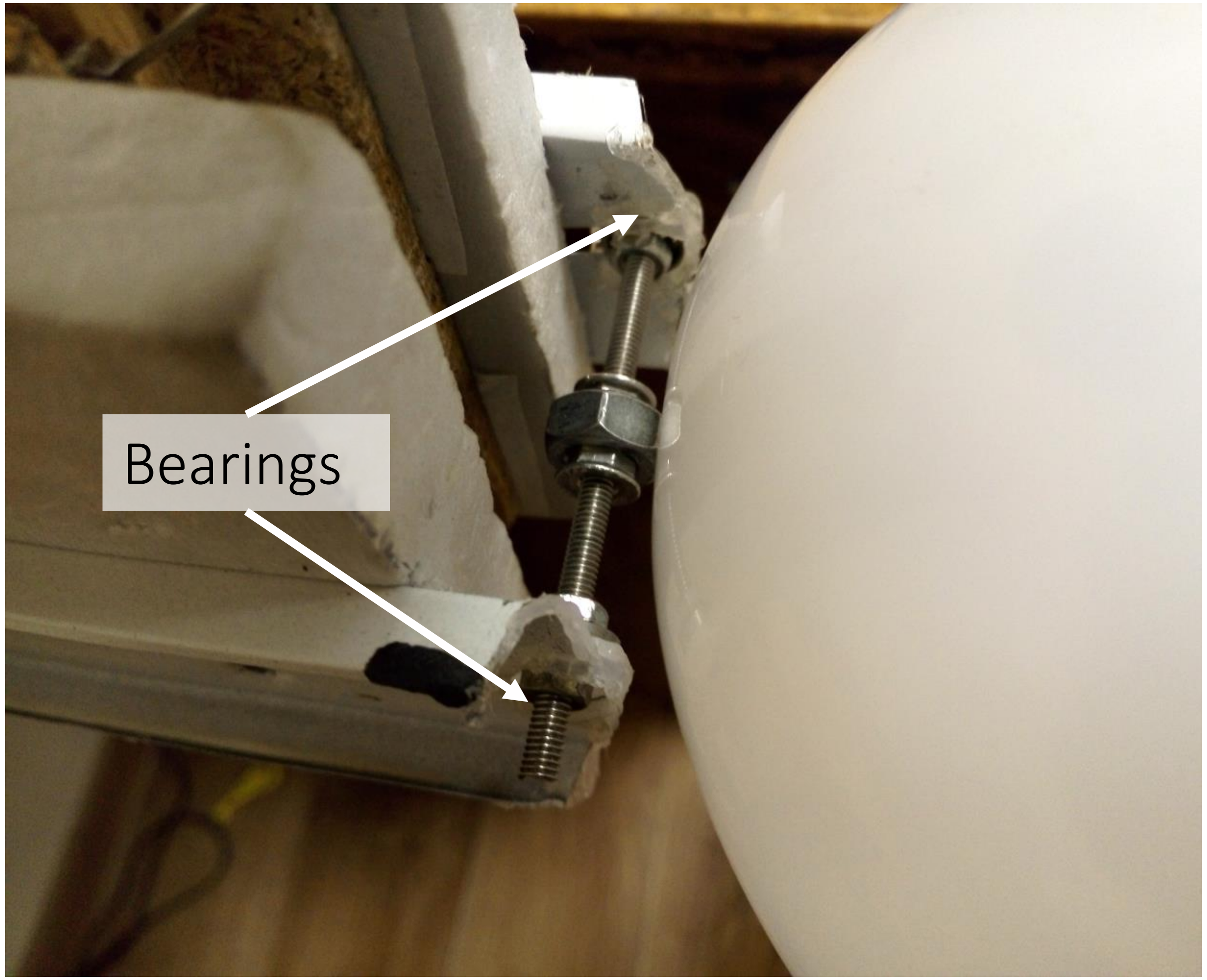
(timbre)

Second model experiment

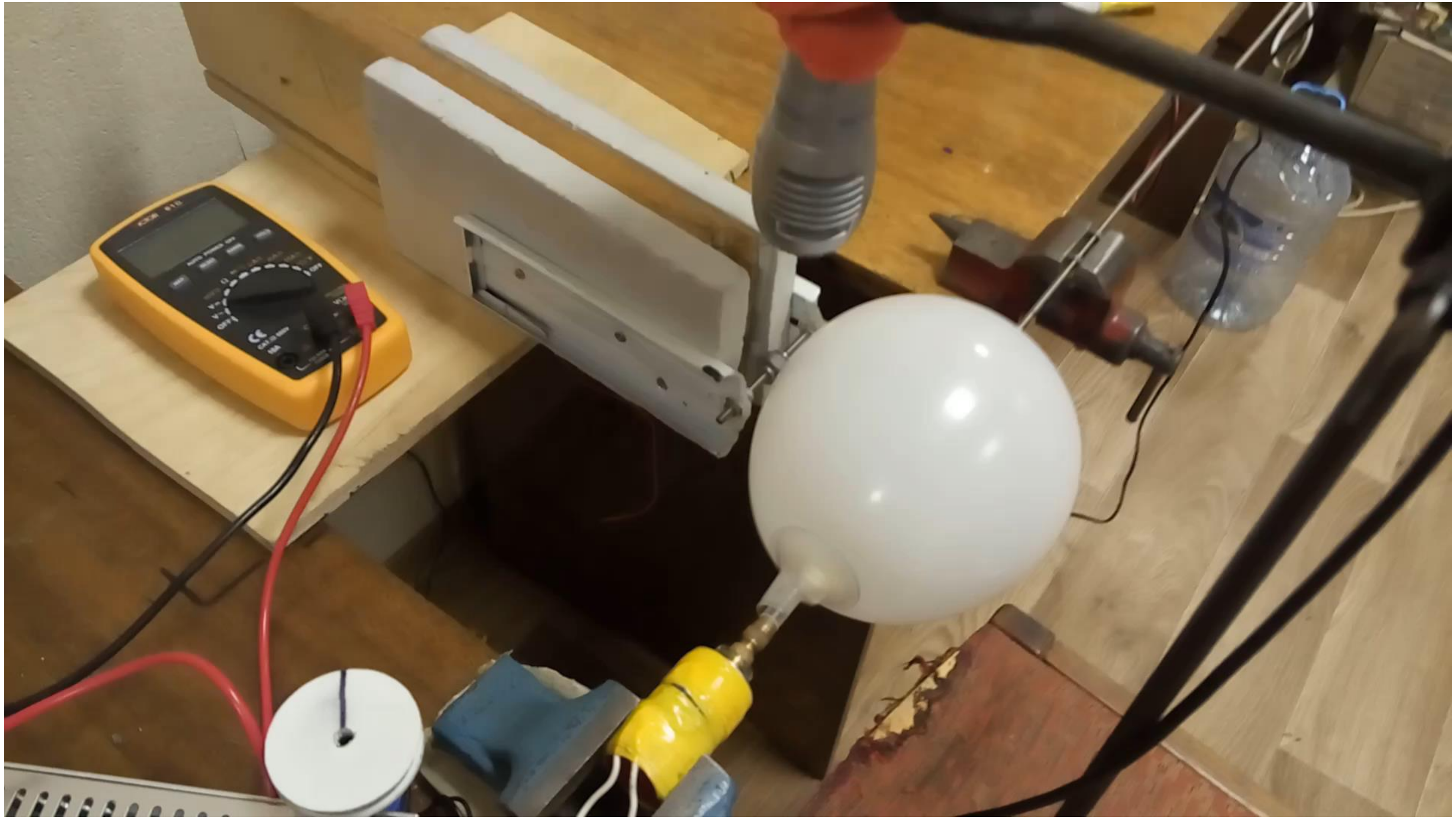


The second setup





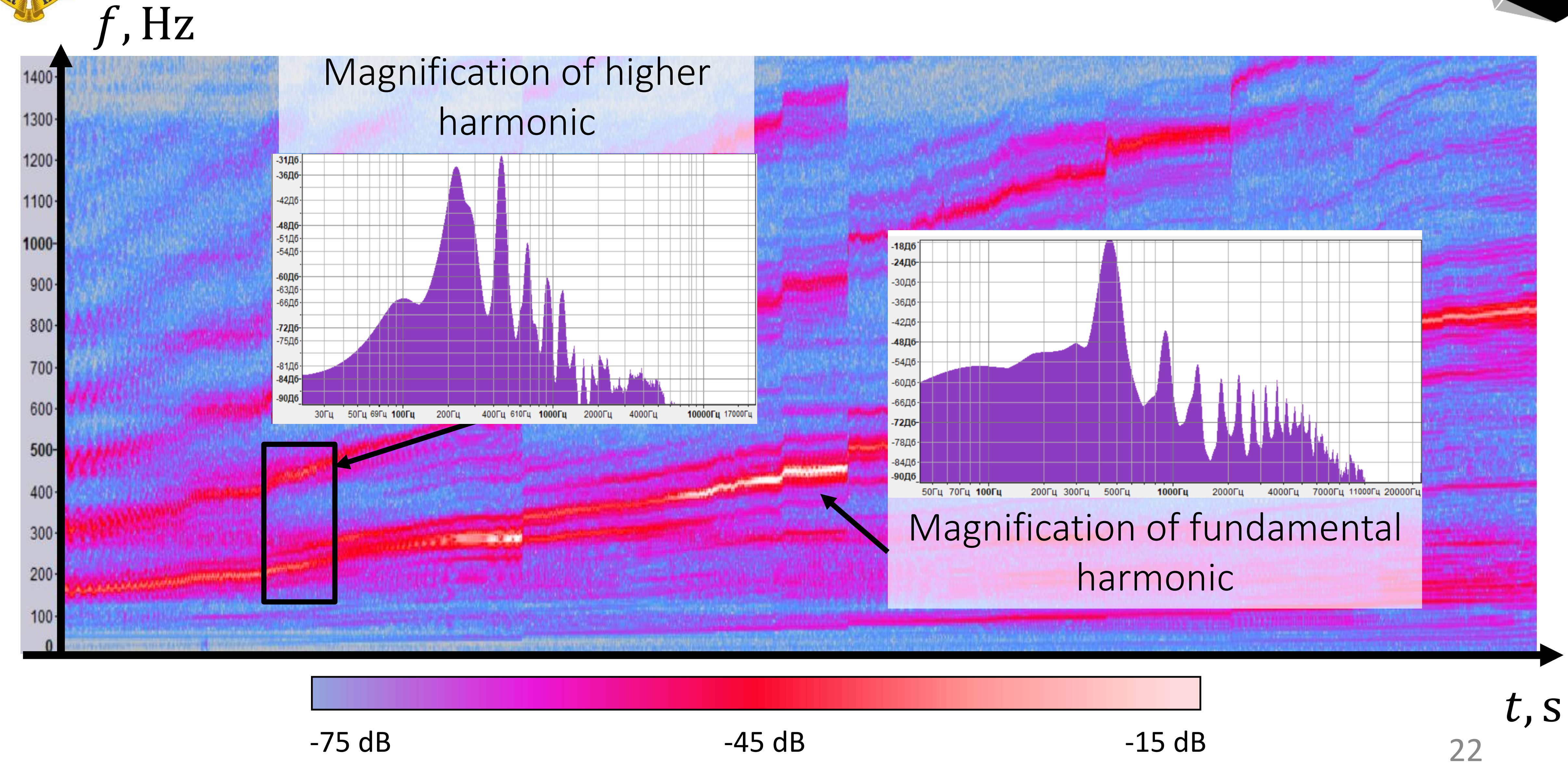
Technique of experiment



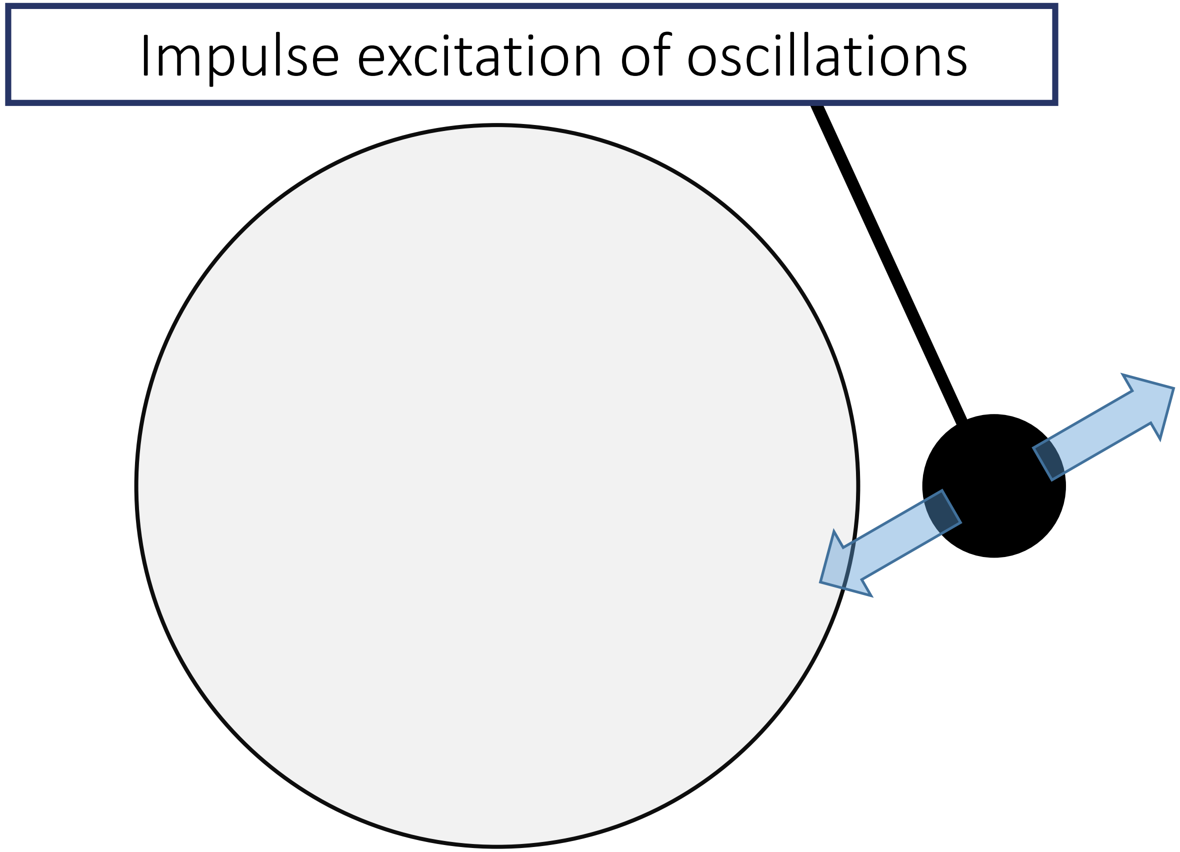
$\Delta V \sim 0.01$ V

$\Delta f \sim 1.6$ Hz

Timber vs frequency

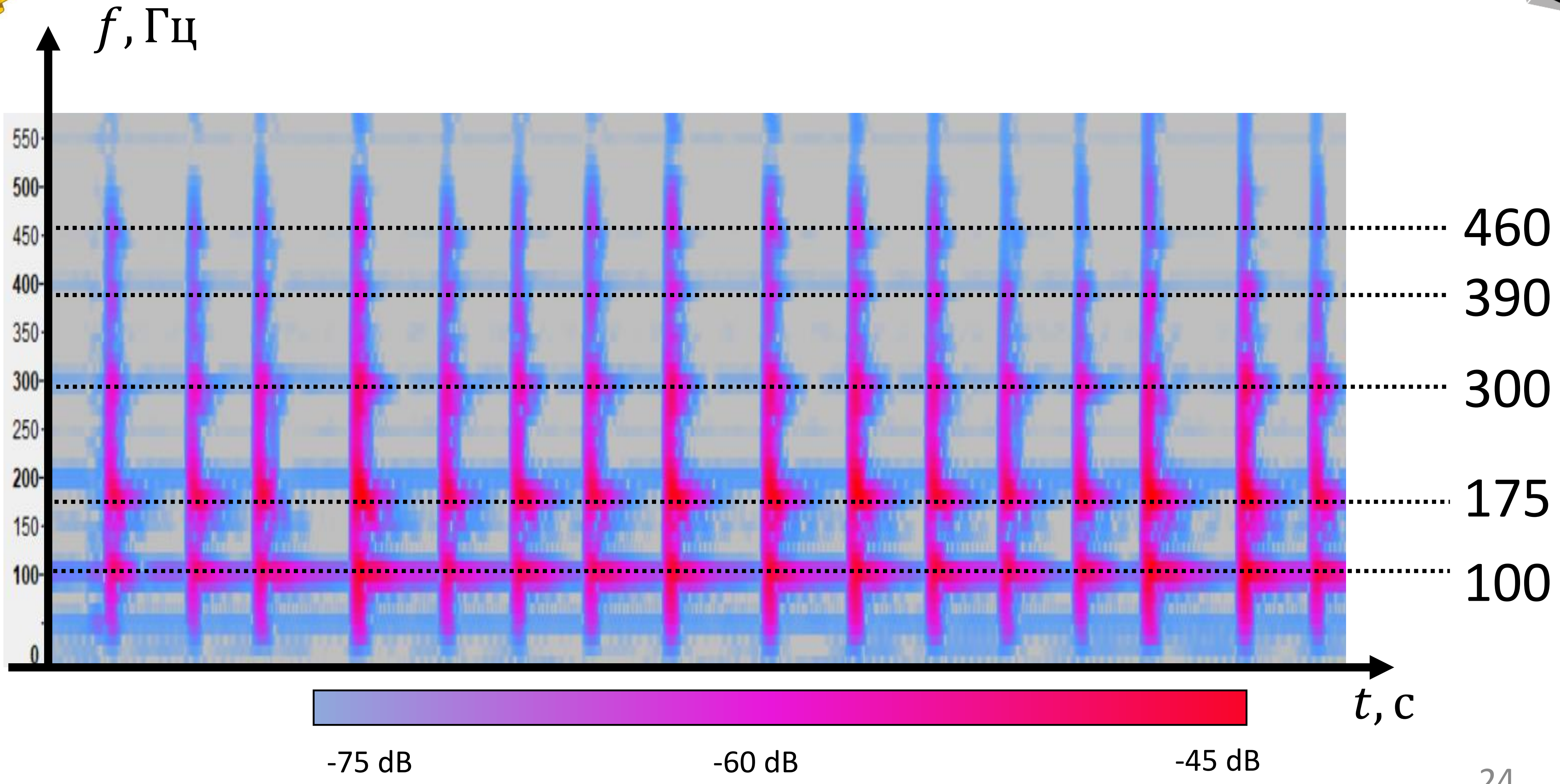


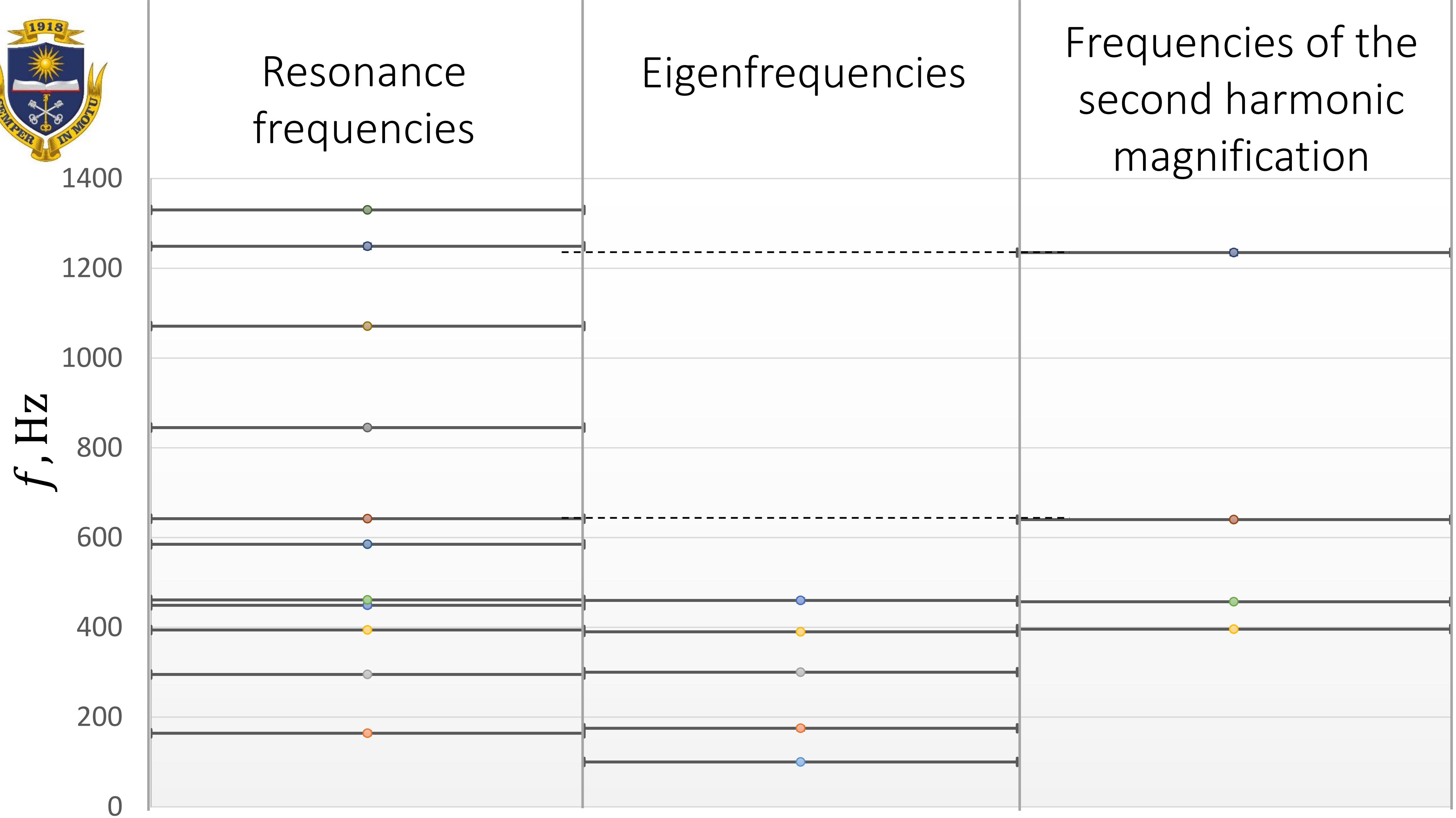
Estimation of balloon eigenfrequencies



[2] « The vibrations of bubbles and balloons » Kirsty A. Kuo and Hugh E.M. Hunt

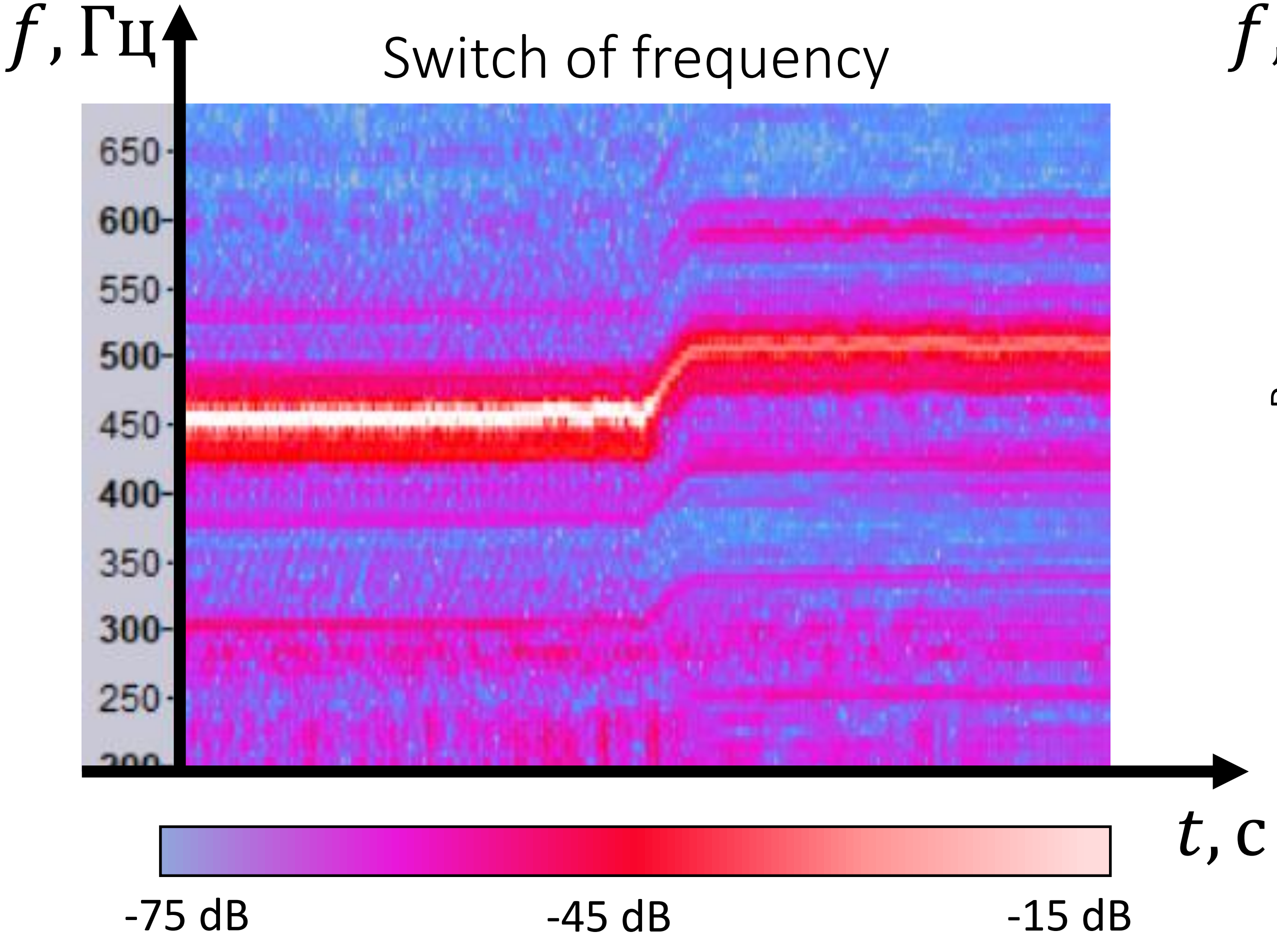
Eigenfrequencies of balloon

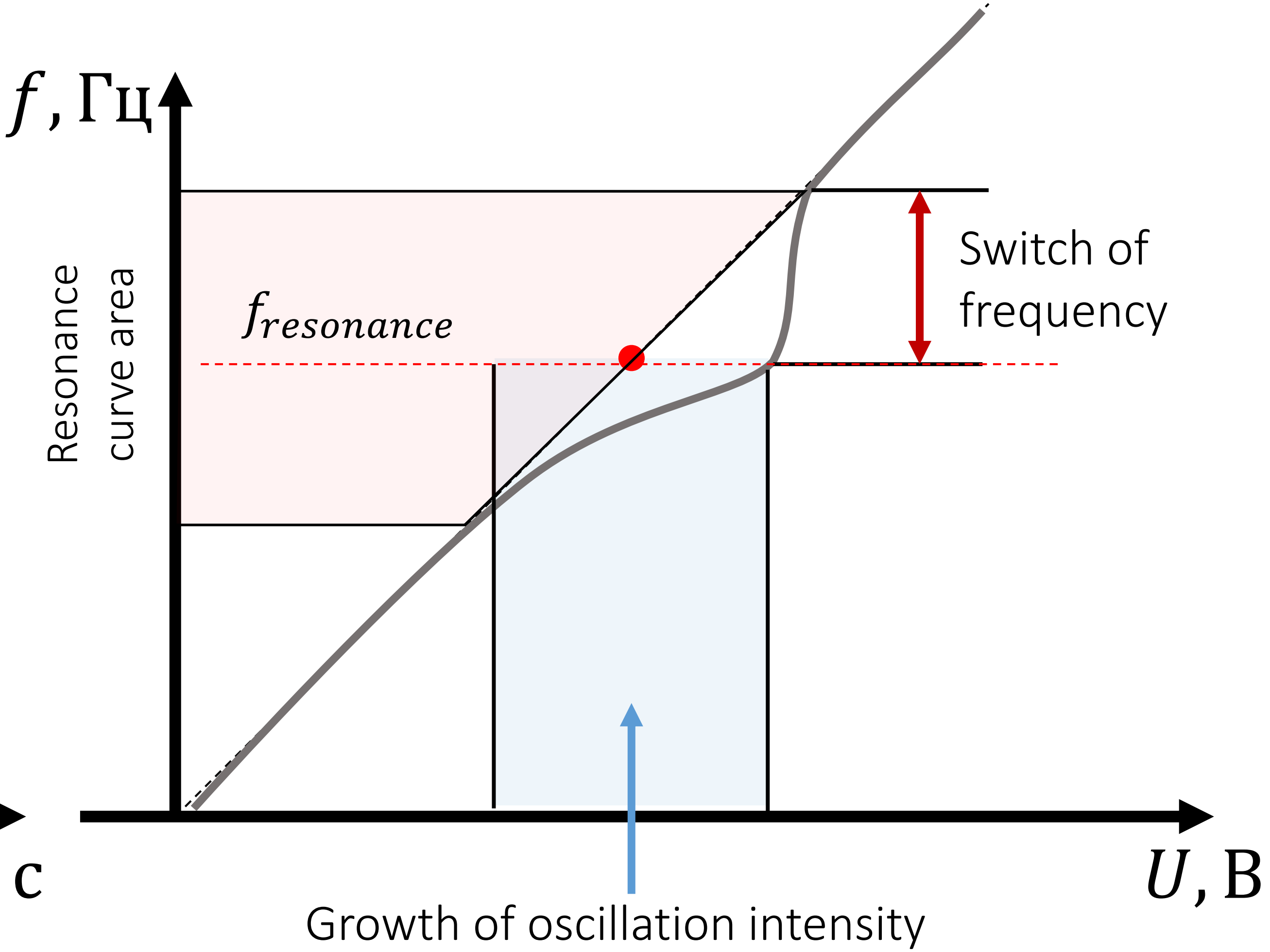




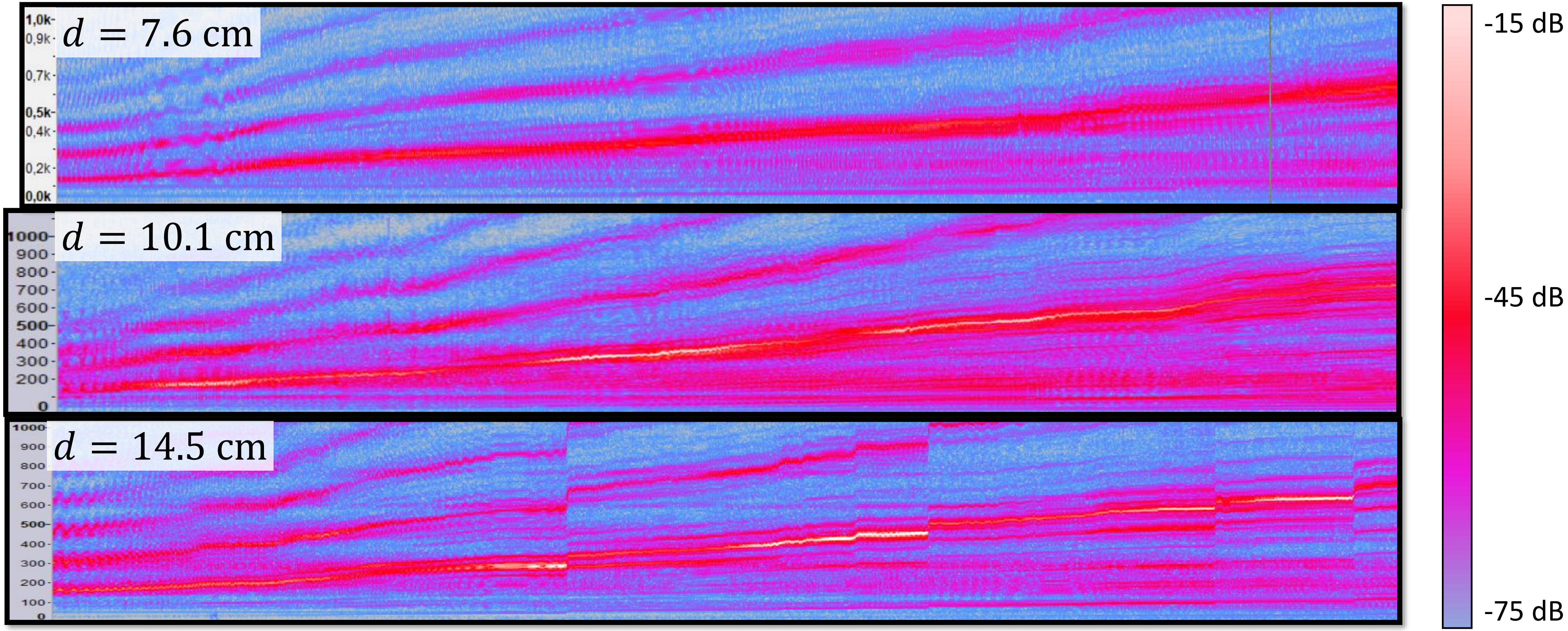
Magnification of both fundamental and higher harmonics are resonance effects

Magnification of the first’ harmonic and switch of frequency



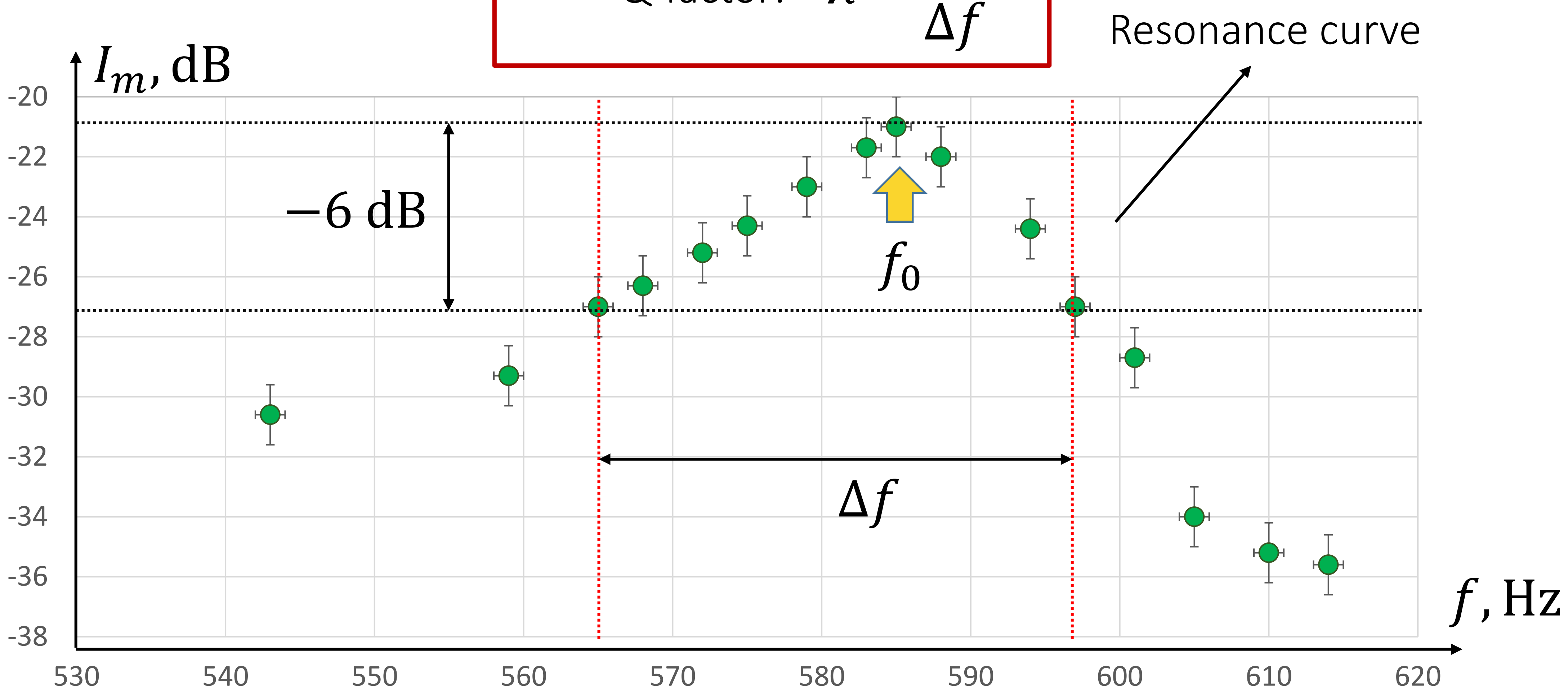


Change in balloon tightness

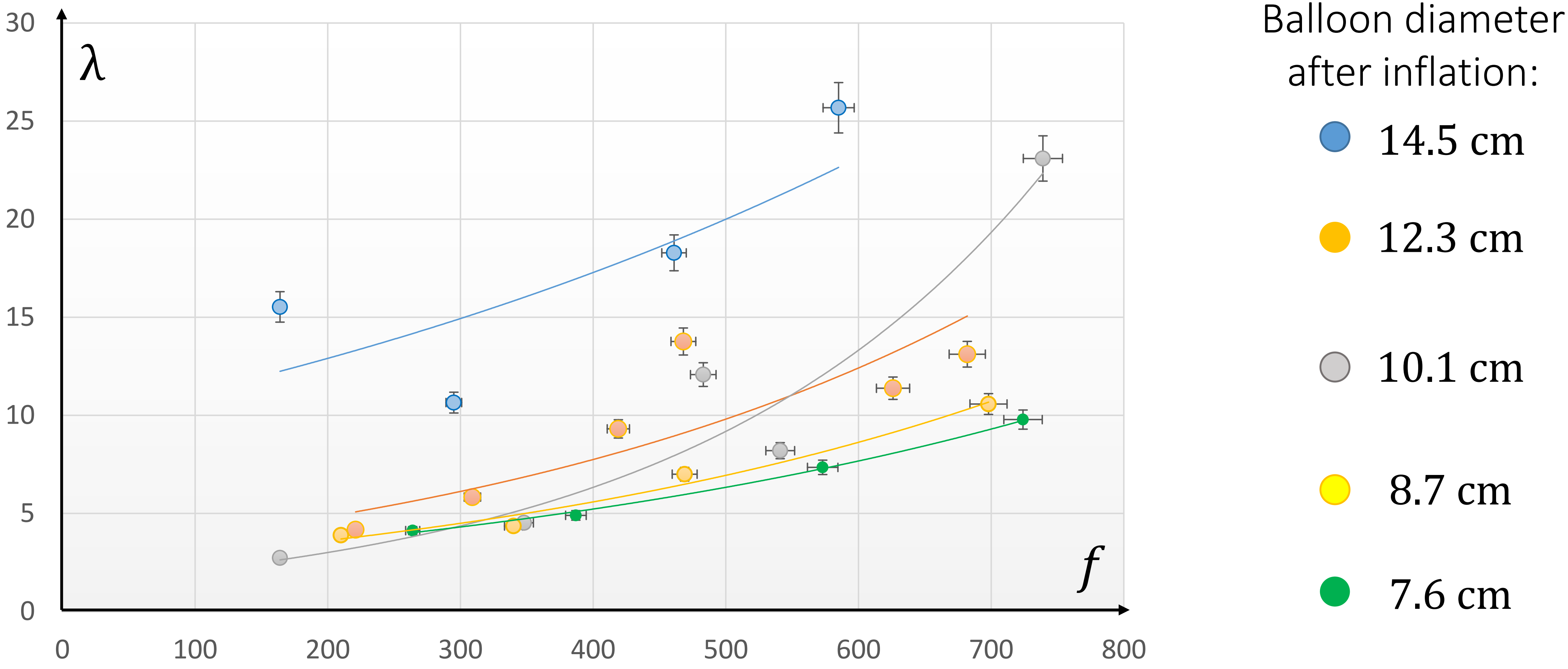


Estimation of system Q-factor

Q-factor: $\lambda = \frac{f_0}{\Delta f}$



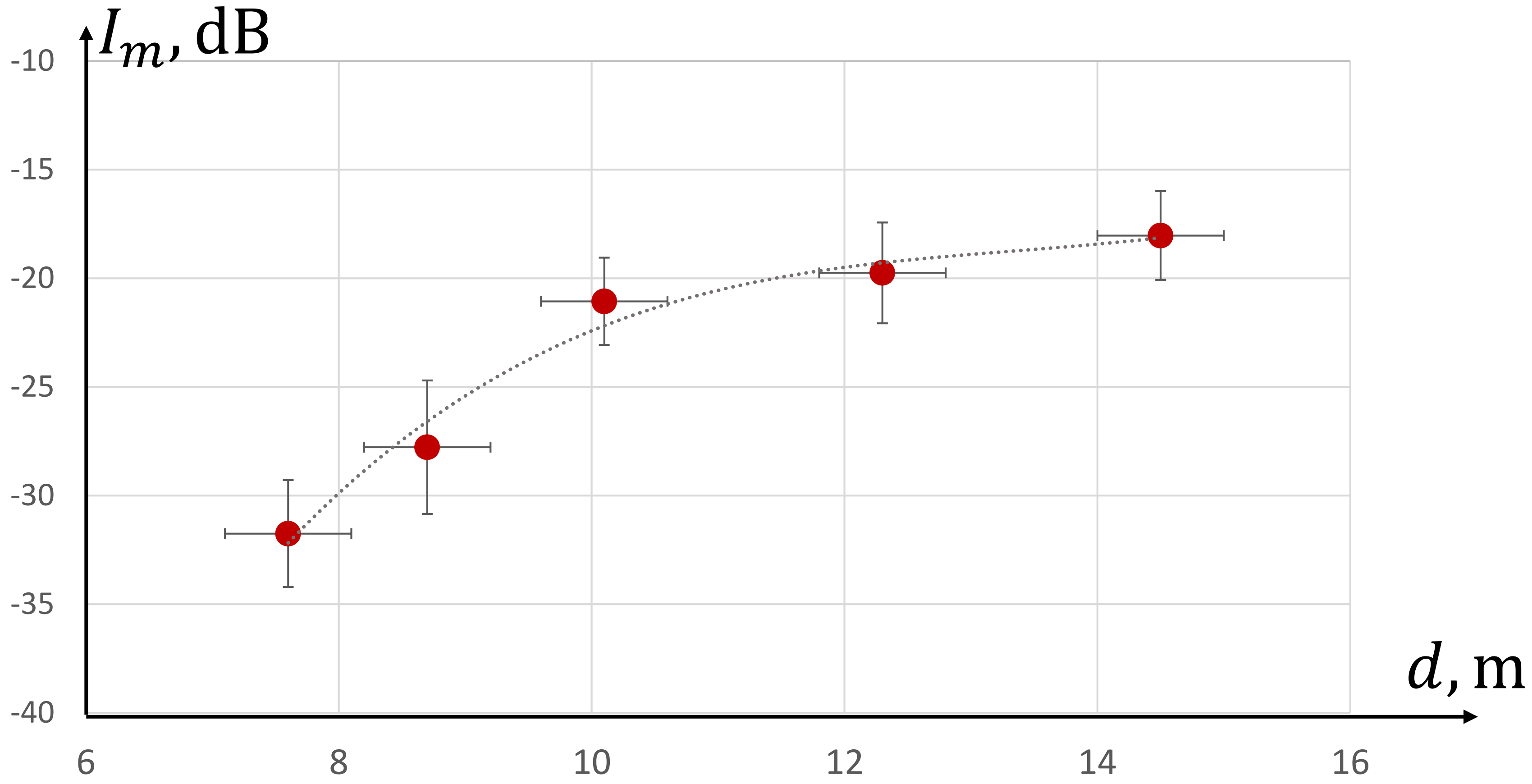
Q-factor vs balloon tightness



Q-factor increases while the tightness growth

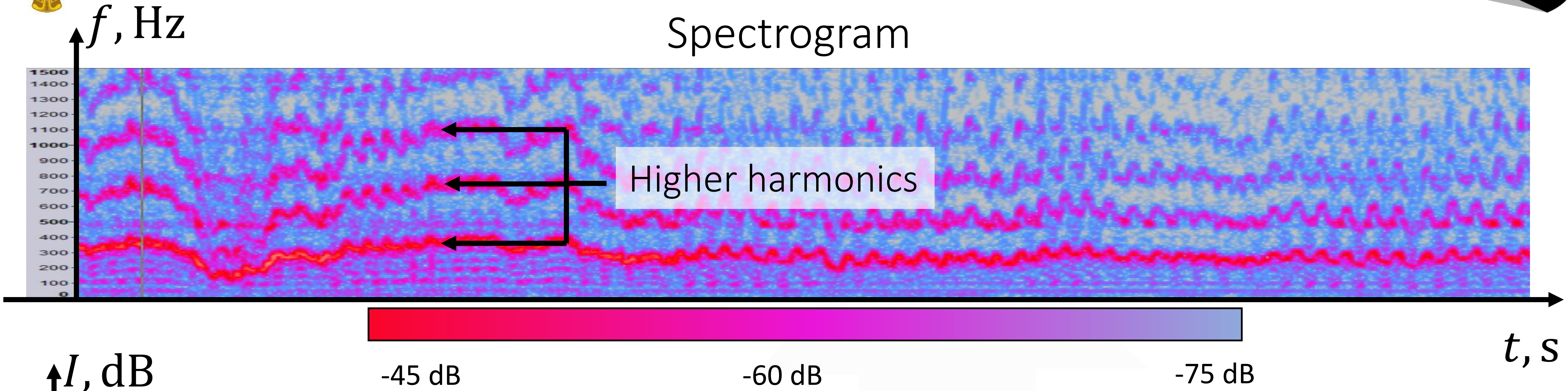
Sound intensity for resonance frequencies

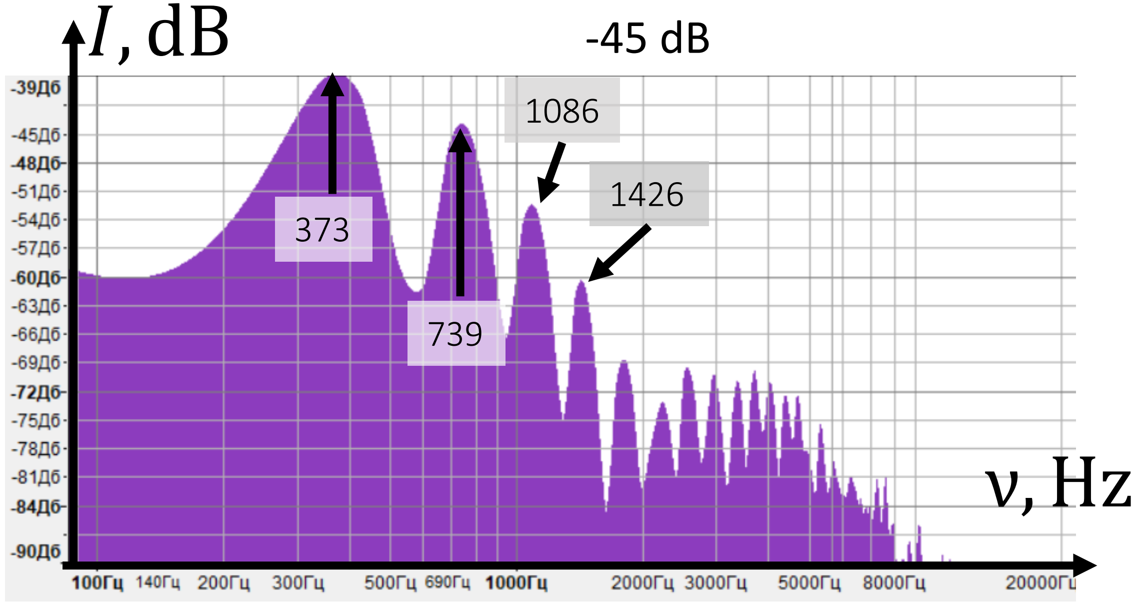
The sound intensity averaged over all the eigenfrequencies

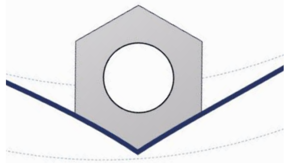


Amplitude of the sound for resonance frequencies increases with the growth of tightness

Magnification of higher harmonic







$$P(t) = P(t+T) \neq \sin(\omega t)$$

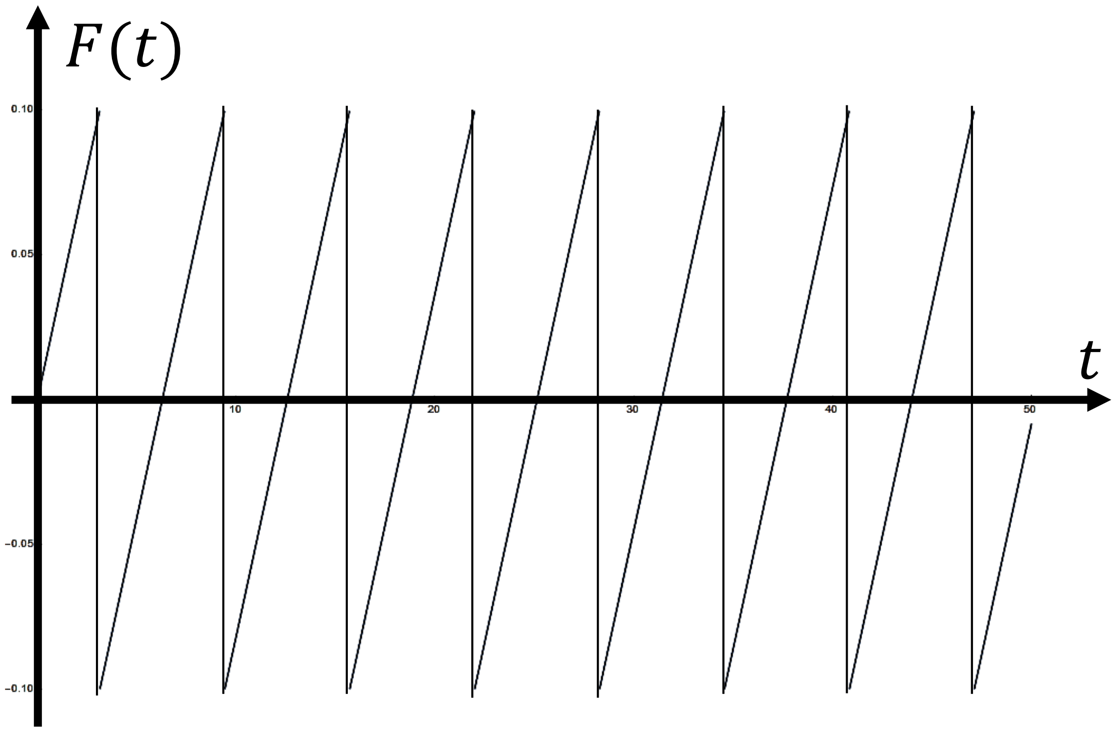
$$P(\omega) = \sum_k A_k \sin(k\omega + \theta_k)$$

Higher harmonics appearance is caused by non-sinusoidal signal

Magnification of higher harmonics (mathematical model)

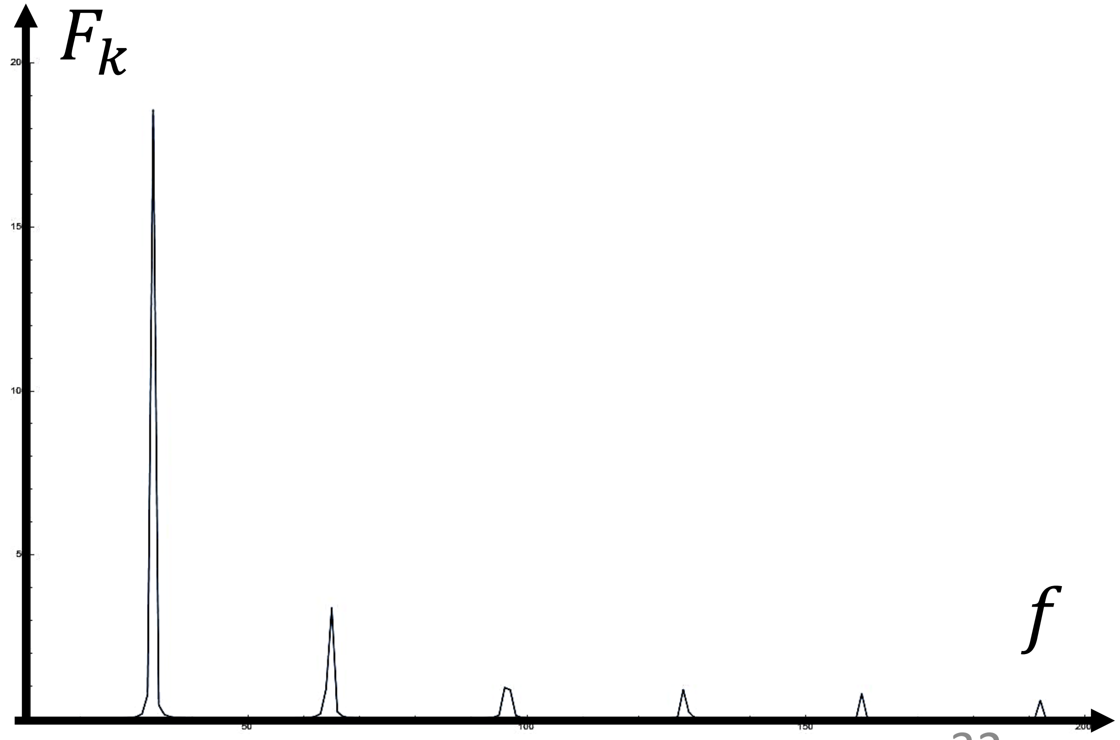
Damped linear oscillator

$$\ddot{x} + \lambda\dot{x} + \omega x^2 = F(t)$$



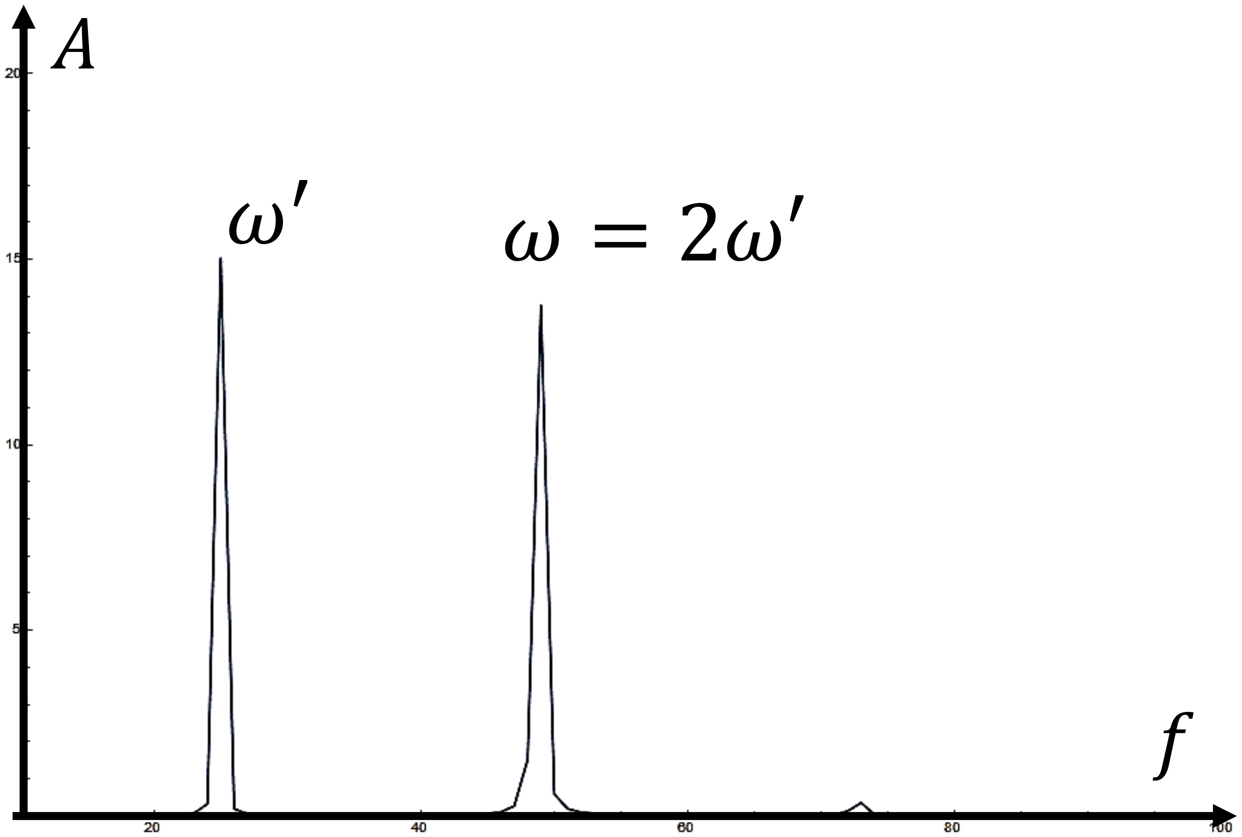
External force spectrum

$$F(\omega') = \sum_k F_k \sin(k\omega' + \theta_k)$$

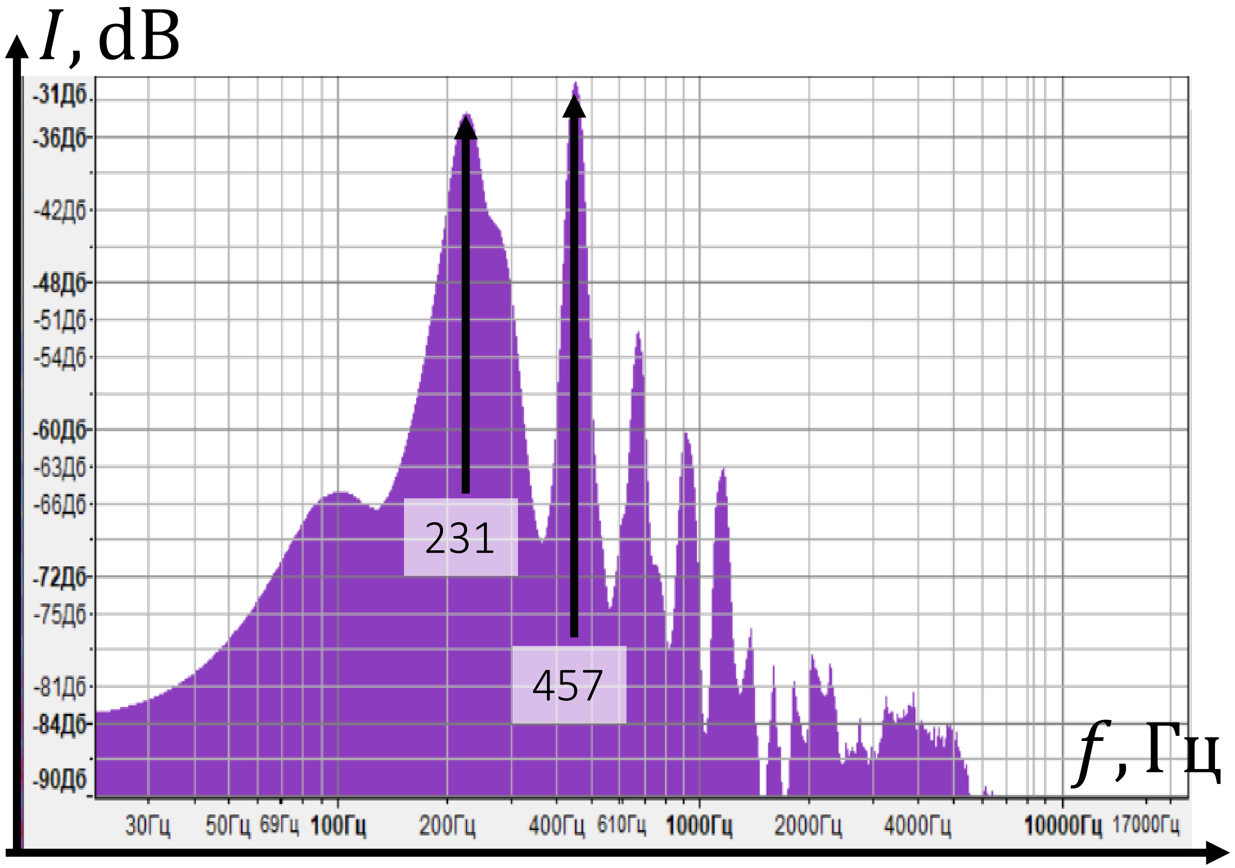


Magnification of second harmonic

Results of the model



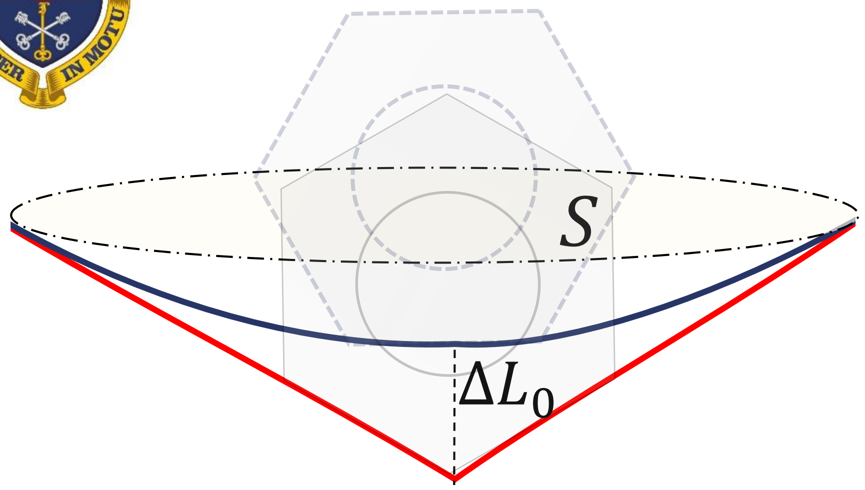
Results of the experimental



Magnification of the higher harmonic is also caused by resonance effects

How characteristics of sound depend on nut size?

Size of nut



q – speed of membrane element

ρ – density of air

$\omega = 2\pi f$ – frequency of forced oscillations of the balloon

c – speed of sound in air

Power emitted by the spherical emitter [1]

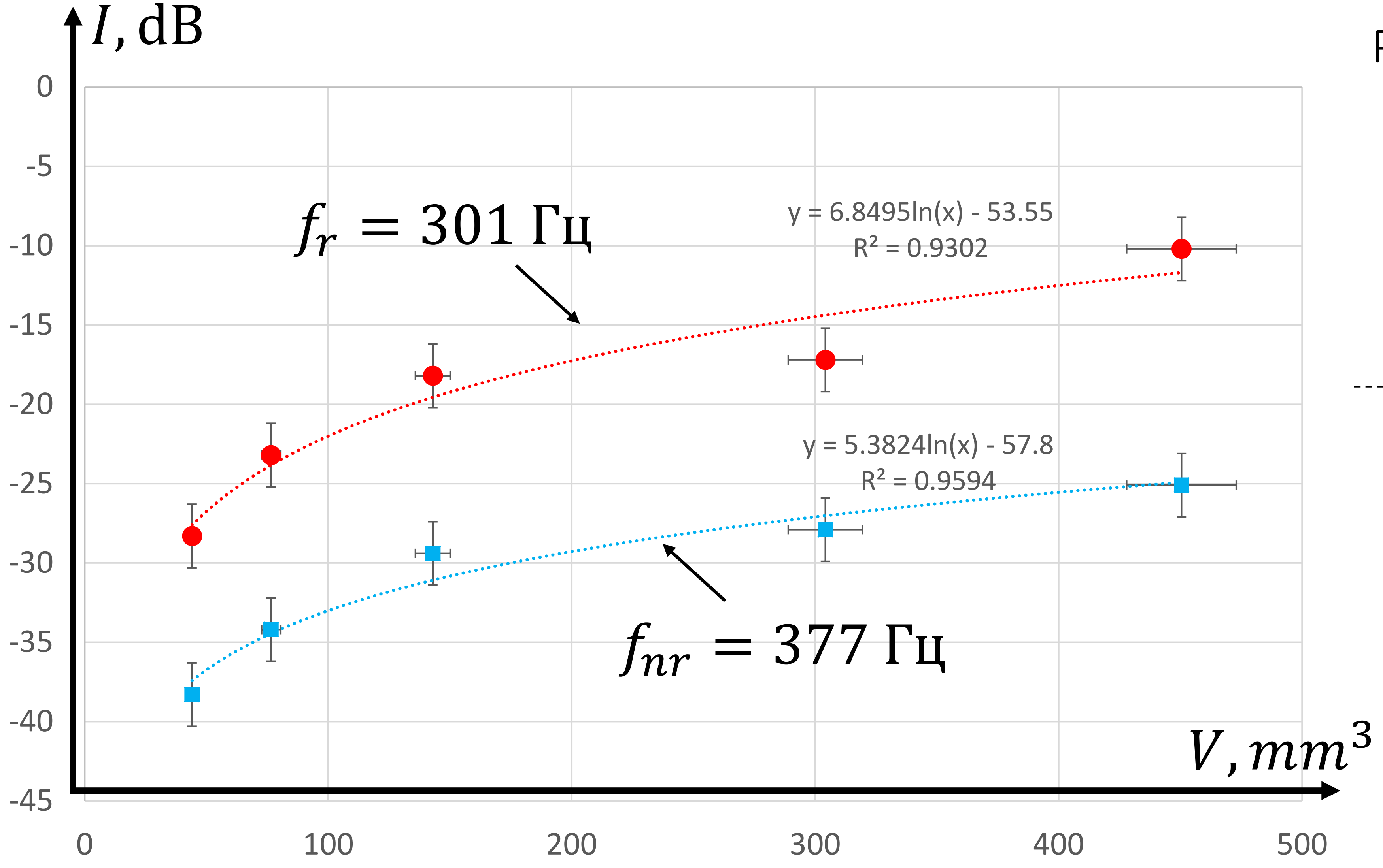
$$\Pi = \frac{\rho\omega^2}{4\pi c} * \frac{Q_0^2}{2}, \; Q_0 = \int_S q(s)ds \sim \omega \Delta L_0 S$$

$$\Pi \sim \omega^4 (S\Delta L_0)^2$$

Intensity of sound increases with nut size increasing

[1] Rzhevkin S. N. «Theory of sound» Pub.: MSU 1960

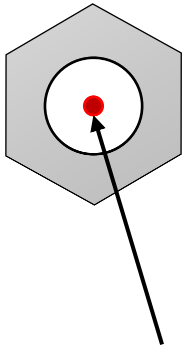
Size of nut



Power emitted by the spherical emitter

$$\Pi \sim \omega^4 (S\Delta L_0)^2$$

$$V = S\Delta L_0$$



Fixed axis of rotating

Conclusions

1) Sound is multifrequent. Fundamental frequency depends on angular speed of nut as

$$f = 6\Omega$$

2) We can obtain strong resonance effects: magnification of first and higher harmonics. The important parameter is Q factor of the system, which determines resonance properties and depends on tightness of surface of balloon
3) Intensity of sound increases with increasing of nut size (if axis of nut’s rotation oscillates negligibly).

References

[1] Rzhevkin S. N. «Theory of sound» Pub.: MSU 1960

[2] « The vibrations of bubbles and balloons » Kirsty A. Kuo and Hugh E.M. Hunt

Thank you for your attention!