Problem #2 “Cutting the air”

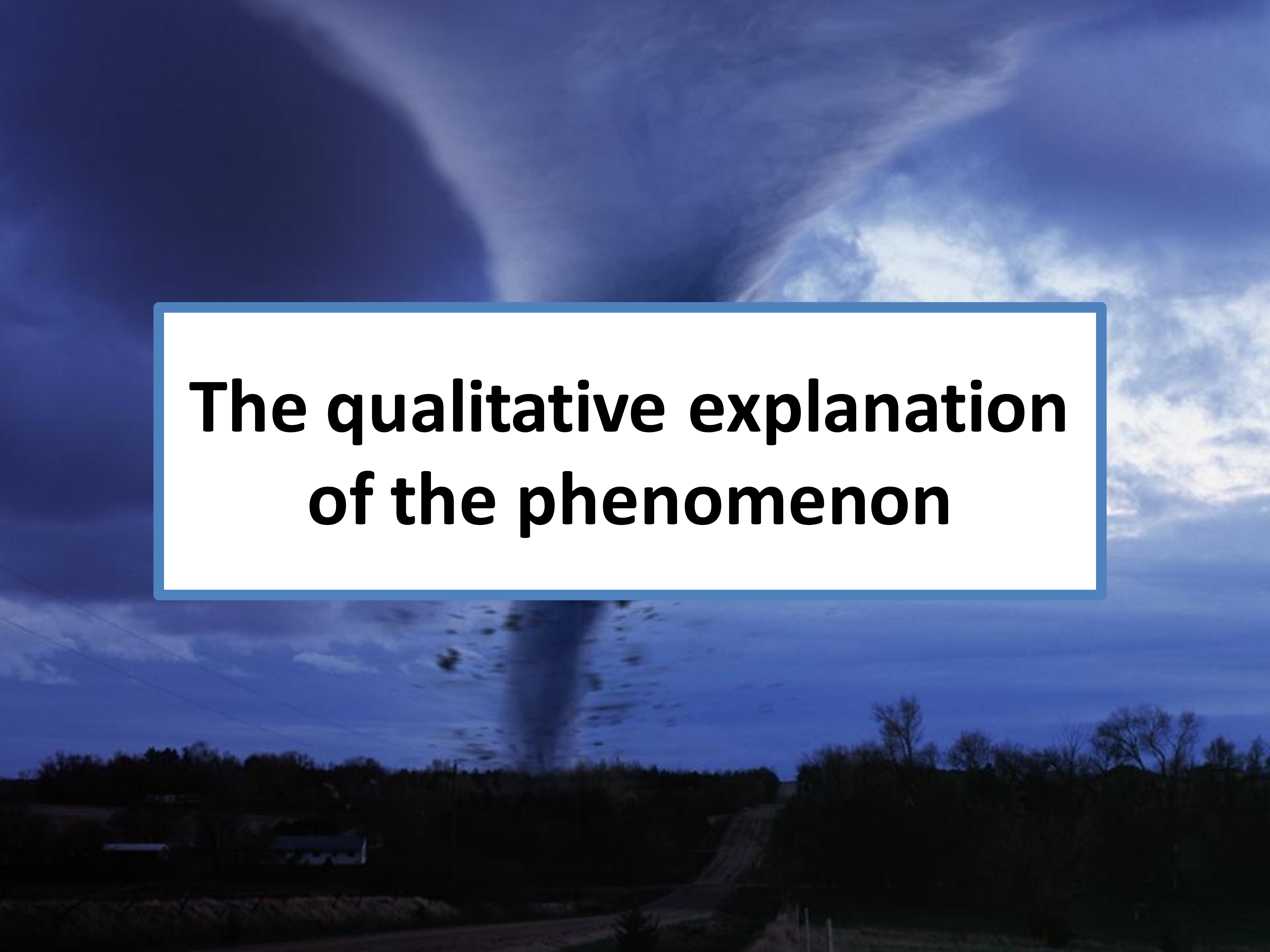
Reporter:
Anton Khvalyuk

The problem

When a piece of thread (e.g., nylon) is whirled around with a small mass attached to its free end, a distinct **noise** is emitted. Study the ***origin*** of this noise and the ***relevant parameters***.

The work plan

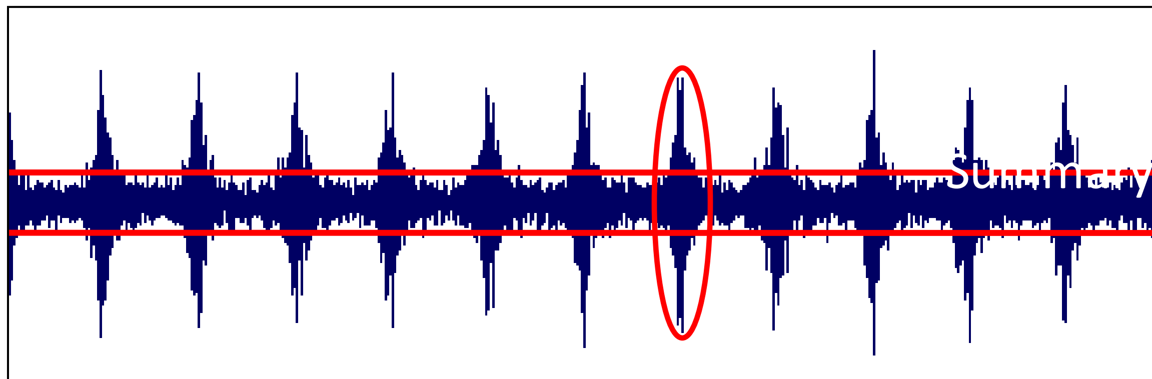
Qualitative explanation	Experiments	Theory	Comparing	Summary



The qualitative explanation of the phenomenon

Characteristic phenomena

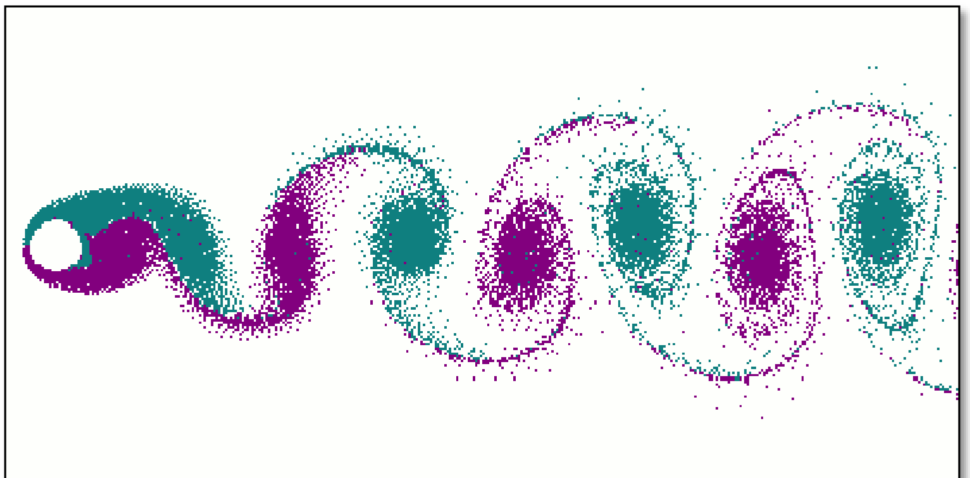
- The appearance of the sound itself
- The appearance of the characteristic pulsations



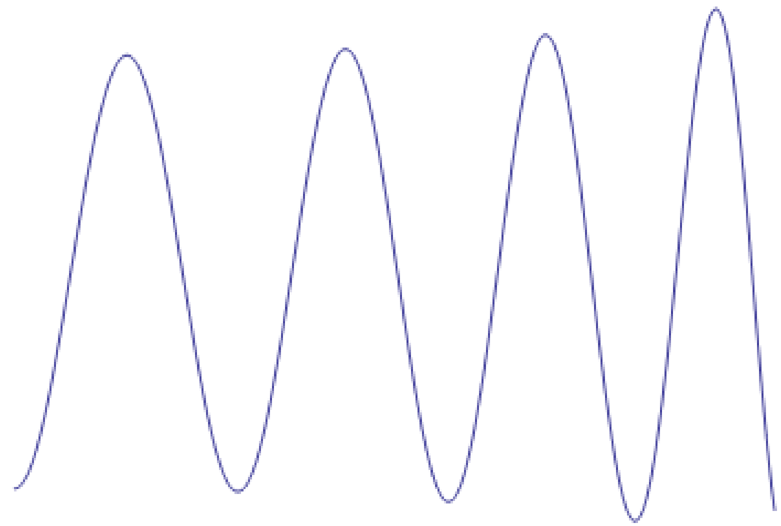
The visualization of the sound

Possible reasons of the phenomena

1) The appearance of the sound



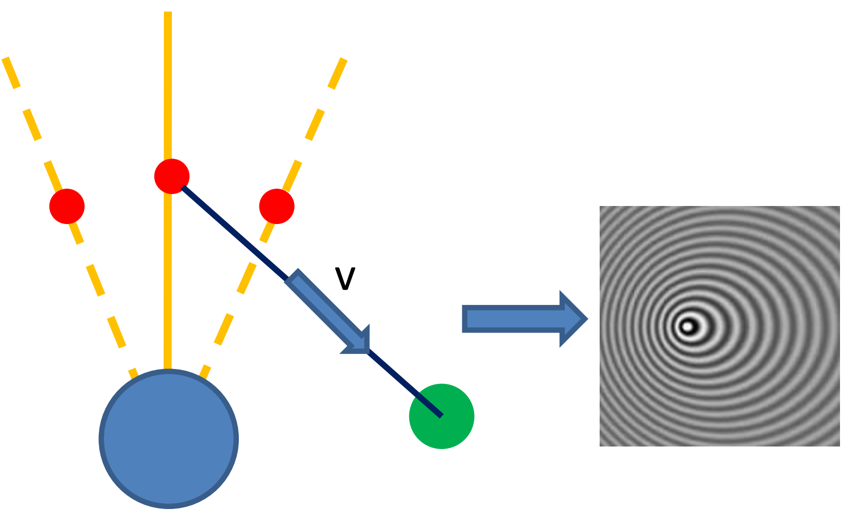
Consequent vortex shedding from the surface of the thread



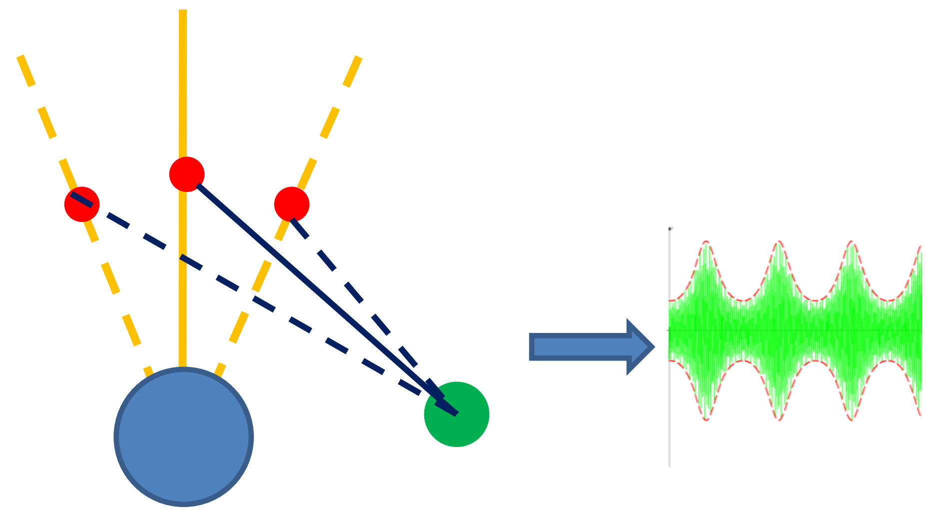
Vibrations of the thread

Possible reasons of the phenomena

2) The appearance of the pulsations

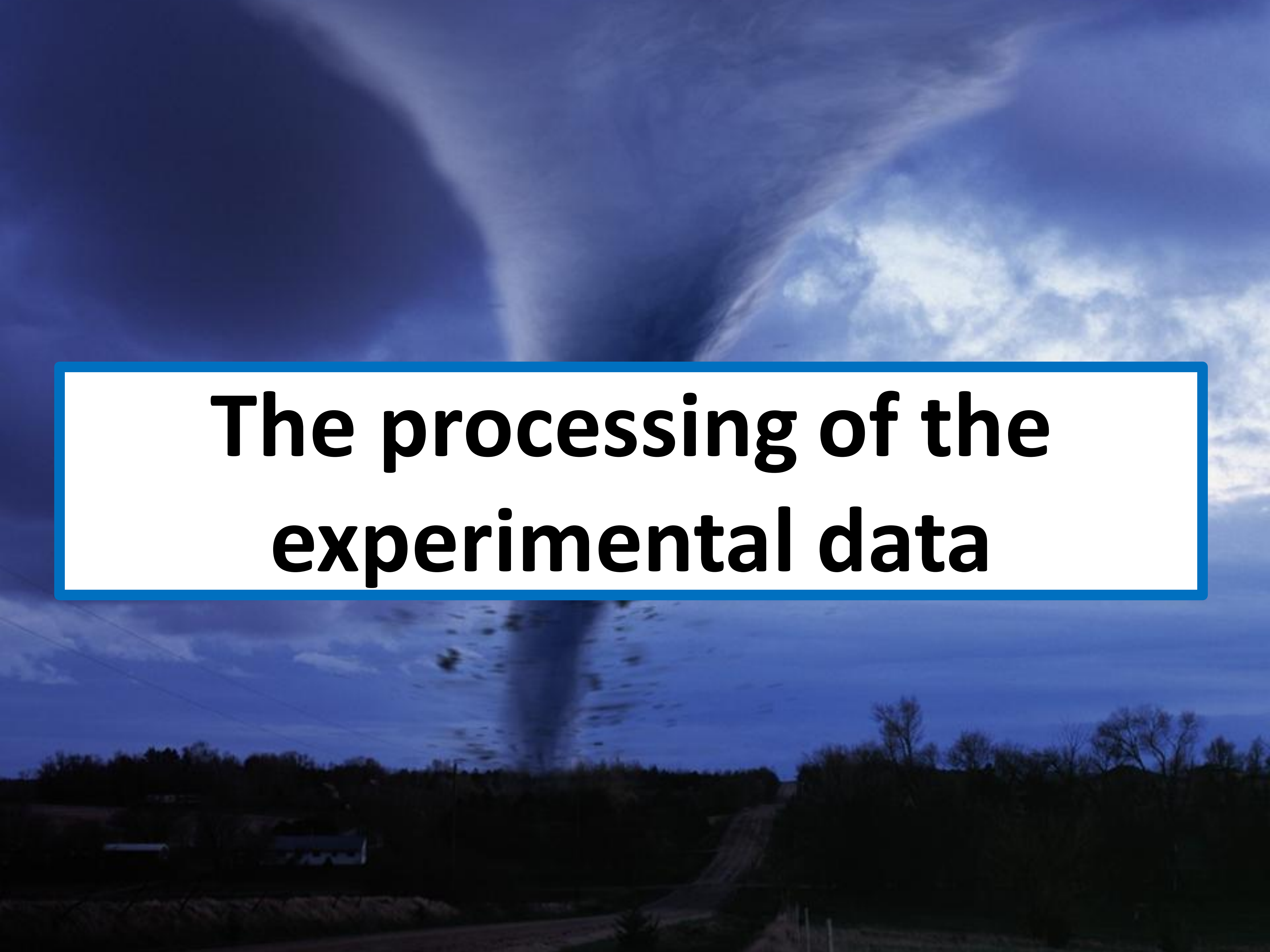


Doppler effect
(Doppler shift)

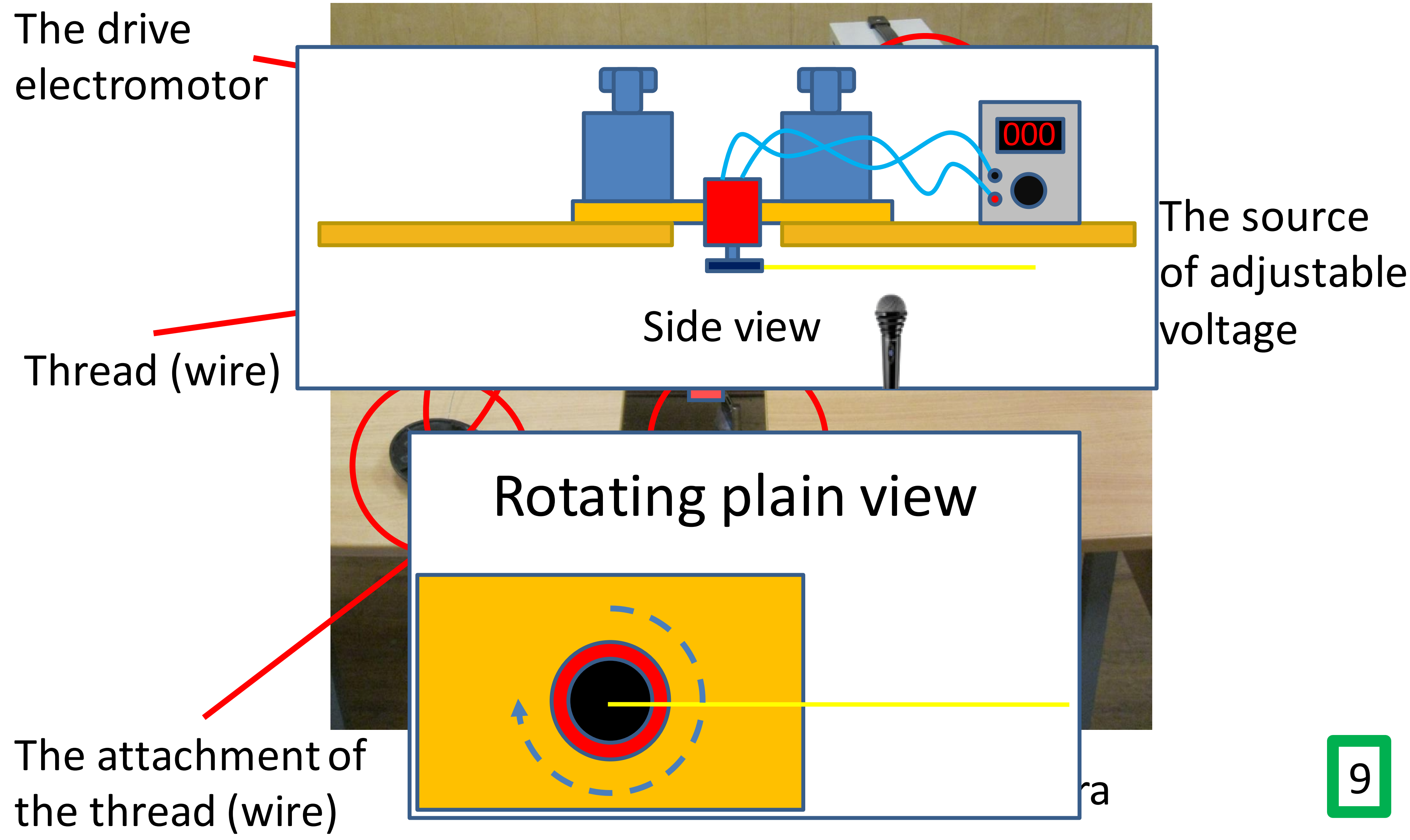


Rotation of the thread

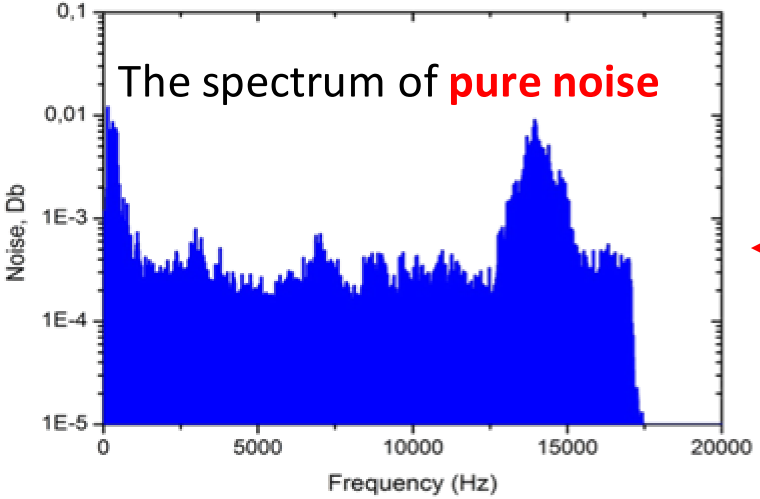
The processing of the experimental data

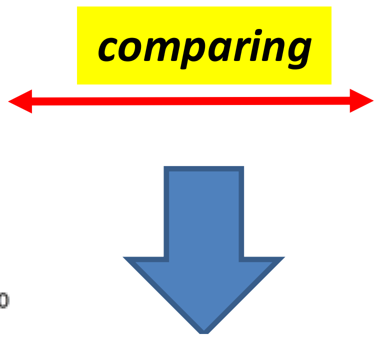


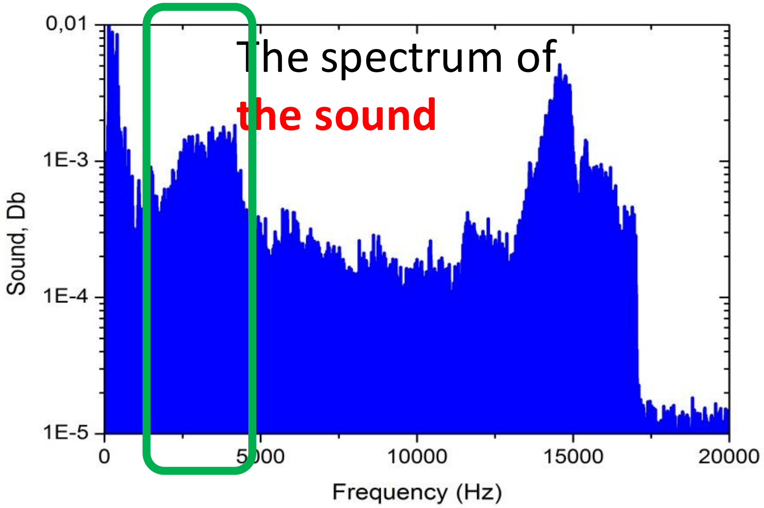
The experimental setup

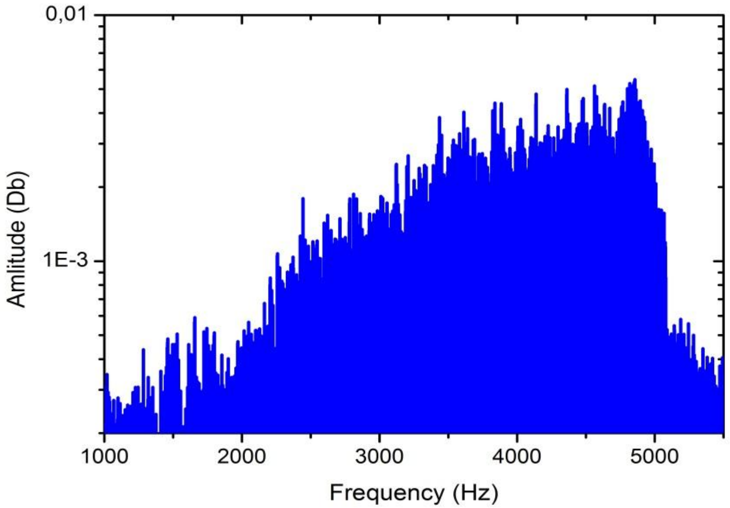


Defining of the boundaries of the useful spectrum



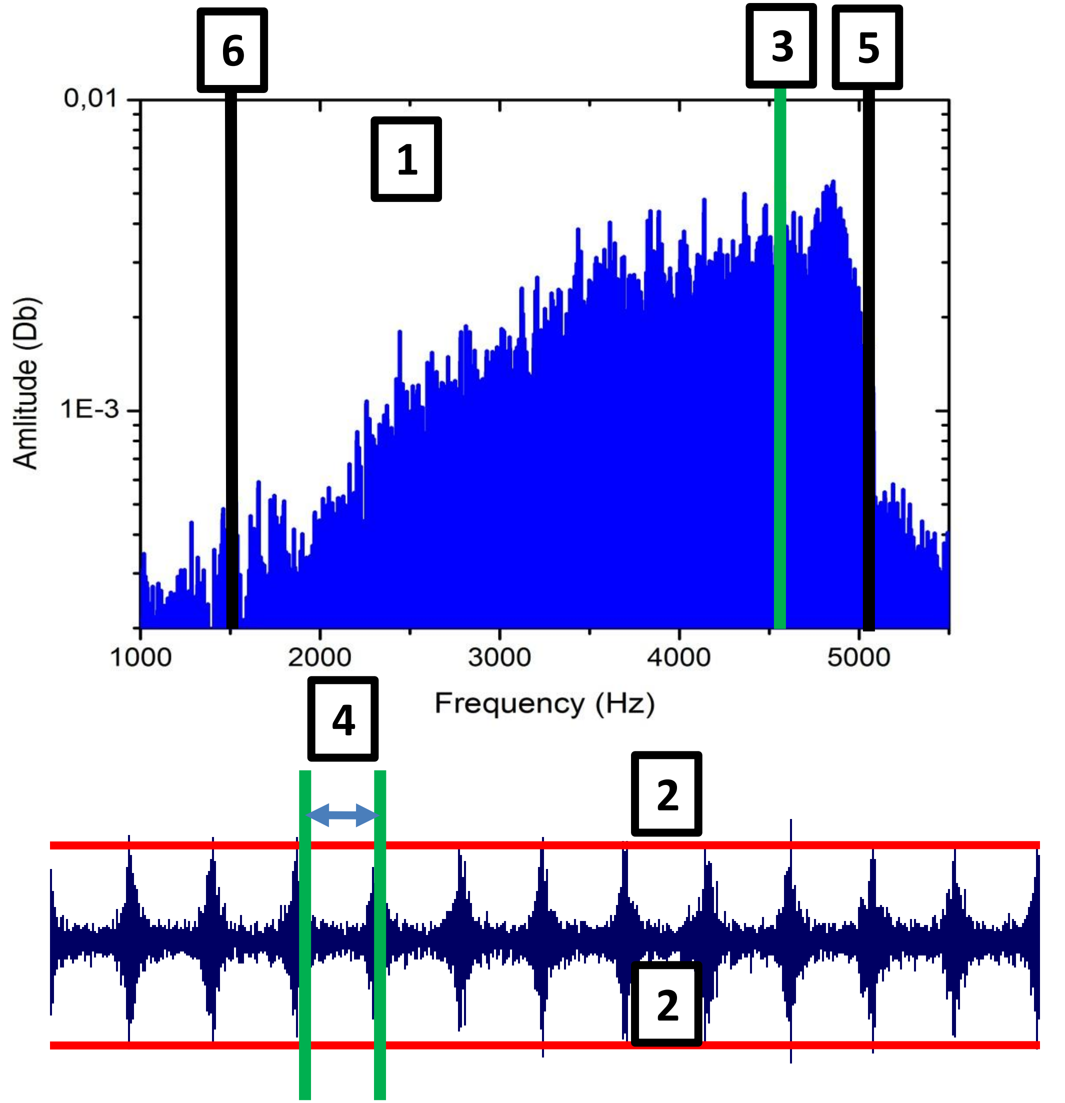






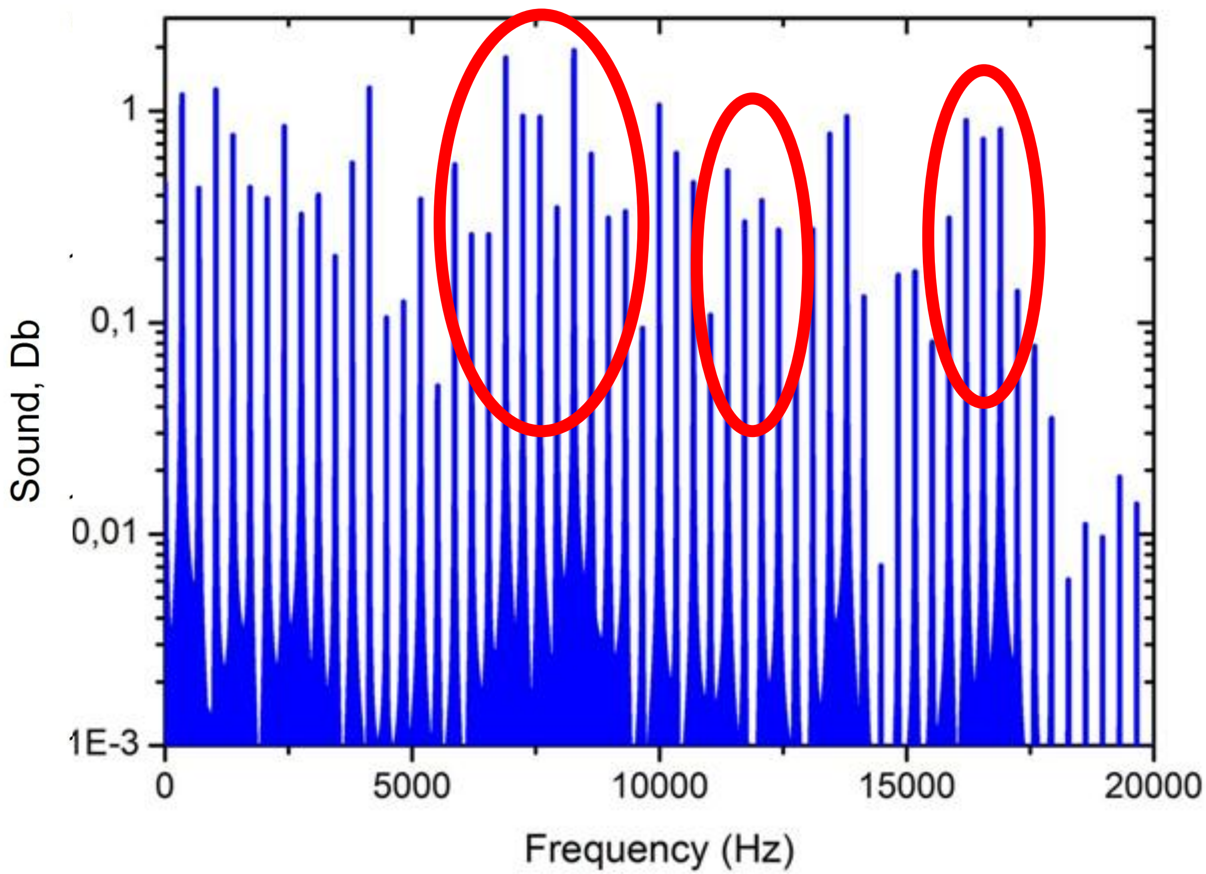
The characteristics of the sound

- The sound spectra (1)
- The volume of the sound (2)
- "The characteristic frequency" (peak in the spectrum) (3)
- The frequency (period) of the pulsations (4)
- The maximum frequency (5)
- The minimum frequency (6)



The experimental part

The characteristics of the sound depending on the material of the thread



Any material

The dependence of the maximum frequency on the rotation frequency

$$\begin{cases} f_{\max} = \alpha_1 f_0 \\ f_{\min} = \alpha_2 f_0 \end{cases}$$

$$\alpha_1, \alpha_2 \sim l$$

$$f = \beta l f_0$$

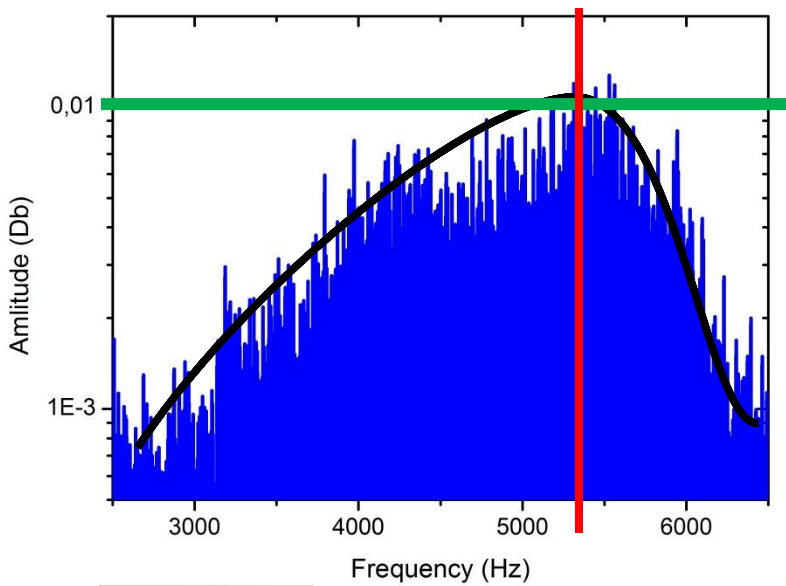
The dependence of the maximum frequency on the diameter of the thread

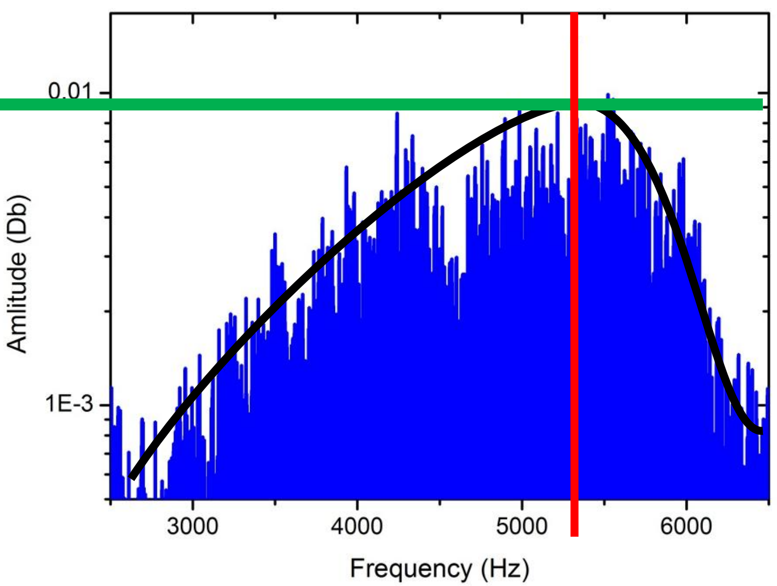
$$\alpha_1, \alpha_2 \sim \frac{1}{d}$$

$$f = \gamma \frac{l f_0}{d}$$

The influence of the bob

The influence of the bob on the spectrum



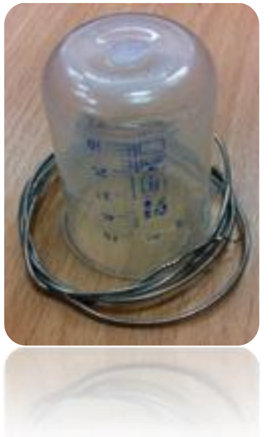


The same
volume of the
sound

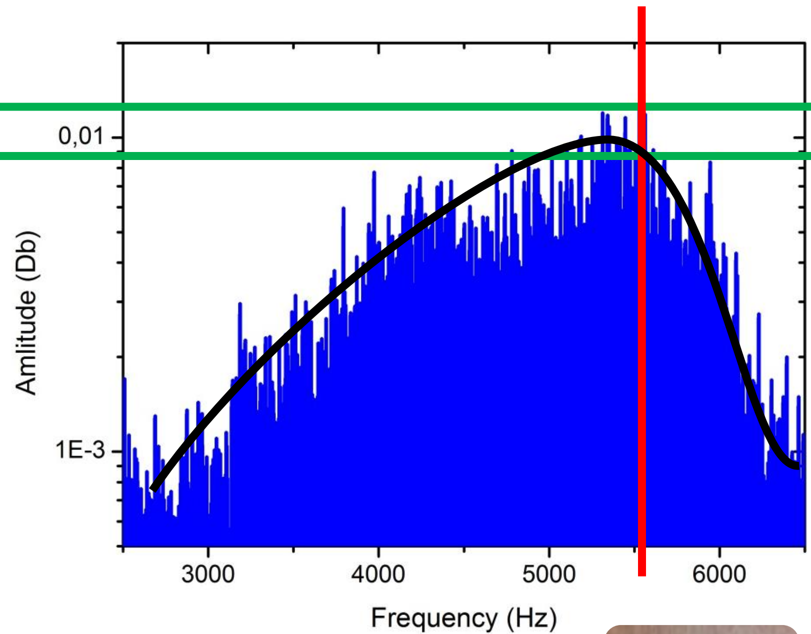
The same envelope

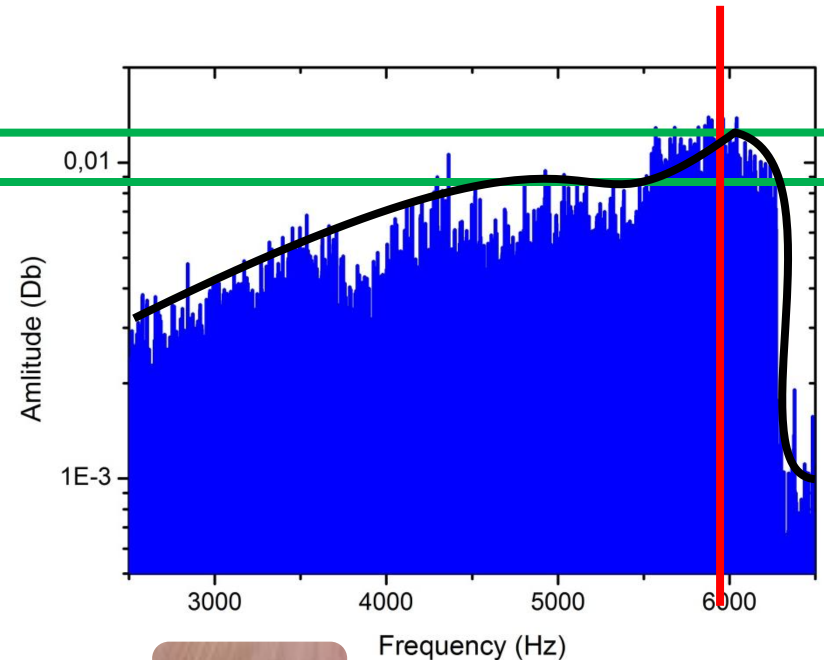
$f_{char} = 5.3\ kHz$

The same characteristic frequency



The influence of the little bob on the spectrum





The volume of the thread with out a bob is lower

$f_{char} = 5.5kHz$

The volume of the thread with a smaller bob is higher

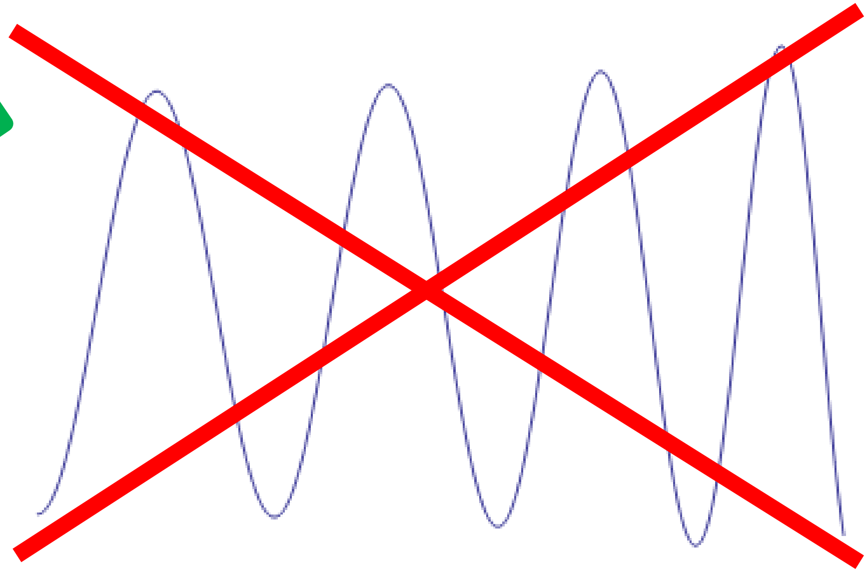
$f_{char} = 5.8kHz$

Different characteristic frequencies

Different envelopes

The final causes of the sound

Consequent vortex shedding from the surface of the thread

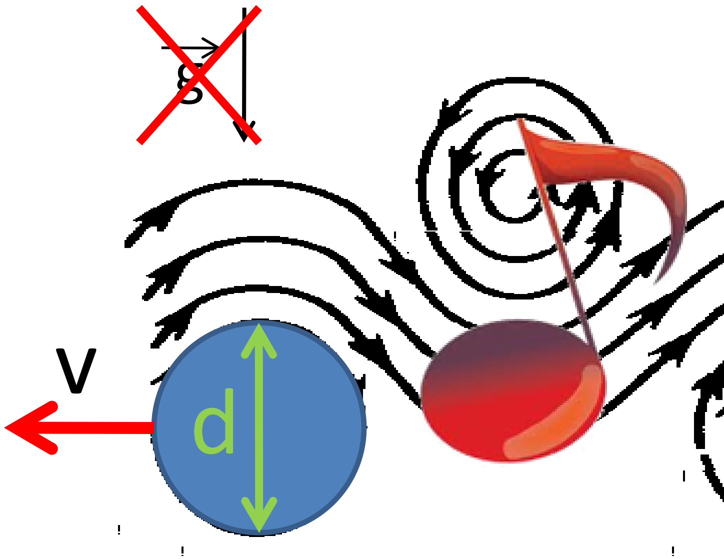


Vibrations of the thread

The theoretical part

The main principles and approaches

- The angular velocity of the thread is constant (The influence of gravity on the angular velocity can be neglected)
- The sound is explained by consequent vortex shedding from the thread surface (Karman vortex street)
- The frequency of vortex shedding coincides with the frequency of the sound
- The vortices are created by the energy, carried away by the vortex flow

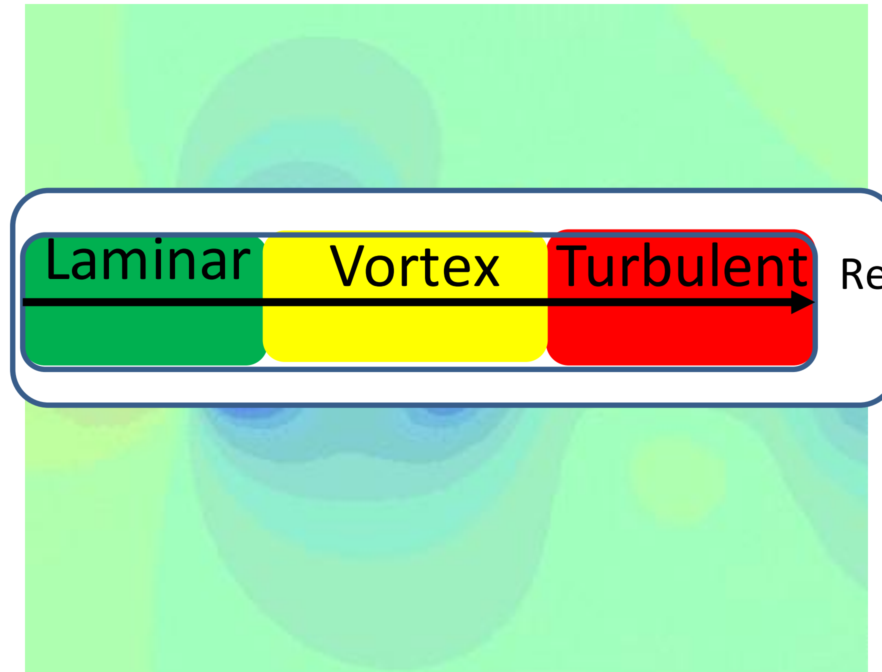


Side view

$$w_0 = const$$

The Strouhal equation

Vincenc Strouhal
(April 10, 1850 – January 26, 1922)



$$St = \frac{fd}{v}$$

$$v = 2\pi f_0 x'$$

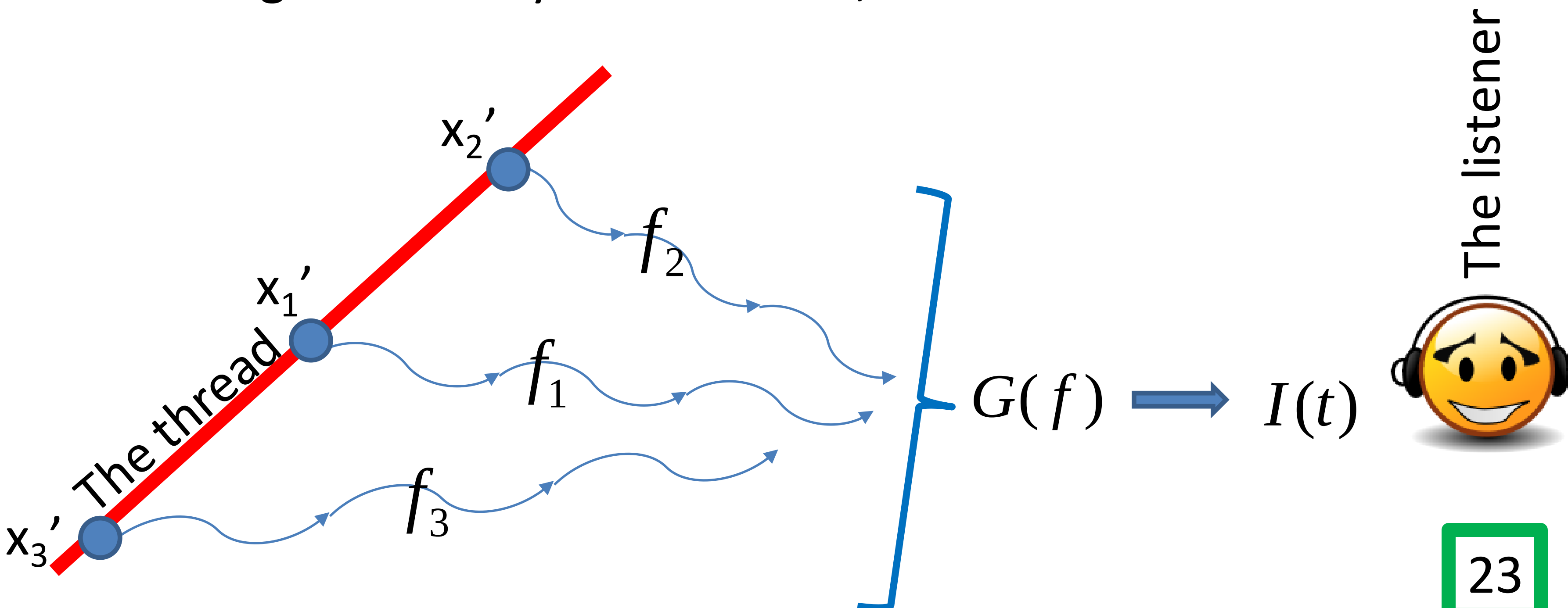
$$f(x') = St\,\frac{2\pi f_0 x'}{d}$$

Notations of the characteristics of the sound

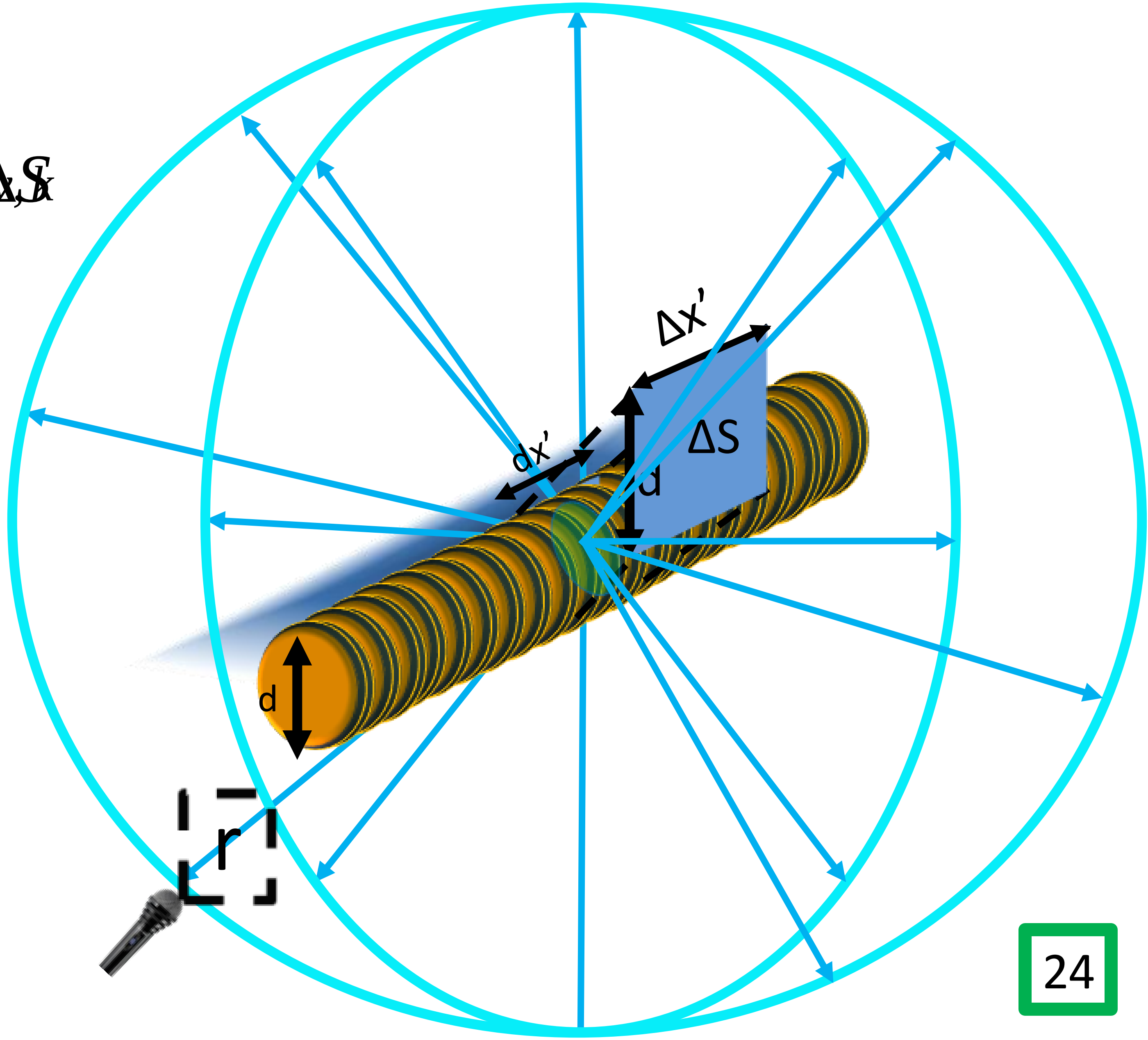
$f(x')$ – frequency, emitted by a small section of the thread;

$G(f)$ – spectral density (spectrum of sound);

$I(t)$ – the integral intensity of the sound;



thread



The theoretical spectrum

$$G(f) = \frac{kC}{8}\rho w_0^3 d \frac{\left(\frac{fd}{St \cdot w_0}\right)^3}{r^2\left(\frac{fd}{St \cdot w_0}, t\right)}$$

$$f = \frac{St w_0 x'}{d}$$

$$x' = \frac{fd}{St w_0}$$

Function of frequency

Function of time

Result of replacement

k is coefficient of losses

C is aerodynamic coefficient

ρ is air density

w_0 is angular velosity

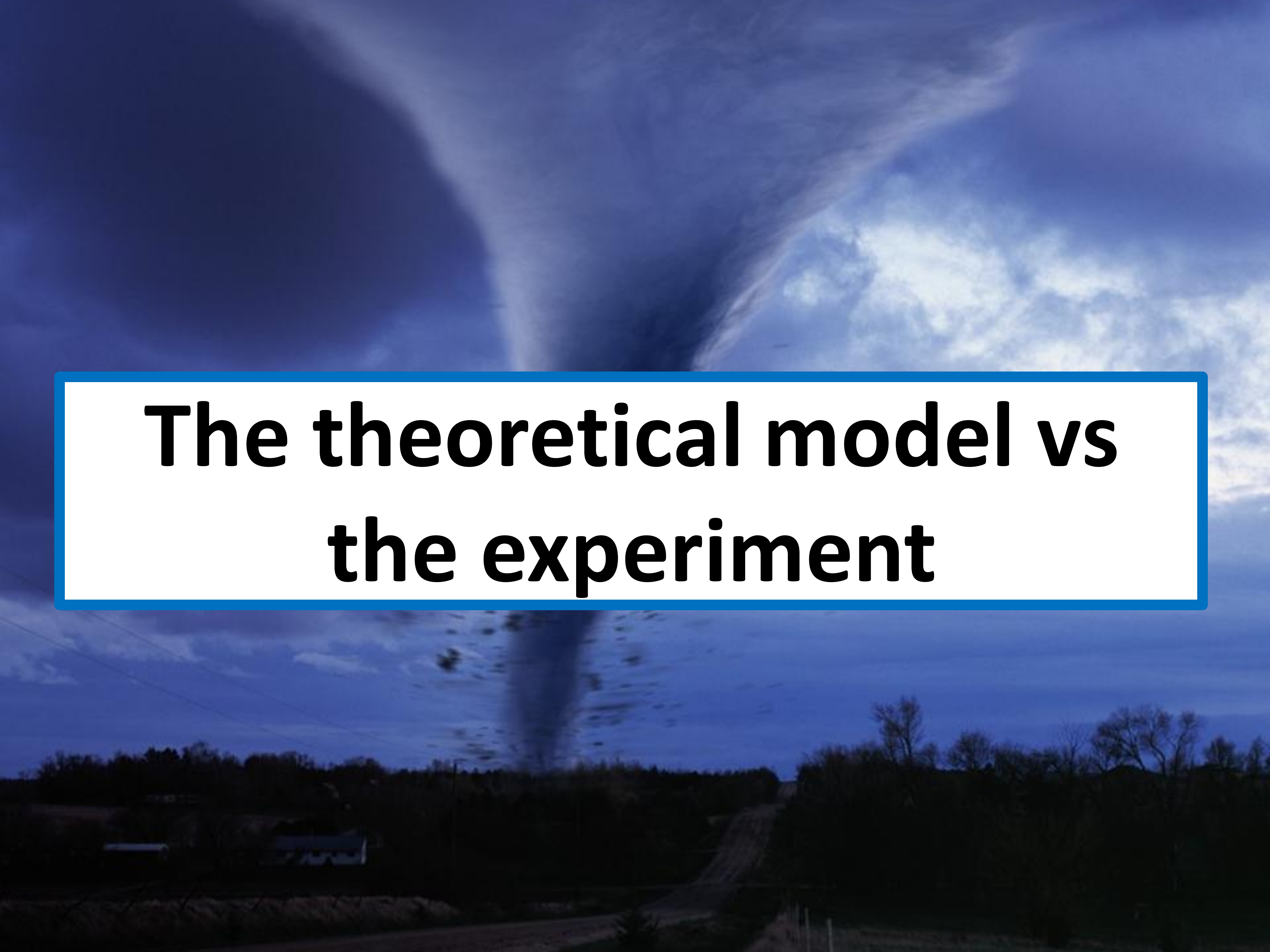
d the diameter of the thread

St is the Strouhal number

f is the sounf frequency

r is the distance to the listener

The theoretical model vs the experiment



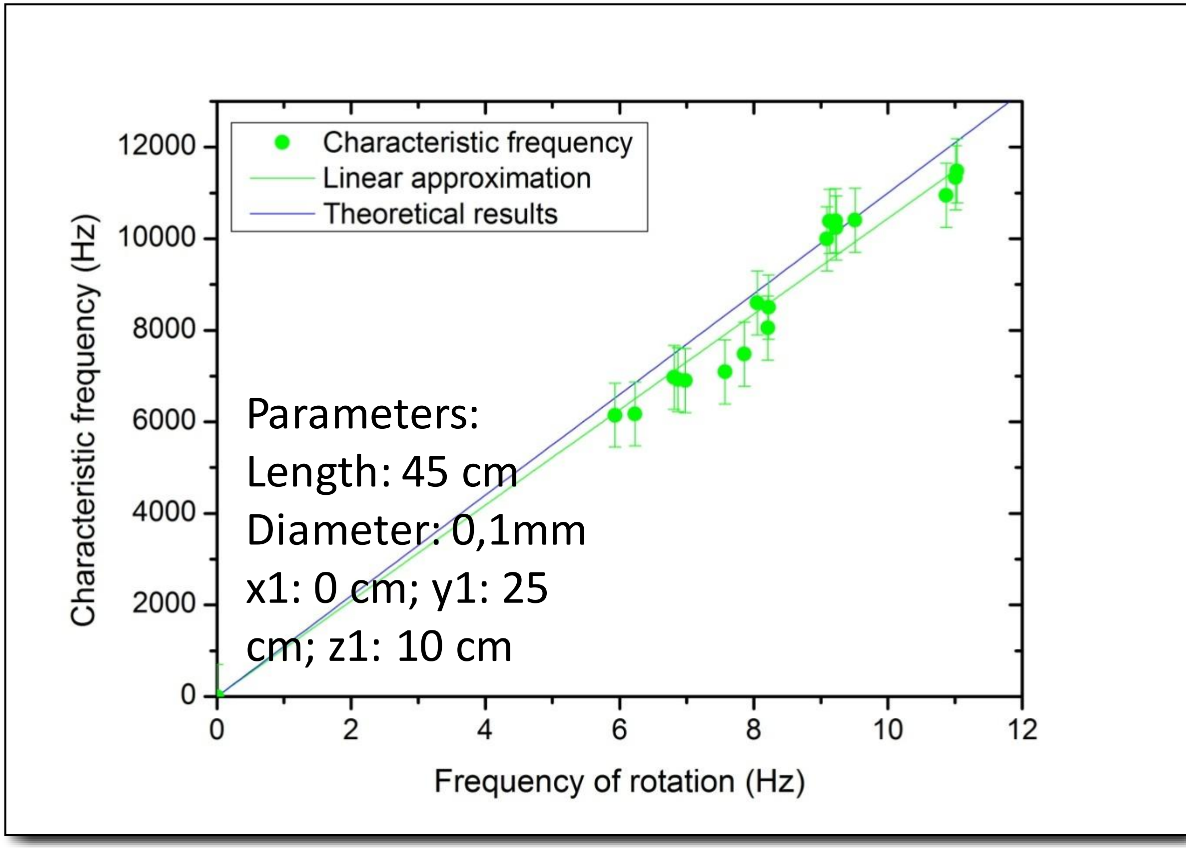
Comparison of experiment and theory. Frequencies

- The maximum frequency
- The minimum frequency
- The characteristic frequency

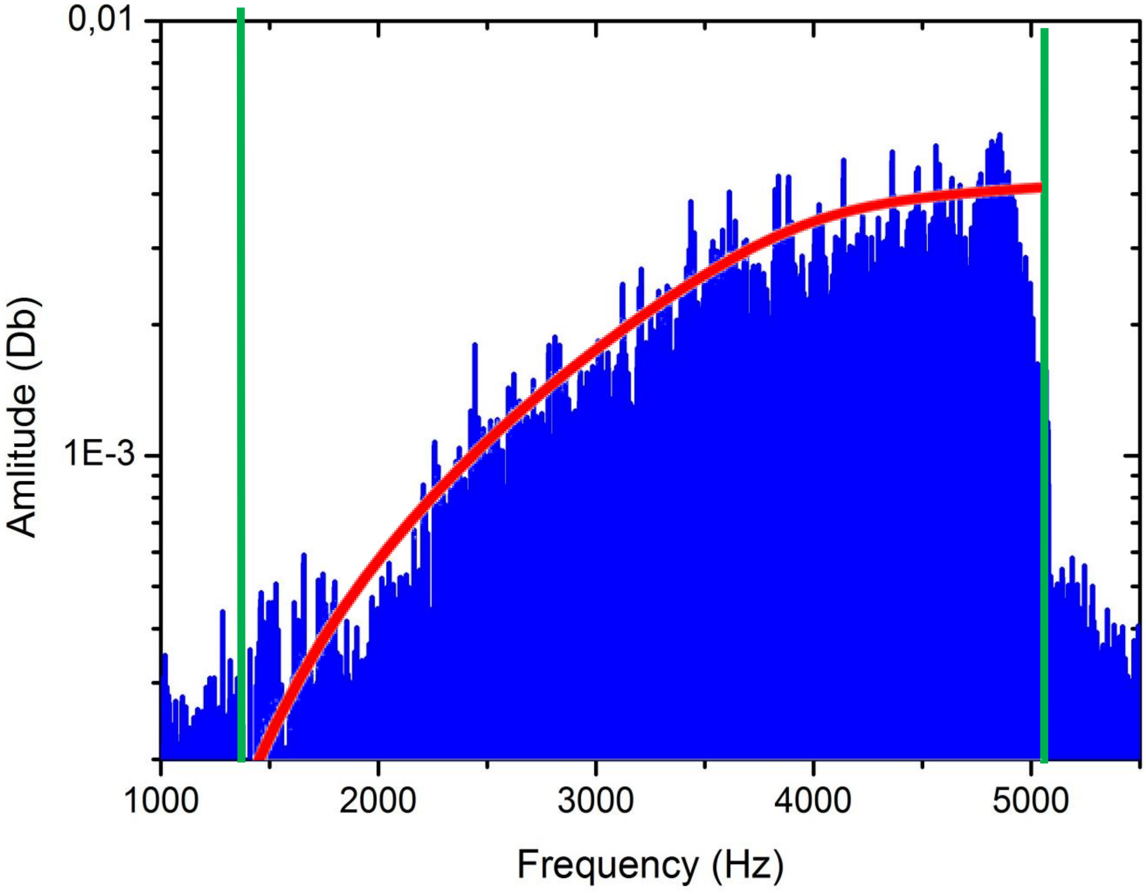
$$f_{\max} = St \cdot \frac{2\pi f_0 l}{d}$$

$$f_{\min} = St \cdot \frac{2\pi f_0 a}{d}$$

$$\begin{cases} f_{char} = \alpha \cdot St \cdot \dfrac{2\pi f_0}{d} \\ \alpha = F(x_1, y_1, z_1) \end{cases}$$



Comparison of experiment and theory. The spectrum

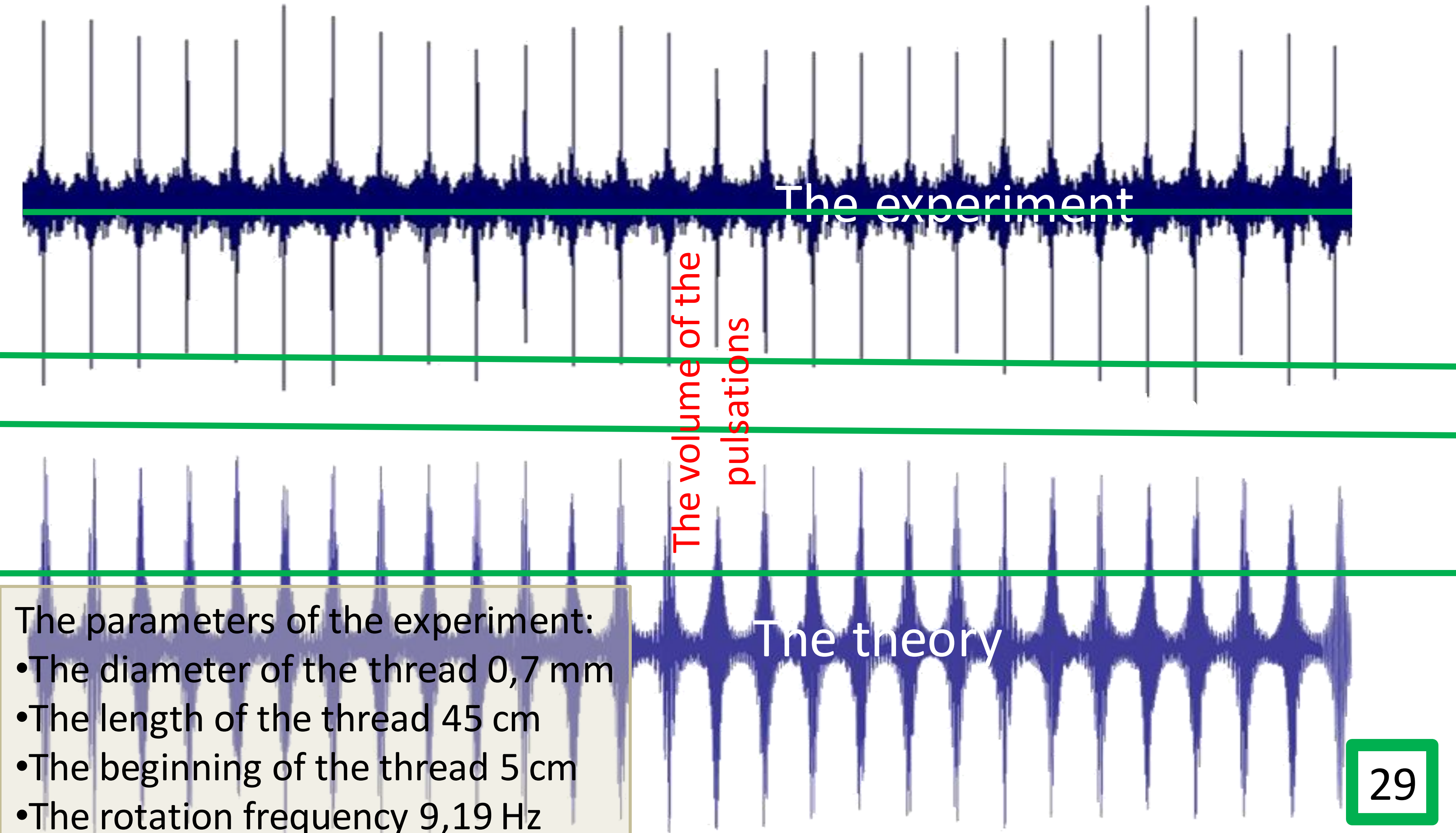


The experimental spectrum

The theoretical spectrum

Parameters:
Length: 45 cm
Diameter: 0,7mm
Frequency of rotation: 9,75 Hz
x1: 0 cm; y1: 25 cm; z1: 10 cm

Comparison the results. The sound



The parameters of the experiment:

- The diameter of the thread 0,7 mm
- The length of the thread 45 cm
- The beginning of the thread 5 cm
- The rotation frequency 9,19 Hz

Conclusions and results

Relevant parameters

- The parameters of the thread
  - Length
  - Diameter
  - Density
  - Young's modulus

Length, Diameter → Aerodynamic properties

Density, Young's modulus → Material properties

- The parameters of the rotation
  - Frequency → The linear velocity
  - Plain of rotation → The influence of gravity

Results of our work

Our work

- Find the origin of th
- Find relevant pa
- Built a theo el

The problem

- Use earches for this

to

quantitative description

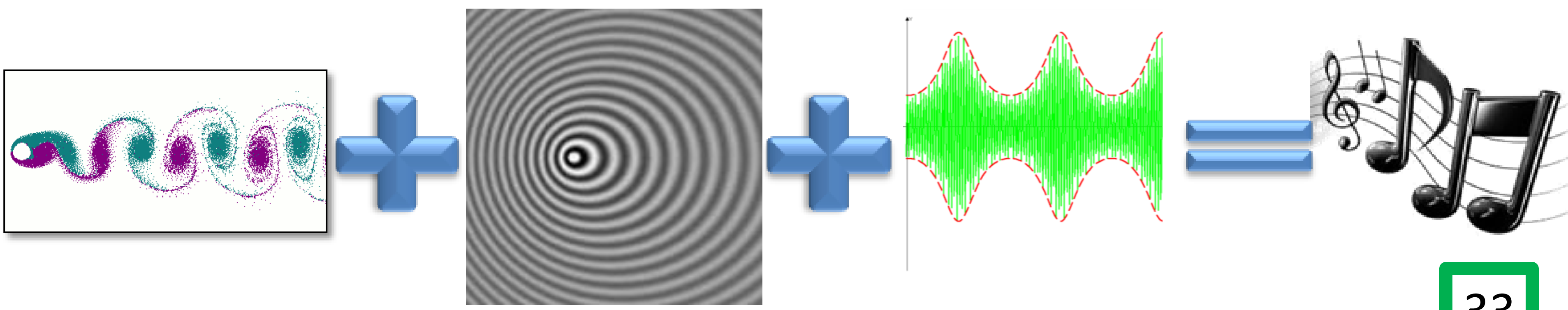
phenomena

- Get all the properties of the sound

Can predict the emitted sound!

The qualitative conclusions

- The sound comes as a result of vortex shedding from the surface of the thread ("Karman vortex street")
- Typical pulsations occur as a result of both the Doppler effect and the changes in signal attenuation with distance



The quantitative conclusions

- The frequency characteristics of each peace of the thread, as well as the whole thread, are defined by the Strouhal equation
- The characteristic frequency is determined by the position of the listener as well as the linear dimensions of the thread, the parameters of the rotation
- Shape of the spectrum is determined by the speed and the parameters of the thread
- The presence of a bob just adds its own sound, which depends only on its size and shape.

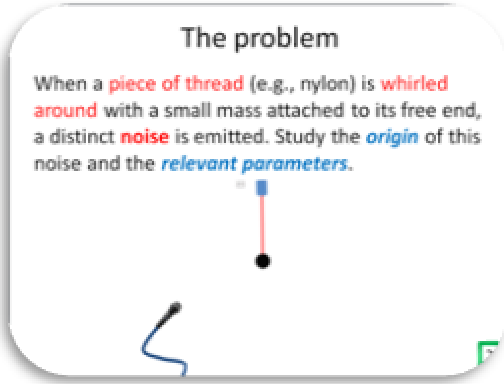
$$St = \frac{fd}{\upsilon} + r(x,t) +$$

+

=


Thank you for your attention!

Overview


The problem
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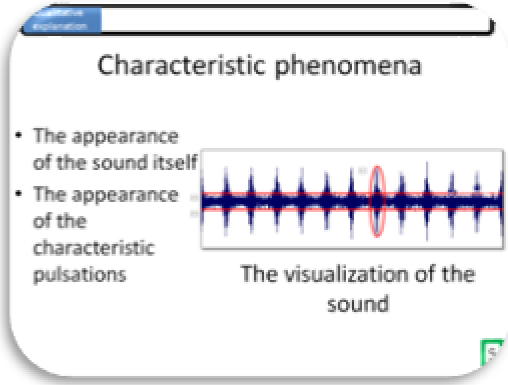
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The appearance of the sound itself
The appearance of the characteristic pulsations
The visualization of the sound
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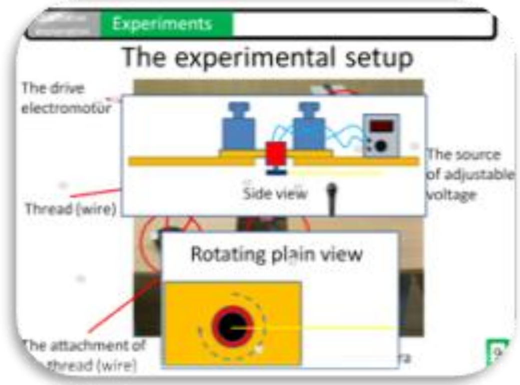
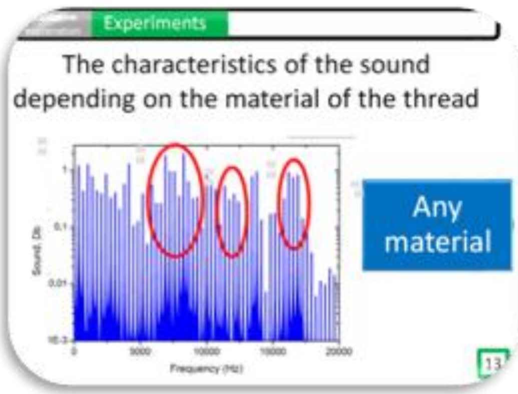

Experiments
The experimental setup
The drive electromotor
The source of adjustable voltage
Side view
Thread (wire)
Rotating plain view
The attachment of thread (wire)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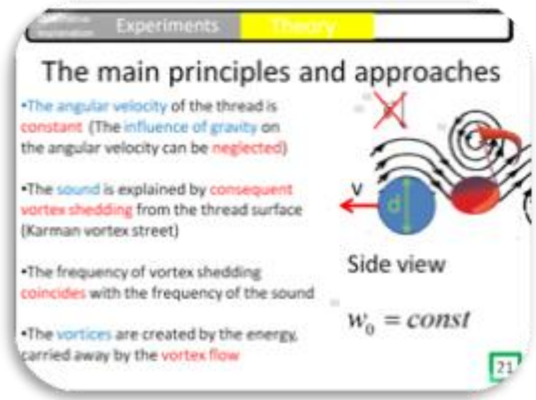
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V
d
Side view
$w_0 = const$
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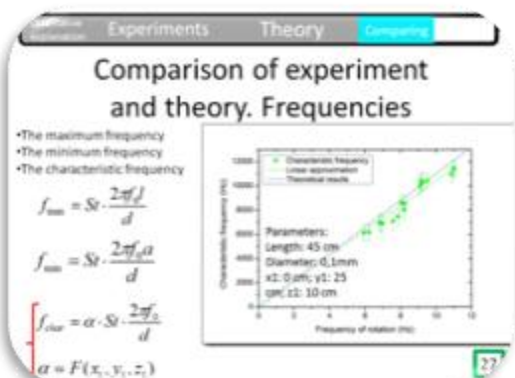
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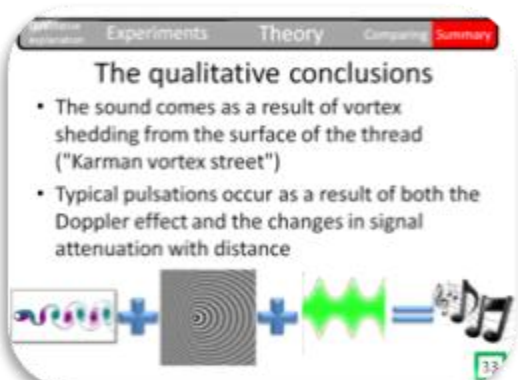
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Typical pulsations occur as a result of both the Doppler effect and the changes in signal attenuation with distance
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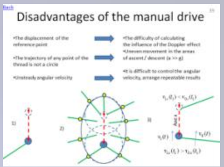
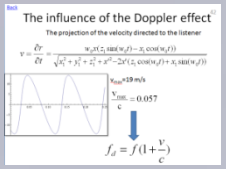
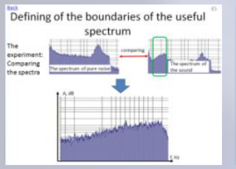
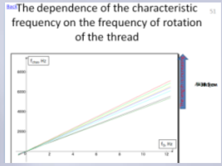
Thank you for your attention!

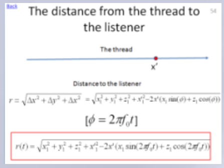
List of additional slides

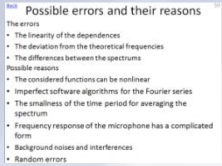


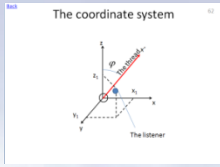


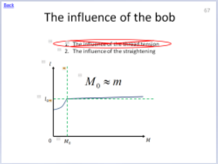












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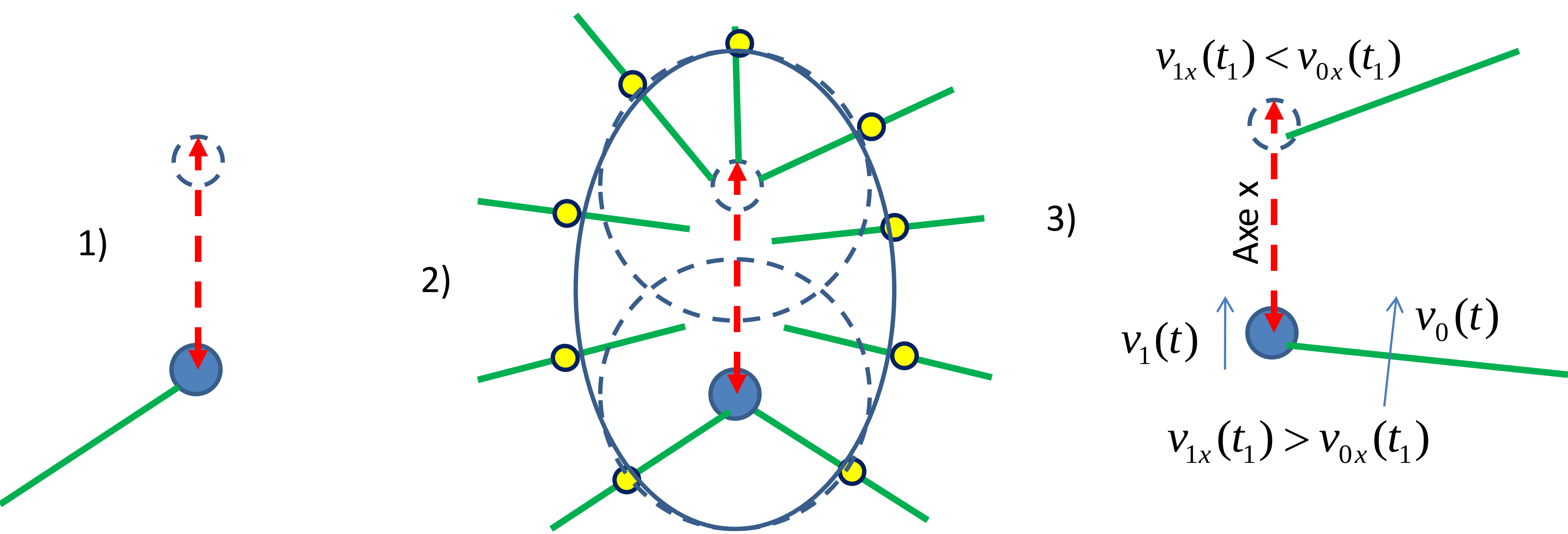
Disadvantages of the manual drive

- The displacement of the reference point → The difficulty of calculating the influence of the Doppler effect
- The trajectory of any point of the thread is not a circle → Uneven movement in the areas of ascent / descent (a >> g)
- Unsteady angular velocity → It is difficult to control the angular velocity, arrange repeatable results



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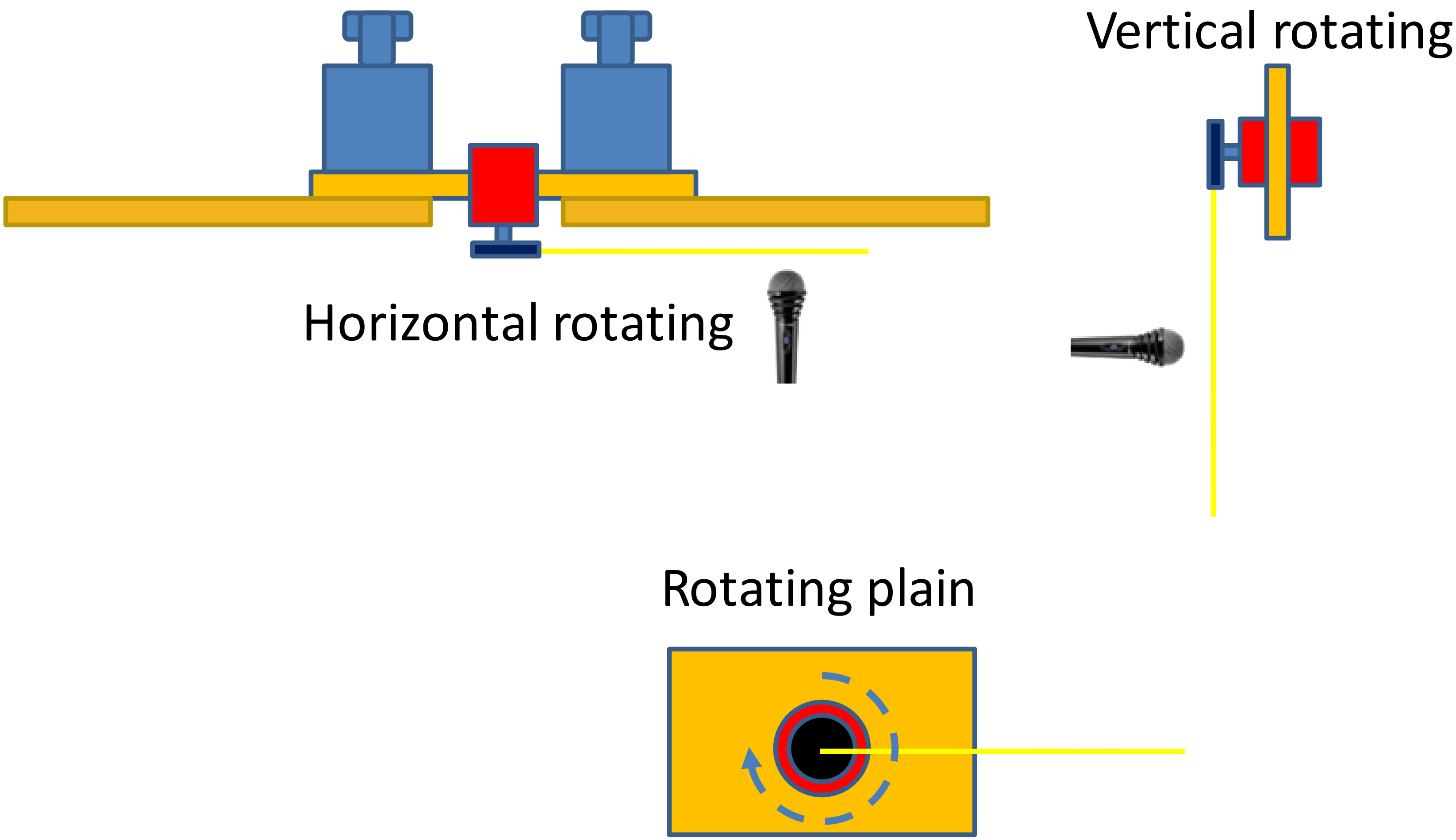
Our experimental setup



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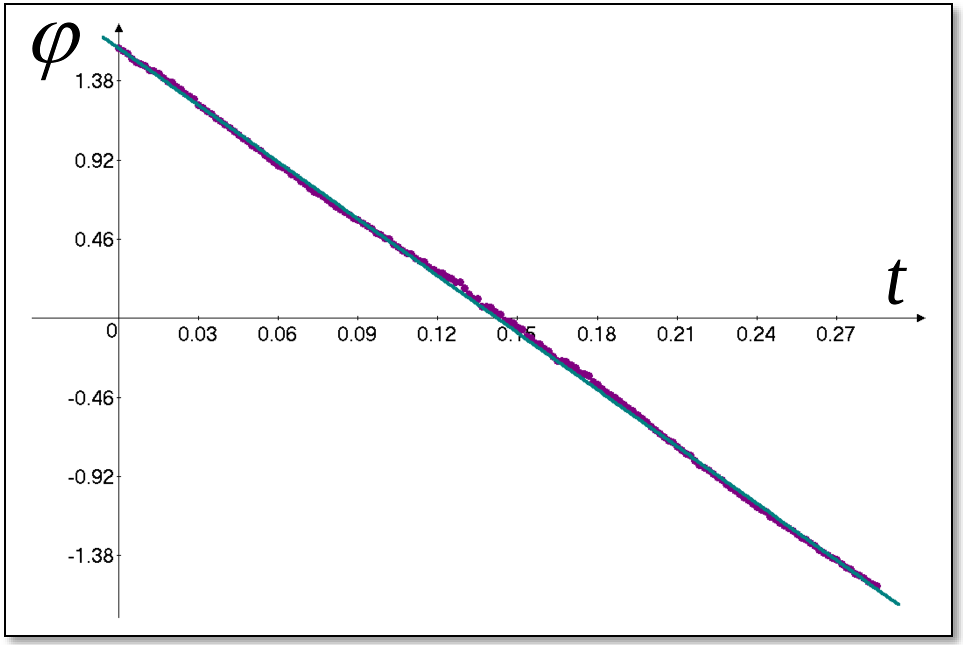
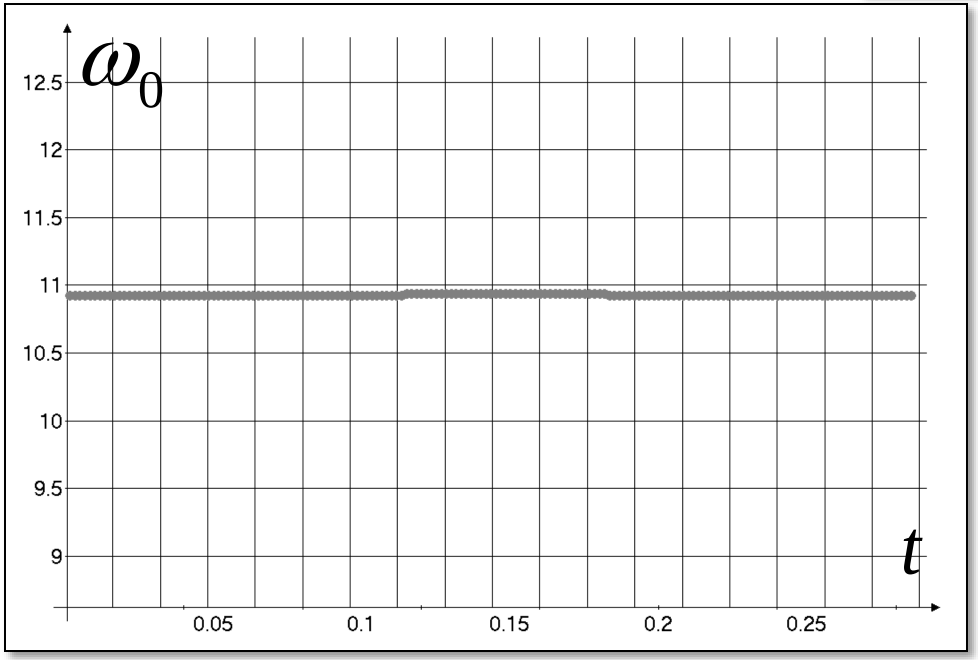
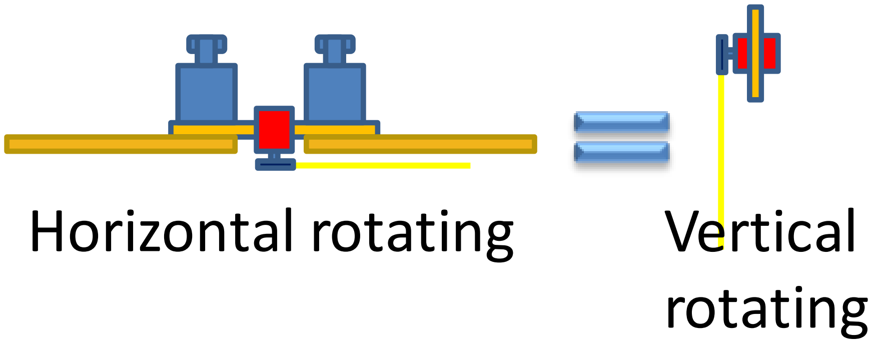
Consideration of motion of the thread

$$\varphi = \varphi_0 - \omega_0 t$$

$$\omega_0 = const$$







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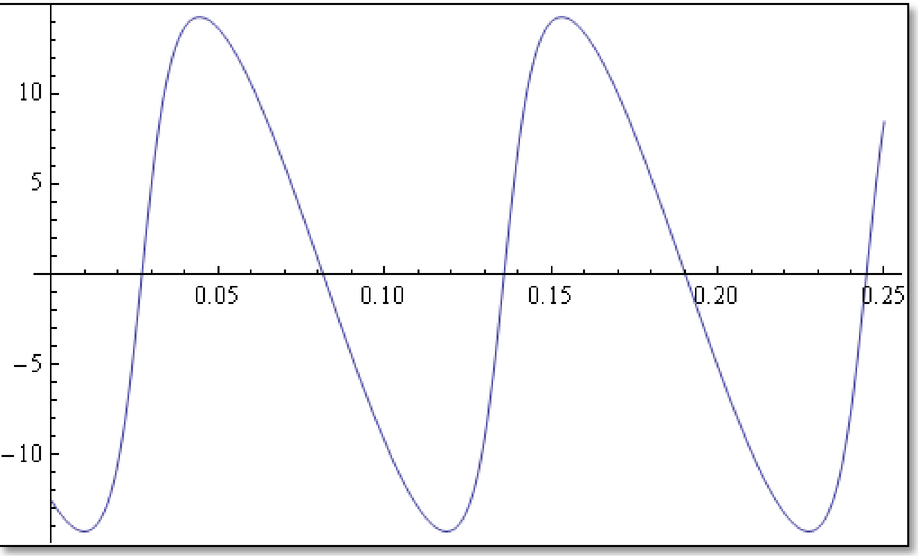
The influence of the Doppler effect

The projection of the velocity directed to the listener

$$v = \frac{\partial r}{\partial t} = \frac{w_0 x(z_1 \sin(w_0 t) - x_1 \cos(w_0 t))}{\sqrt{x_1^2 + y_1^2 + z_1^2 + x'^2 - 2x'(z_1 \cos(w_0 t) + x_1 \sin(w_0 t))}}$$



v_{max}=19 m/s

$$\frac{v_{max}}{c} = 0.057$$

$$f_d = f(1 + \frac{v}{c})$$

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The influence of the Doppler effect

$$G(f+\Delta f)=F(f)$$

Δf – the change in frequency due to Doppler shift

Valid for any f

$$G(f)=F(f-\Delta f)$$

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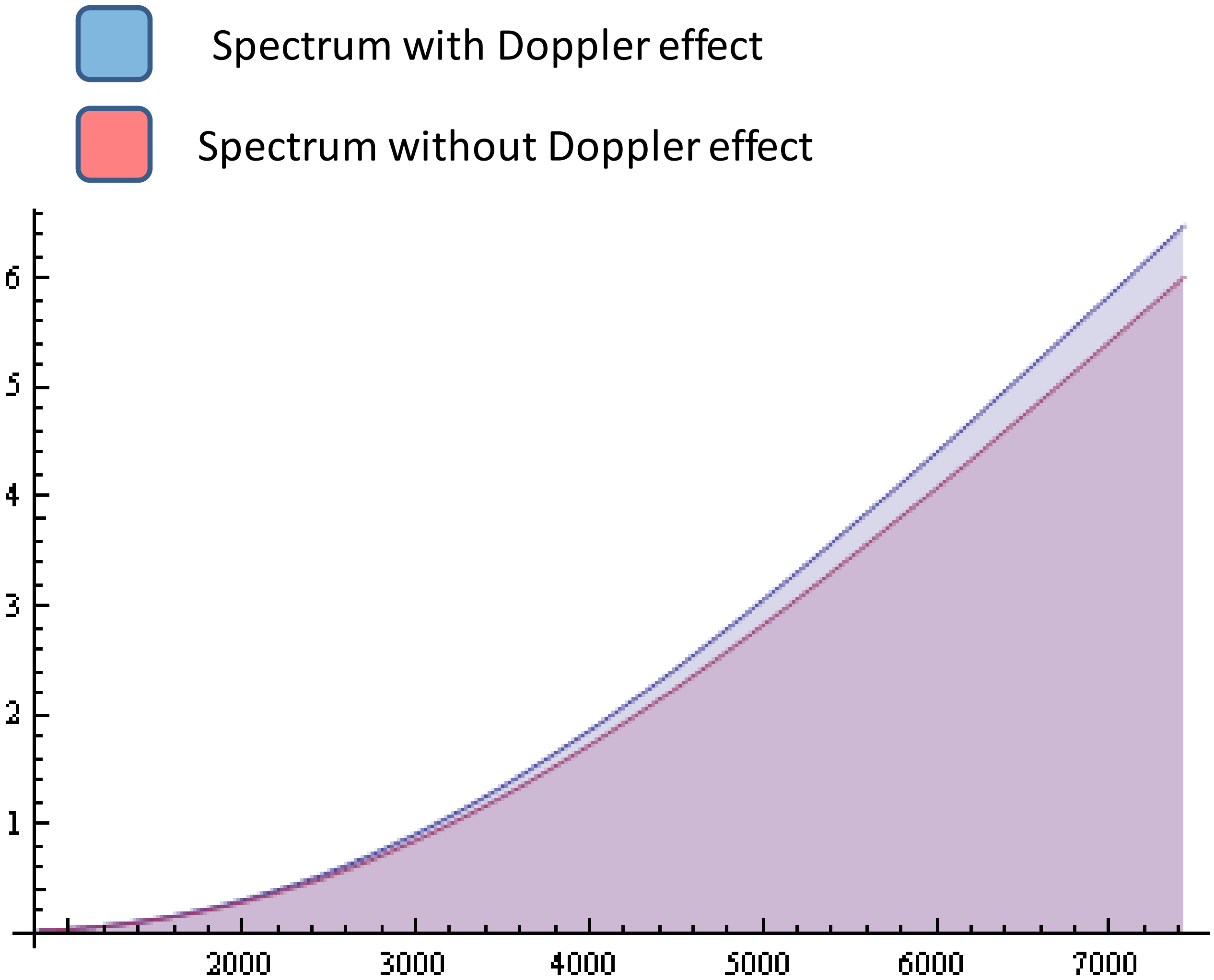
Comparing the spectra



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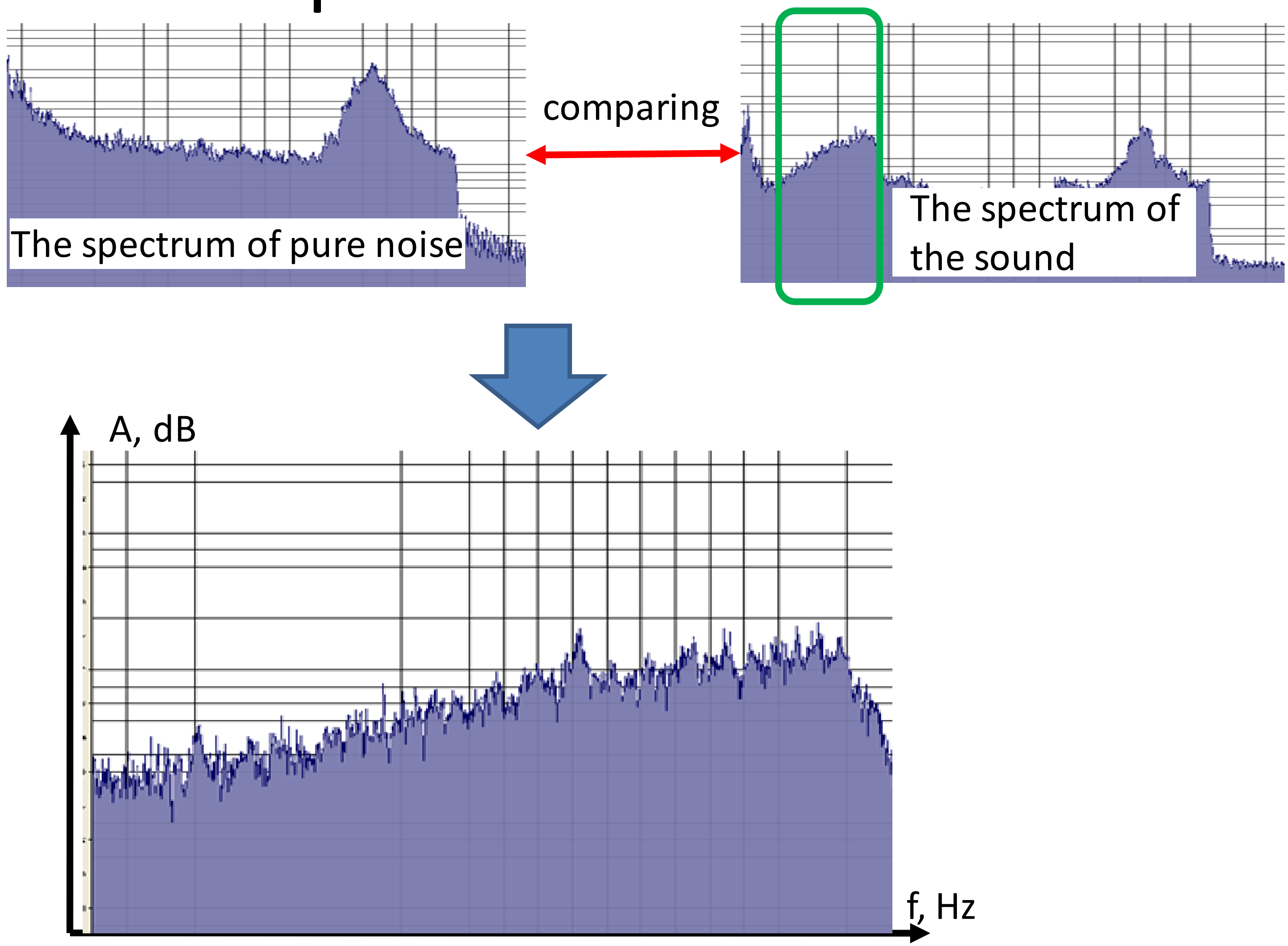
Defining of the boundaries of the useful spectrum

The experiment: Comparing the spectra



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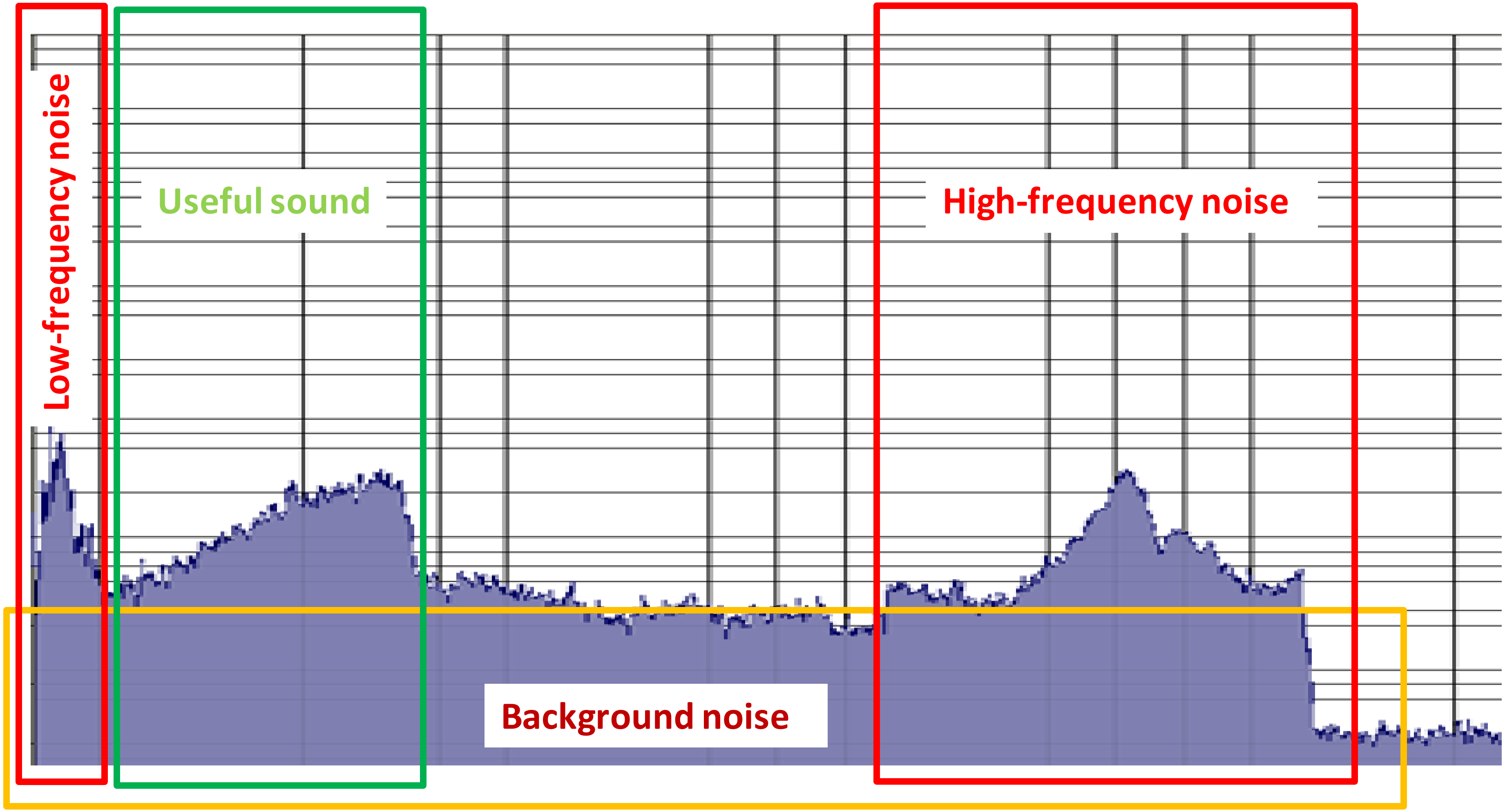
Improving the quality of the spectrum



Type of noise	Ways of suppression
Low-frequency noise of the electromotor	Manual removal of noise
High-frequency noise of the electromotor	High-pass Filter
Background noise	Noise suppressor

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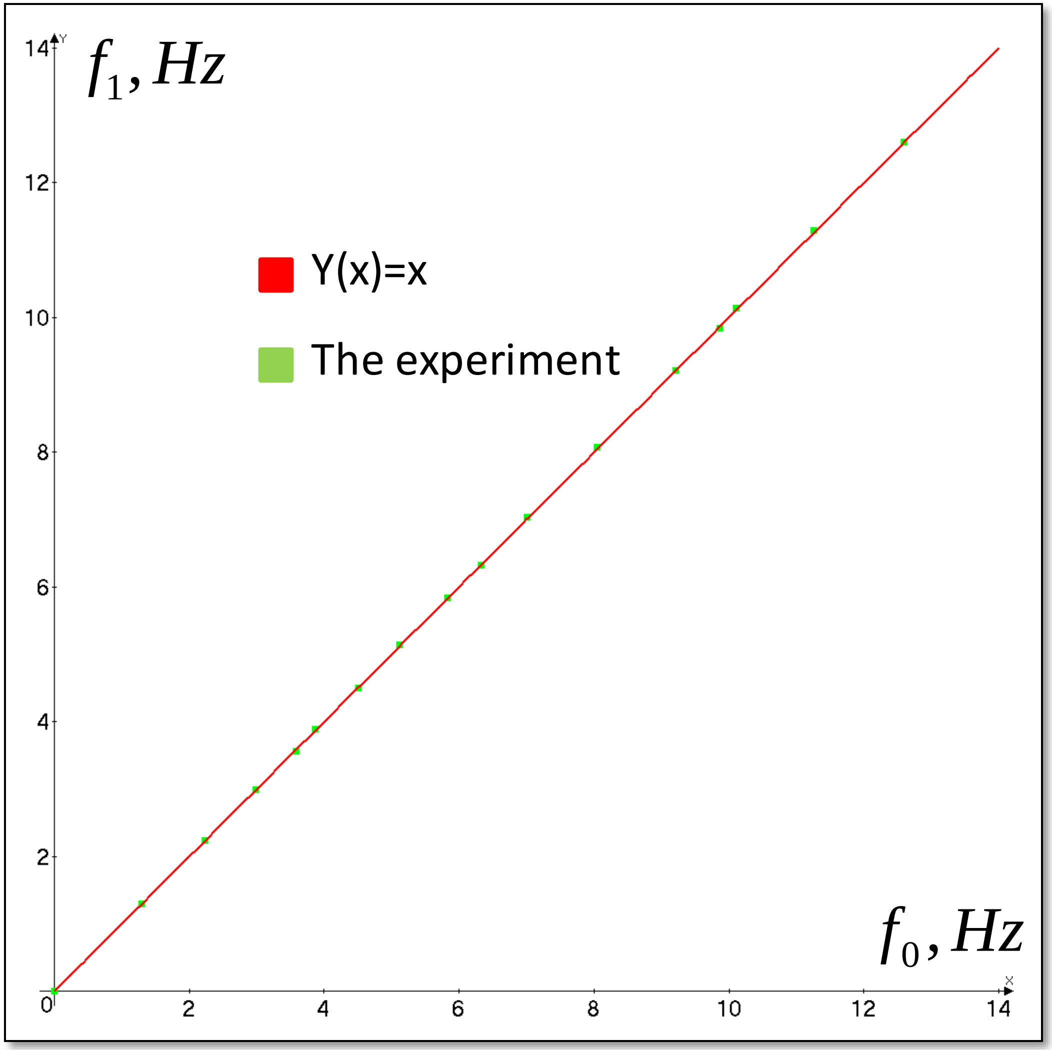
The dependence of the pulsation frequency on the frequency of rotation



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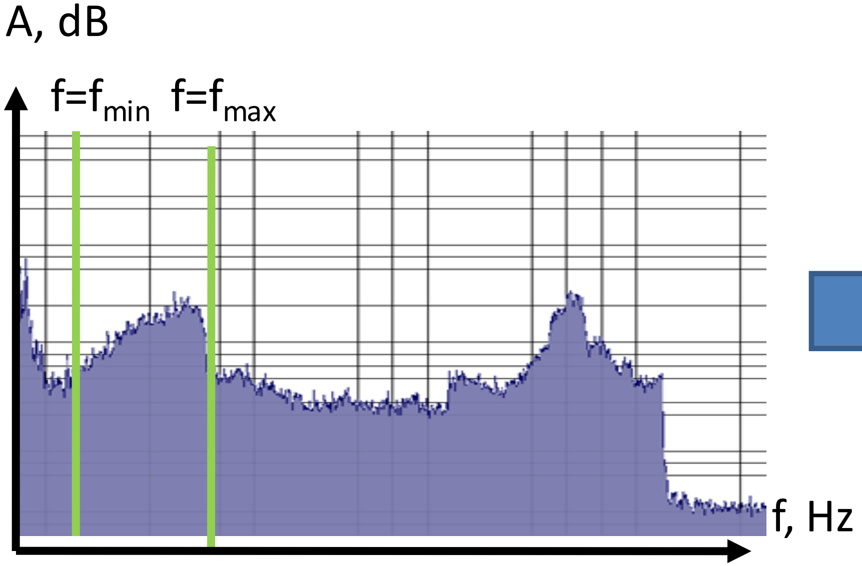
The vortex shedding frequency

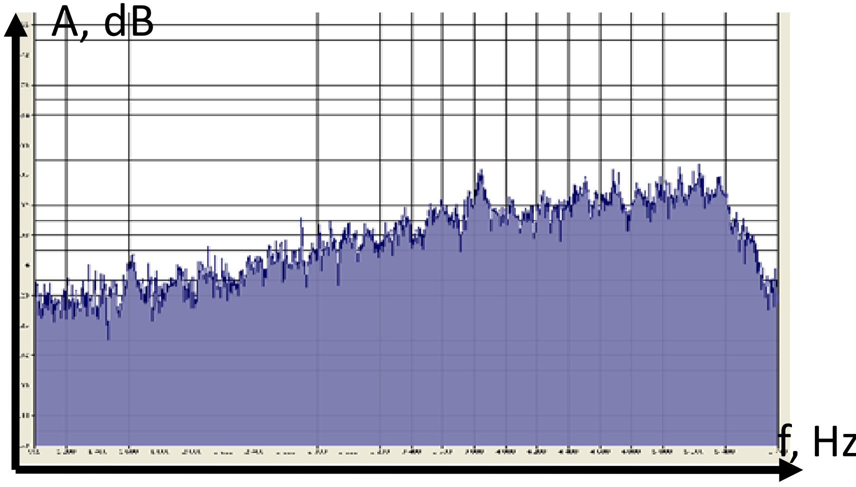
The Strouhal formula

$$St = \frac{fd}{\upsilon}$$

$$f_{max} = St \cdot \frac{2\pi f_0 l}{d}$$

$$f_{min} = St \cdot \frac{2\pi f_0 a}{d}$$





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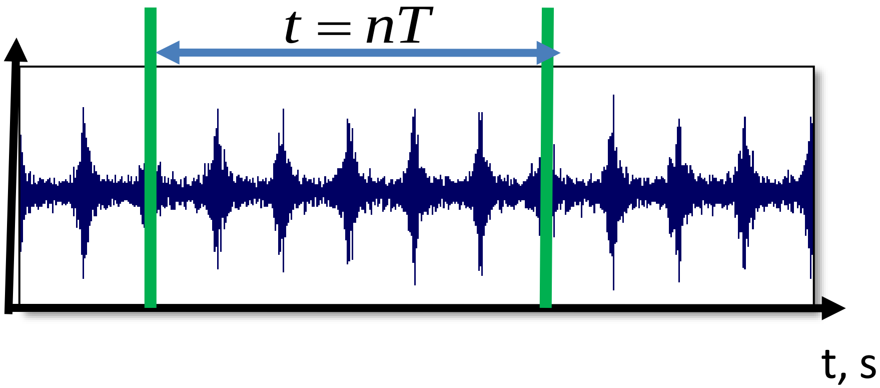
Data processing

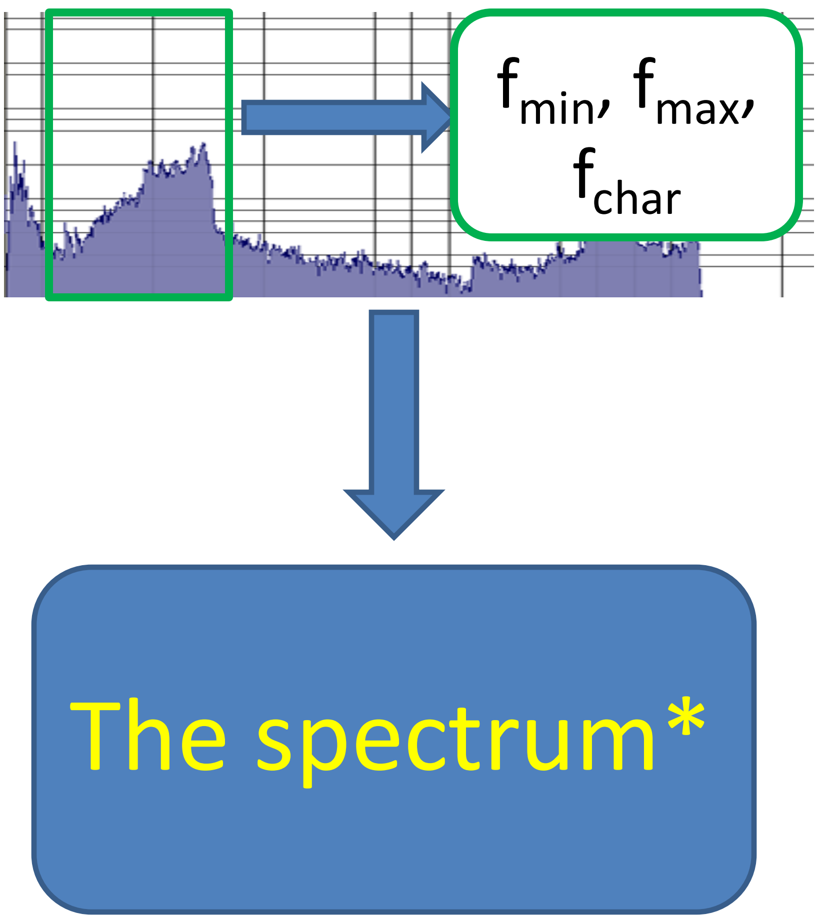
Processing of the record

The rotation frequency



Processing of the spectrum*

Determining the sound characteristic



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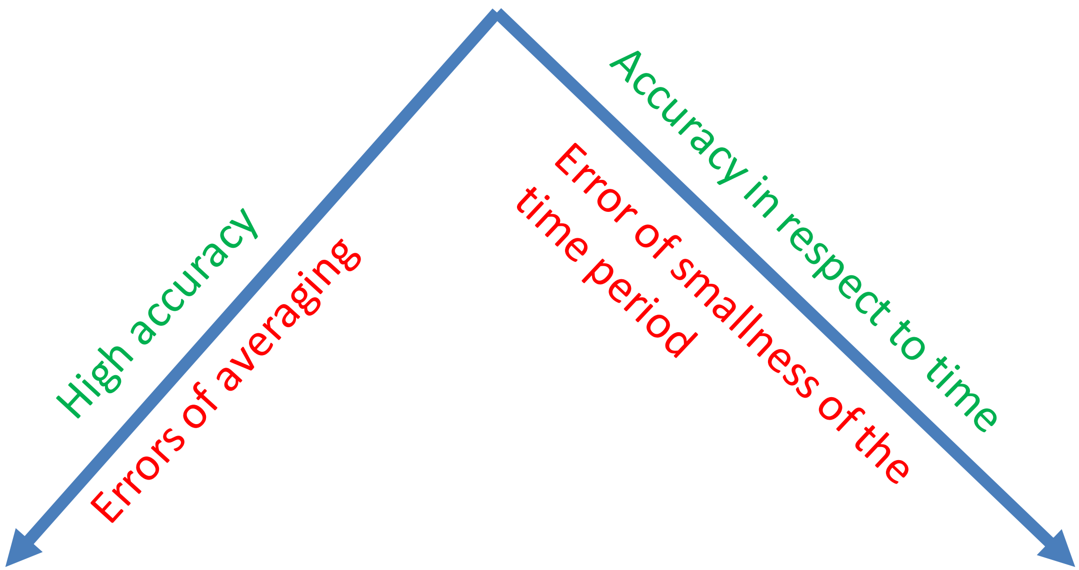
Using the spectrum



The average spectrum

The instant spectrum

Obtaining the characteristic frequency

Getting directly the sound spectrum

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Conversion the theoretical data

The theory

$$F(f,t,x')$$

$$A(f,t,x') = \lg F(f,t,x')$$

The experiment

$$\lg \frac{(F_1 + F(f,t,x'))^n}{F_0}$$

$$n \log_{10}(F_1 + F(f,t,x')) + C$$

C =lg(F_0) - the shift of the value on the axis Y

n- coefficient, depending on the type of the value

F_1 – the shift of the on the axis Y (egg., noise)

The experiment

The constants ***n***, ***C***, ***F_1***

Comparing

The theory

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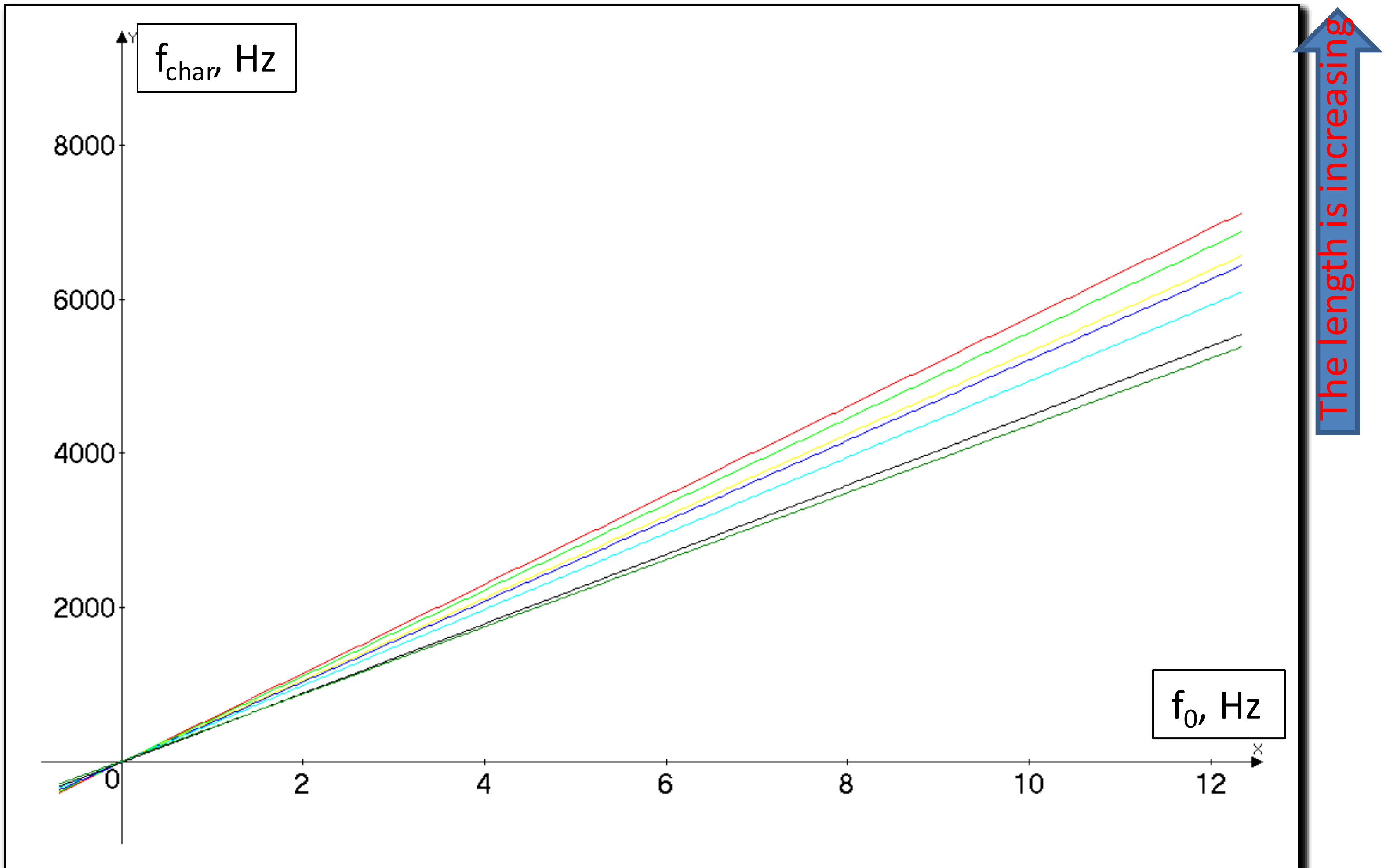
The dependence of the characteristic frequency on the frequency of rotation of the thread



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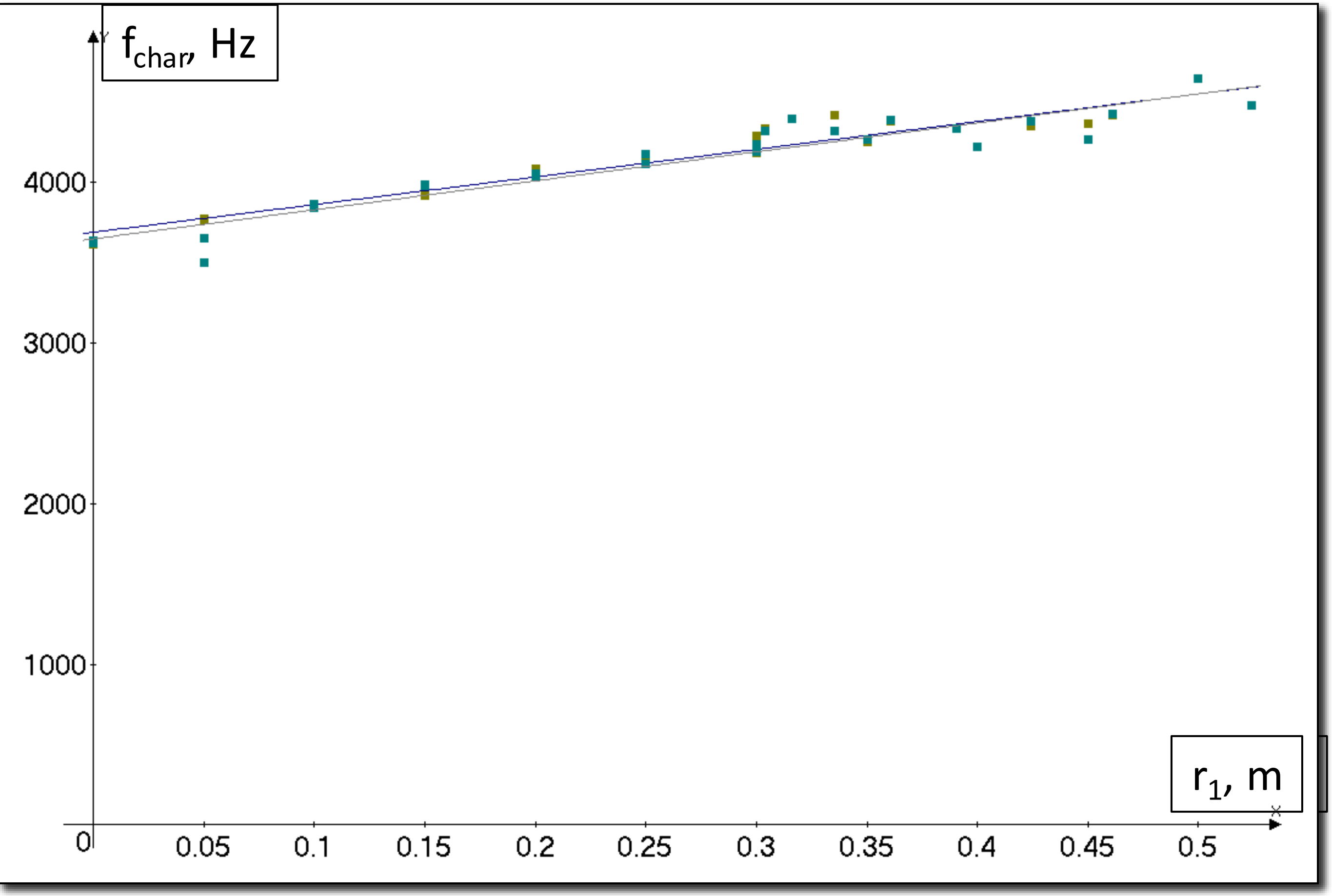
The dependence of the characteristic frequency on the position of the listener



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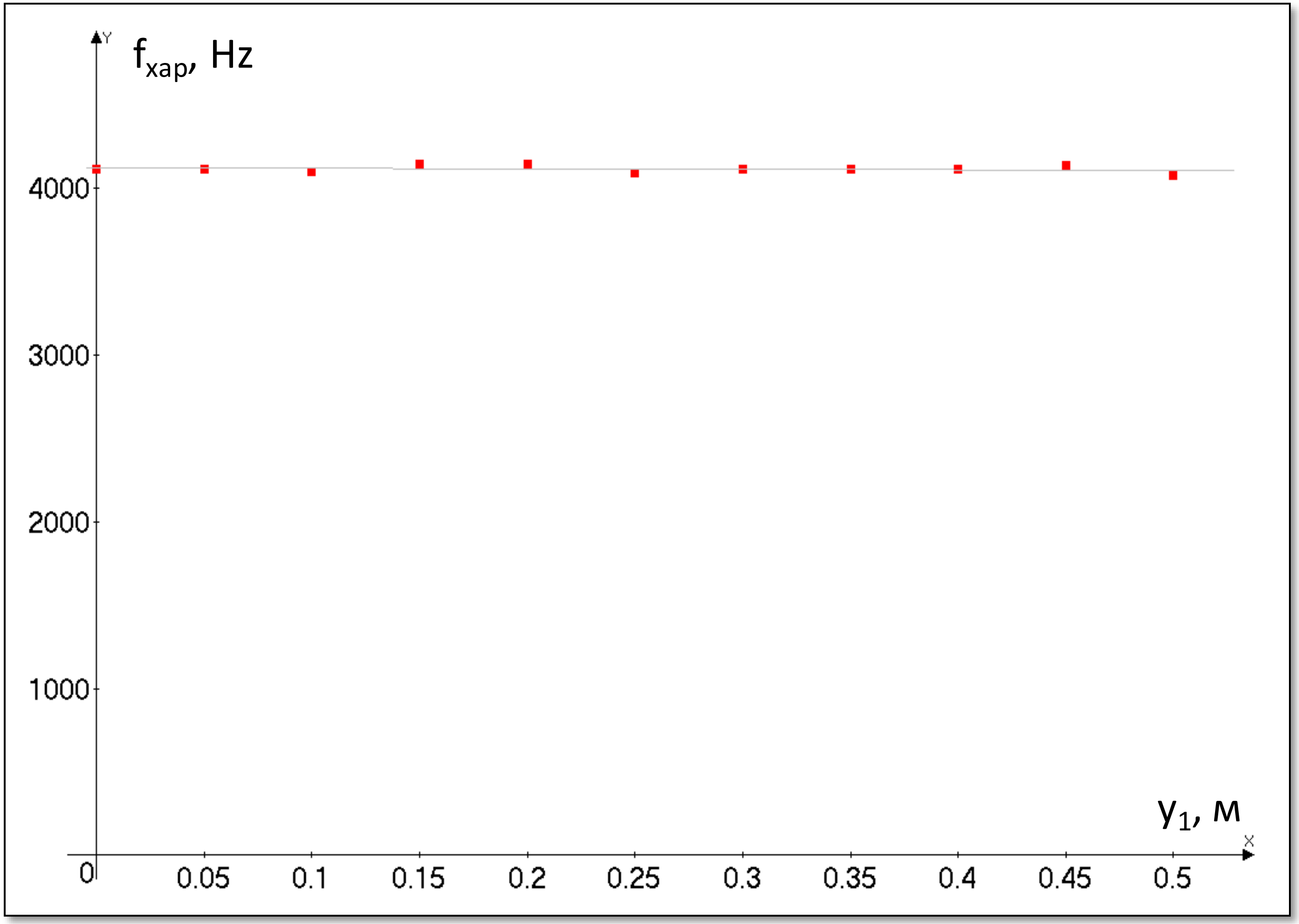
The dependence of the characteristic frequency on the position of the listener



The coordinate y1 does not change the relative frequency distribution - it only determines the overall level of the spectrum. Can be described as the distance to the plane of rotation

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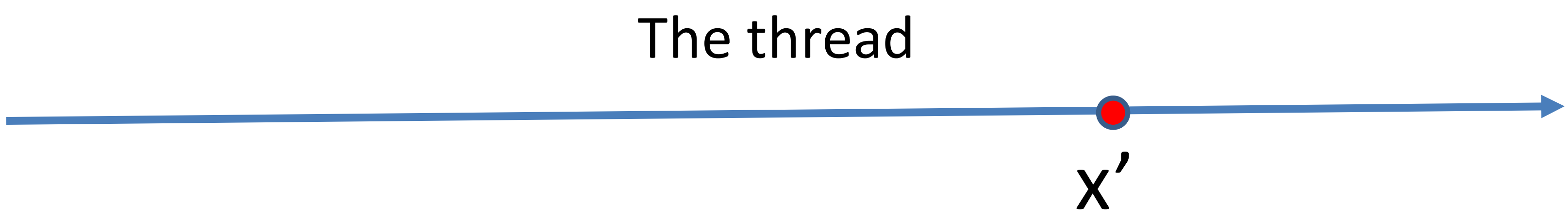
The distance from the thread to the listener



Distance to the listener

$$r = \sqrt{\Delta x^2 + \Delta y^2 + \Delta x^2} = \sqrt{x_1^2 + y_1^2 + z_1^2 + x'^2_1 - 2x'(x_1 \sin(\phi) + z_1 \cos(\phi))}$$

$$[\phi = 2\pi f_0 t]$$

$$r(t) = \sqrt{x_1^2 + y_1^2 + z_1^2 + x'^2_1 - 2x'(x_1 \sin(2\pi f_0 t) + z_1 \cos(2\pi f_0 t))}$$

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Spectrum and the intensity

$$f(x') = St \cdot w_0 \frac{x'}{d}$$

$$G(f) = \frac{dI}{df} \quad \Rightarrow \quad G(f,t) = \frac{dI}{dx'}\frac{dx'}{df} = \frac{dI(t)}{dx'}\frac{d}{St \cdot w_0}$$

$$\left[\quad \frac{\partial I(x',t)}{\partial x'} = \frac{\partial I(\frac{fd}{St \cdot w_0},t)}{\partial(\frac{fd}{St \cdot w_0})} \quad \right]$$

$$G(f) = \frac{kC}{8}\rho w_0^3 d \frac{(\frac{fd}{St \cdot w_0})^3}{r^2(\frac{fd}{St \cdot w_0},t)}$$

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The spectrum and the sound pressure

The mathematical definition of the inverse Fourier transform

$$p(t) = \int_0^\infty A(f)\cos(2\pi f \cdot t + \varphi(f))df$$

$$A(f) \sim \sqrt{G(f)} \qquad f_{\min} = St \cdot \frac{2\pi f_0 a}{d} \qquad f_{\max} = St \cdot \frac{2\pi f_0 l}{d}$$

$$p(t) = \int_{f_{\min}}^{f_{\max}} \alpha\sqrt{G(f)}\cos(2\pi(f + \Delta f)\cdot t + \varphi(f))df$$

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Maximum possible frequency

$$f = St \cdot \frac{v}{d}$$

$$\mathrm{Re} = \frac{\rho d v}{\eta}$$

$$\mathrm{Re} = \mathrm{Re}_{cr}$$

$$f_{\max} = St \cdot \mathrm{Re}_{cr} \cdot \frac{\eta}{\rho d^2}$$

$[d = 1cm]$, $f_{max} = 6{,}7\ kHz$

$$\mathrm{Re}_{cr} = \frac{2\pi f_0 l \rho d}{\eta}$$

$f_0 = 15Hz$

$l = 3m$

$$d_{\max} = 1cm!!!$$

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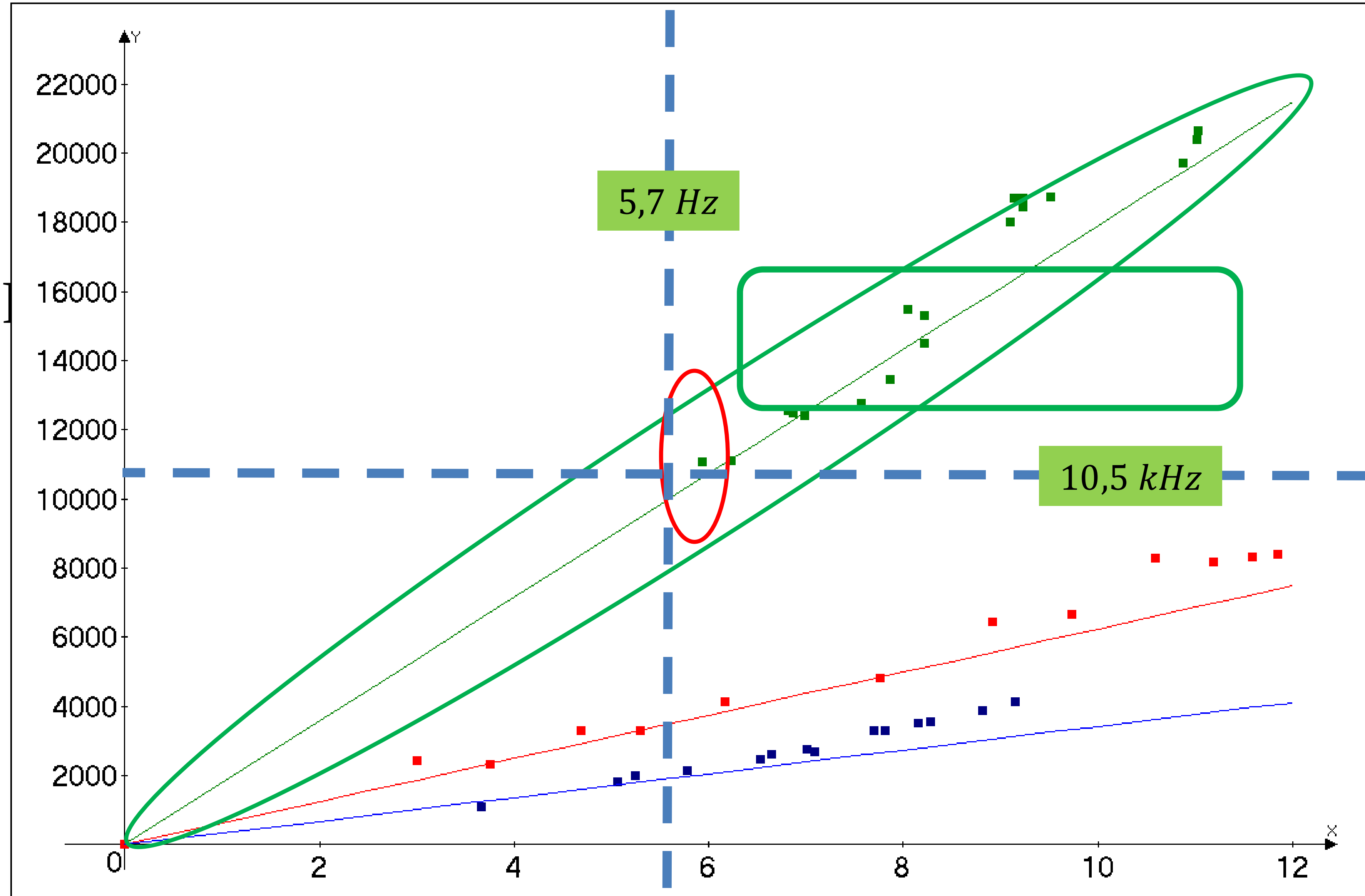
Minimum possible frequency



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Consideration of the thread oscillation

$$f = f_0\sqrt{(n-1)(2n+1)}$$

Sound power level decreases with each harmonic

$P(f)$ is a decreasing function

The first five frequencies :

$$f_{10} = 0\,f_0 \qquad = 0Hz$$
$$f_{11} = 2{,}236\,f_0 = 26.832Hz$$
$$f_{12} = 3{,}742\,f_0 = 44.904Hz$$
$$f_{13} = 5{,}196\,f_0 = 62.352Hz$$
$$f_{14} = 6{,}633\,f_0 = 79.596Hz$$

F. Morse. "Vibrations and Sound"

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Possible errors and their reasons

The errors

- The linearity of the dependences
- The deviation from the theoretical frequencies
- The differences between the spectrums

Possible reasons

- The considered functions can be nonlinear
- Imperfect software algorithms for the Fourier series
- The smallness of the time period for averaging the spectrum
- Frequency response of the microphone has a complicated form
- Background noises and interferences
- Random errors

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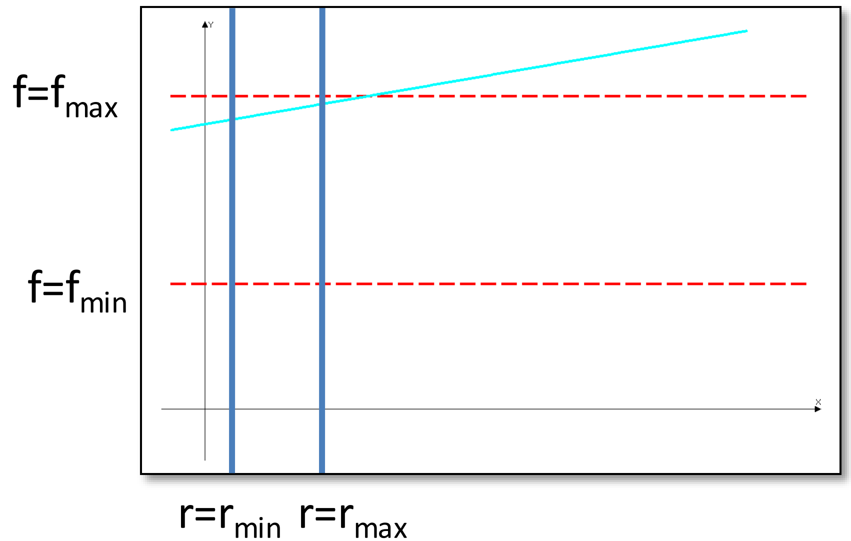
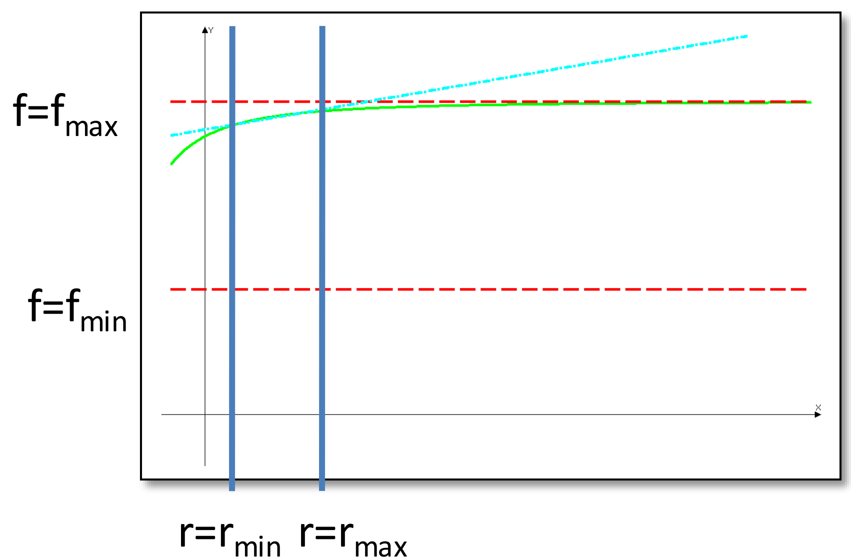
Mathematical properties of the characteristic frequency

- Experimentally, it is fetched only on a short distance from the thread;
- Theoretically, will approach the maximum frequency as $r \to \infty$;





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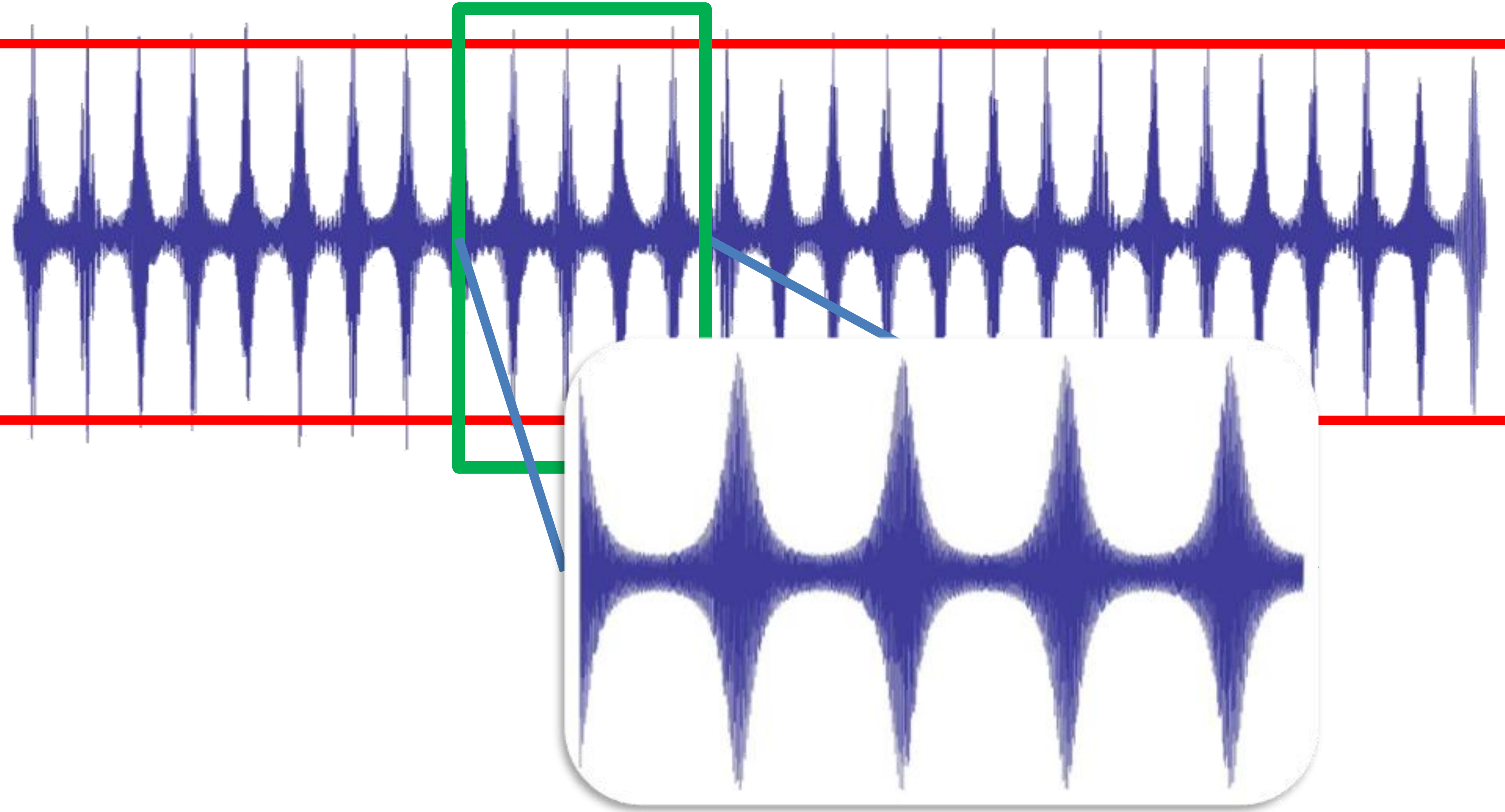
Errors of calculating



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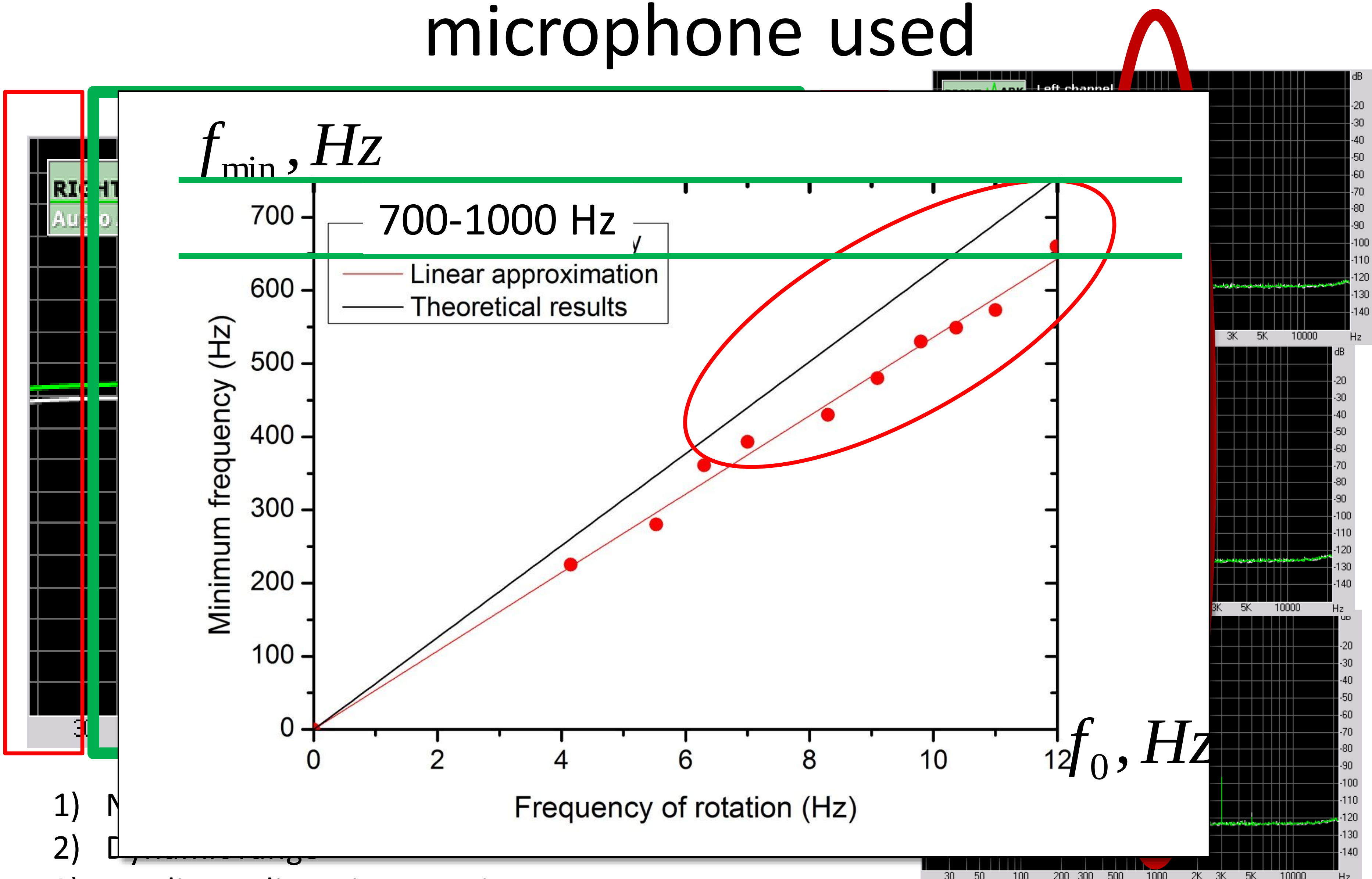
Frequency response of the microphone used



1) N
2) D
3) Nonlinear distortions + noise

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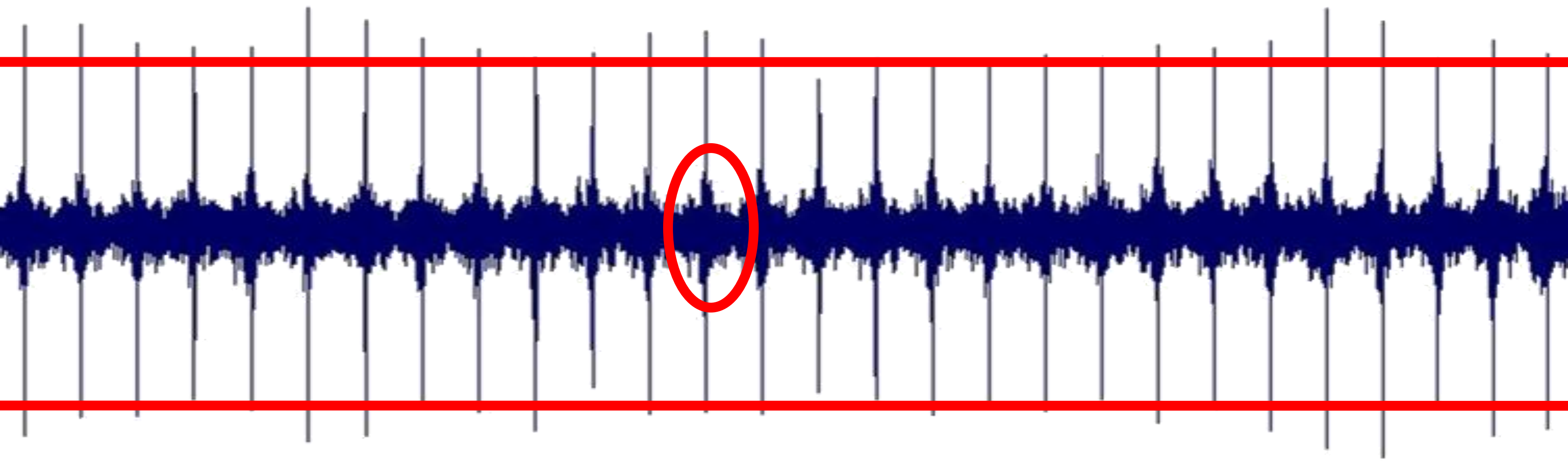
Errors of recording



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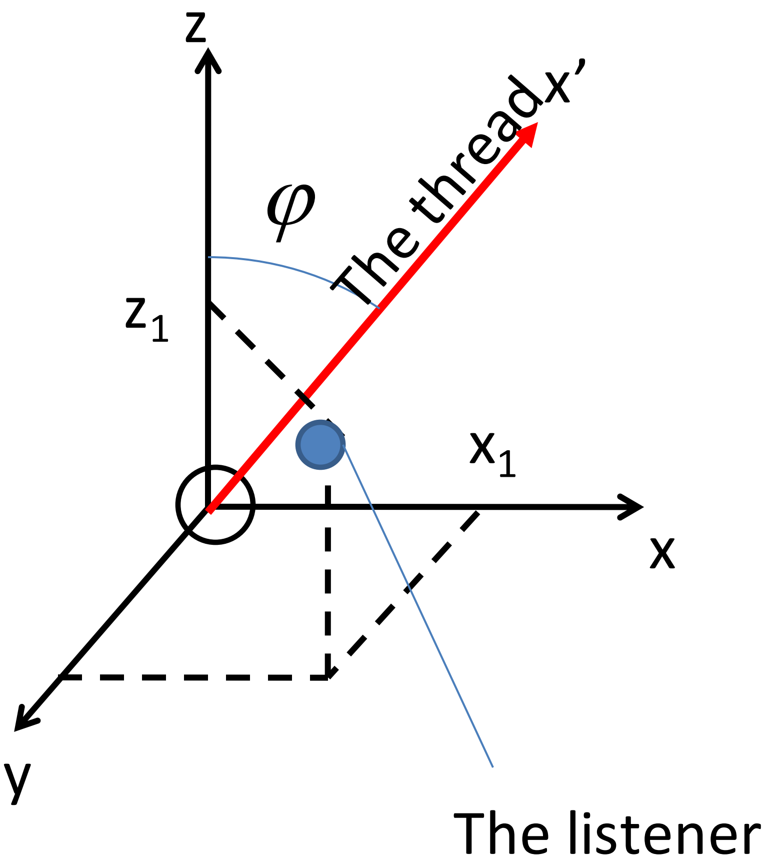
The coordinate system



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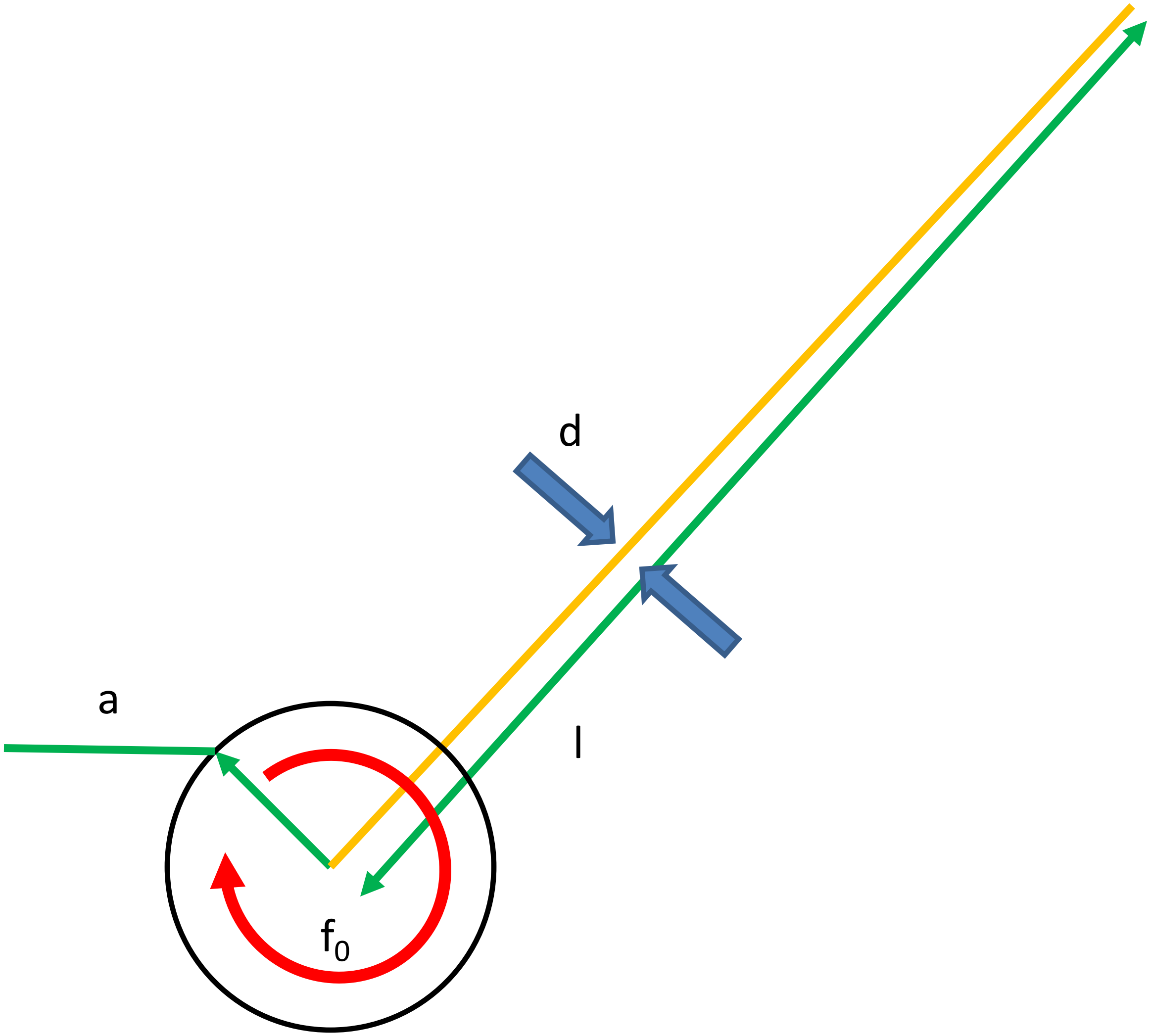
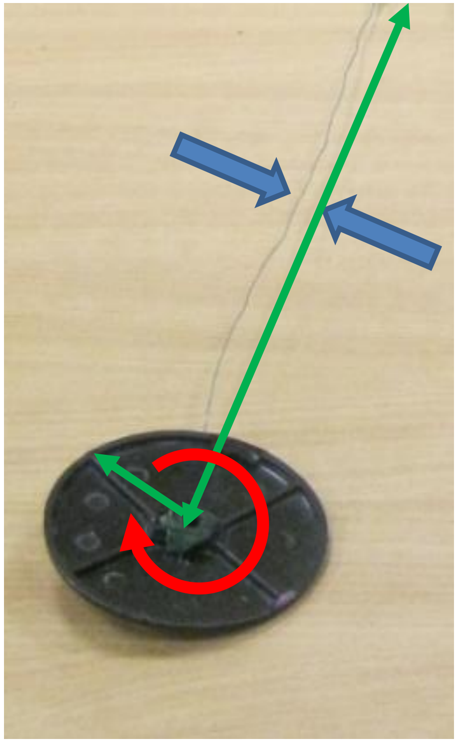
Parameters of the thread and rotation





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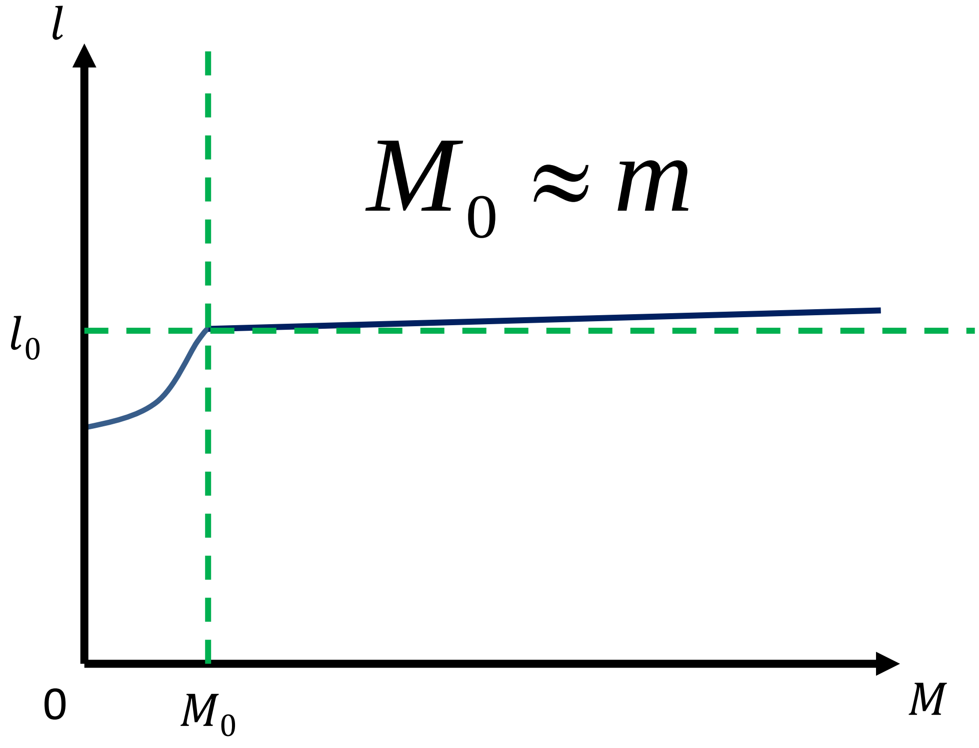
The influence of the bob

1. The influence of the thread tension
2. The influence of the straightening



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The Strouhal equation