Basic idea

- The substructure consists of ribs of powder normal to stream direction
- The ribs are formed due to vortices of the size of the distance between the ribs, which we have observed with a very fine powder
- The vortices form because of:
    - alternating air current in the tube
    - air boundary layer adherence (viscosity)

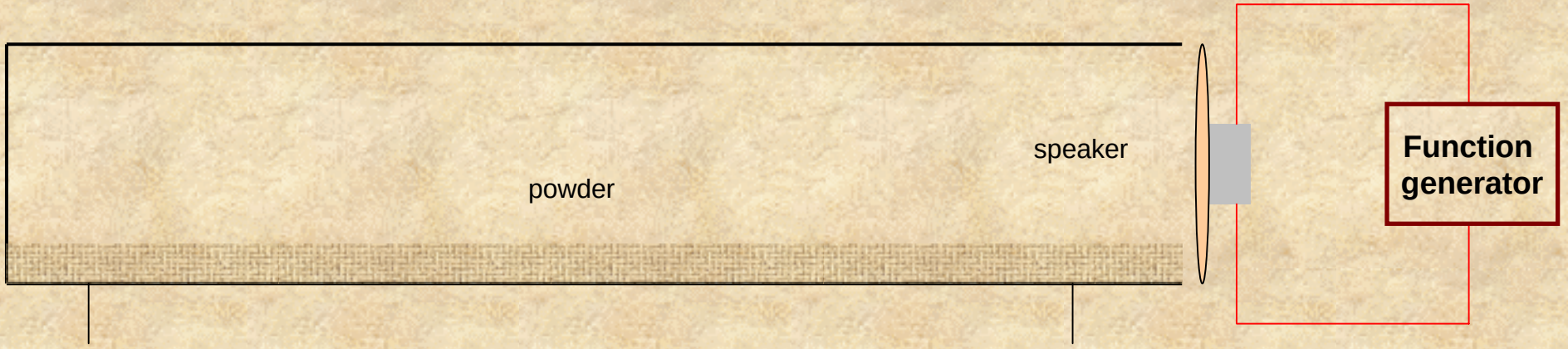
Experimental approach

- Parameters:
  - Tube dimensions (lenght, radius)
  - Sound intensity
  - Sound frequency
  - Powder material
- Measured quantities:
  - Distance between the ribs
  - Number of ribs

Apparatus

- To obtain standing waves in the tube we used two sound sources:
  - Speaker
  - An aluminium rod

Apparatus shematic:



Apparatus cont.

The function generator

The speaker (8Ω/50-20000Hz)

- The greatest advantage of the speaker is the posibility of observing the standing structures

Structure characteristics

- The ribs are highest at the pressure nodes

- The distance between the ribs is getting smaller with increasing frequency
- The ribs appear only at resonance frequencies of the tube
- The structures are very regular to a certain sound intensity, above which turbulences occur

Turbulent streaming in the tube

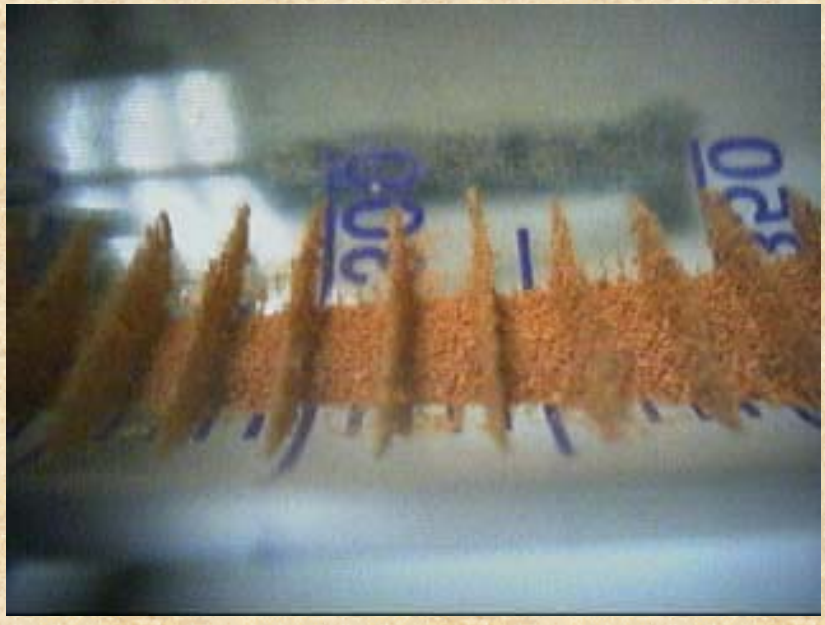
- The ribs can be very high and thin (sometimes just one layer of particles)

- There is continued transport of material between the ribs

- If a very fine powder is used (eg. carbo animalis) vortex motion can be seen

- At greater amplitudes of sound the particles levitate and spin because of the abrupt pressure changes

- With increasing frequency the height of the ribs decreases



Increasing frequency

- Several powders were applied for the rib formation:

1. Carbo animalis
   - Very light – enables seeing vortices
   - Usually wet

2. Cork powder
   - Not as light, but very dry
   - Gives best structures

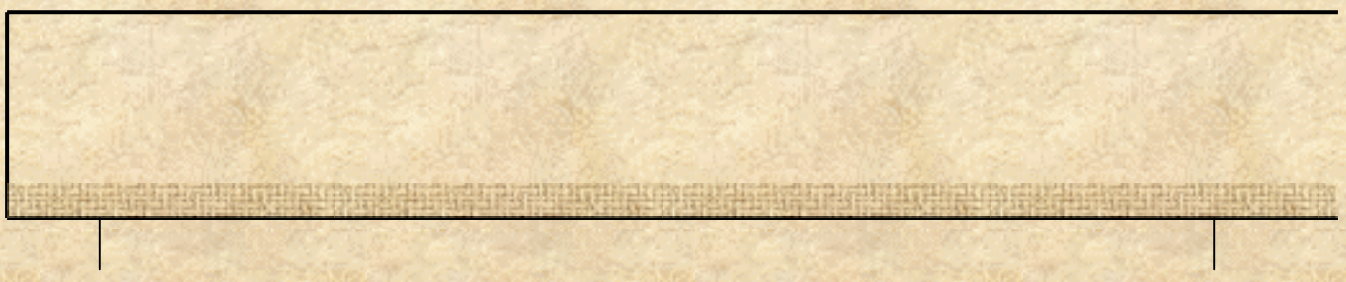
Explanation

- In the experiment vortex motion of carbo animalis was observed
- That proves that the cause of rib formation are air vortices
- An analogy between the Kund structures and sand ripples can be observed:

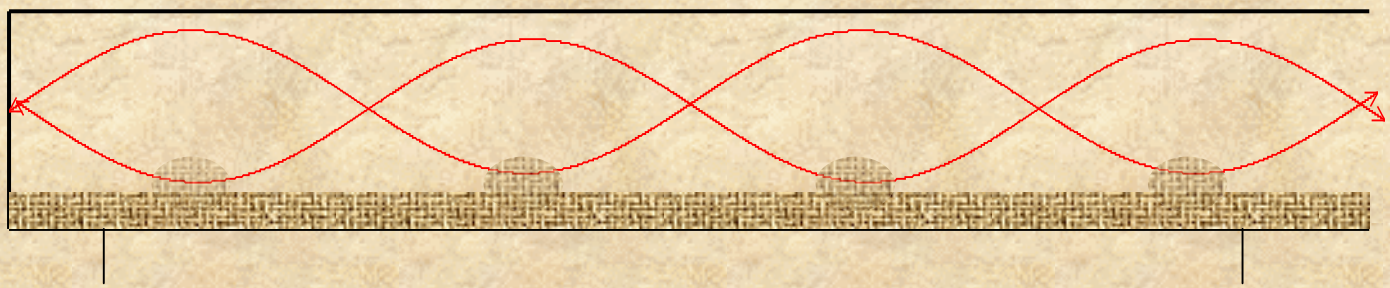
- The formation of vortices can be approached in phases:

1. phase

- In the beginning there is no air motion – the powder stands still

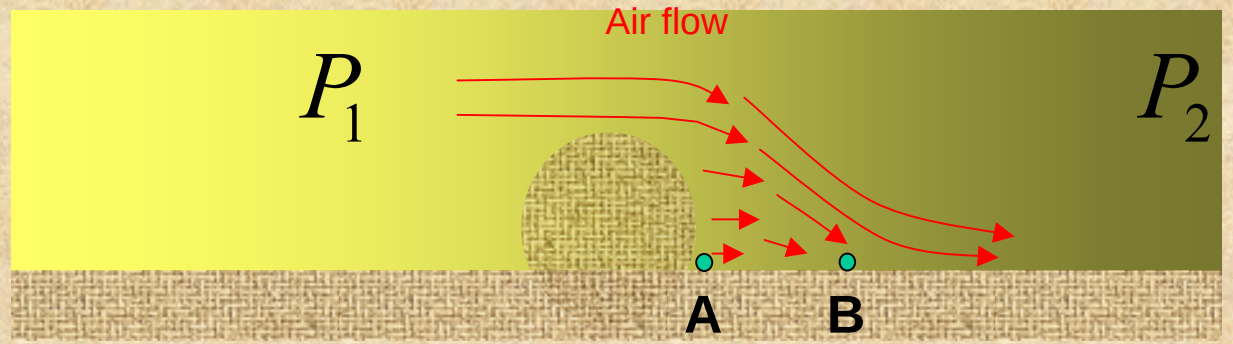


- The resonant frequency of the tube is played
- The powder will aggregate in heaps at the pressure nodes because of the currents



2. phase

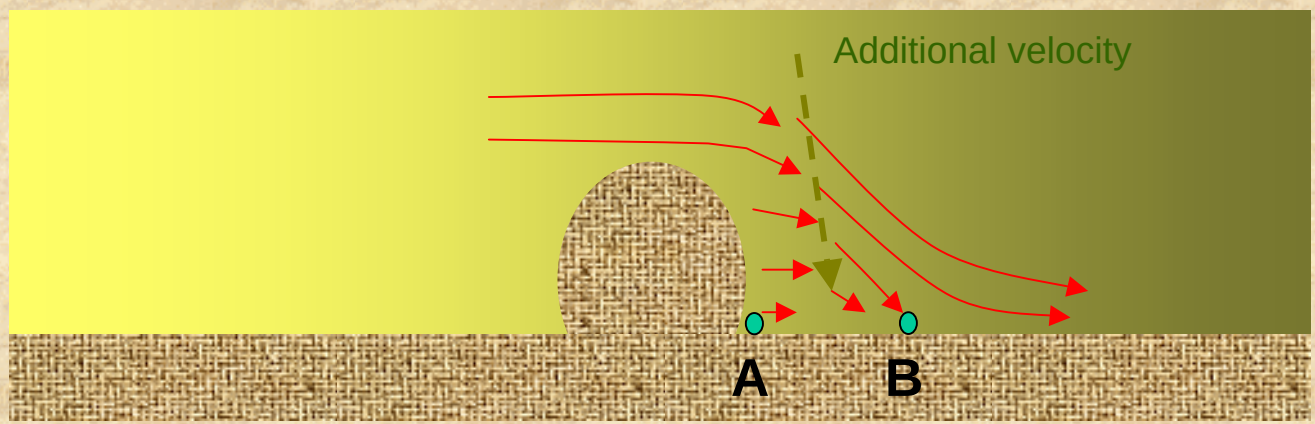
- The pressure on one side of a powder heap is greater then the pressure od the other side
- The air flows towards the lower pressure region:



P_i – pressures

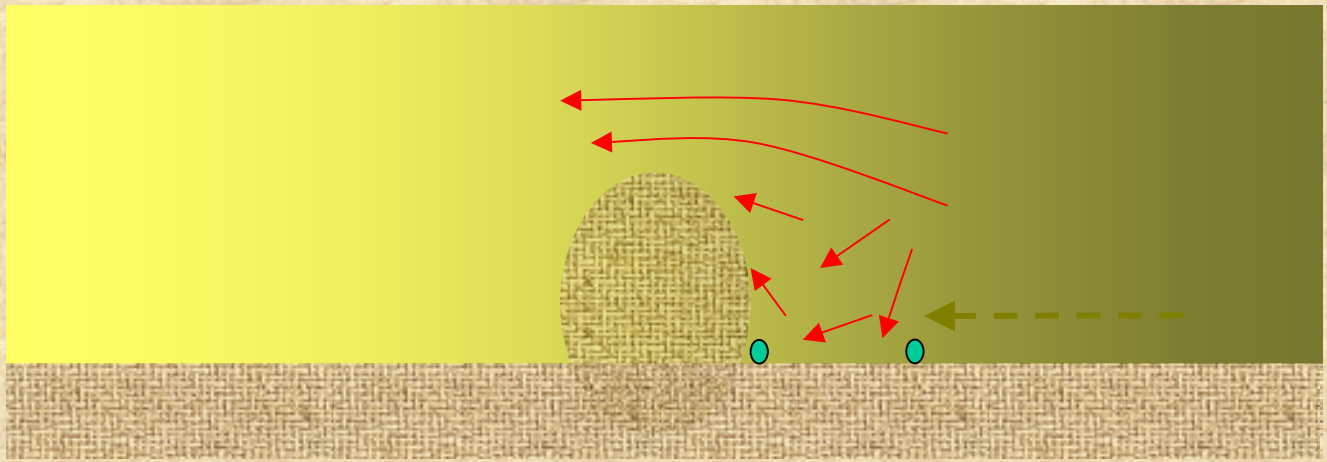
$$P_2 < P_1$$

- Because of friction between the fast air layer and the layer adherent to the powder the faster air drags the slower air lowering the pressure between the points **A** and **B**
- The pressure will be equalizing from above because of the greater pressure beyond the heap
- That means that the air gains additional downward velocity:



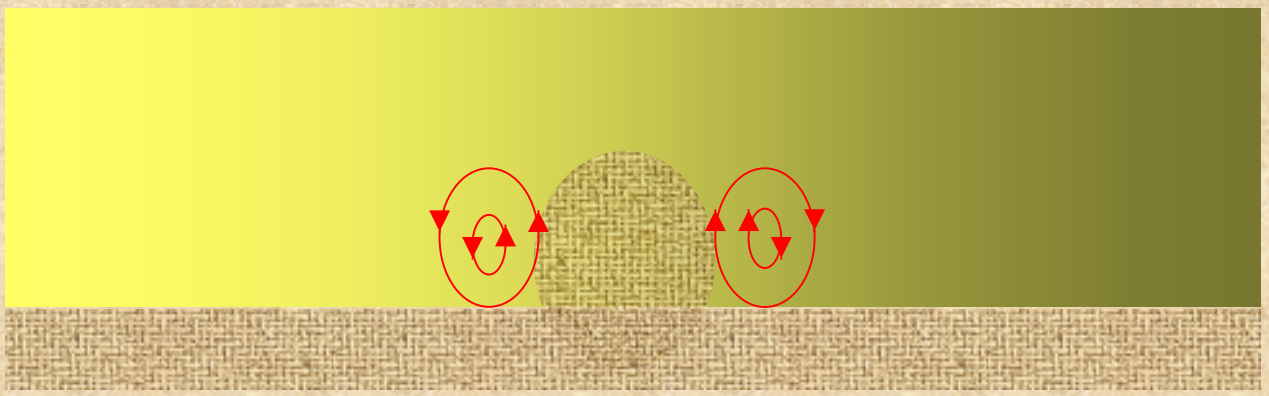
3. phase

- Now the current direction changes (the current is alternating) and the pressure gets greater on the other side
- The pressure is still equalizing, but now from downwards



- **Further time development**

- Because of the alternating current, phases 2. and 3. alternate
- This results in circular motion on both sides of the powder heap:



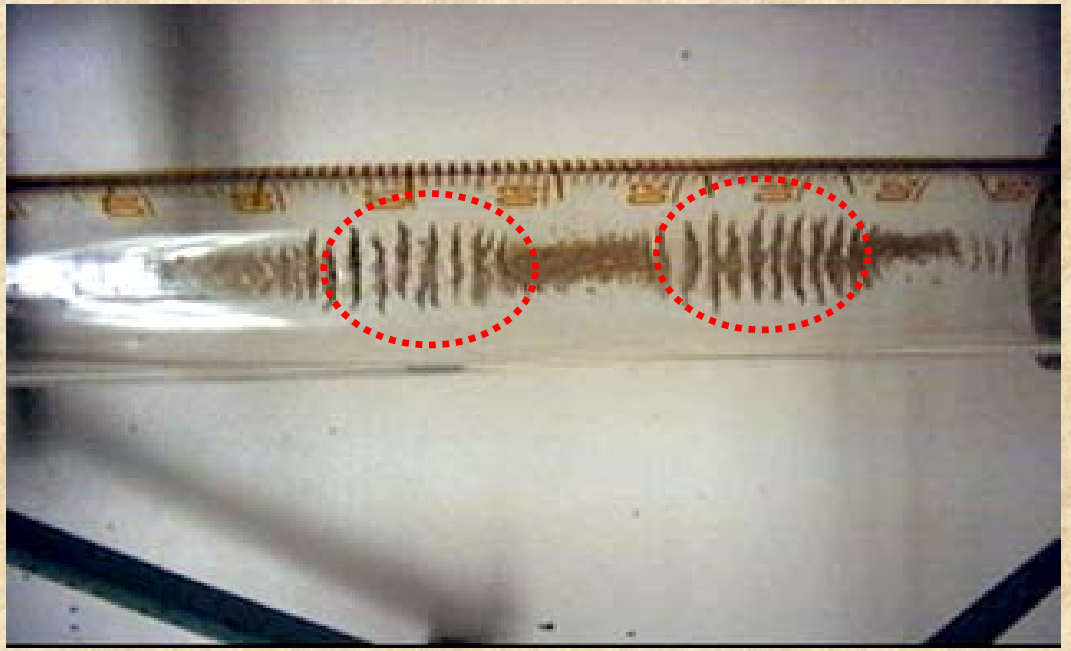
- The formed vortices will cause the occurence of new heaps and new vortices
- So the observed regular structures are formed

- If the air velocity increases, the flow will become more chaotic - turbulences
- Additional vortices and nonregular formations form
- This process can be beautifully observed

Regular structures
(low amplitude)

Turbulences
(high amplitude)

- The vortex intensity is proportional to flow velocity
- Thus the highest ribs are formed at the pressure nodes where the velocity is maximum



- At the velocity nodes there are no ribs because the air doesn’t move there

- The structures occur only at resonance frequencies because only then the sound intensity (and flow velocity) is large enough for vortex formation
- The distance between the ribs depends on frequency because of simple energy and angular momentum conservation:
    - With increasing frequency the air velocity also increases
    - This means that the vortices spin faster

- Angular momentum conservation:

$$\omega_0 r_0^2 = \omega r^2$$

$$\omega \sim \upsilon$$

$$\Rightarrow r \sim r_0 \sqrt{\frac{\upsilon_0}{\upsilon}}$$

ω_0 – initial angular velocity

r_0 – initial vortex radius

ω – angular velocity at higher frequency

r – vortex radius at higher frequency

υ – sound frequency

- Comparison with the experimental data yelds:

Function fit: $r = a\upsilon^b$

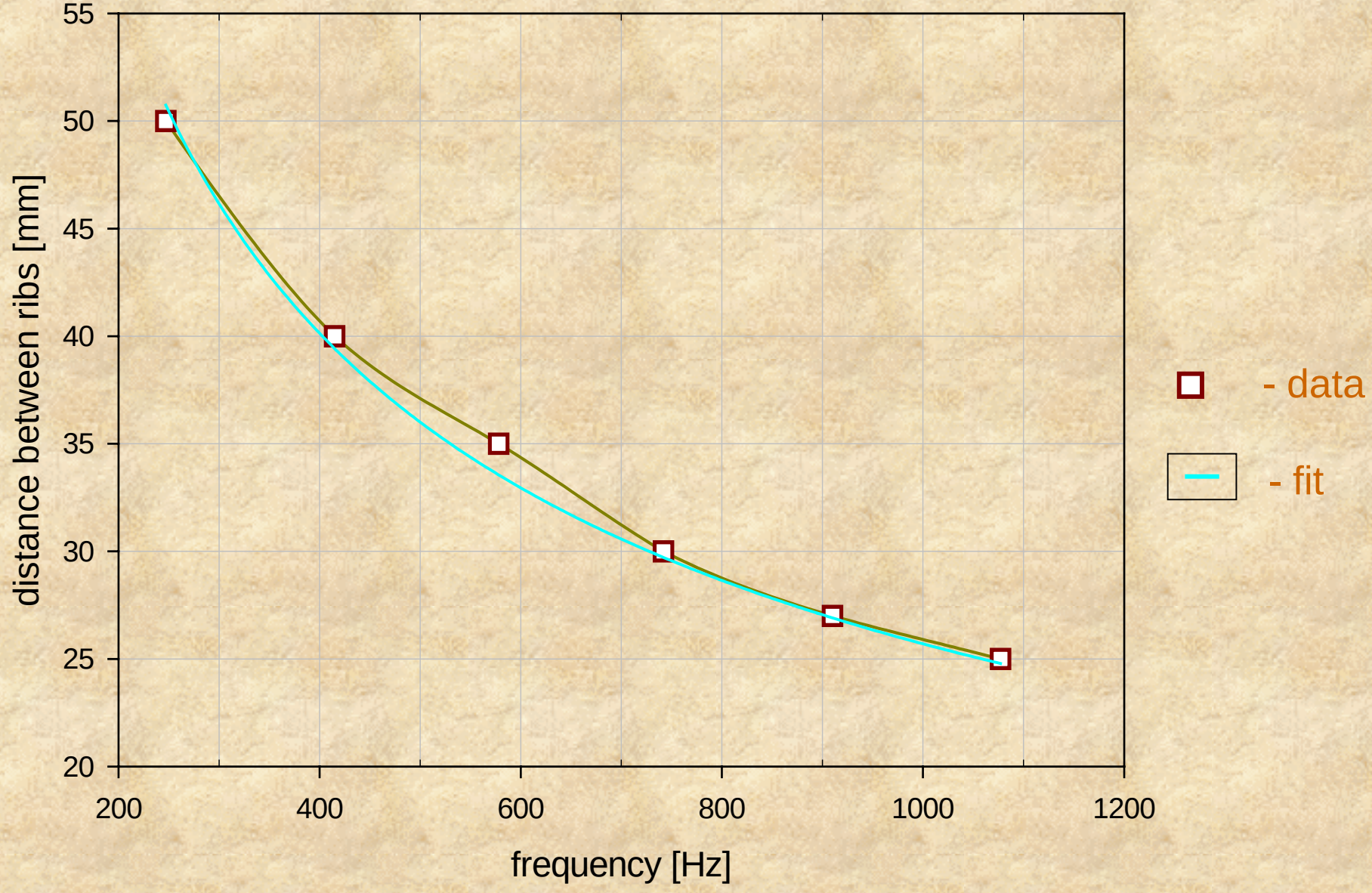
Determined parameters *a* and *b:*

$$b = -0.4864 \approx -0.5$$

as predicted!

$$a = 739{,}8268 \approx 740$$

- coefficient of proportionality


55
50
45
40
35
30
25
20
distance between ribs [mm]
200
400
600
800
1000
1200
frequency [Hz]
- data
- fit

Conclusion

- Cause of rib forming in Kundt's tube:

  Vortices formed by

  - The alternating air current
  - Adherent boudary layer of air
- Proof:
  - Vortices detected experimentally
  - The theory gives a correct prediction of the variaton of rib distance with frequency of emmited sound