The acoustics of organs and other wind instruments

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Image: Julien Bertrand, Public domain, via Wikimedia Commons

There are four main types of wind instrument

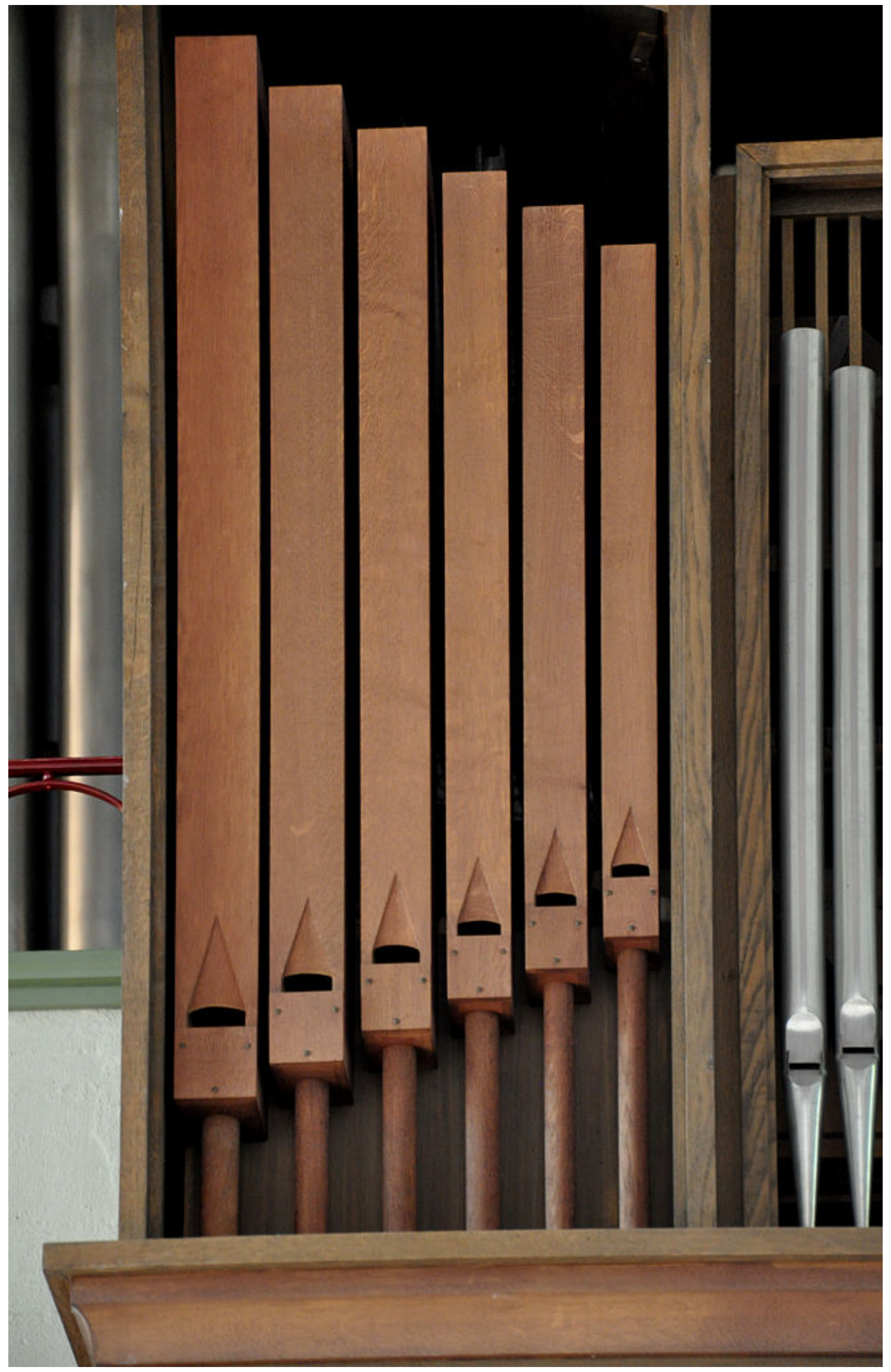
Reed instruments

Air-jet instruments

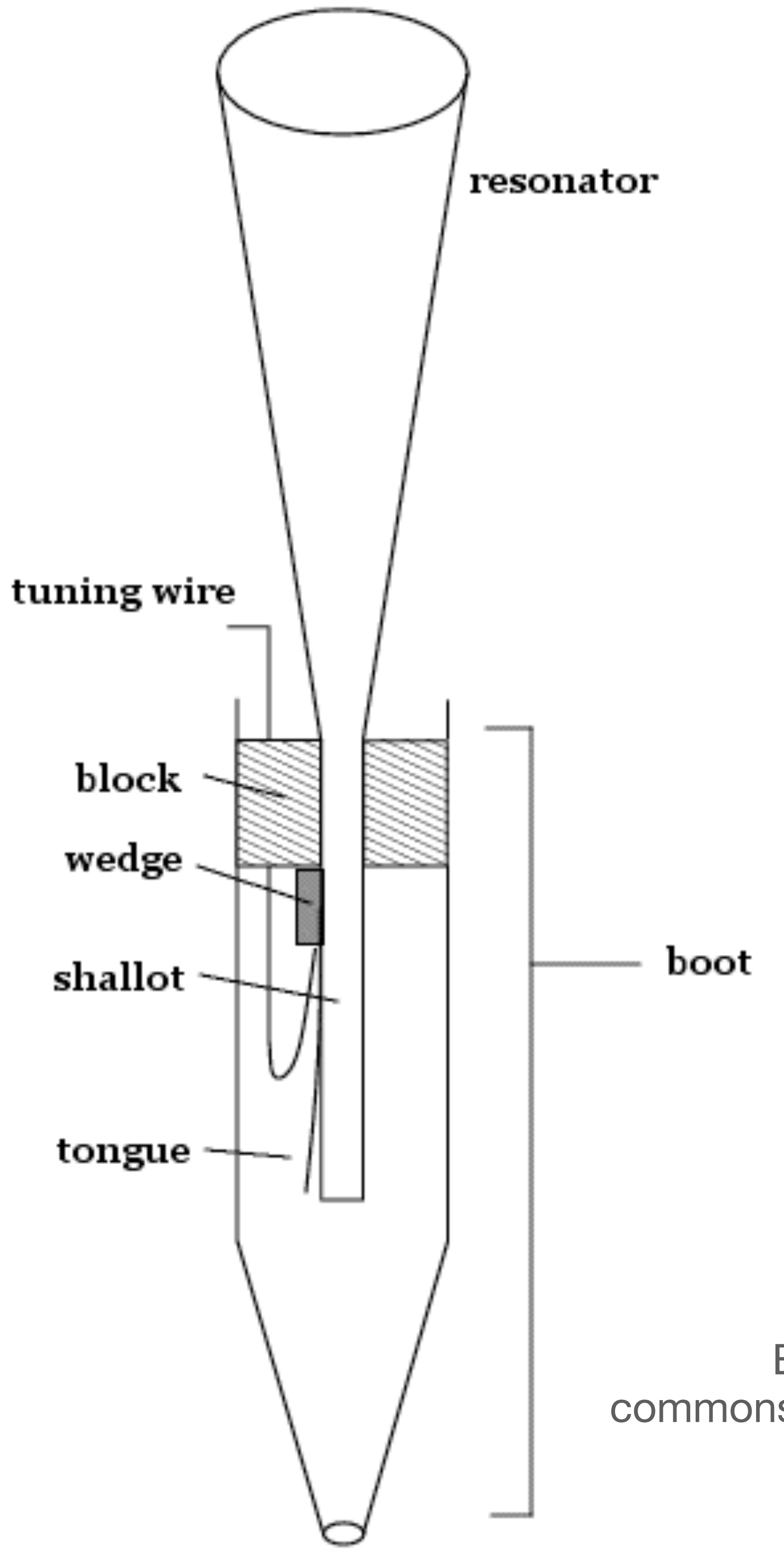
“Brass” instruments

Free-reed instruments

There are two main types of organ pipe



Flue pipes



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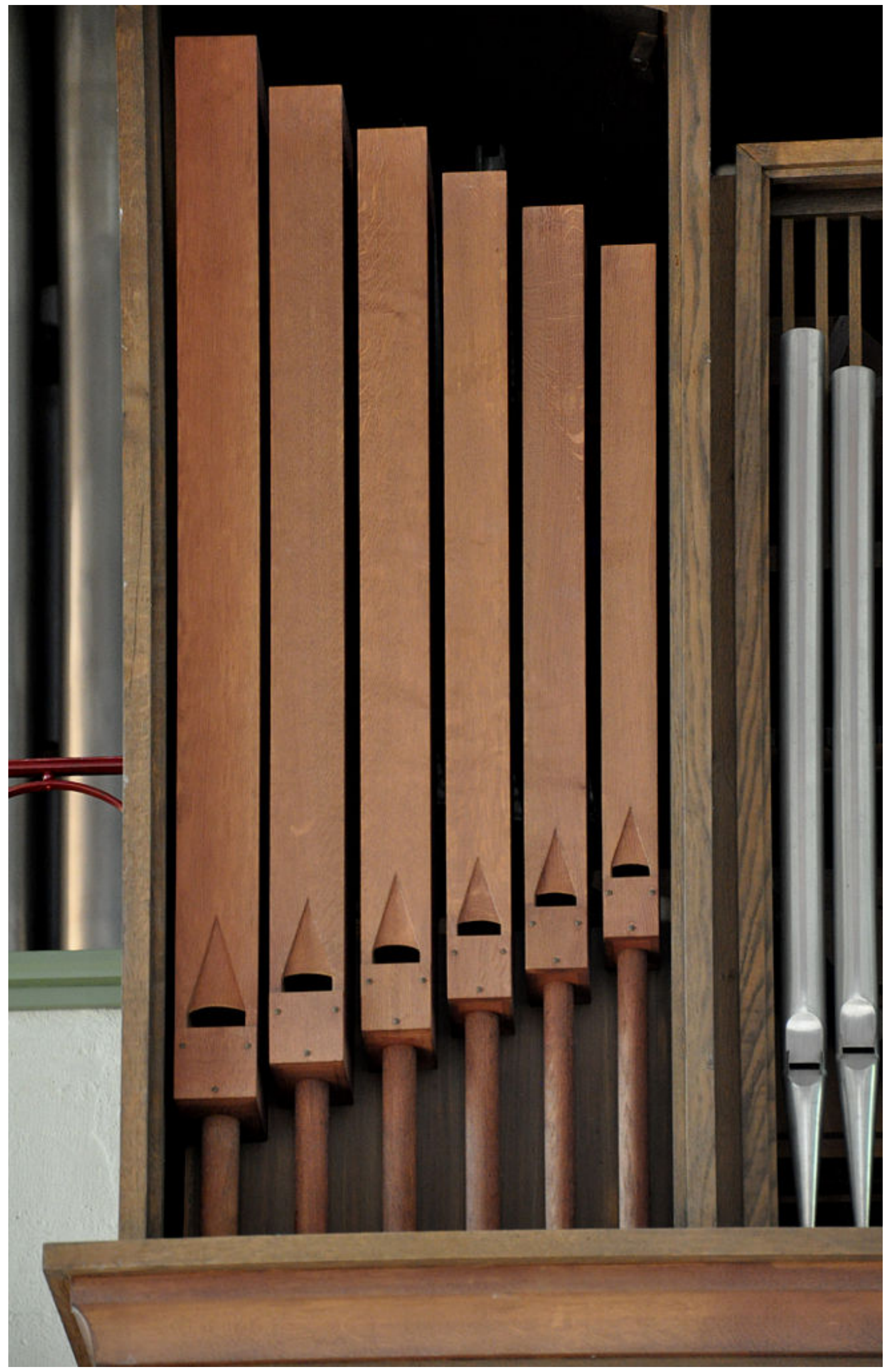
Reed pipes

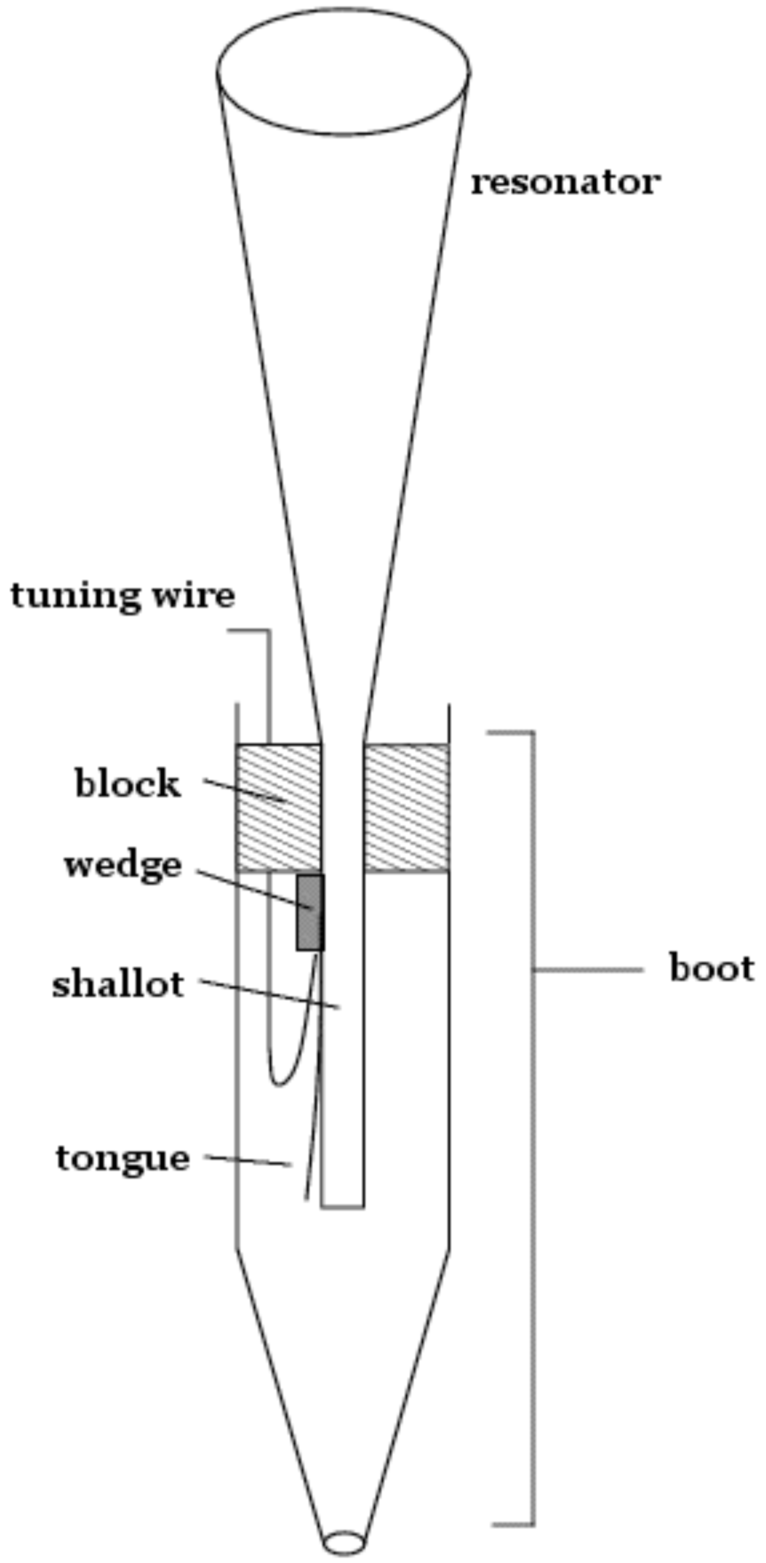
So how do these map on to the wind instrument family?

You might think they correspond to these two:

Air-jet instruments

Reed instruments





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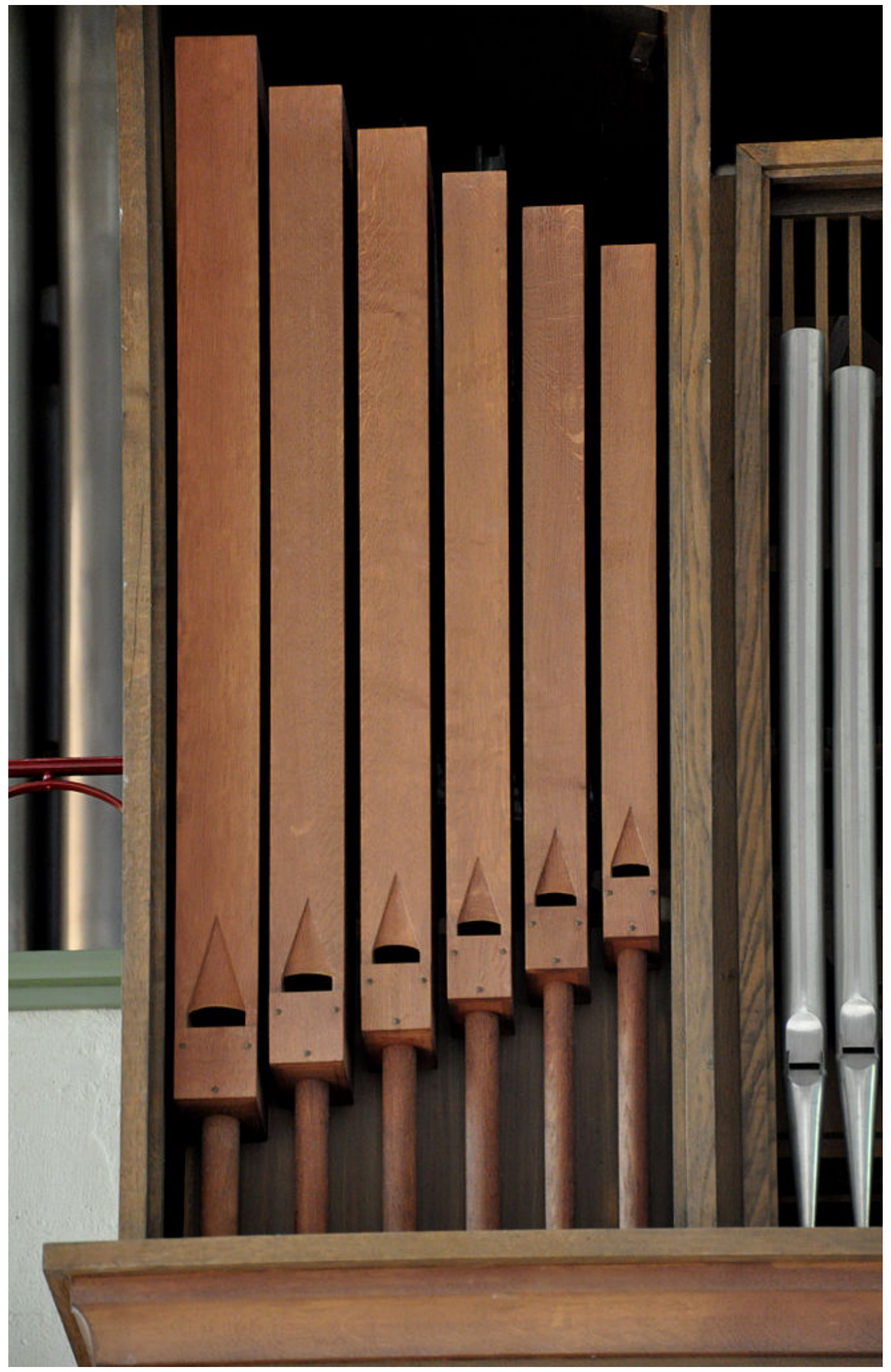
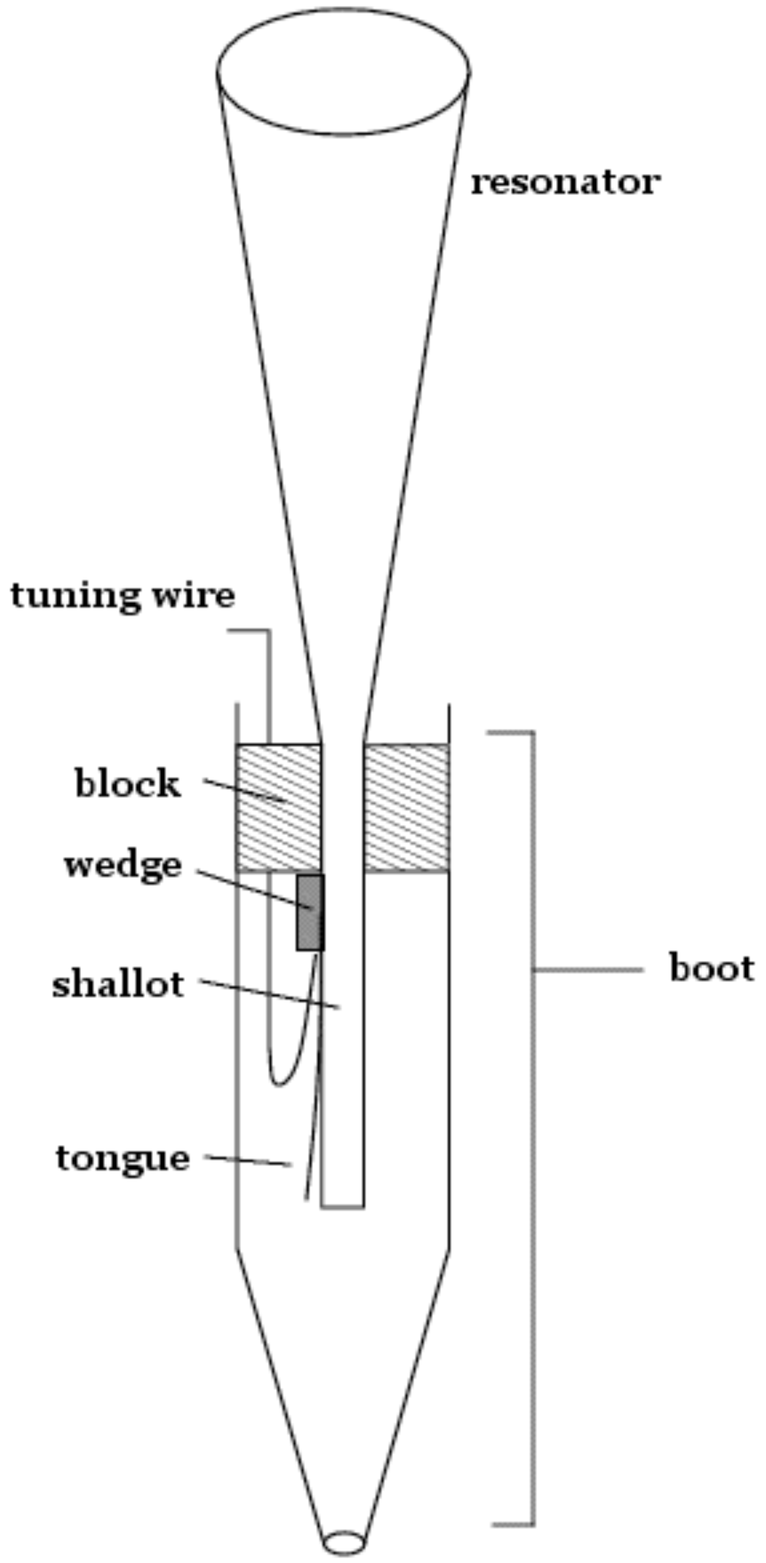




But to understand this we need to fill in some background…

Resonances in pipes

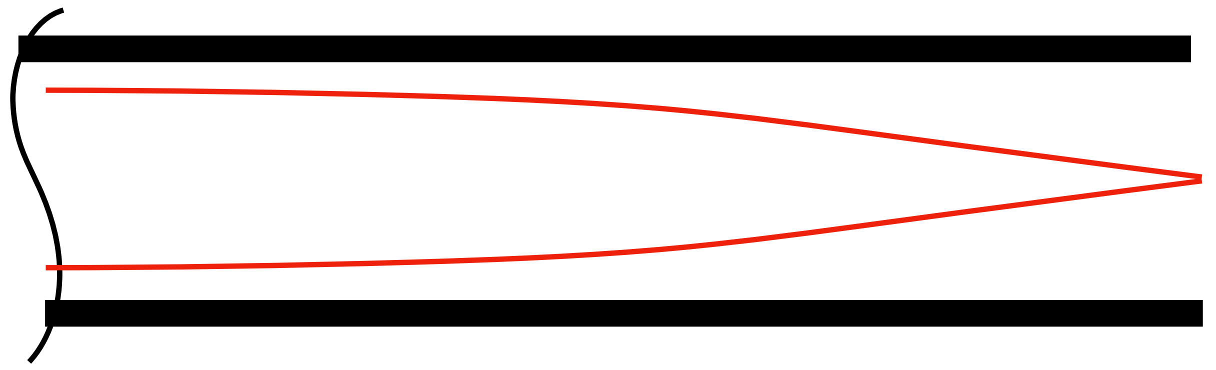
How air-jet instruments work

Orchestral reed instruments versus free reeds

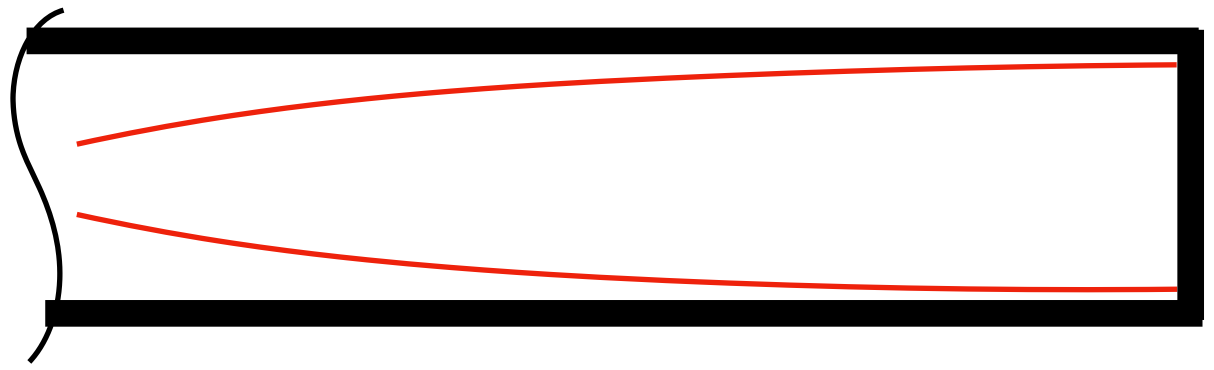
Resonances of straight pipes

What happens to sound waves at the end of a pipe?

If the end is open to the outside air, there must a nodal point of sound pressure

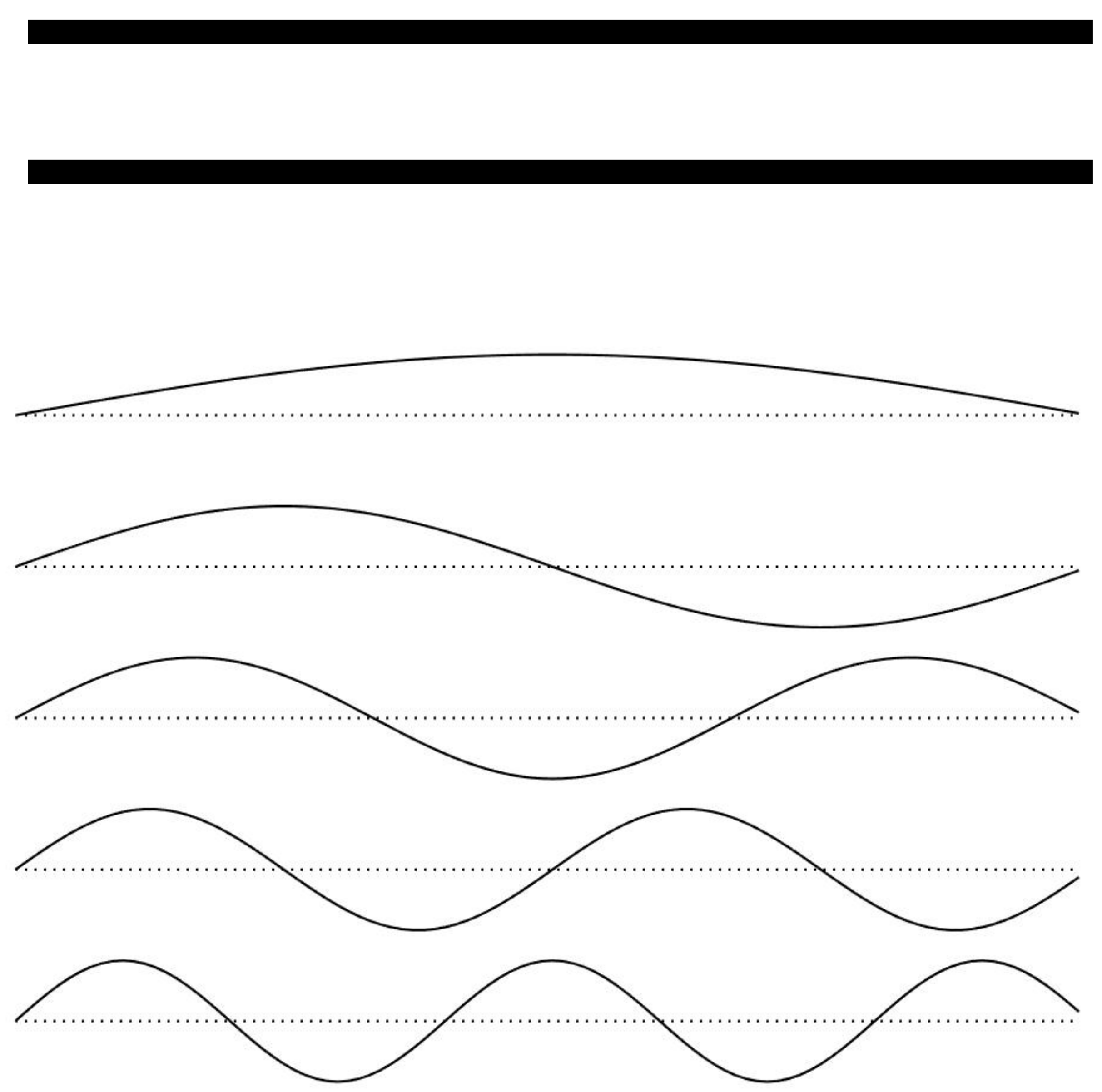


If the end is closed, there can be no air flow.
This means there must be an antinode of sound pressure



Resonances of straight pipes

Open at both ends:



Frequency ratios

1

2

3

4

5

A node of pressure at both ends

E.g. flute, open flue pipe

Resonances of straight pipes

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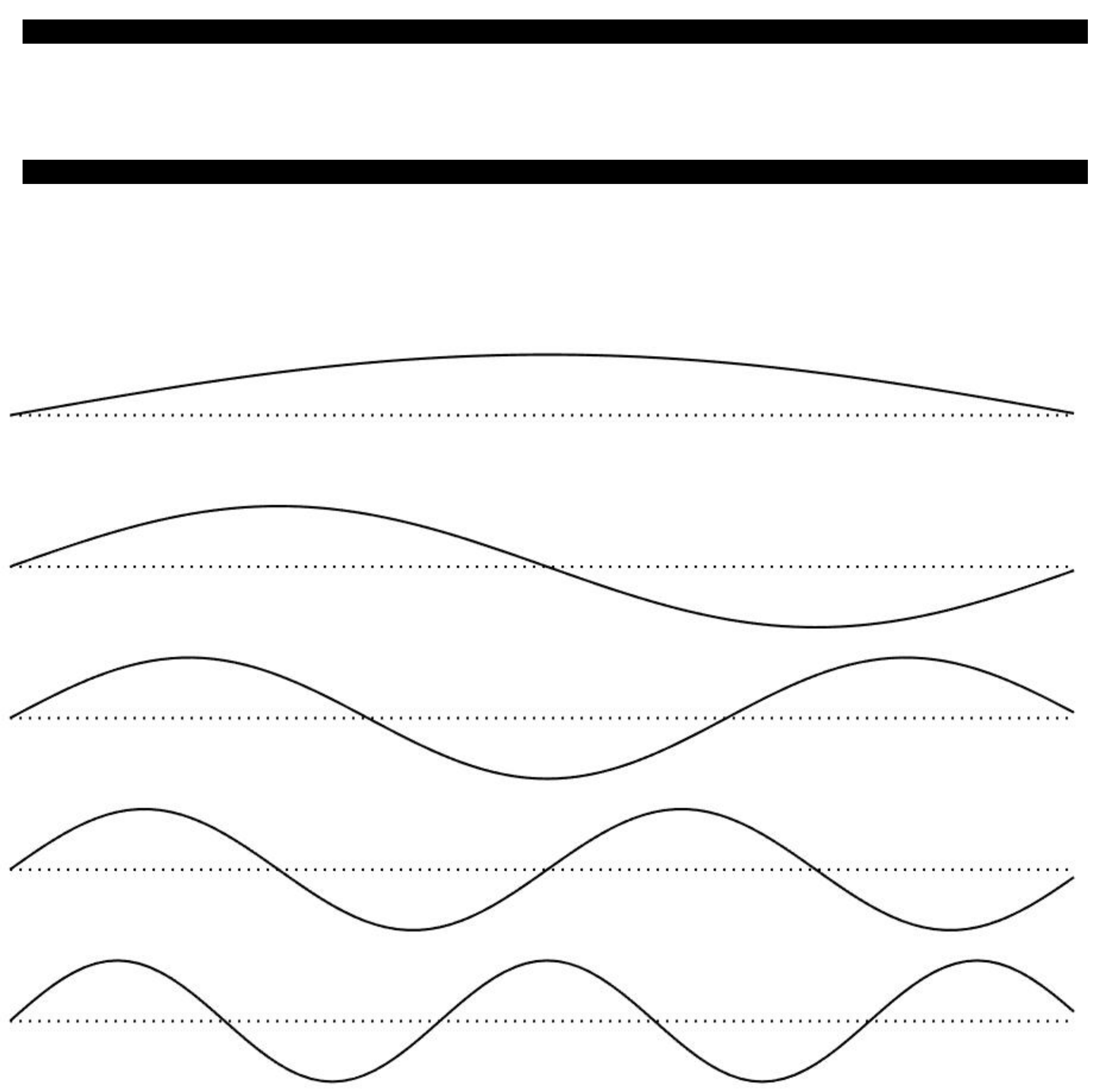

Frequency ratios

1
2
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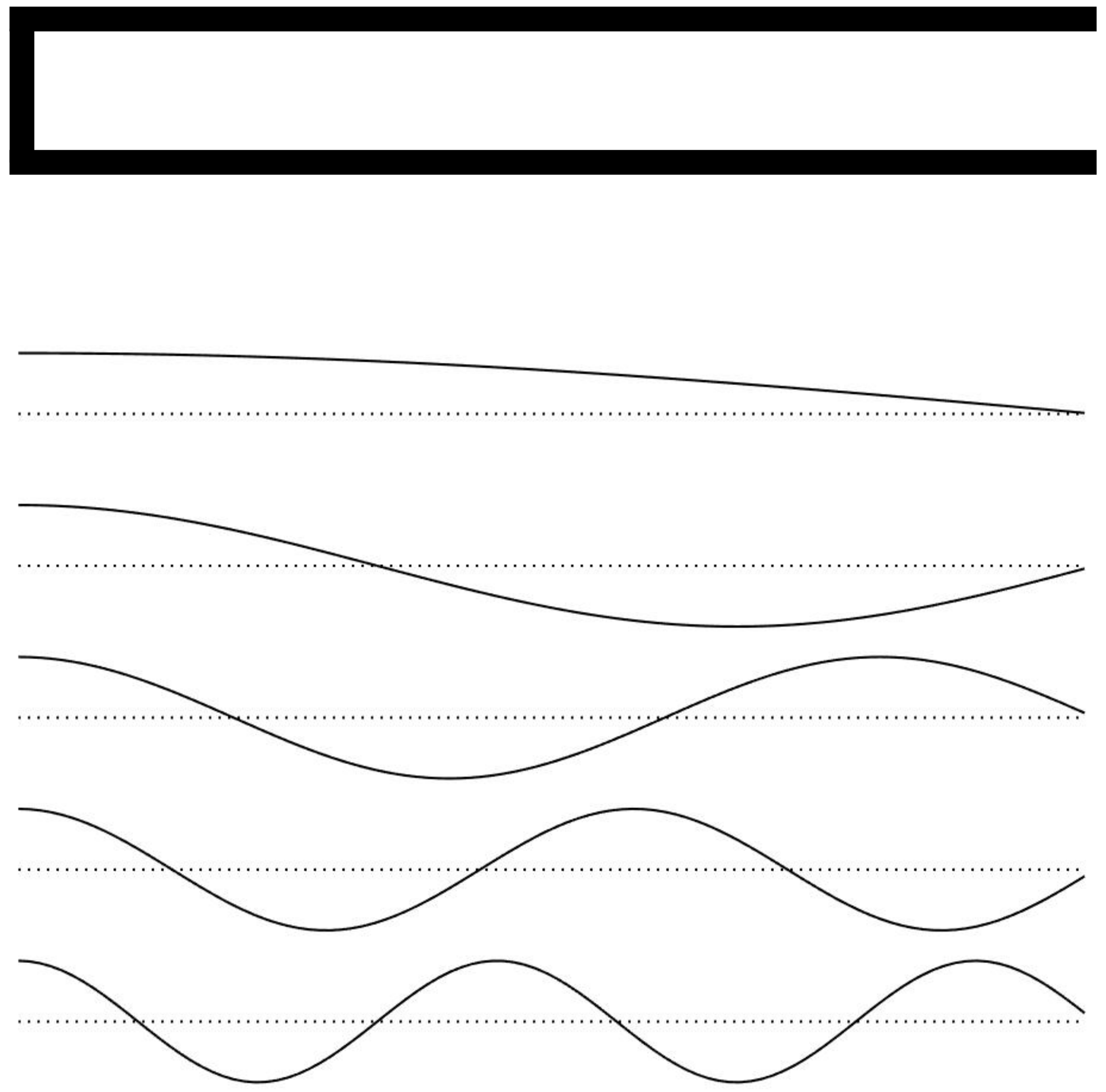
Closed at one end:



Frequency ratios

0.5 or 1
1.5 or 3
2.5 or 5
3.5 or 7
4.5 or 9

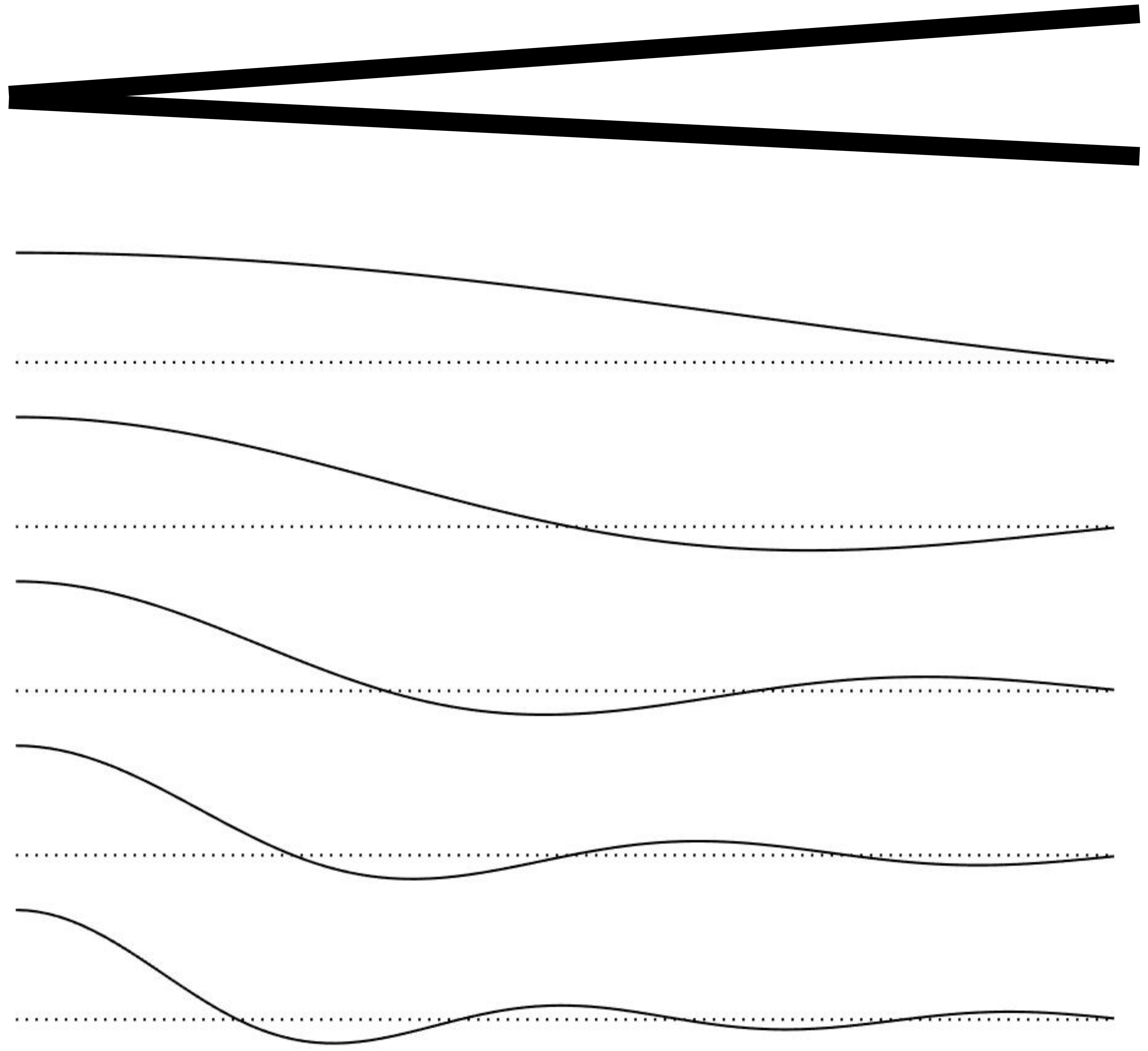
A node of pressure at both ends

E.g. flute, open flue pipe

An octave lower, for same length

E.g. clarinet, stopped flue pipe

Resonances of conical pipes



Frequency ratios

1

2

3

4

5

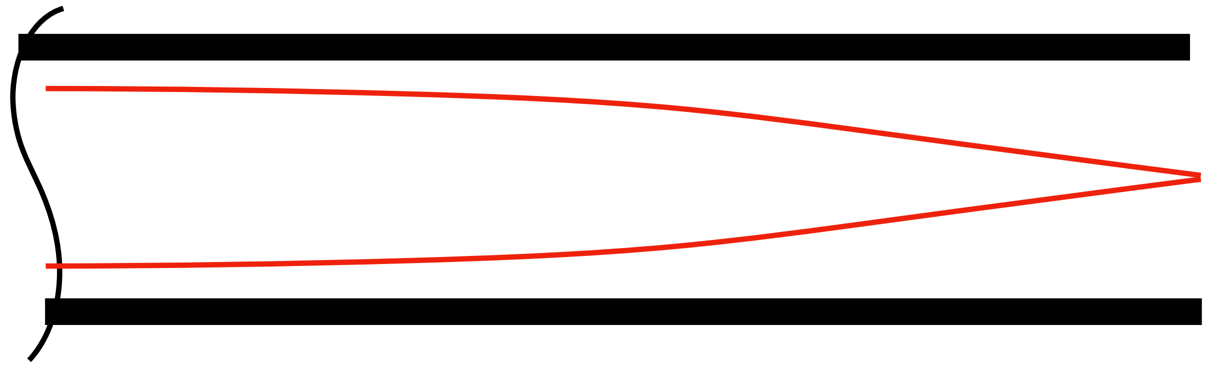
(Same as open-open straight tube of the same length)

E.g. oboe, saxophone

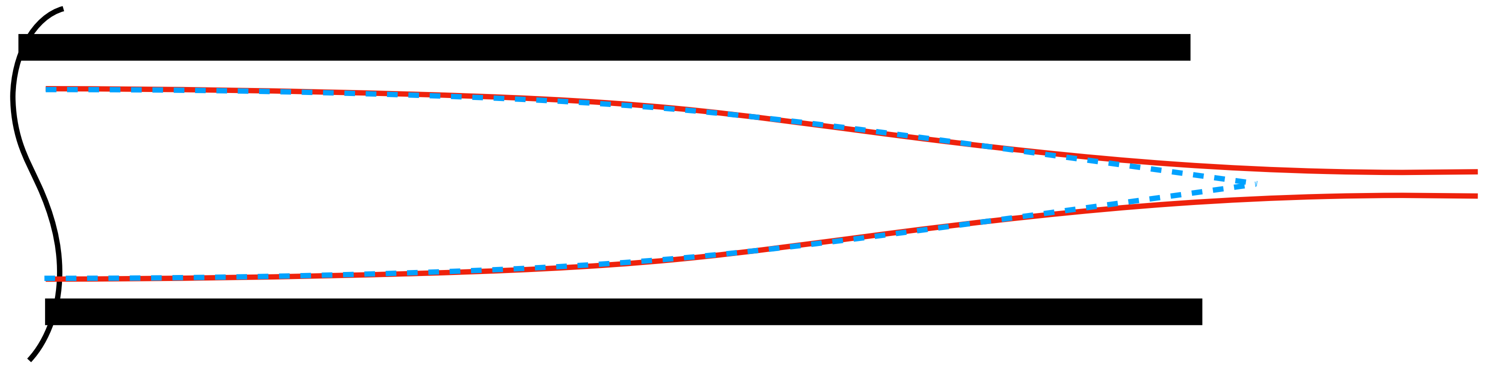
But it's a bit more complicated…

Where exactly does a pipe end?

Simplest theory has a node of pressure at an open end



But really the pressure fades away, just outside the end



The pressure wave behaves as if the pipe ended where the blue dotted lines meet.
This is just outside the pipe, by a distance that depends on the pipe radius.

The distance beyond the end is called the "end correction"

Flue pipes and air-jet instruments

Flutes, recorders, tin whistles, ocarinas, and flue organ pipes all work in the same way

A jet of air is directed towards a sharp edge

The jet is unstable

If there is an acoustic resonator nearby, the jet behaviour may “lock in” to the resonance frequency

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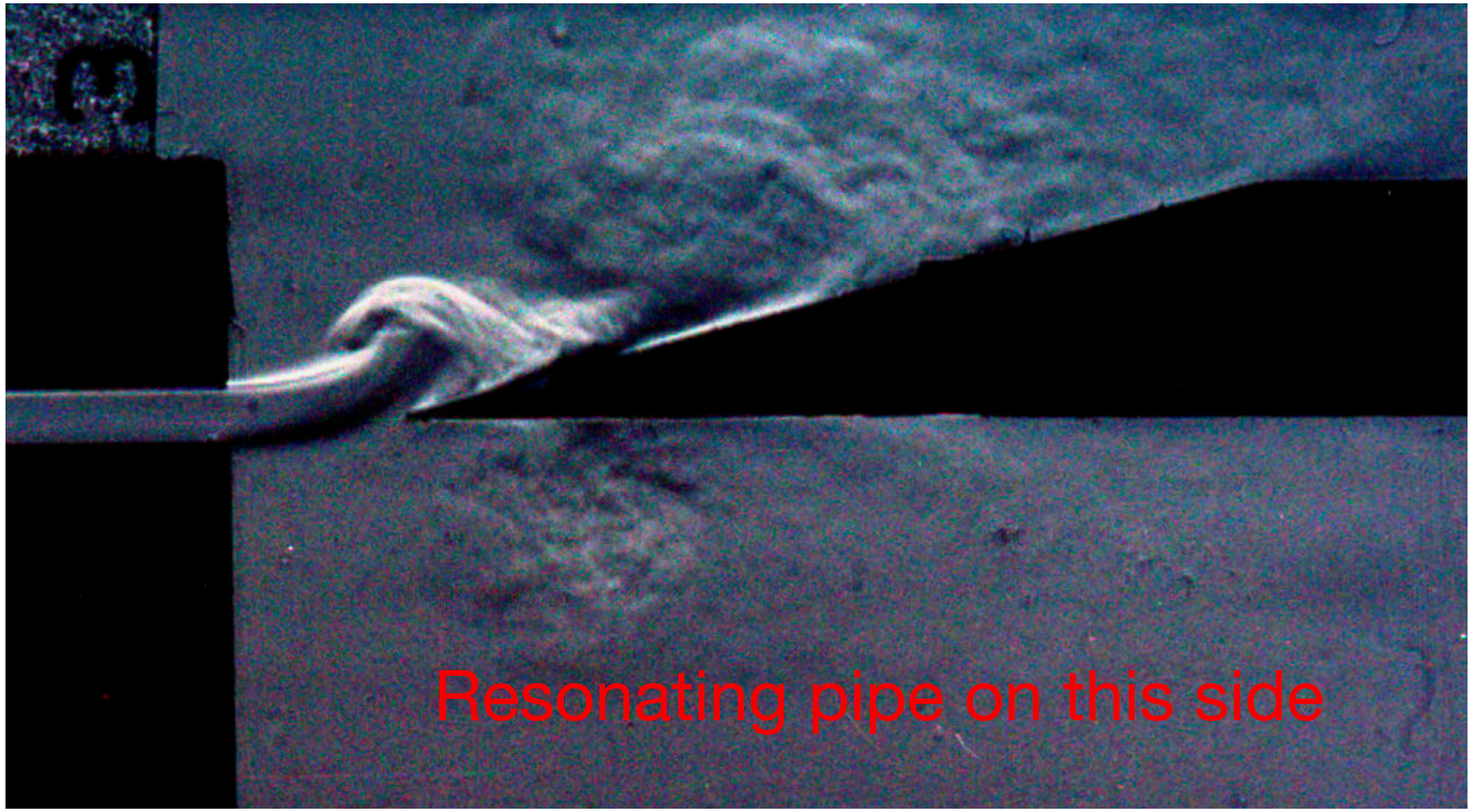
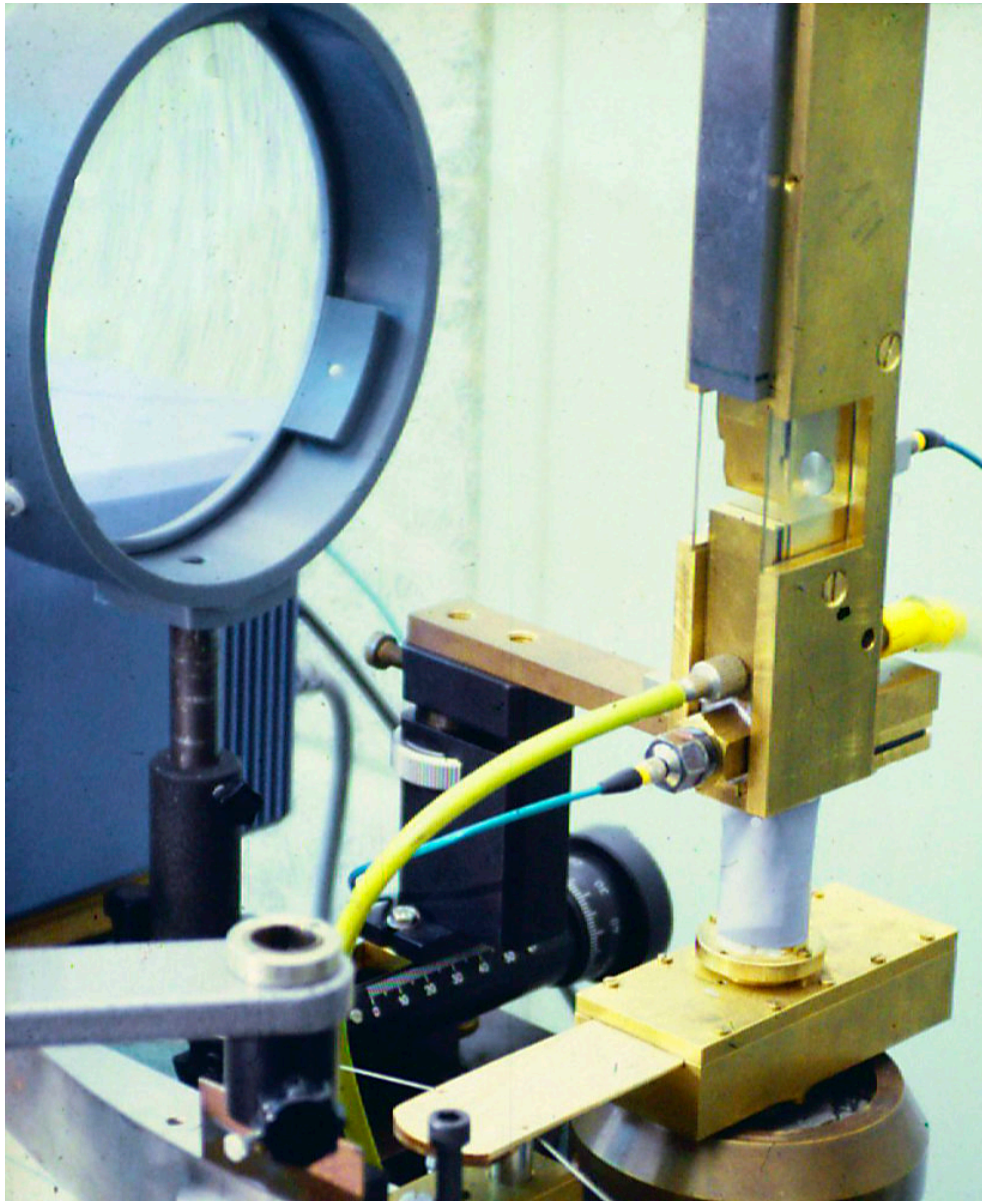
Here is what happens, illustrated using a “laboratory organ pipe”

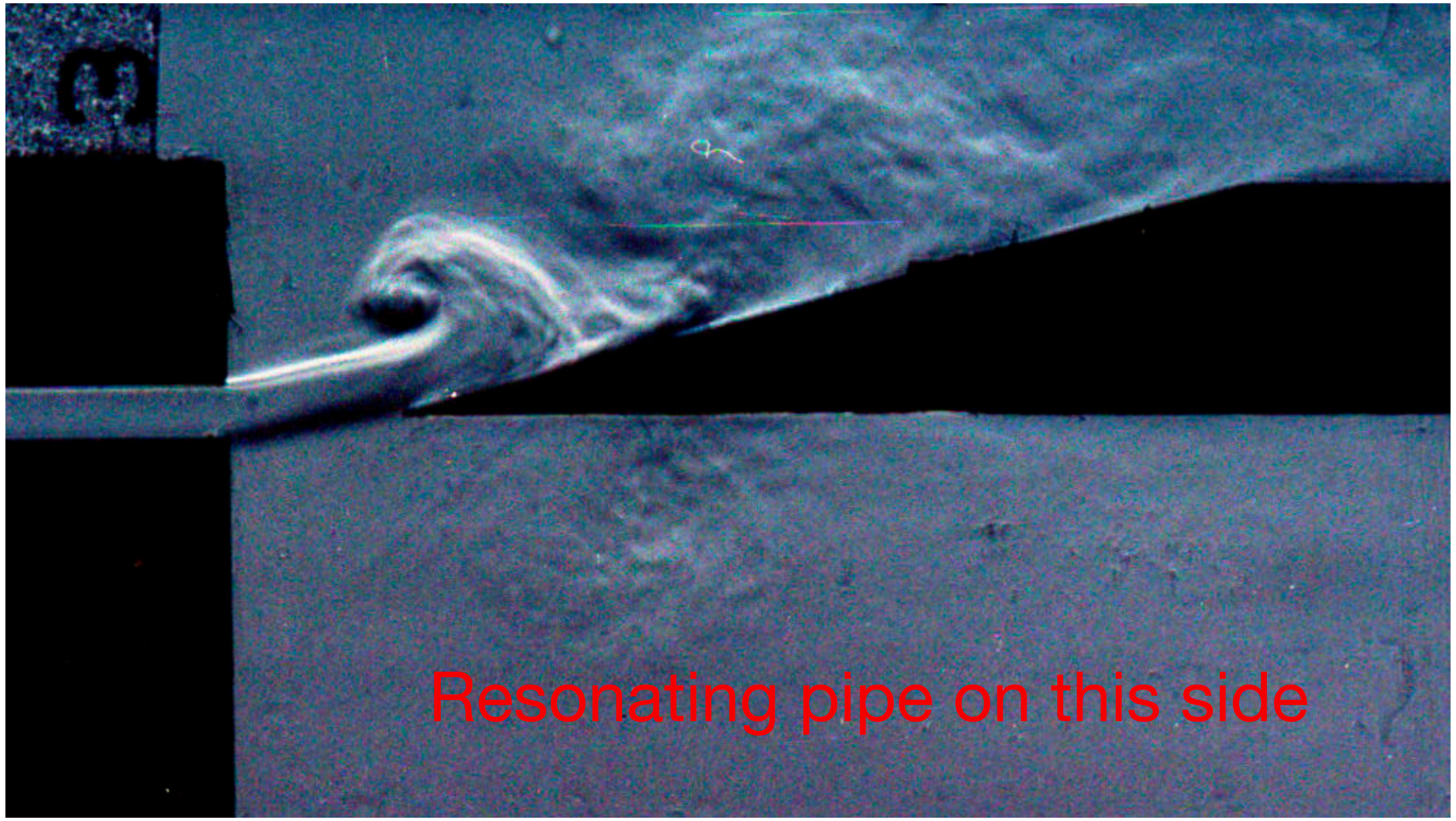




Measurement of steady oscillation in a flue pipe

Visualised by schlieren imaging

Images courtesy of Mico Hirschberg (Eindhoven)



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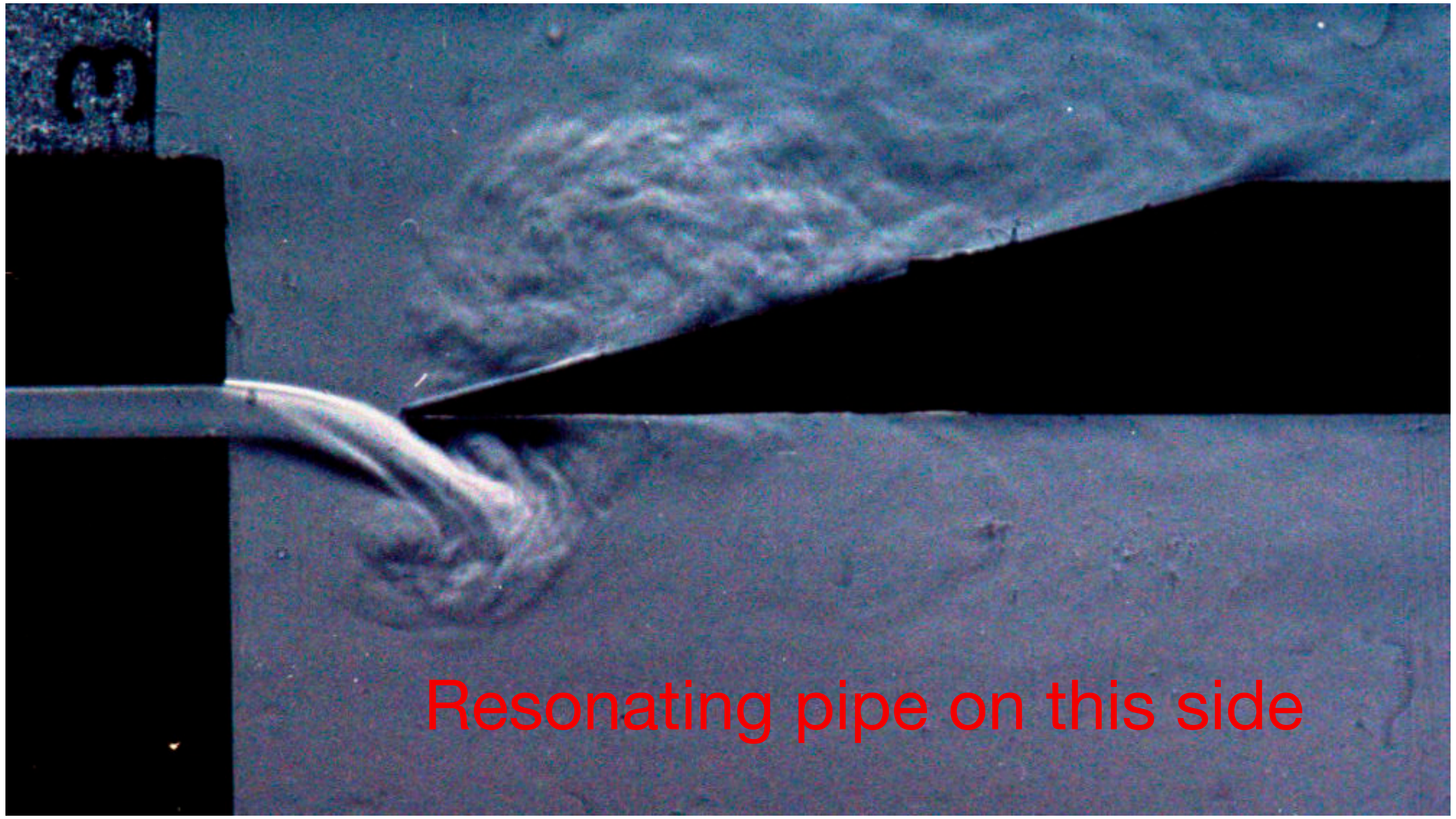

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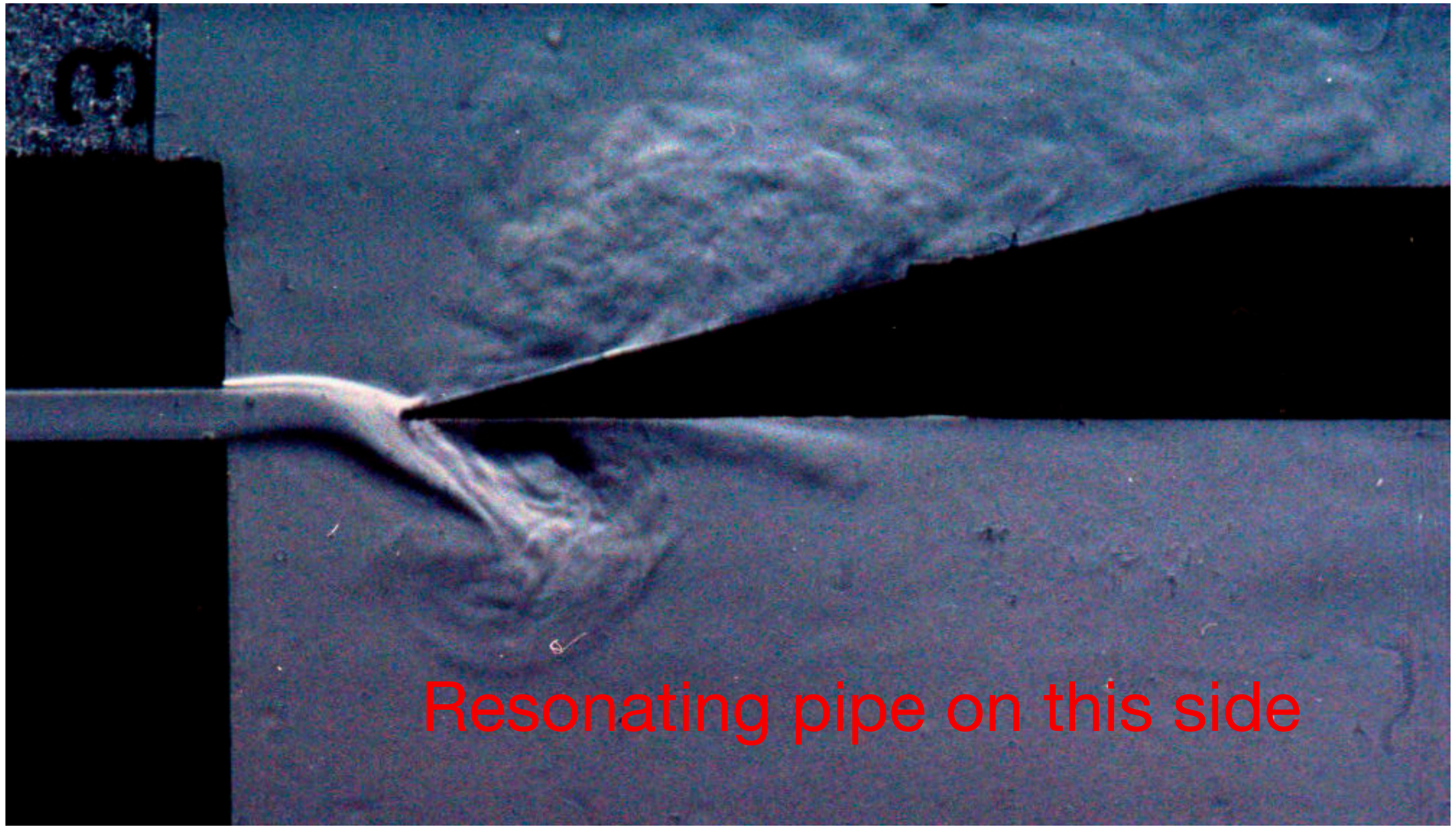

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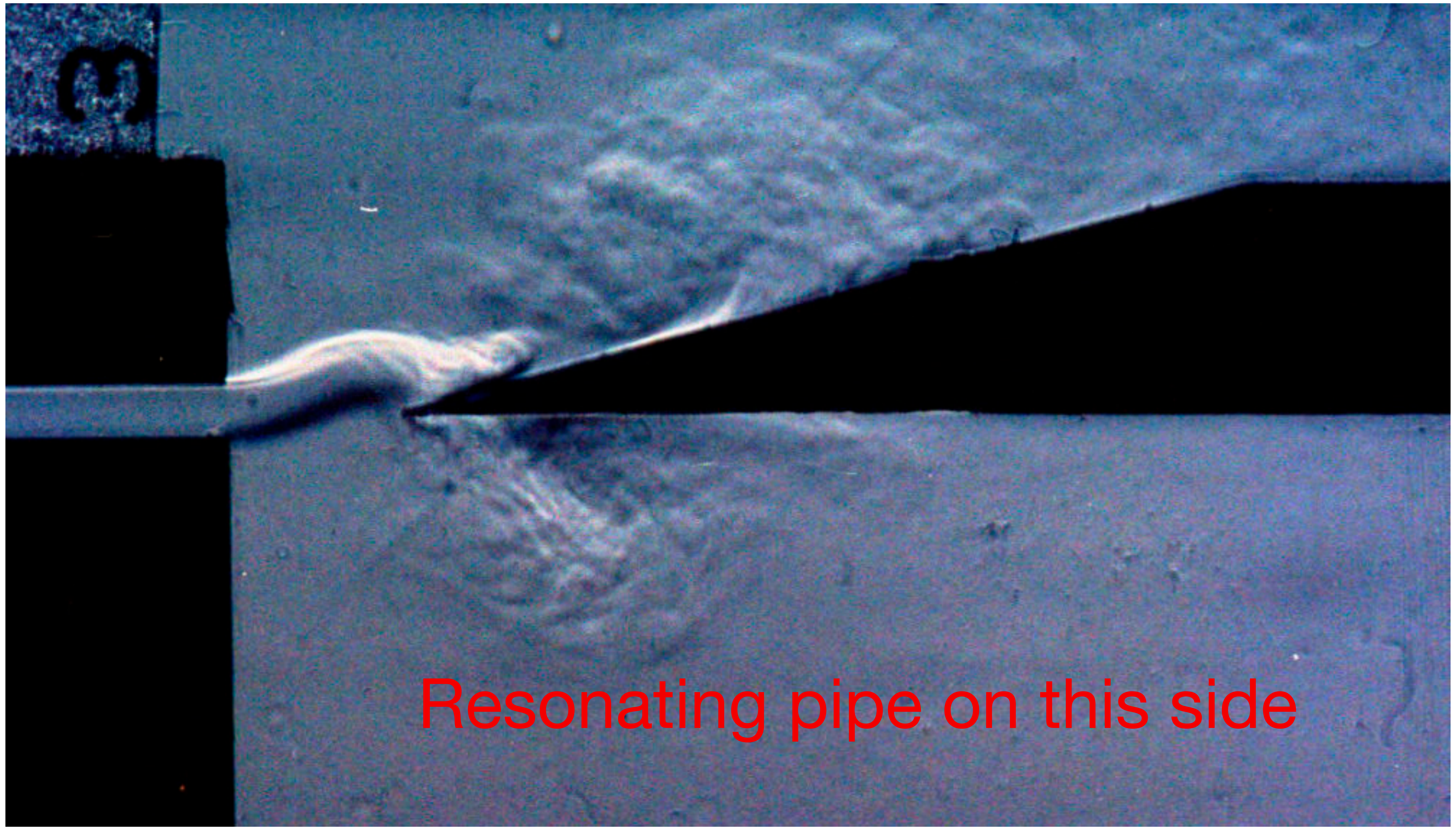

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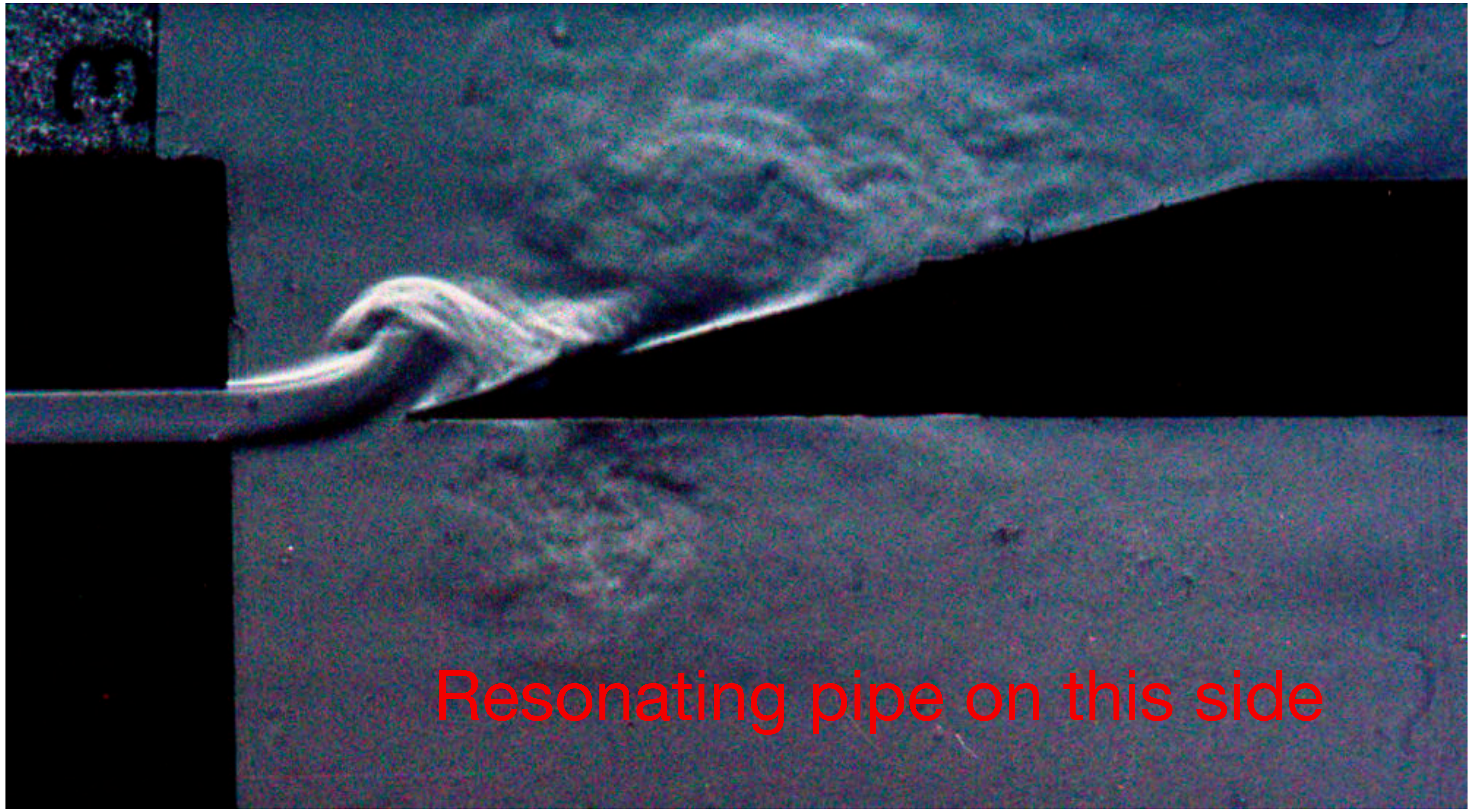

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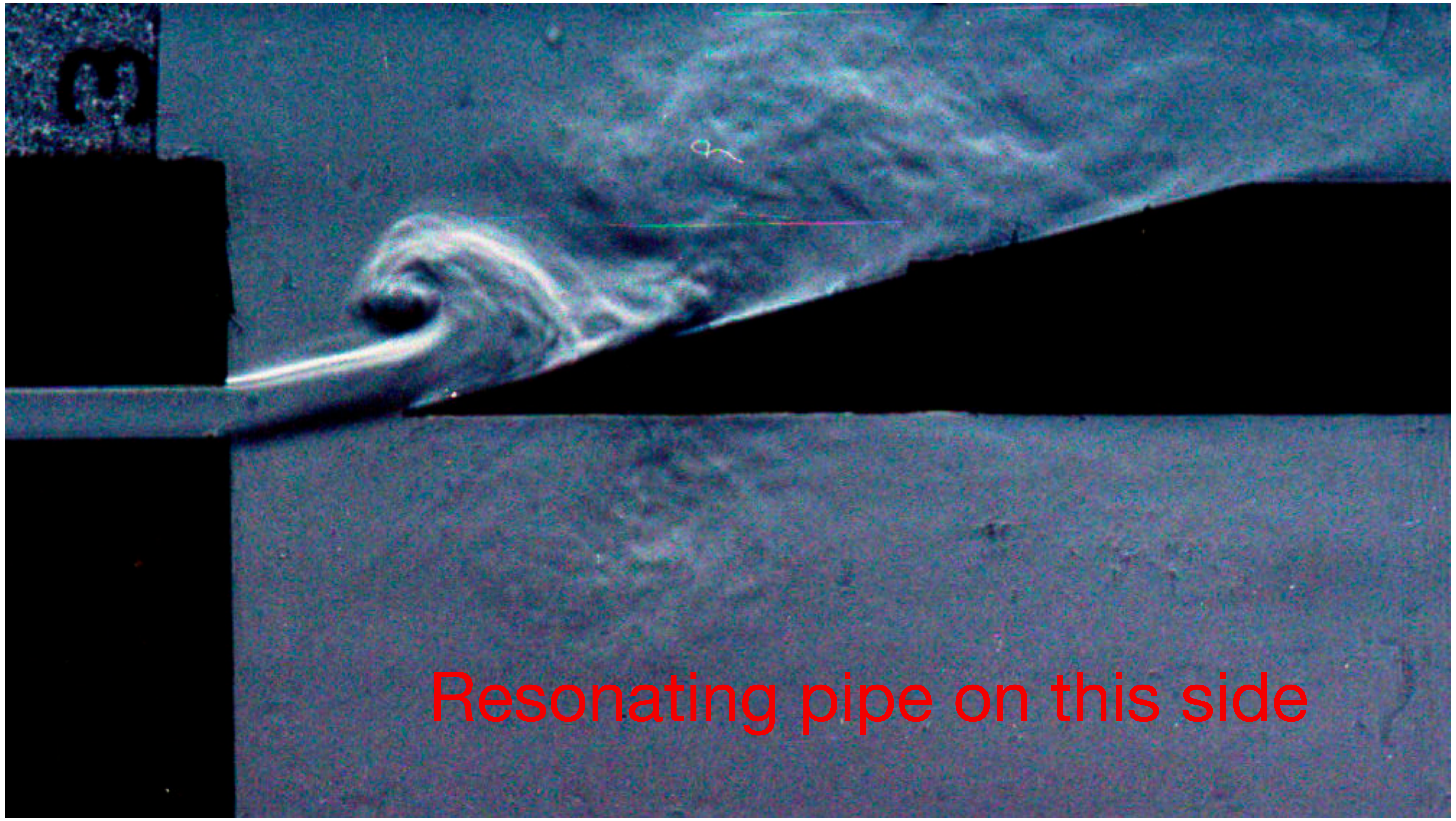

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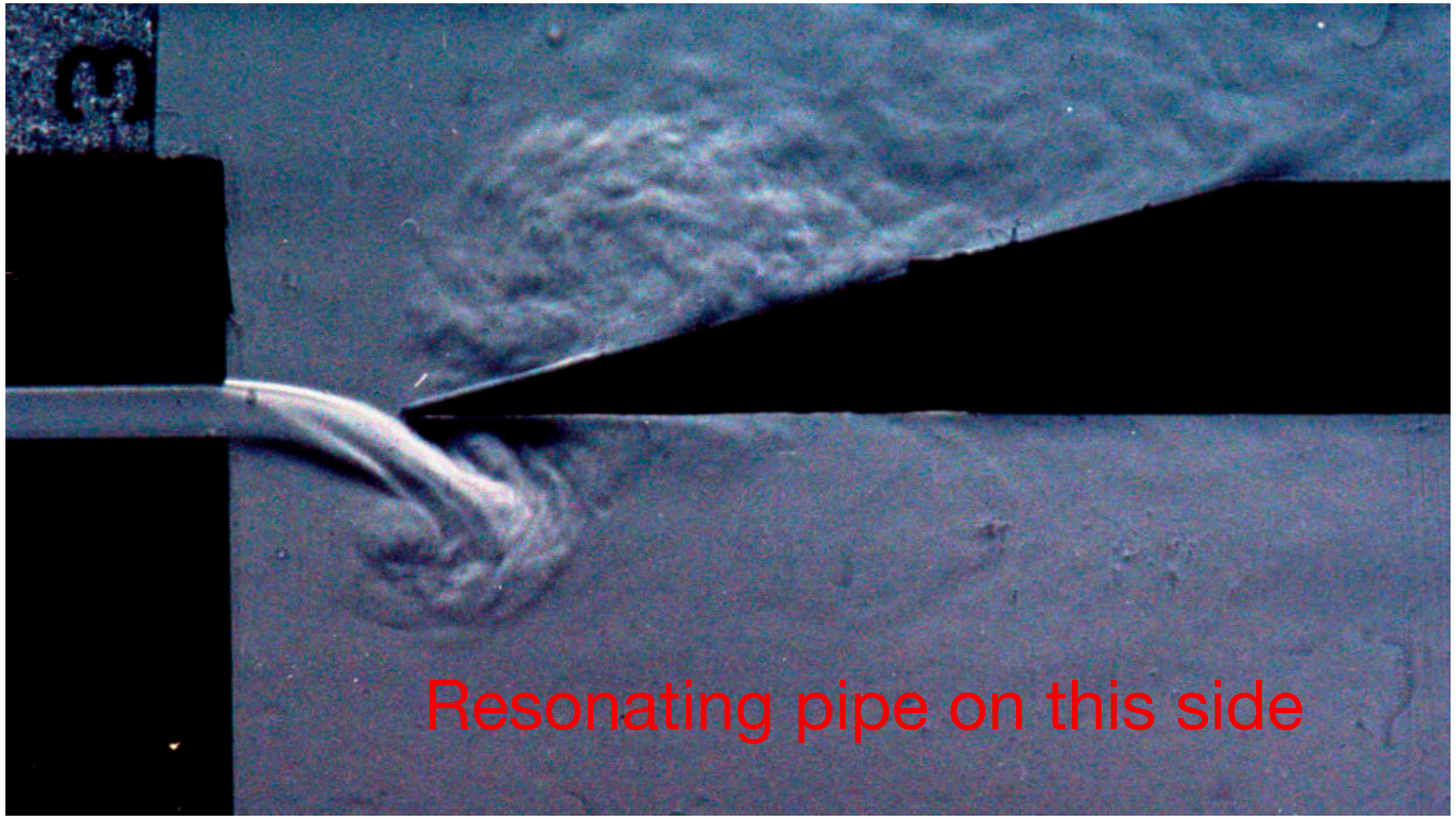

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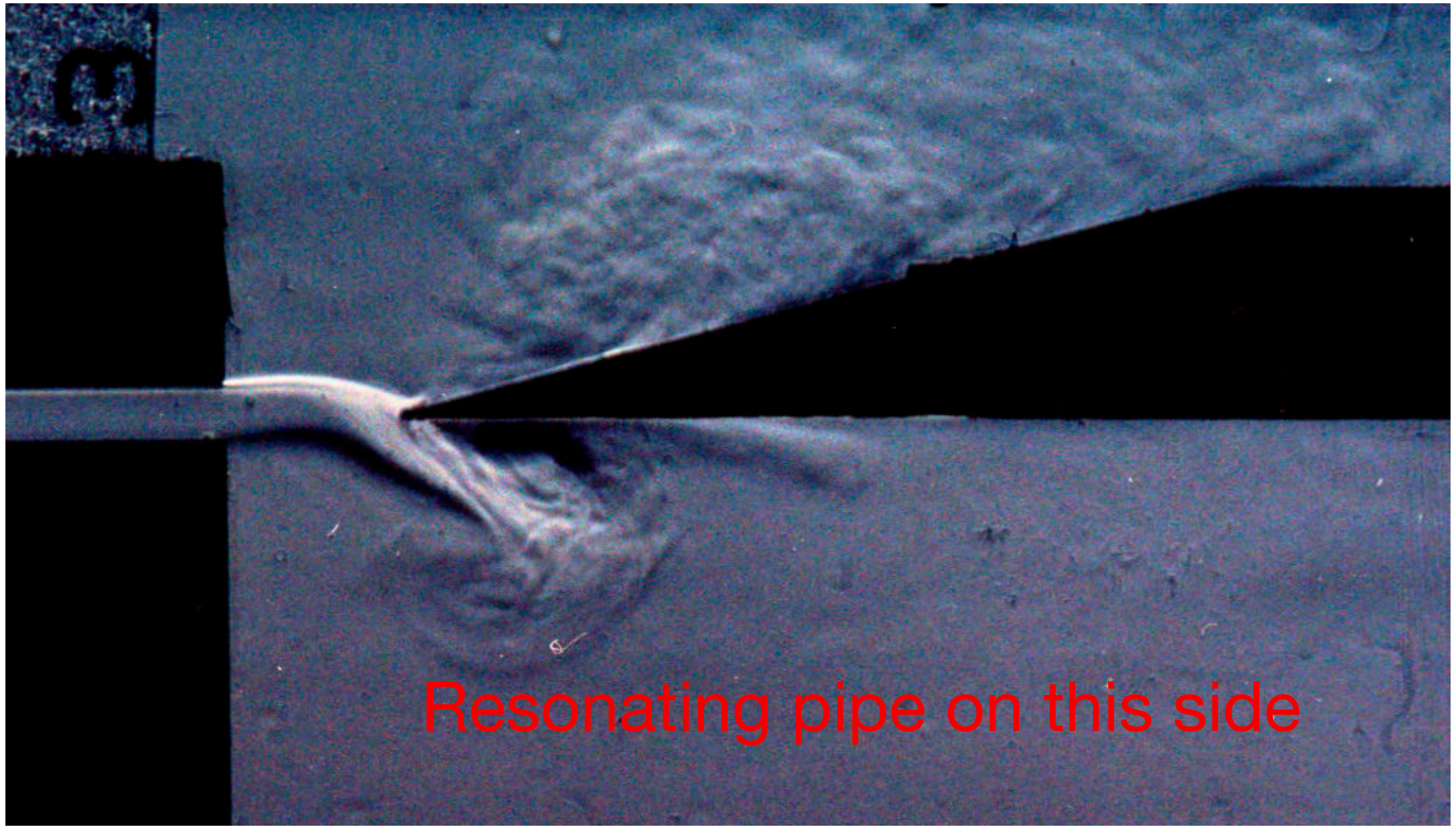

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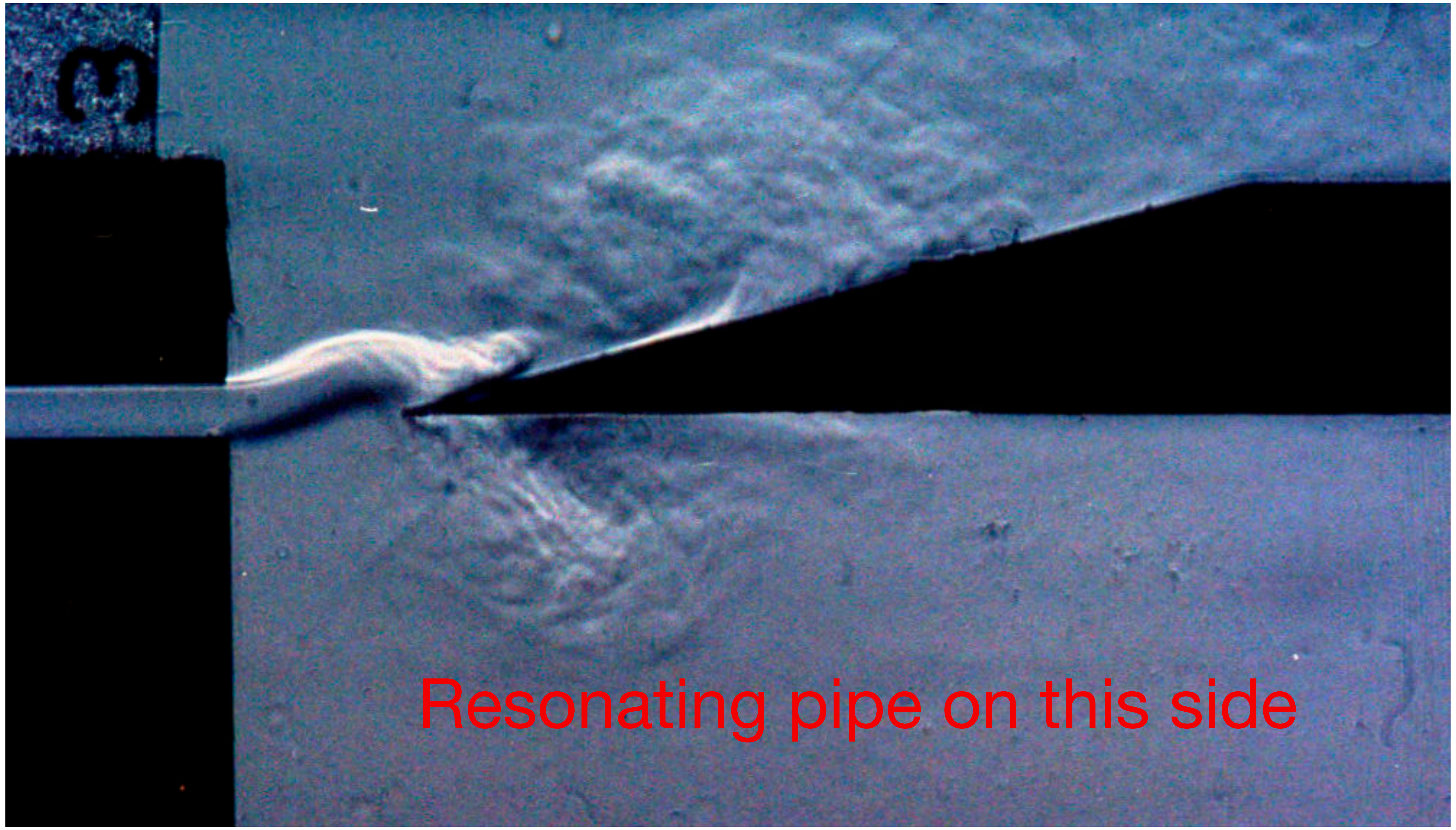

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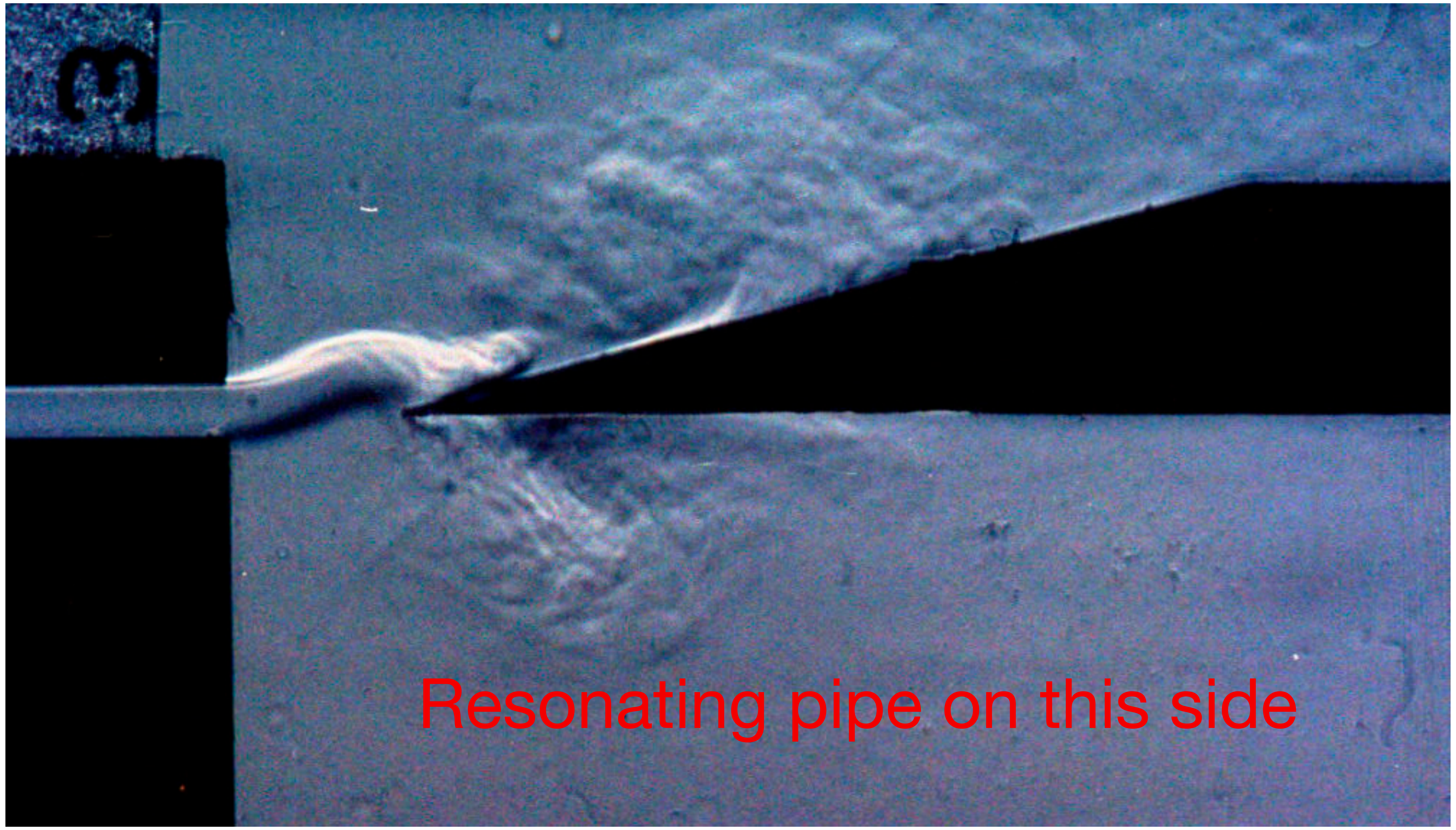
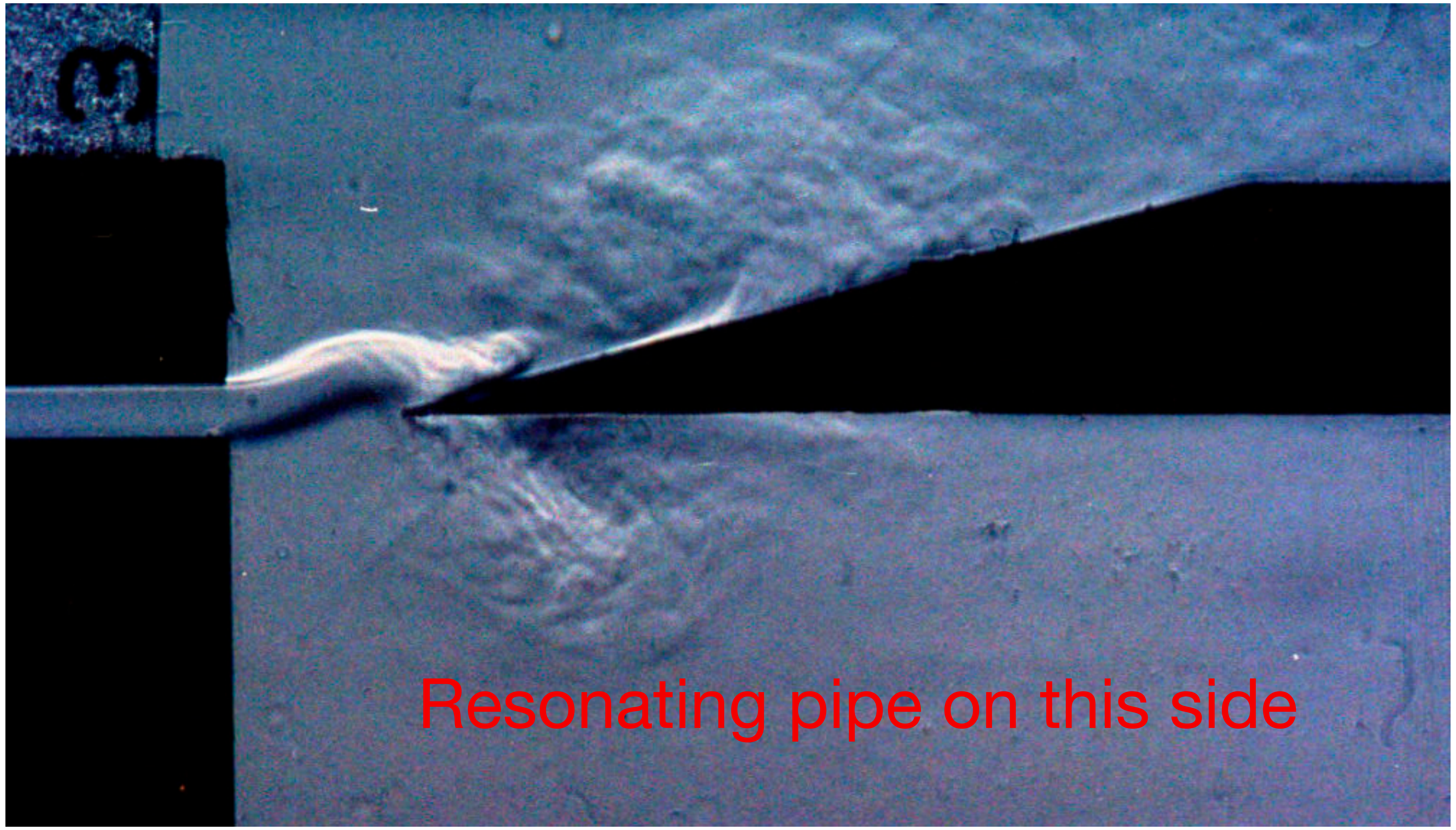


The fluid dynamics is complicated!
We won't try to go into details here



The behaviour depends on:
- the thickness and speed of the air jet;
- the distance to the sharp edge;
- the sharpness of that edge (metal may be sharper than wood).

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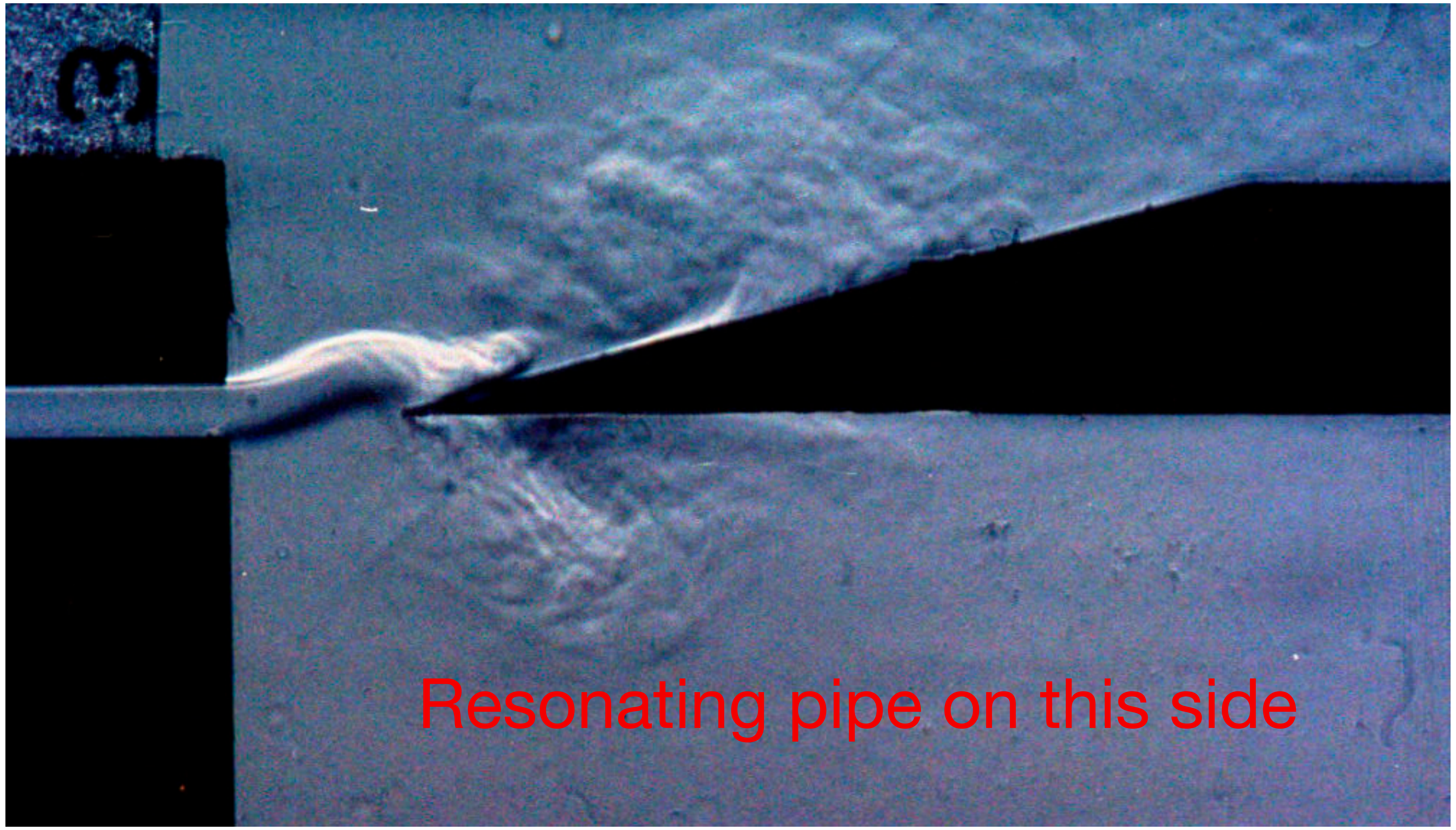

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The pitch is always close to the pipe resonance, but a faster air jet makes the pitch go a little sharp because the travel time to the sharp edge is reduced.

Too fast, and the pipe ceases to sound

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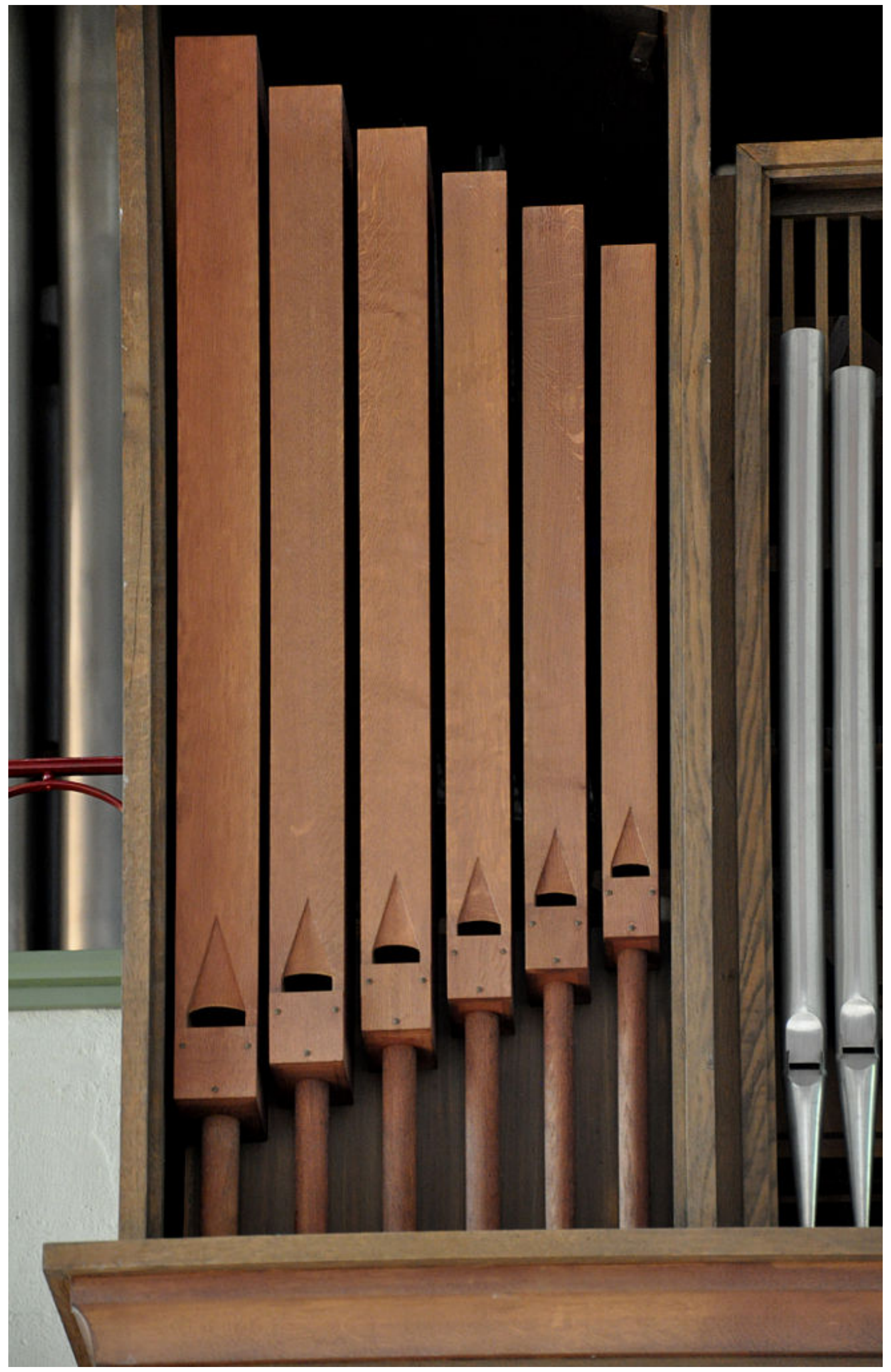
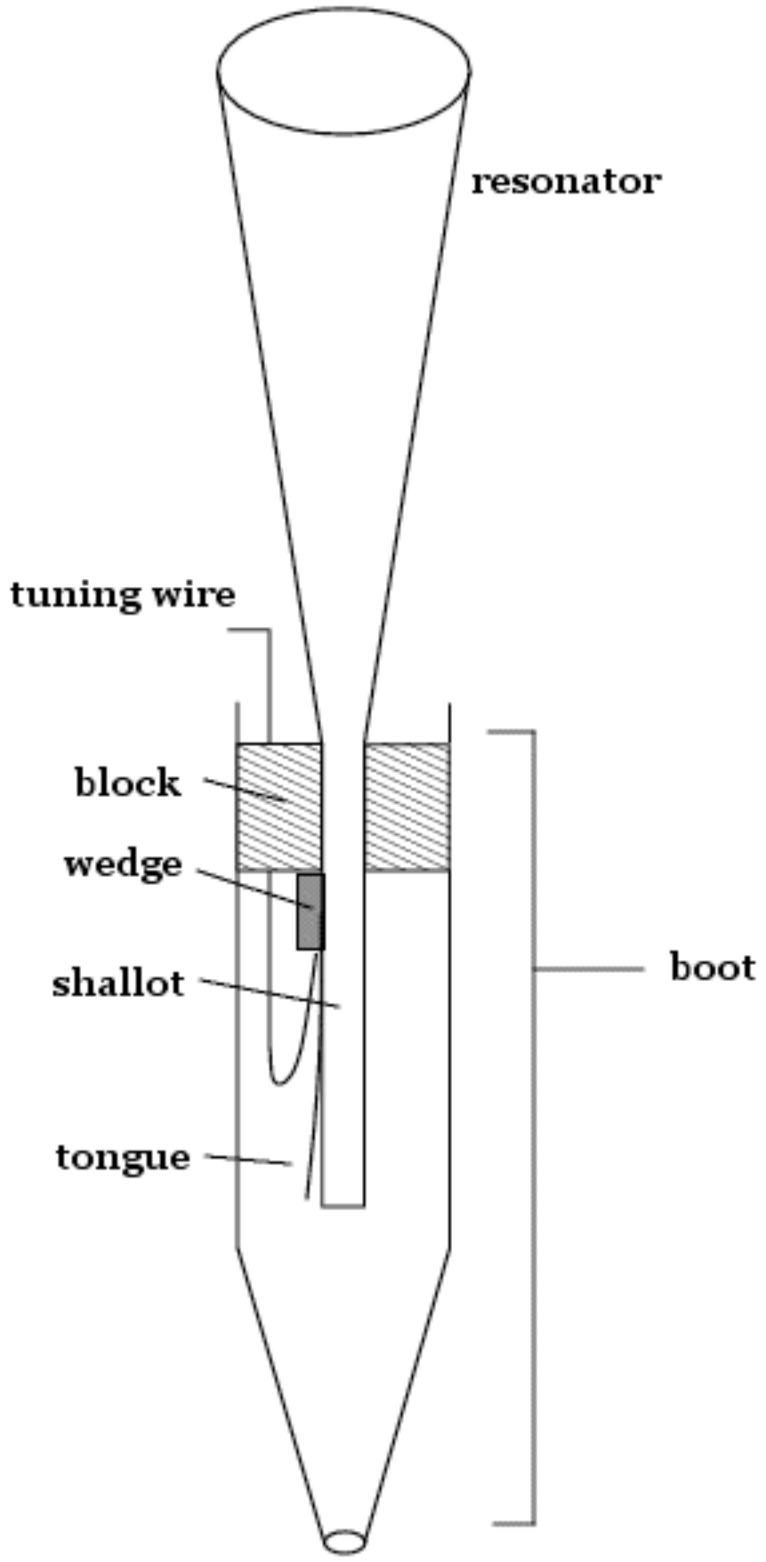
Back to the question of reed pipes:

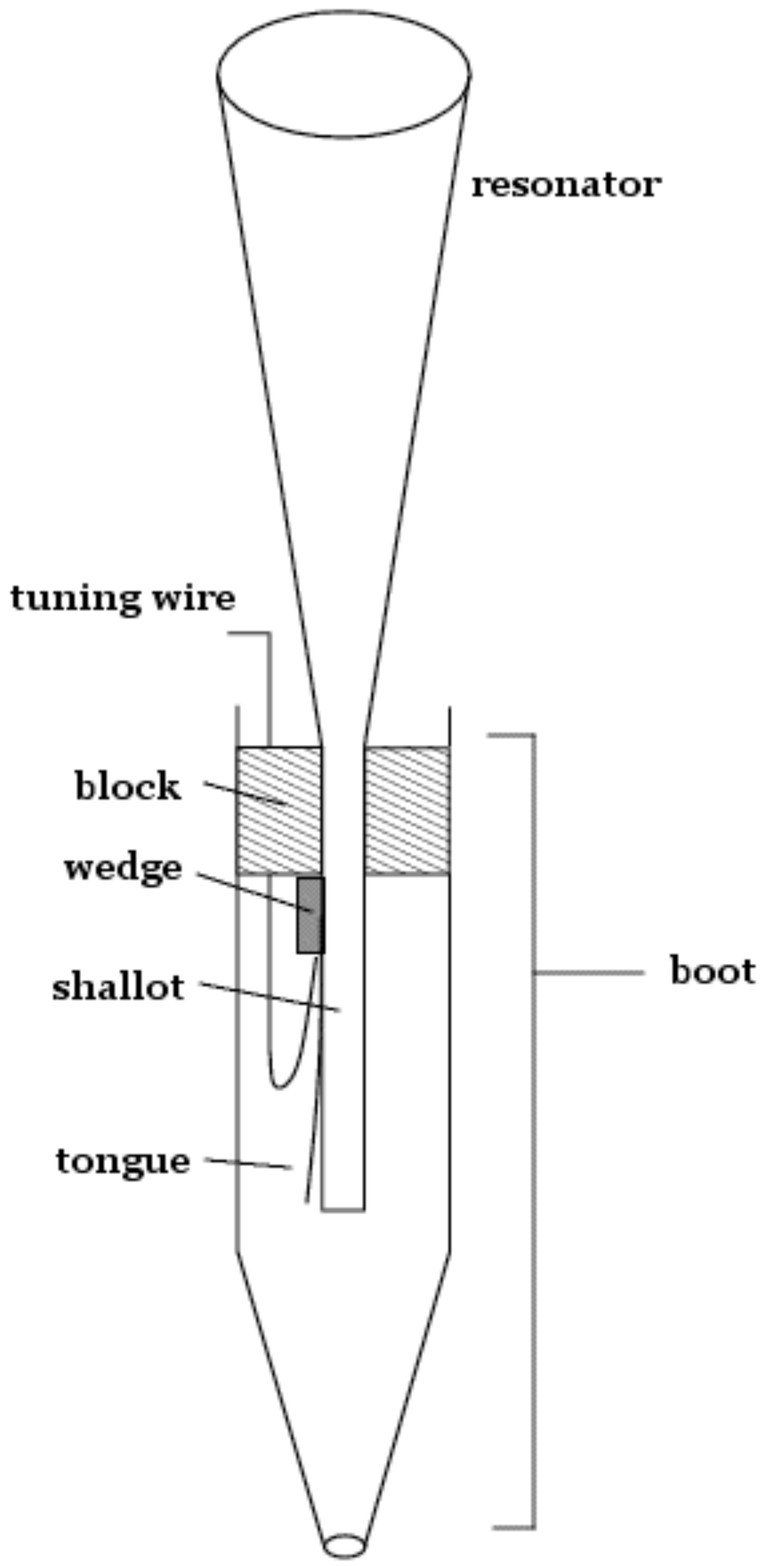
Air-jet instruments

Reed instruments





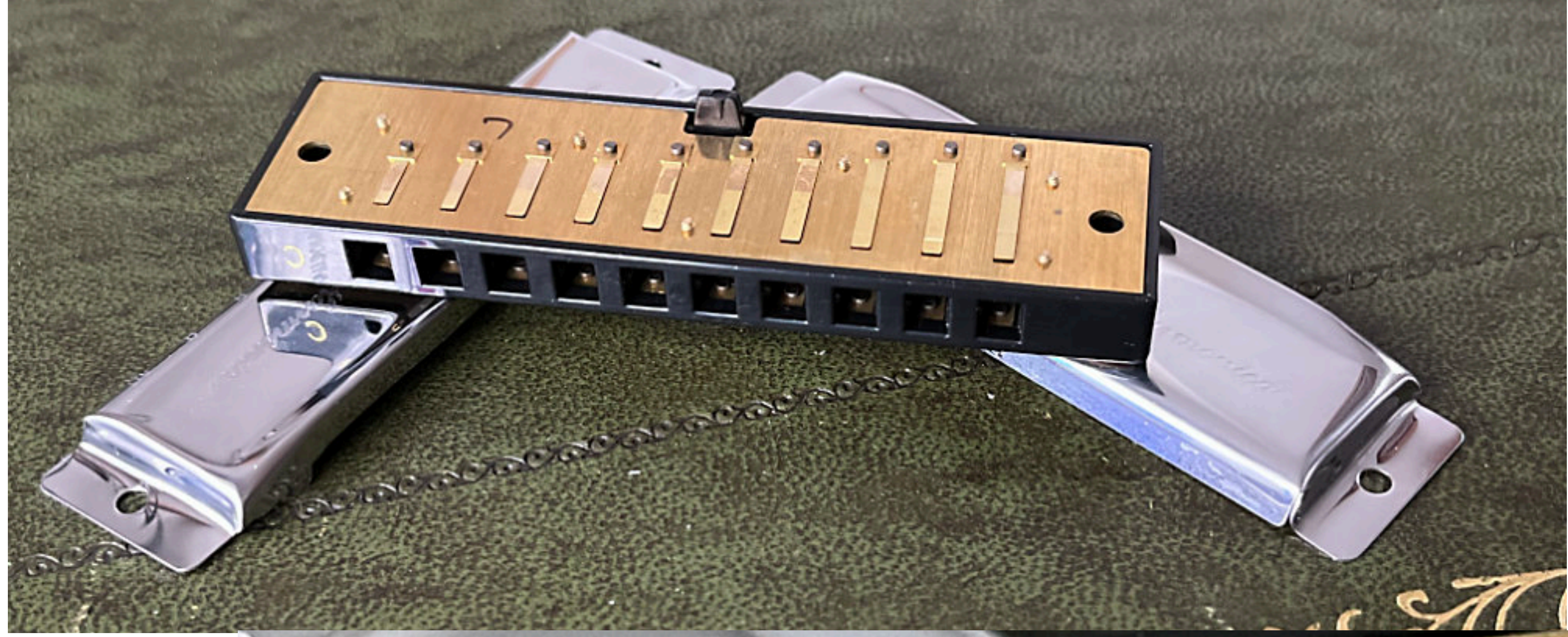
Actually, reed pipes are closest to something like this:



Hmong musicians perform on traditional free-reed instruments in Upper Lang De in Guizhou, China.
Image: Michael Mooney from Chicago, USA, CC BY 2.0 https://creativecommons.org/licenses/by/2.0, via Wikimedia Commons

Reeds, reed resonance and damping

A clarinet mouthpiece and reed, from
https://www.normans.co.uk/blogs/blog/put-reed-clarinet-mouthpiece



Free reeds in a harmonica

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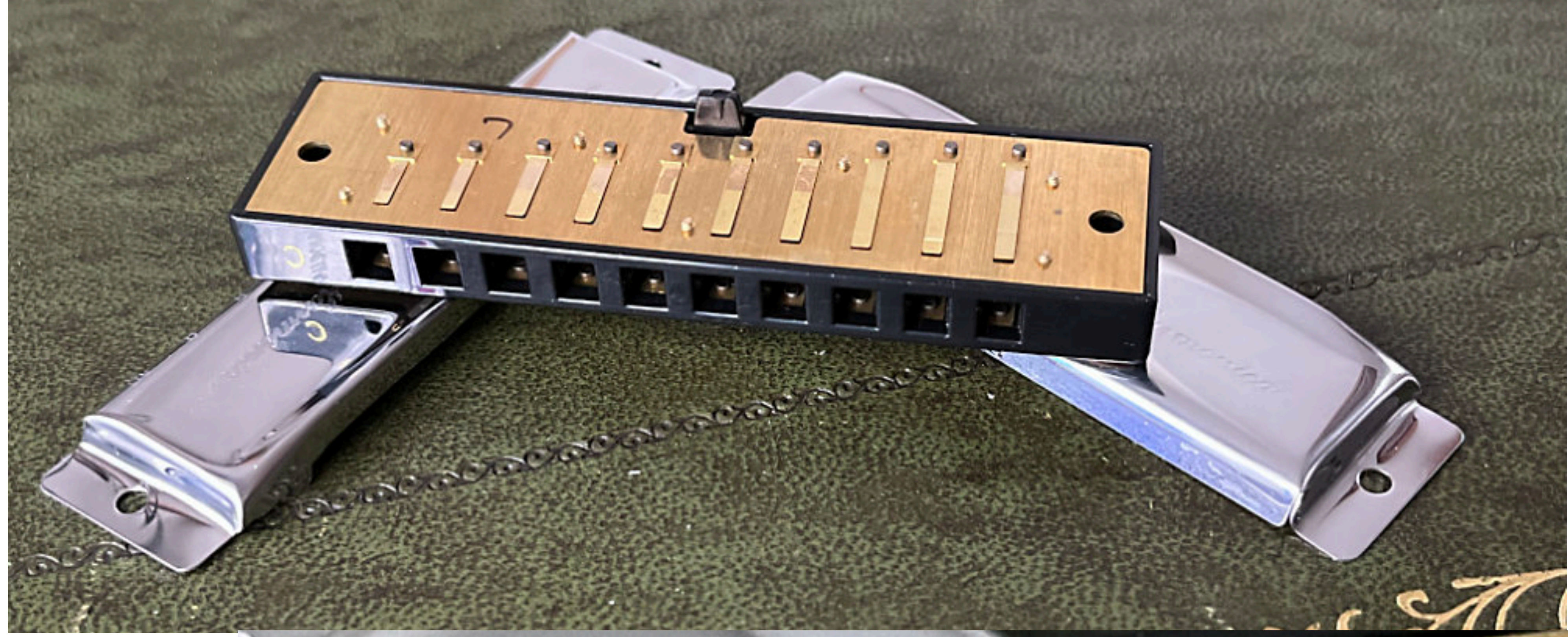

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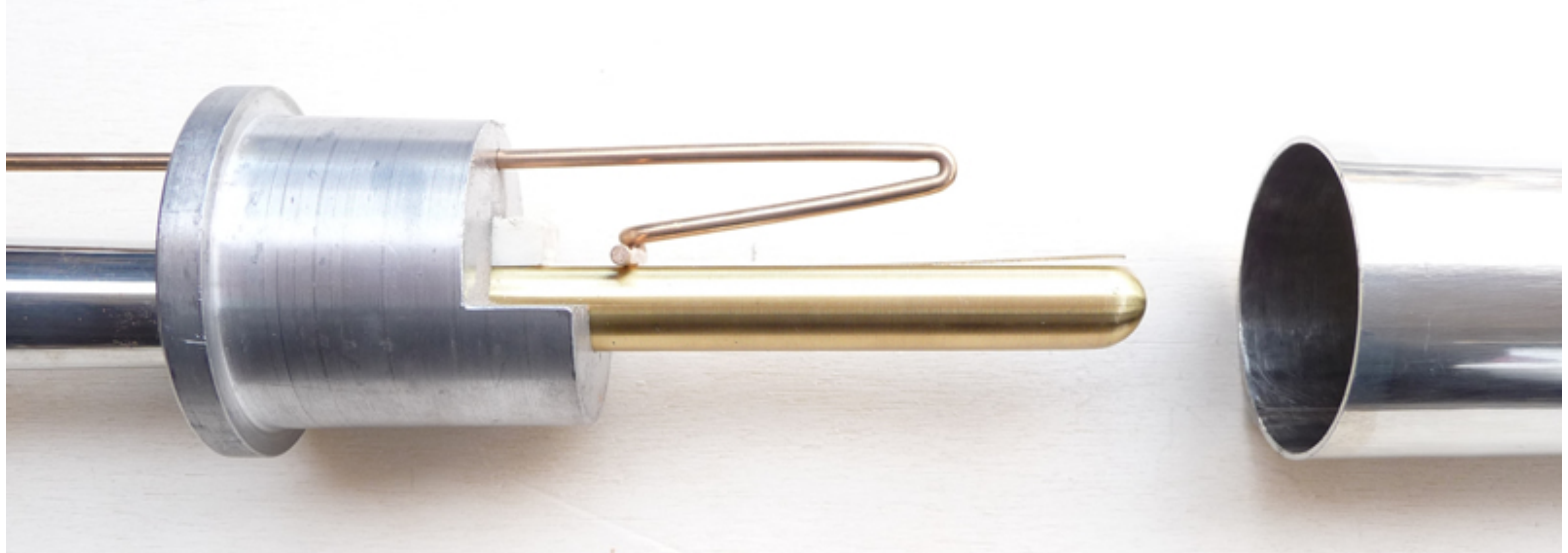

Shallot and reed from a reed pipe
from https://ruffatti.com/en/how-we-build-our-organs/the-pipes/reeds/

Reeds, reed resonance and damping

Pipe reeds are made of metal, like harmonica reeds
Clarinet or oboe reeds are made of cane or plastic

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(demo with metal and plastic bowls)

This makes them more resonant

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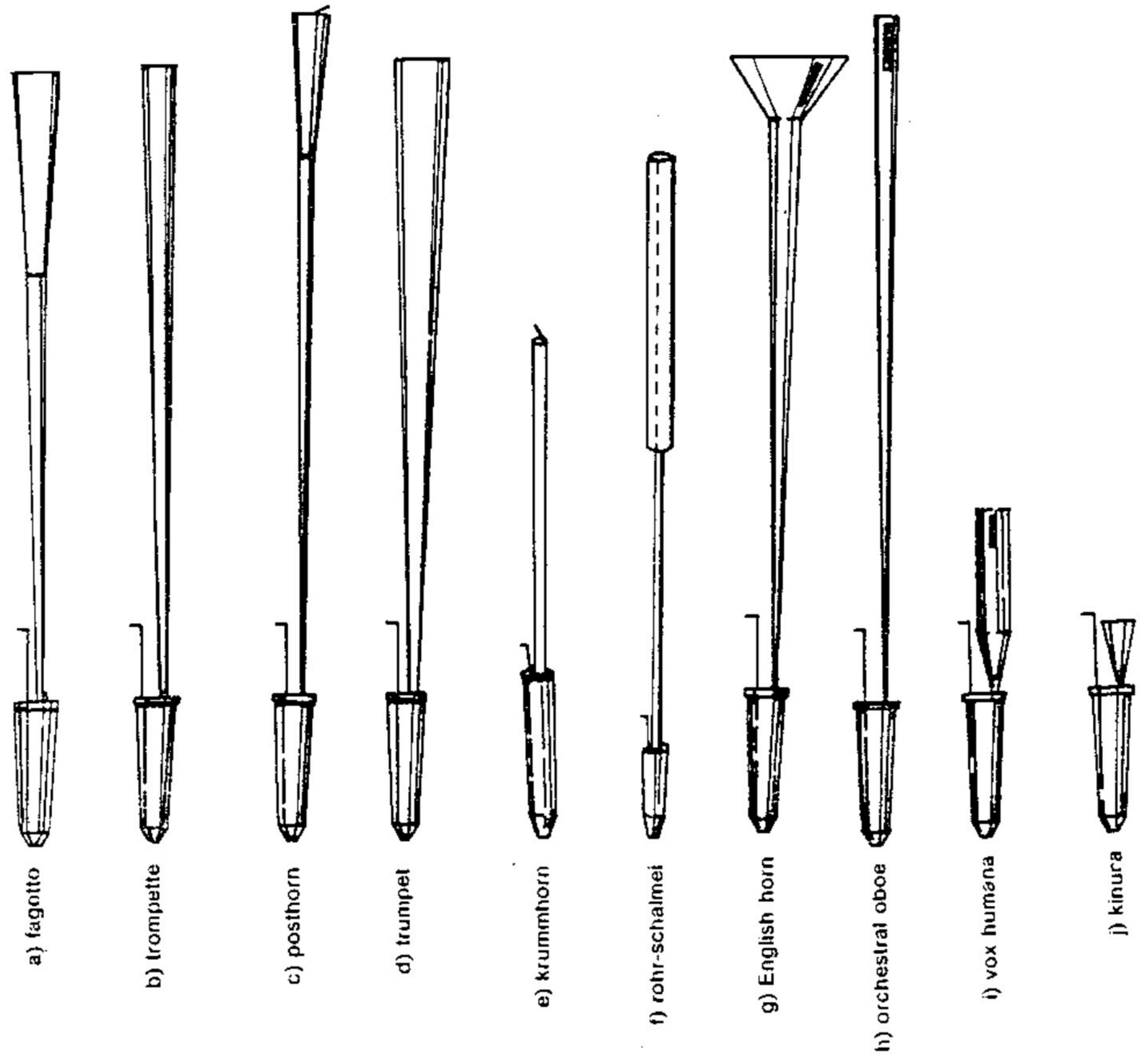
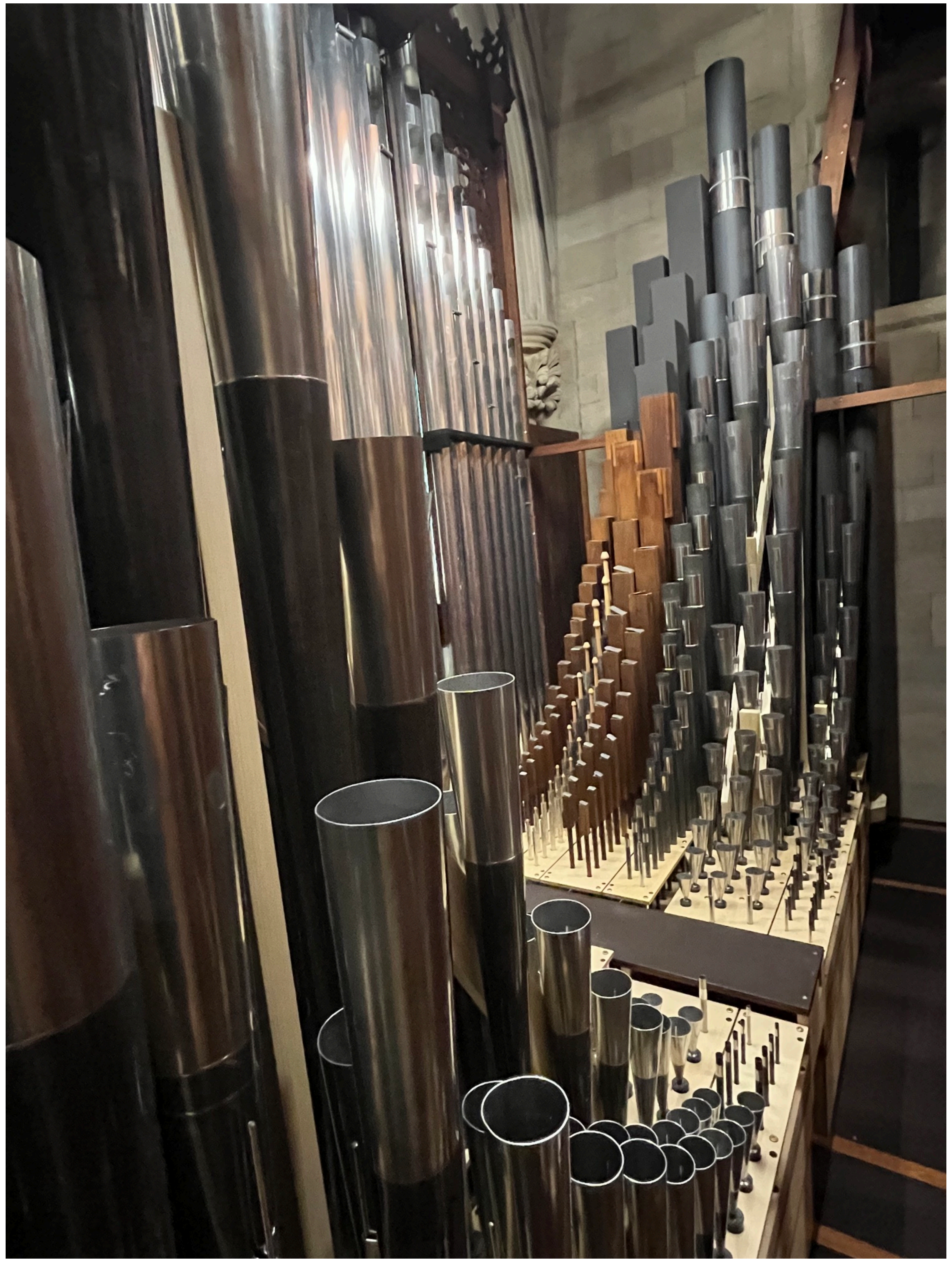
The pipe acts as a FILTER for sound
Different shapes will give different sound qualities

Varieties of reed pipe

A separate pipe for each note means the organ builder can fine-tune the sound of different reed ranks



From W. Strong and G. Plitnik: *Music, Speech, Audio* Soundprint, Provo, UT (1992)



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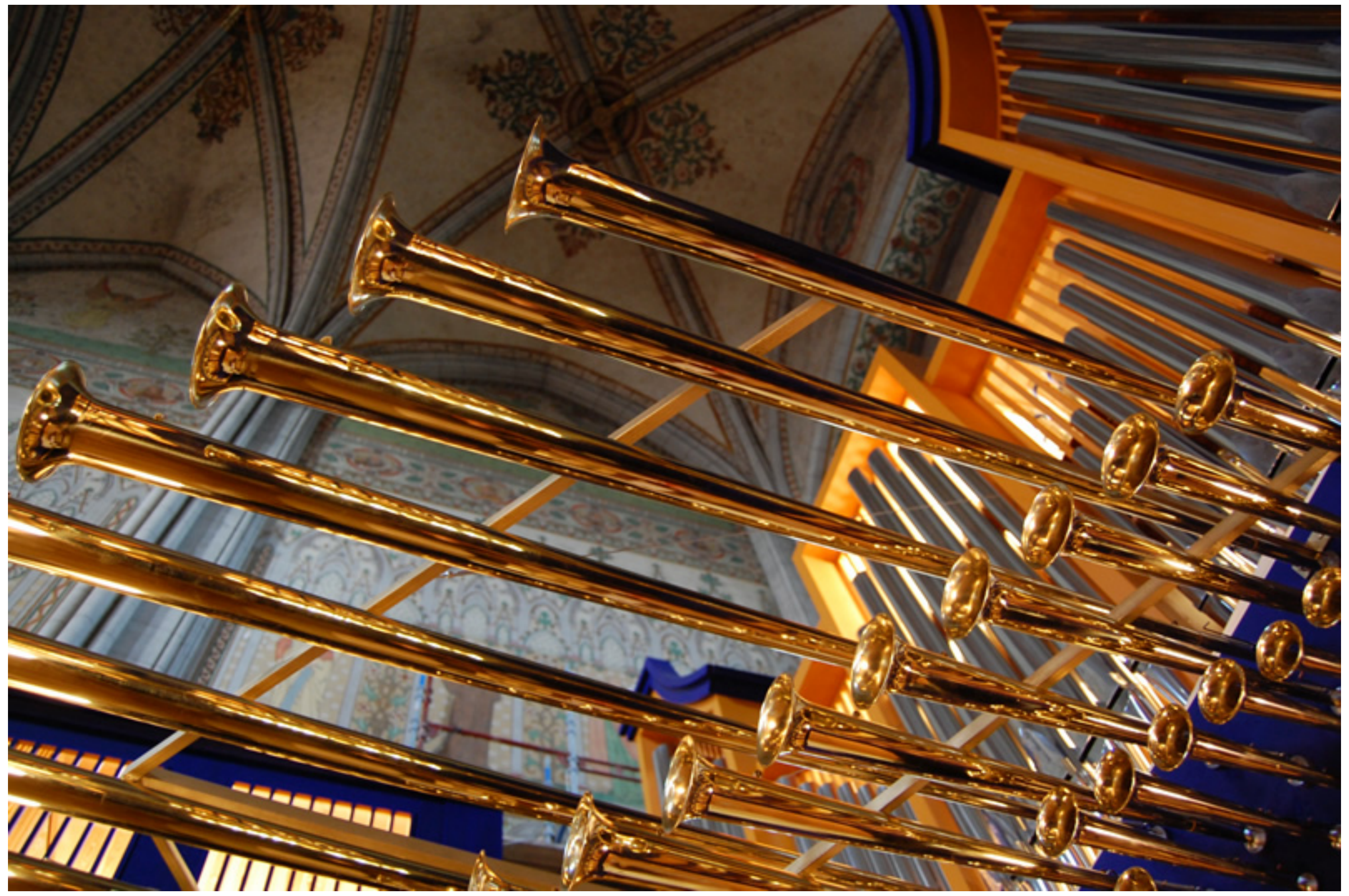
A tuned conical pipe can reinforce EVERY harmonic

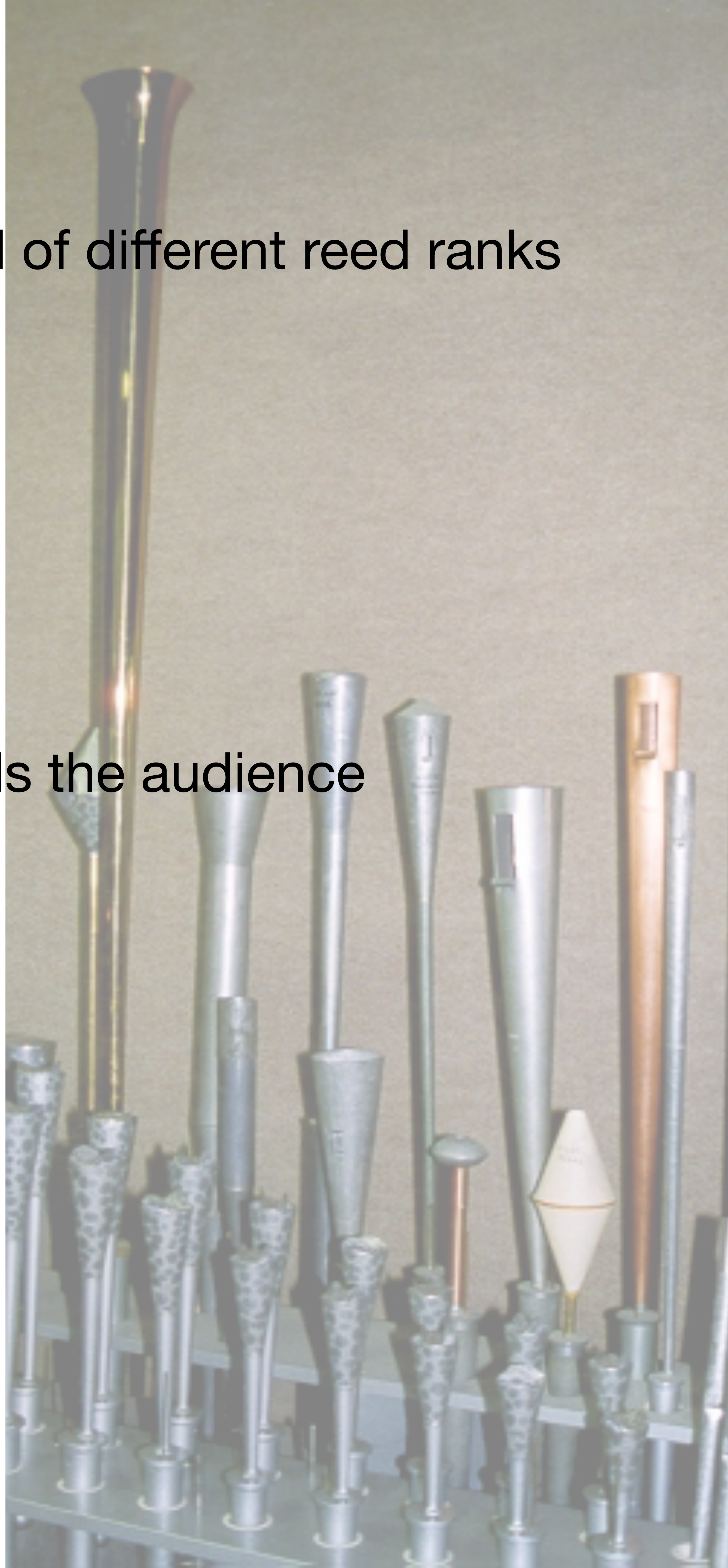
A tuned straight pipe mainly reinforces odd harmonics only

A short pipe can suppress the fundamental and emphasise higher harmonics

A forward-facing “trumpet-shaped” pipe can send more high frequency towards the audience

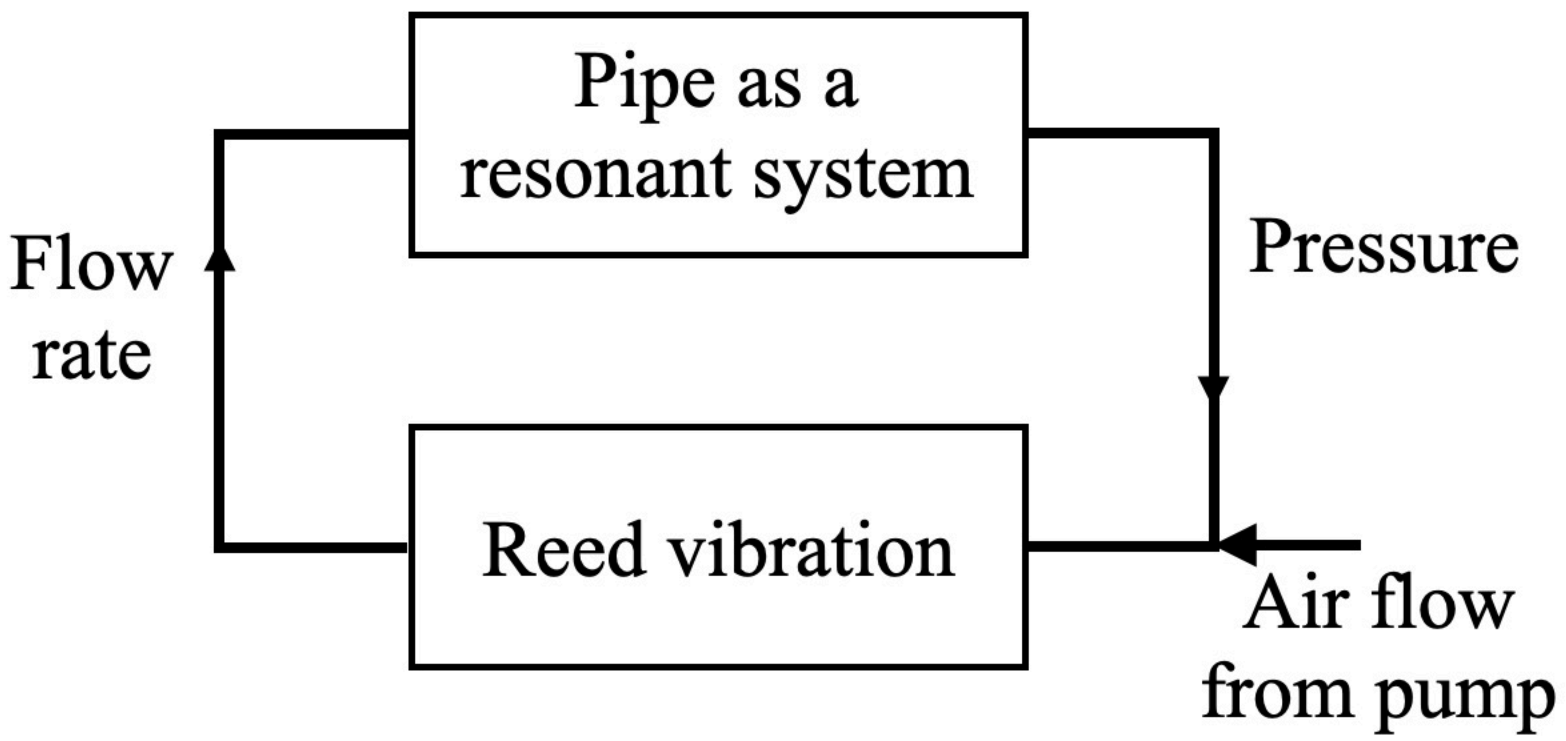


Uppsala cathedral: from
https://ruffatti.com/en/how-we-build-our-organs/the-pipes/reeds/



From: organhistoricalsociety.org

The “Source-filter model”



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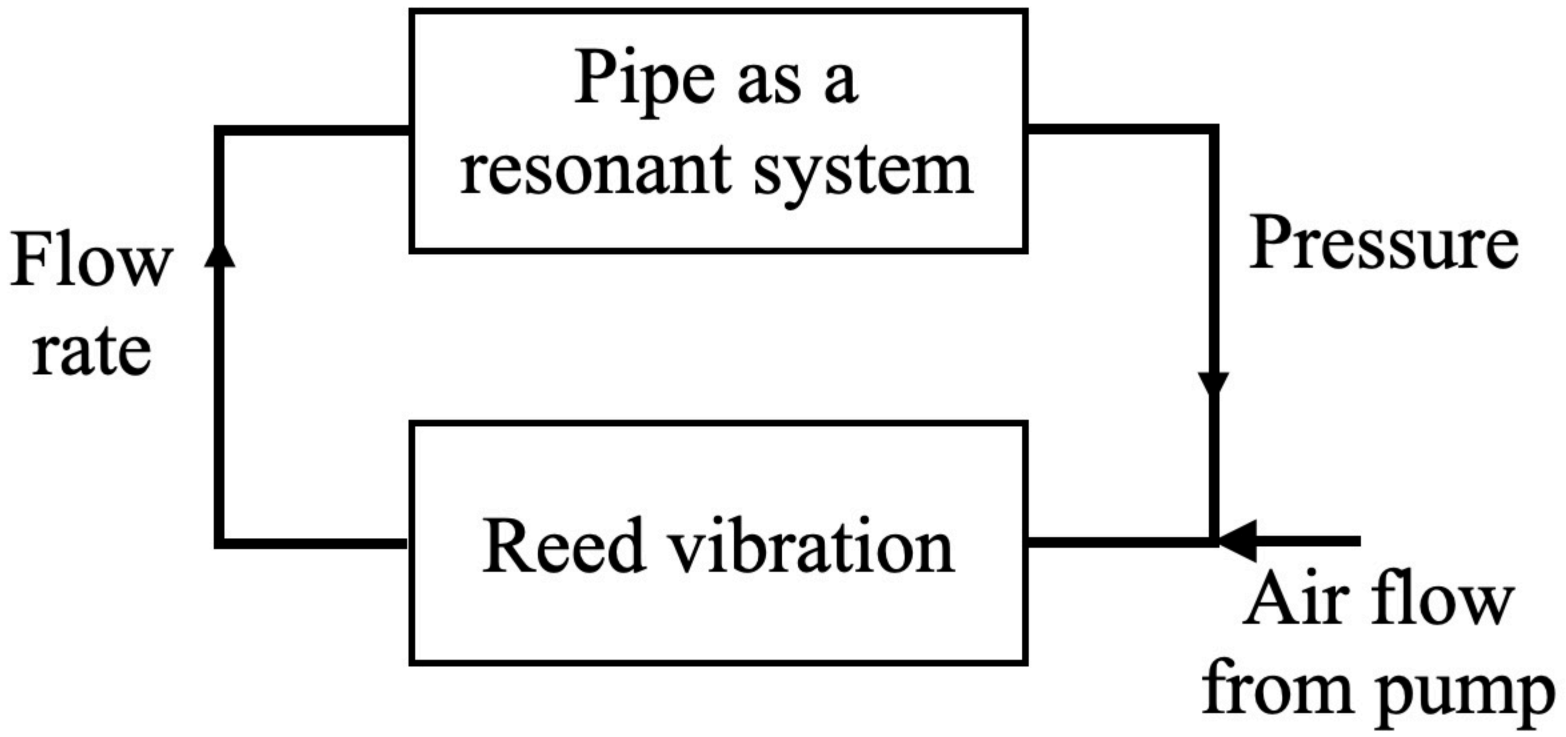

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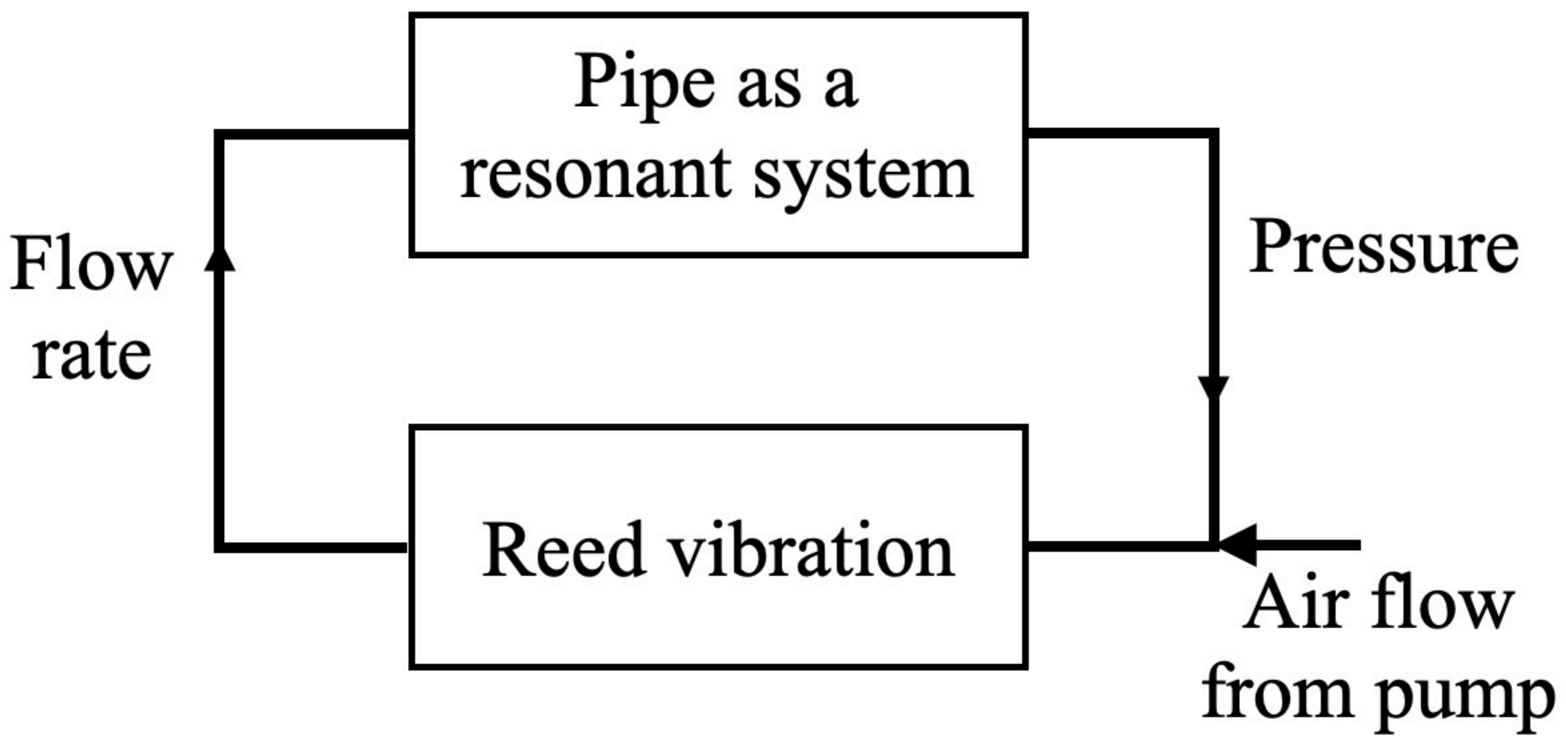
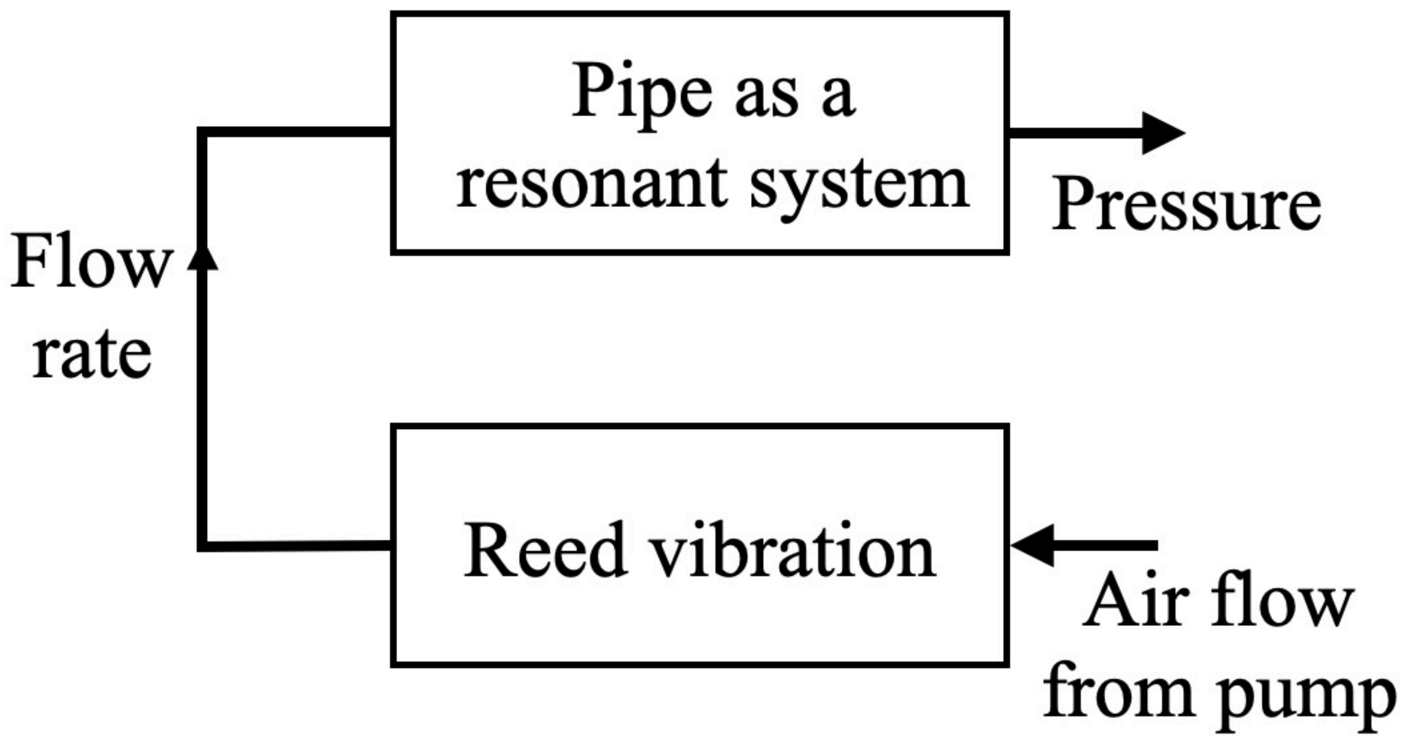
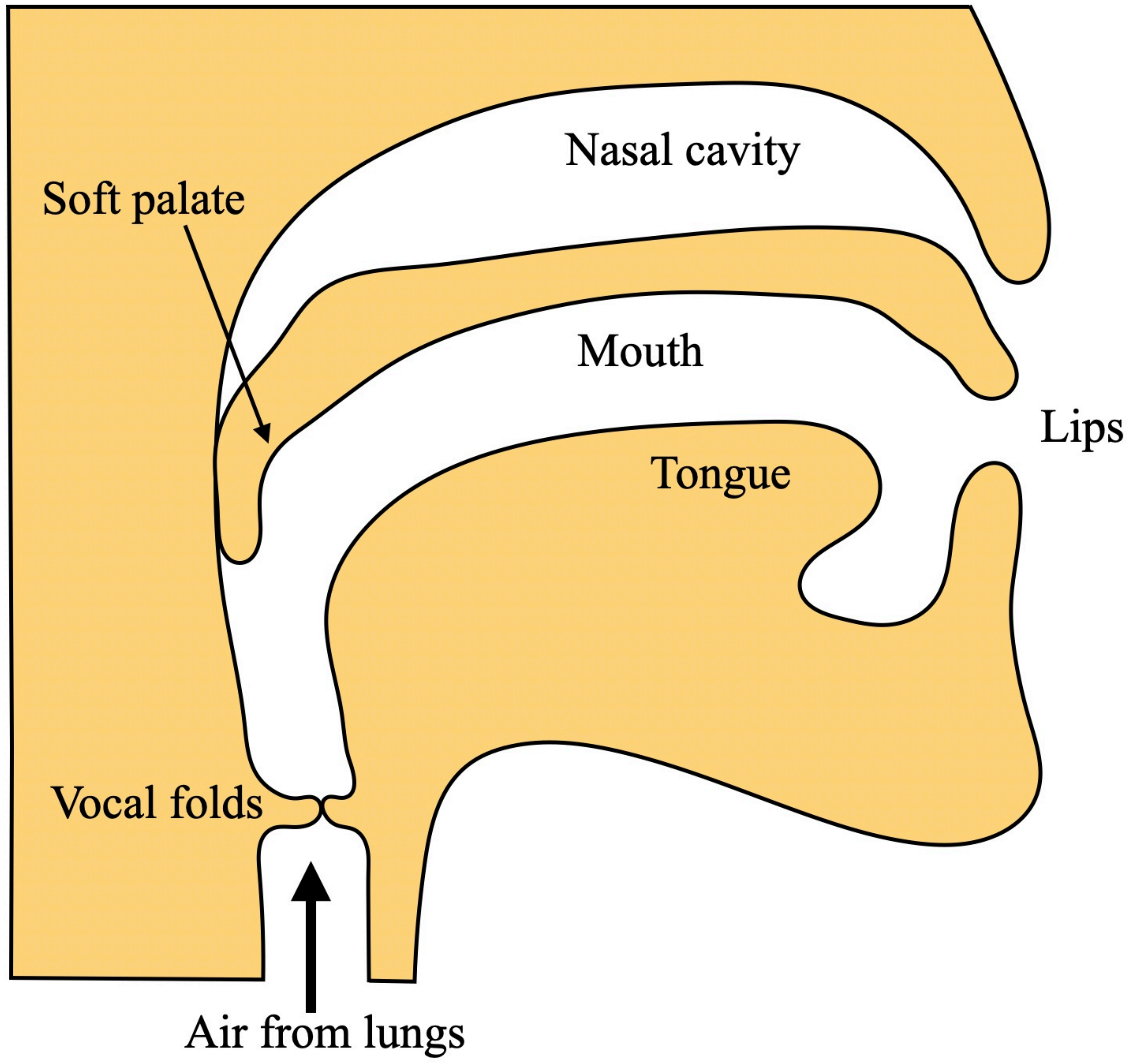




The “Source-filter model”

There is another “wind instrument” that illustrates this: the human voice



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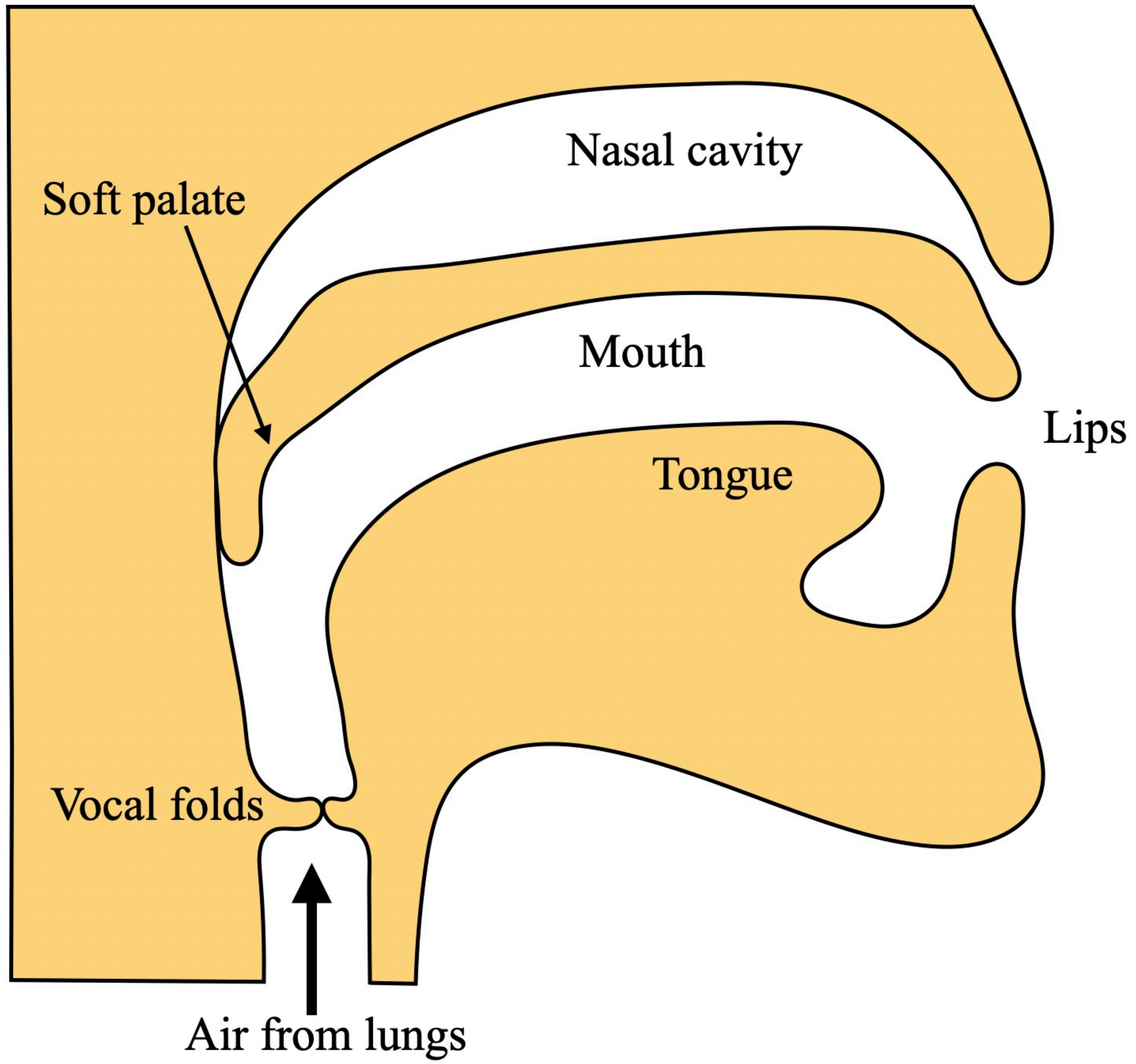

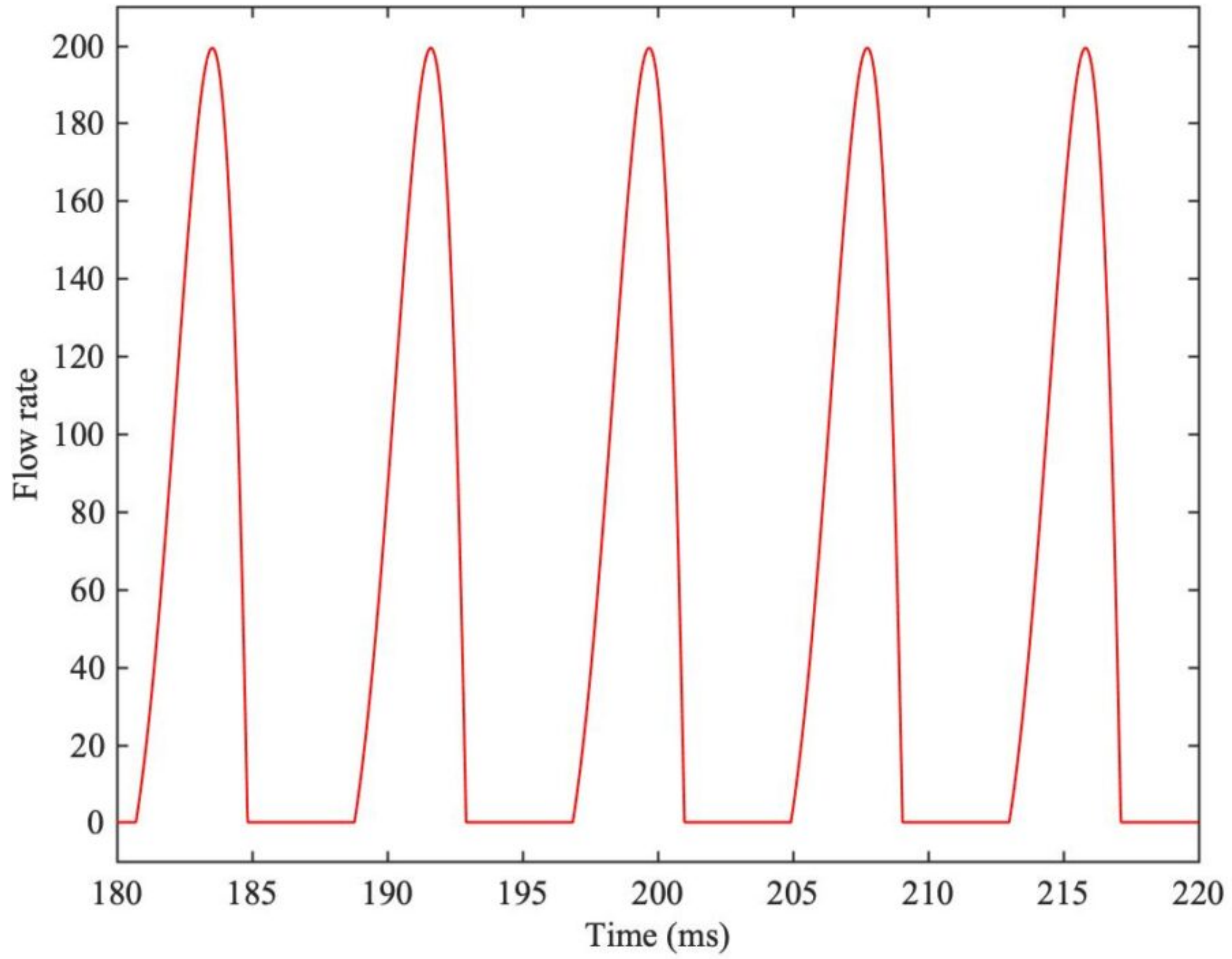

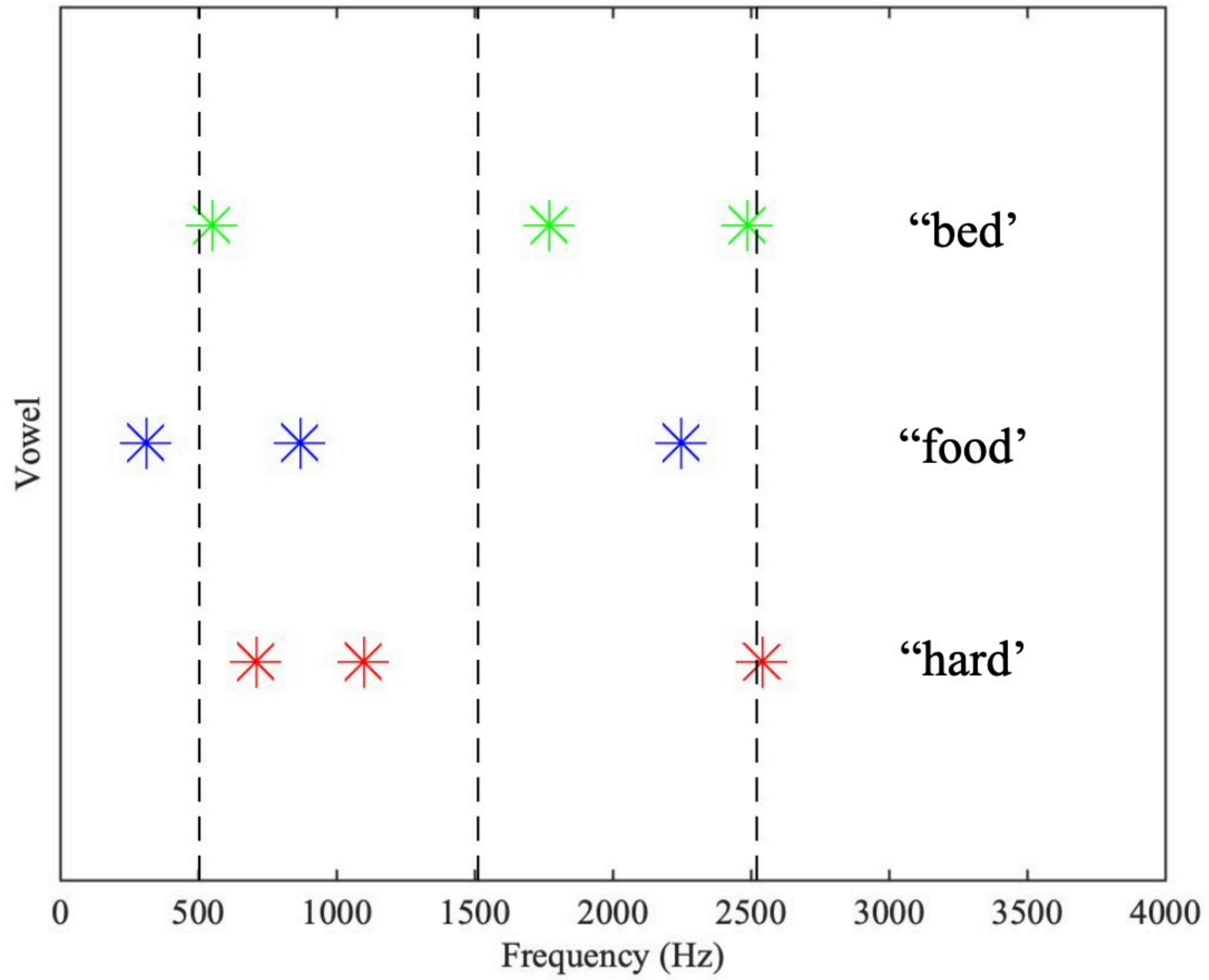


EUPHONICS
The science of musical instruments
For more, see euphonics.org