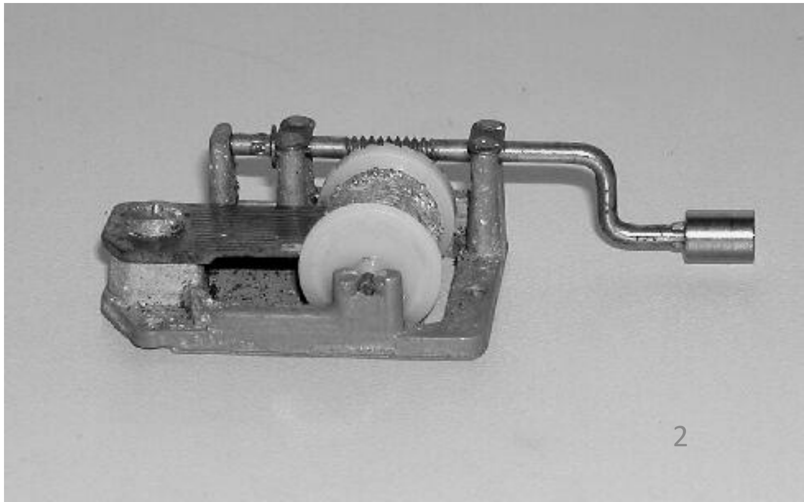
Flue instruments

- Sound source
- Acoustics

Avraham Hirschberg=Avrahamico=Mico

Research at TU/e

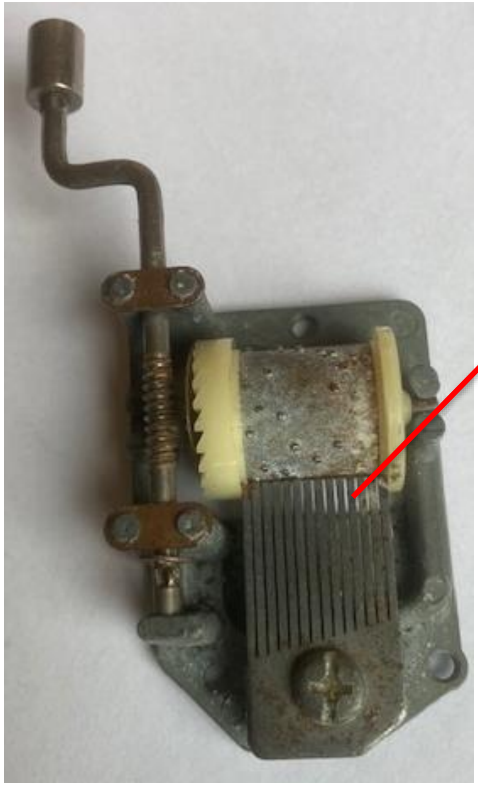
Bram Wijnands
Benoit Fabre
Marc-Pierre Verge
Sylvie Dequand



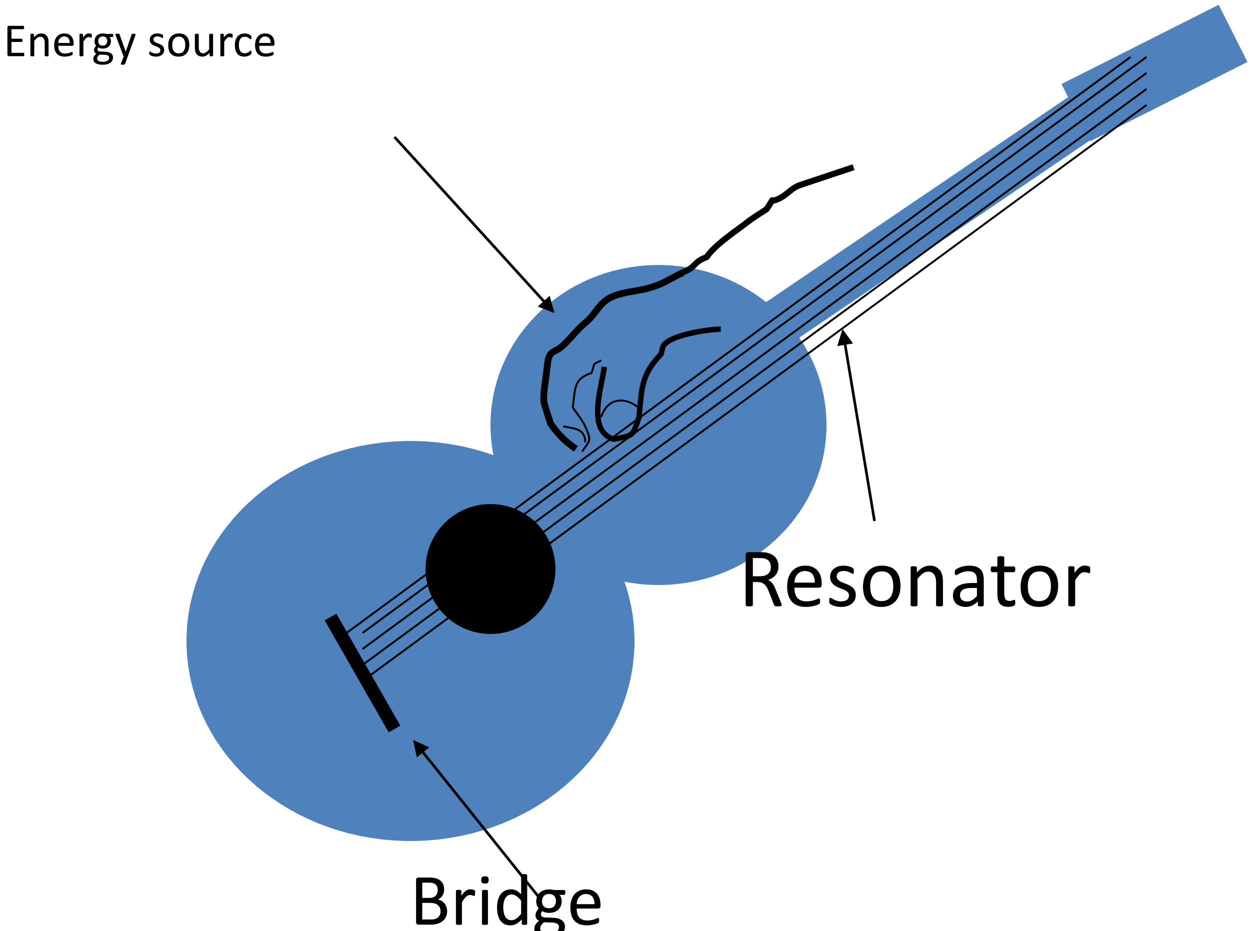
Source of sound (Wall vibration)

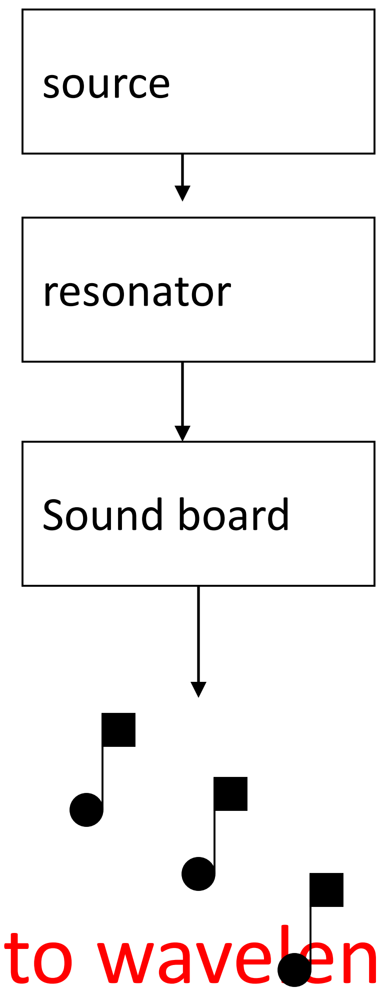
-Sound source
 in musical box is very
inefficient.

-Why?



Musical Instrument





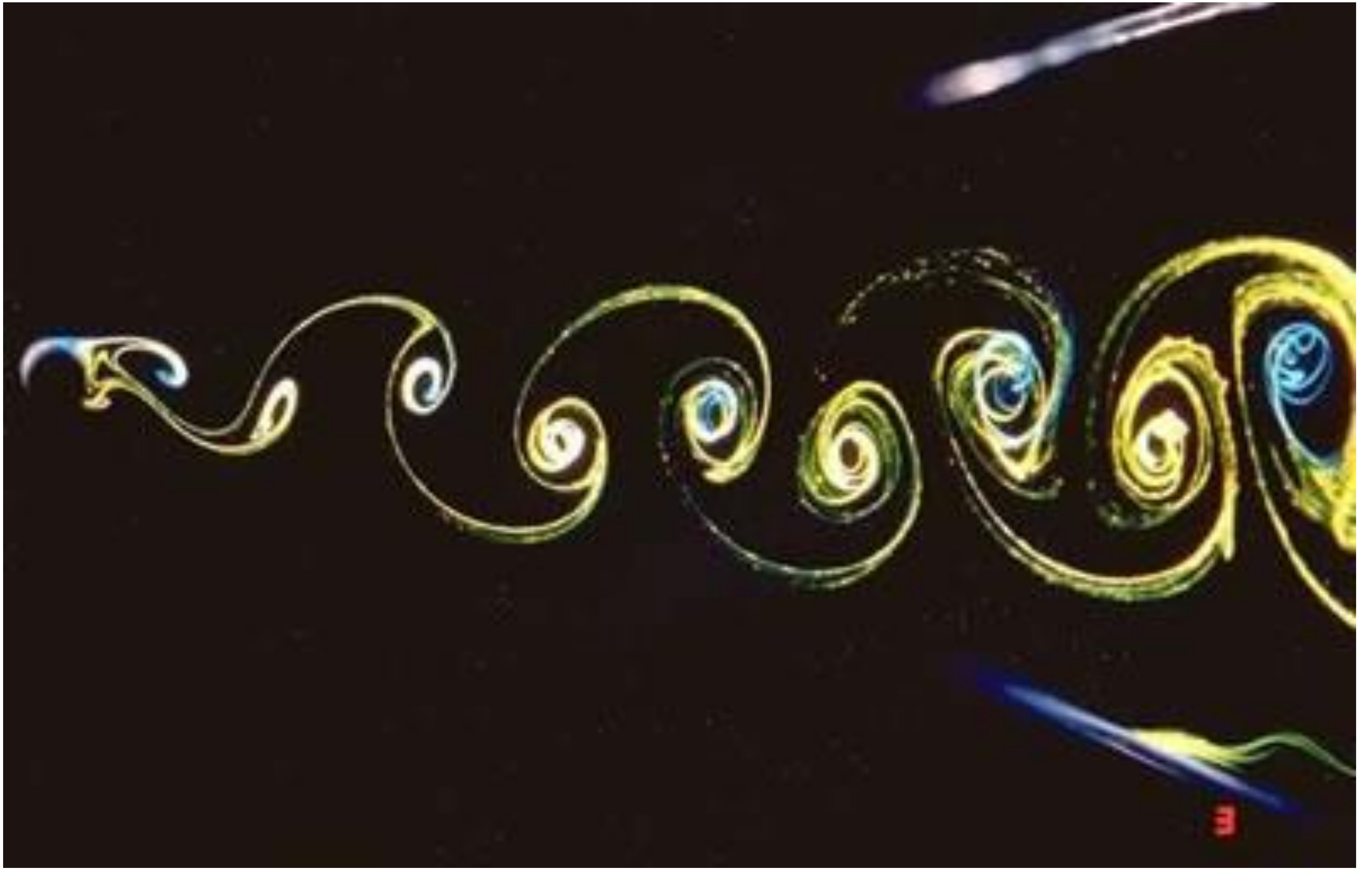
Sound board large compared to wavelength

Aeolian sound sources:
Voice of the wind

-The sound is produced by an unsteady flow without wall vibration.

-Whistling of cylinder in a cross flow…

Lift force:

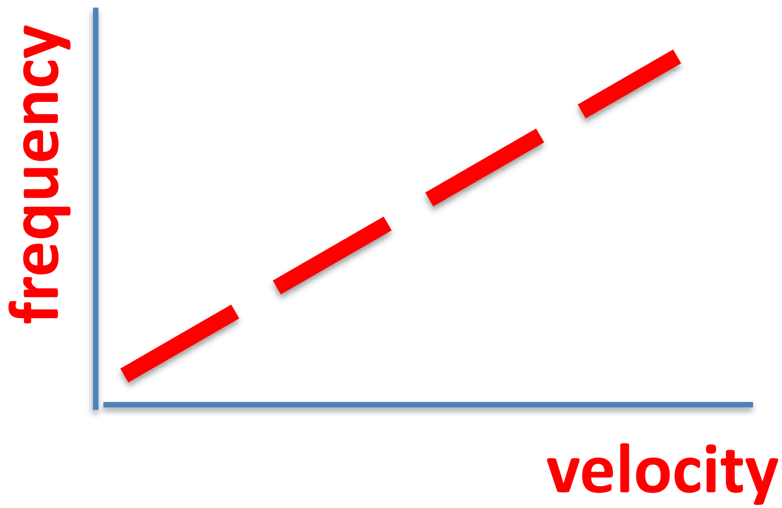


http://www.onera.fr/photos-en/tunnel/images/255551-von-karman.jpg

The whistling frequency f is proportional to the flow velocity U:

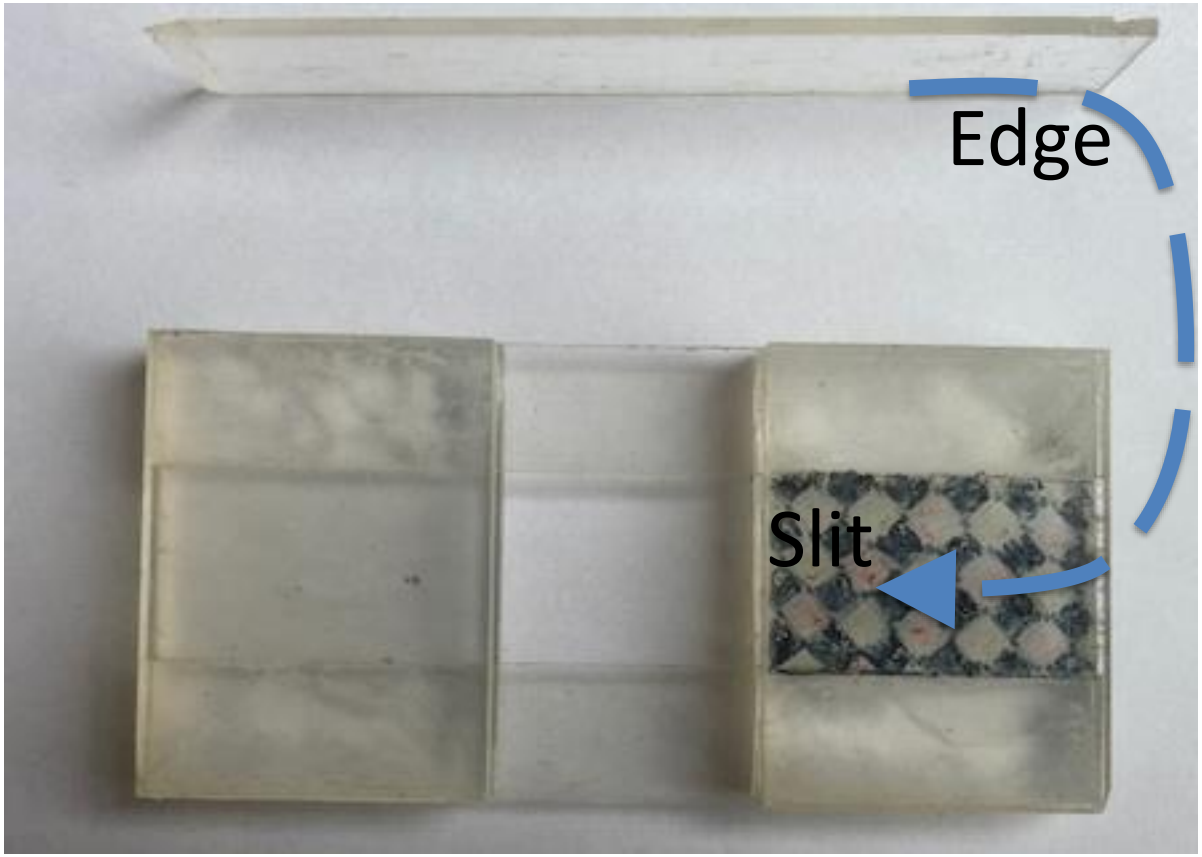
Strouhal number

$$St = \frac{fD}{U} \text{ » } 0.2$$



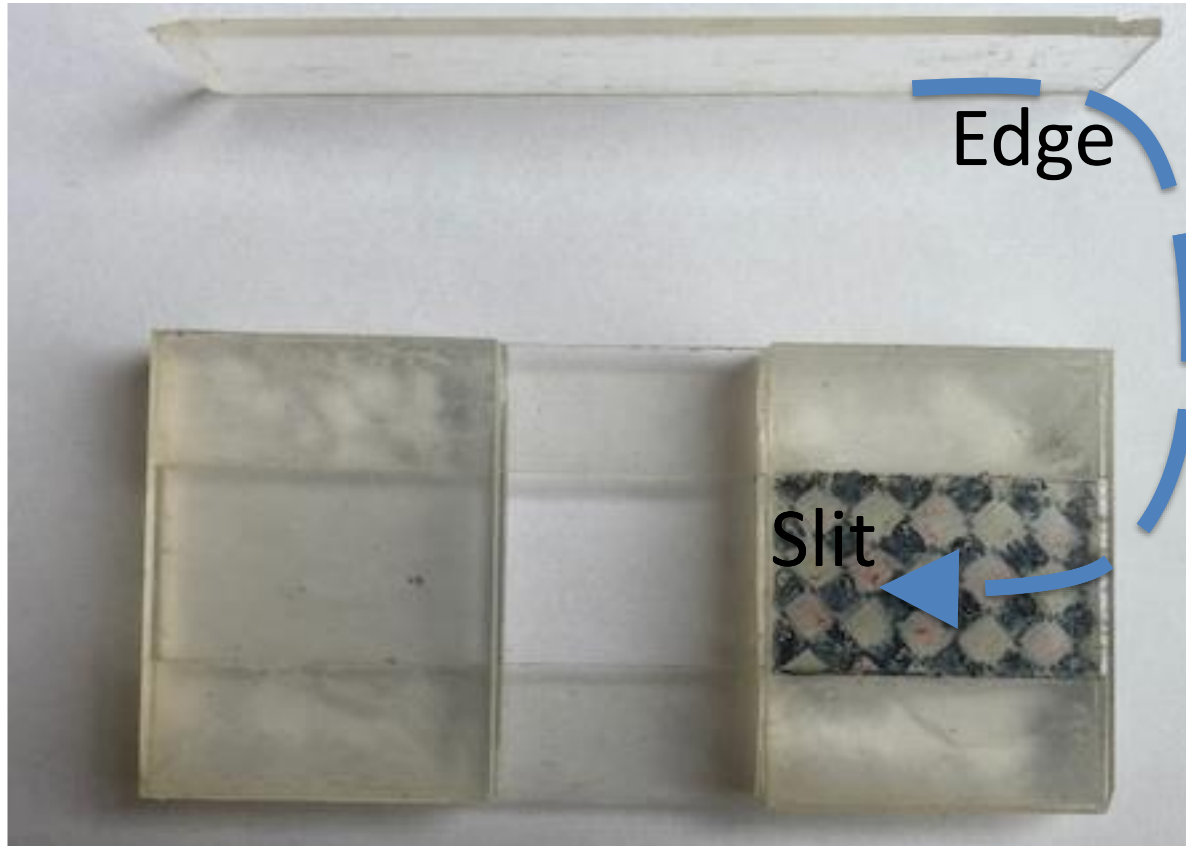
Edge tone

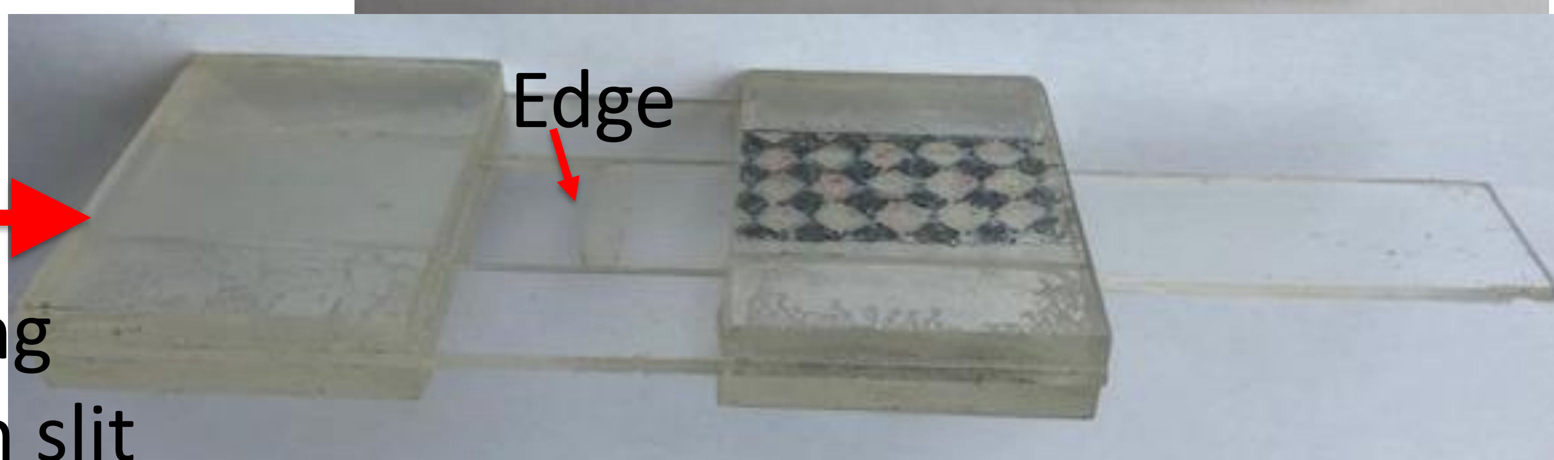
Place edge in slit



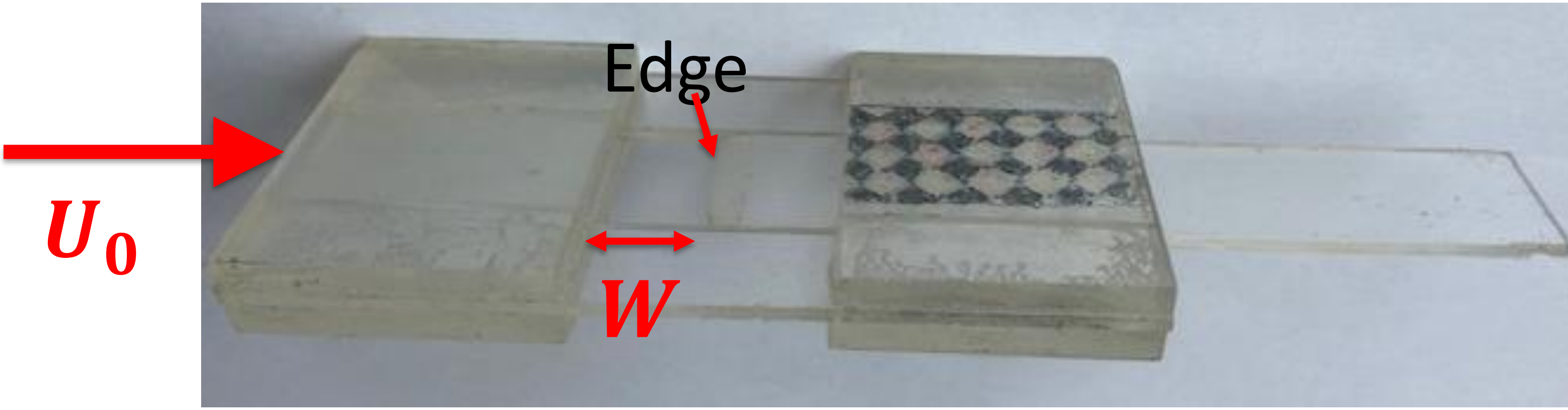
Edge tone

Place edge in slit



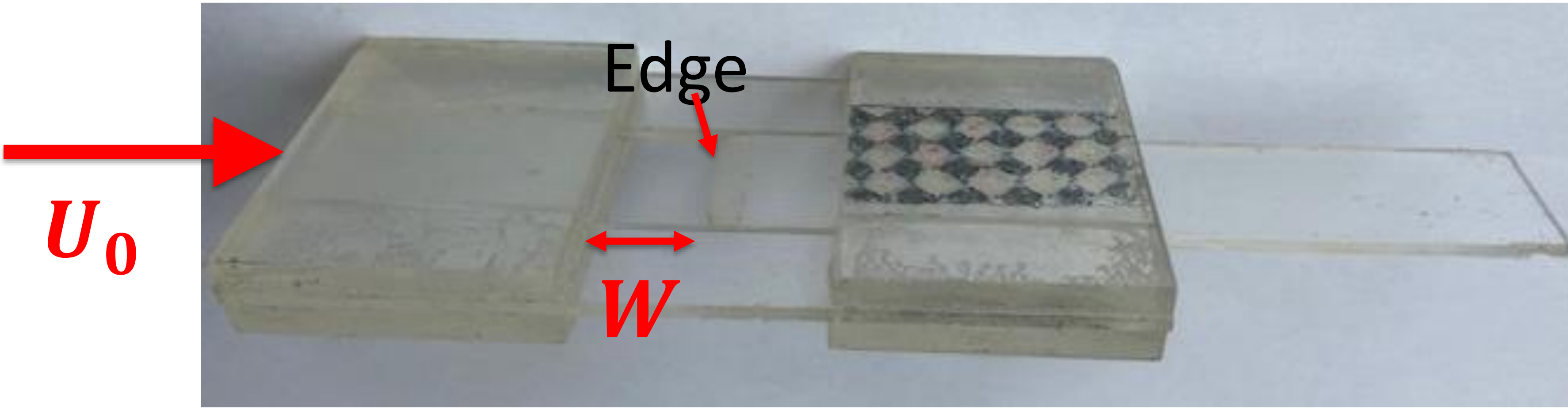


Blowing
Trough slit



-Pitch proportional to flow velocity
(constant Strouhal number)

$$St_W = \frac{fW}{U_0}$$



-Pitch proportional to flow velocity
(constant Strouhal number)

$$St_W = \frac{fW}{U_0}$$

$$U_0 \approx \sqrt{\frac{2\,P_{mouth}}{\rho_0}}$$ **Bernoulli**

Visualisation of

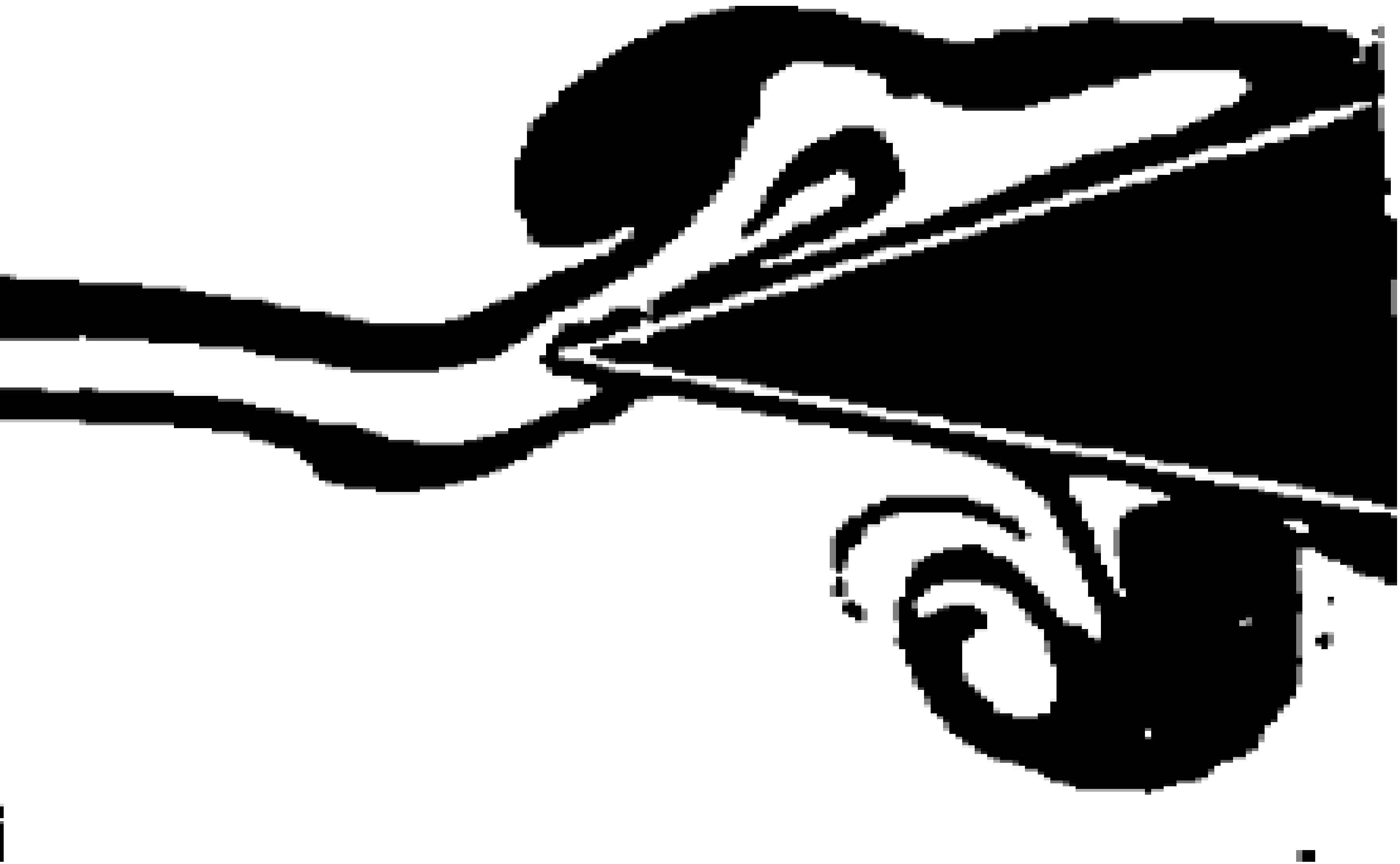
edge-tone oscillation

in water

Kaykayoglu and Rockwell

(JFM 1986)


U_0



Visualisation of
edge-tone oscillation
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Kaykayoglu and Rockwell
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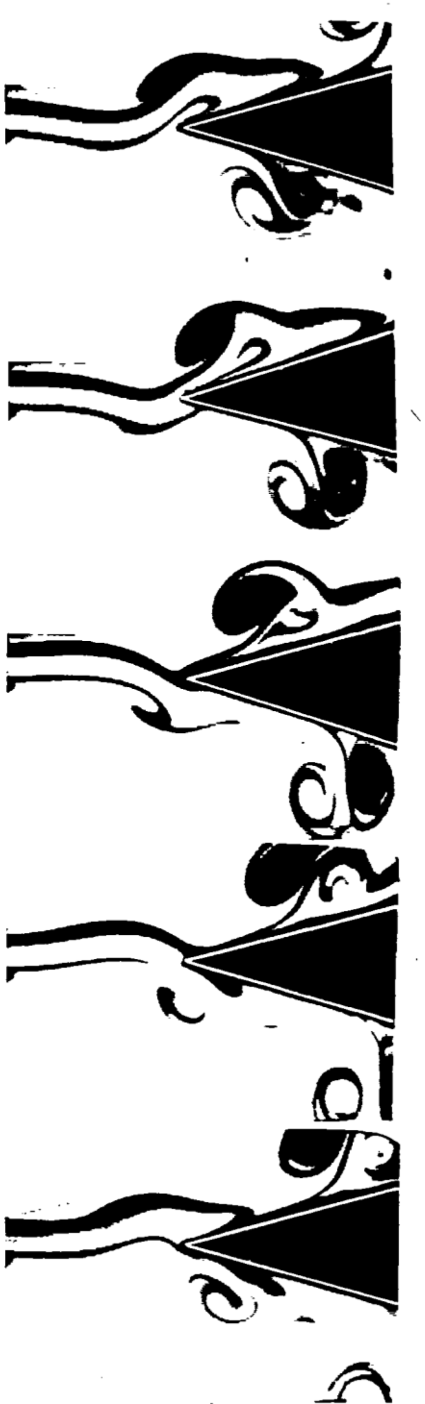
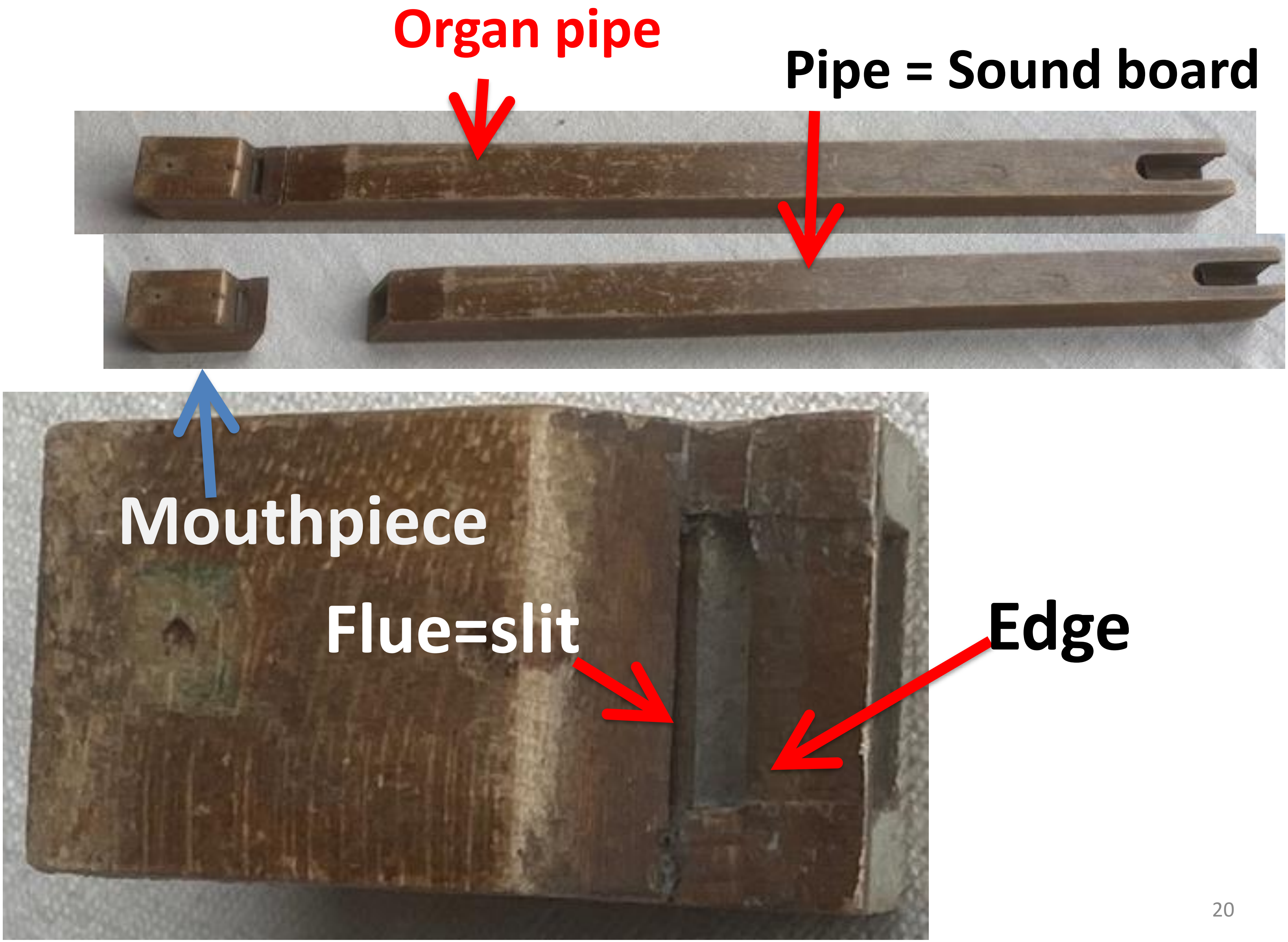
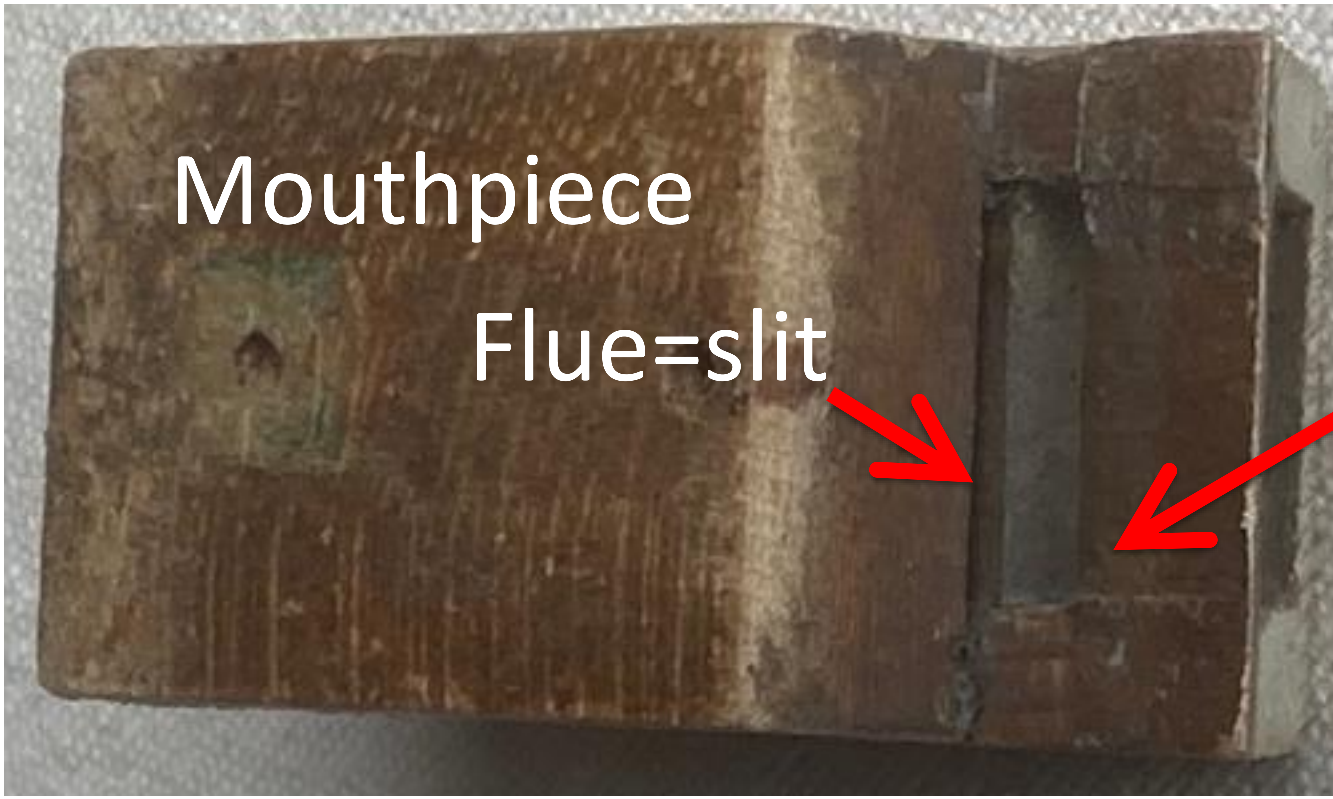



Organ pipe
Pipe = Sound board
Mouthpiece
Flue=slit
Edge

Organ pipe mouthpiece



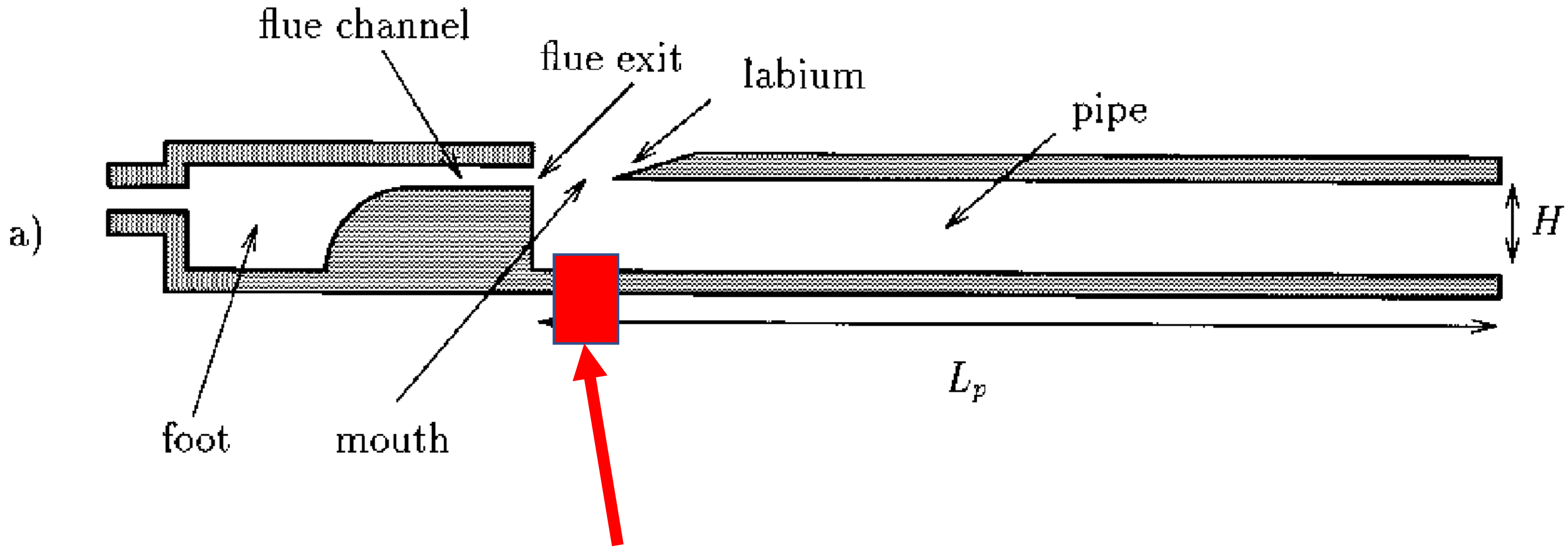
Edge

Edge-tone

Organ pipe

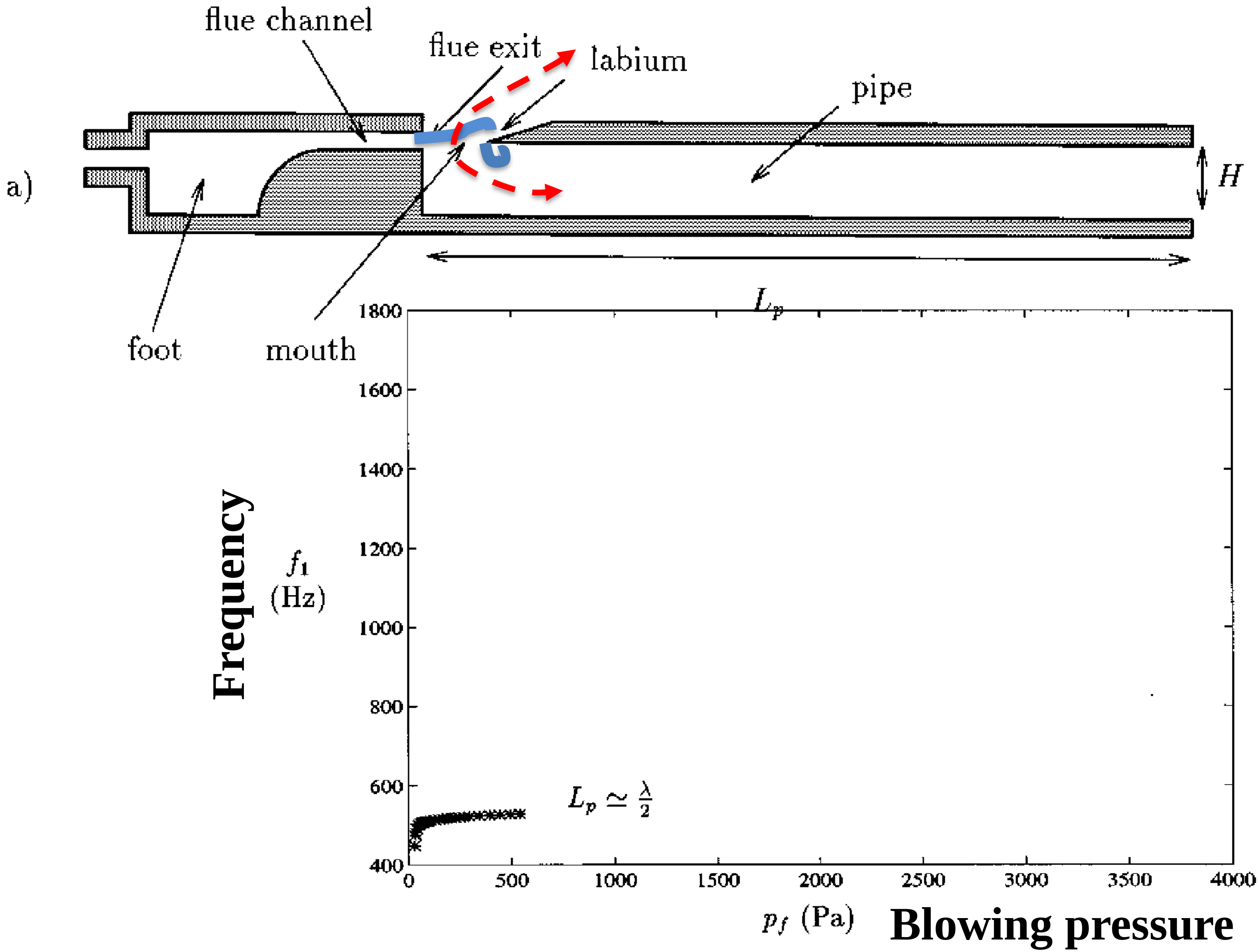
Mouthpiece
(sound source)

Pipe = Sound board
and Resonator



Microphone

Measurements on similar organ pipe

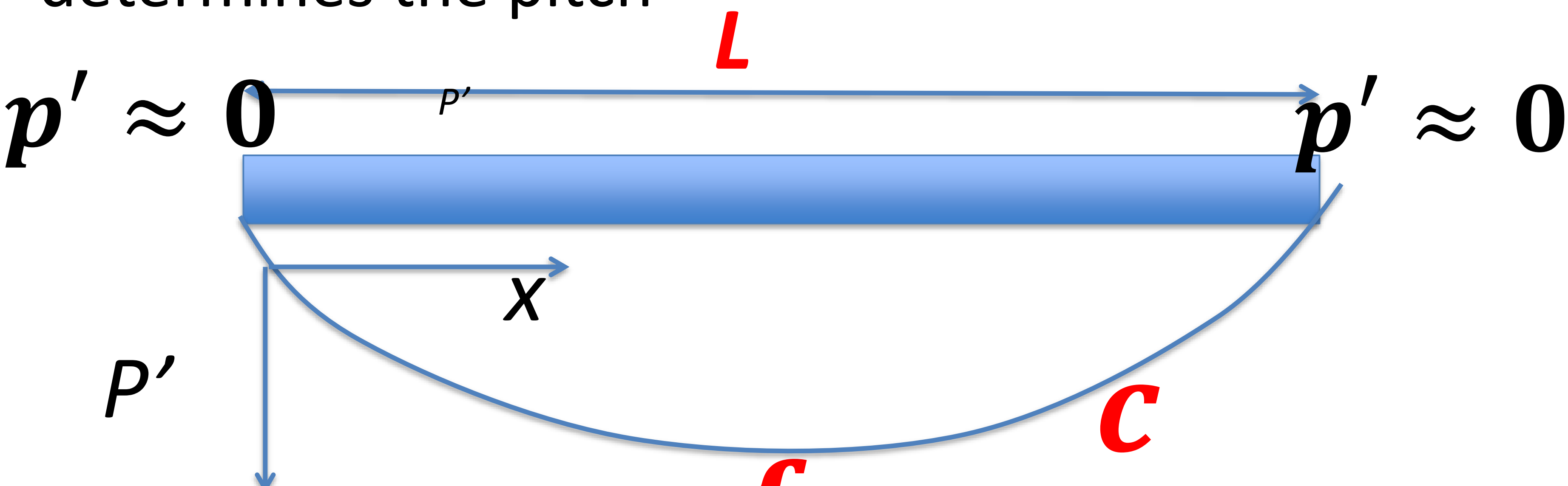


flue channel
flue exit
labium
pipe
a)
H
L_p
foot
mouth
Frequency
f_1 (Hz)
1800
1600
1400
1200
1000
800
600
400
0
500
1000
1500
2000
2500
3000
3500
4000
$L_p \simeq \frac{\lambda}{2}$
p_f (Pa)
Blowing pressure

Sound much louder

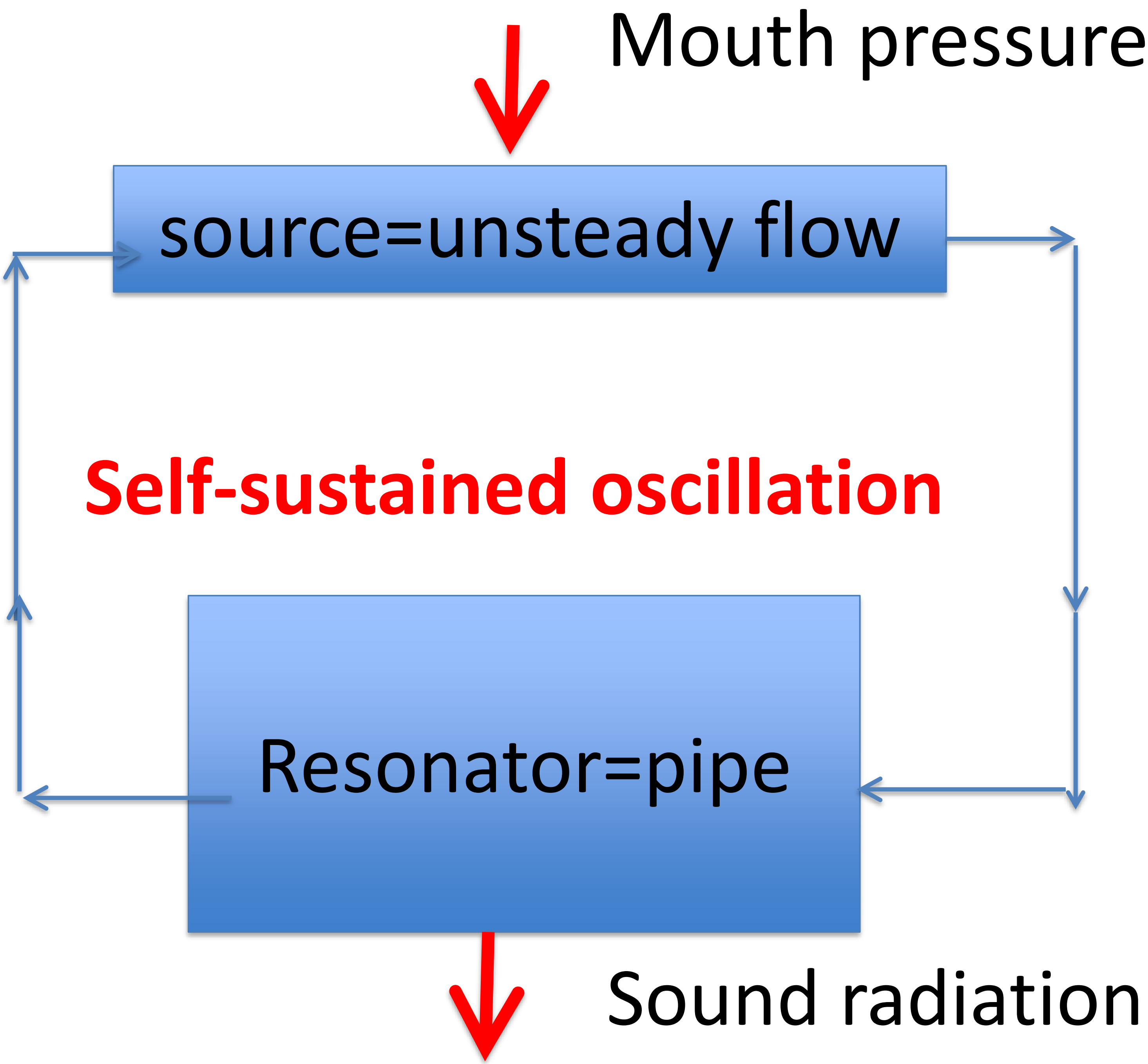
Standing plane waves in pipe determine frequency

Length L of “Resonator (Sound board)” determines the pitch



$$f_1 \approx \frac{c}{2L}$$

C=340 m/s

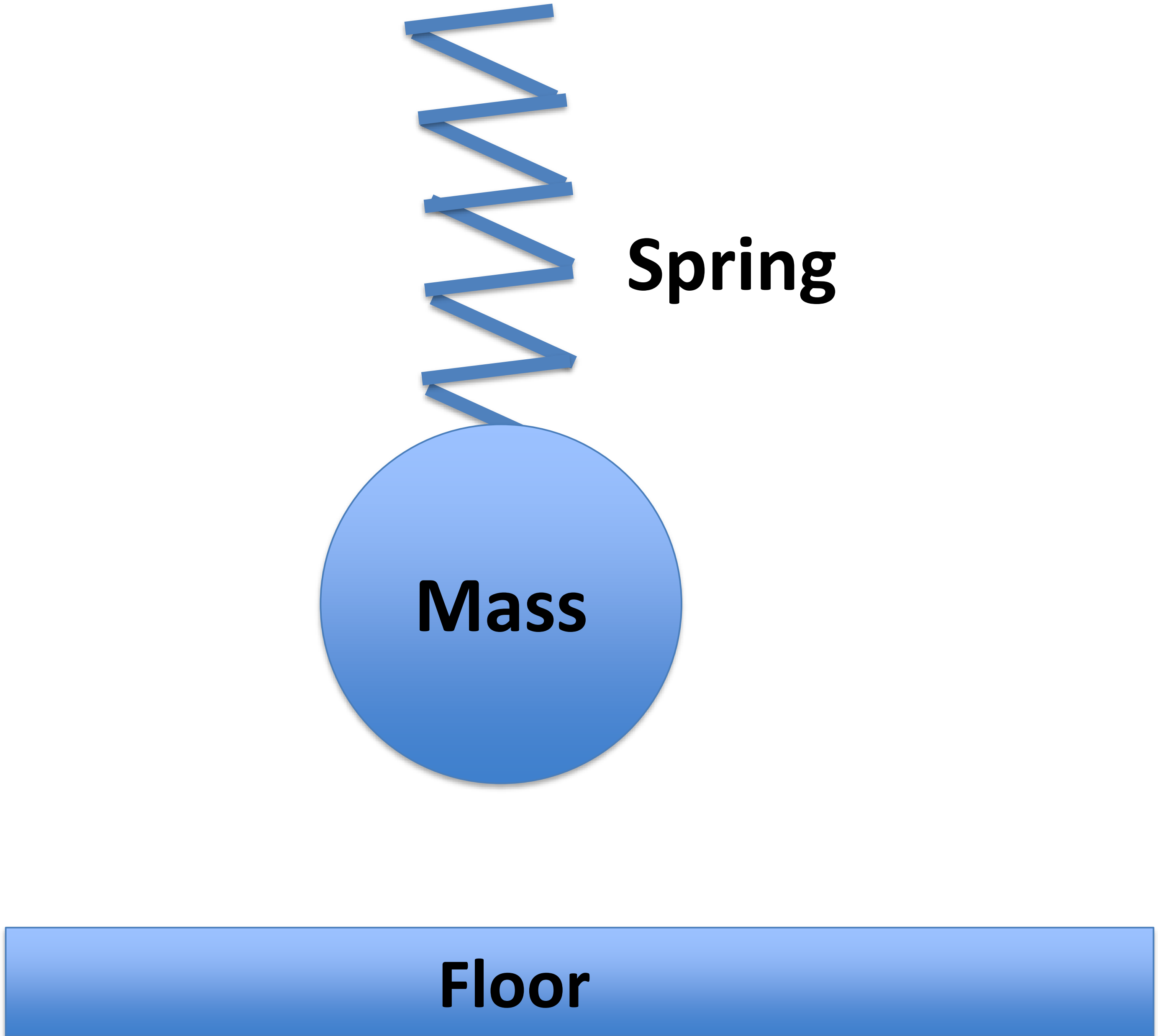

Mouth pressure
source=unsteady flow
Self-sustained oscillation
Resonator=pipe
Sound radiation

NON-LINEARITY ESSENTIAL

TO REACH

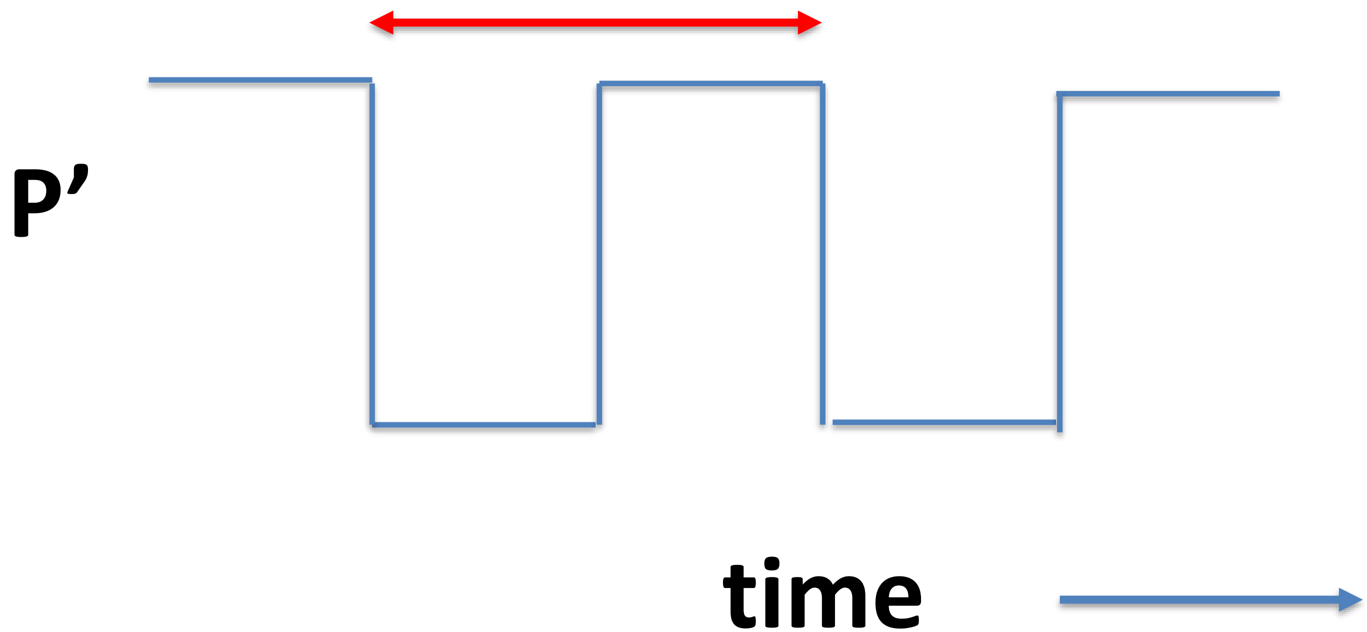
STEADY OSCILLATION AMPLITUDE

Amplitude limiting non-linearity?

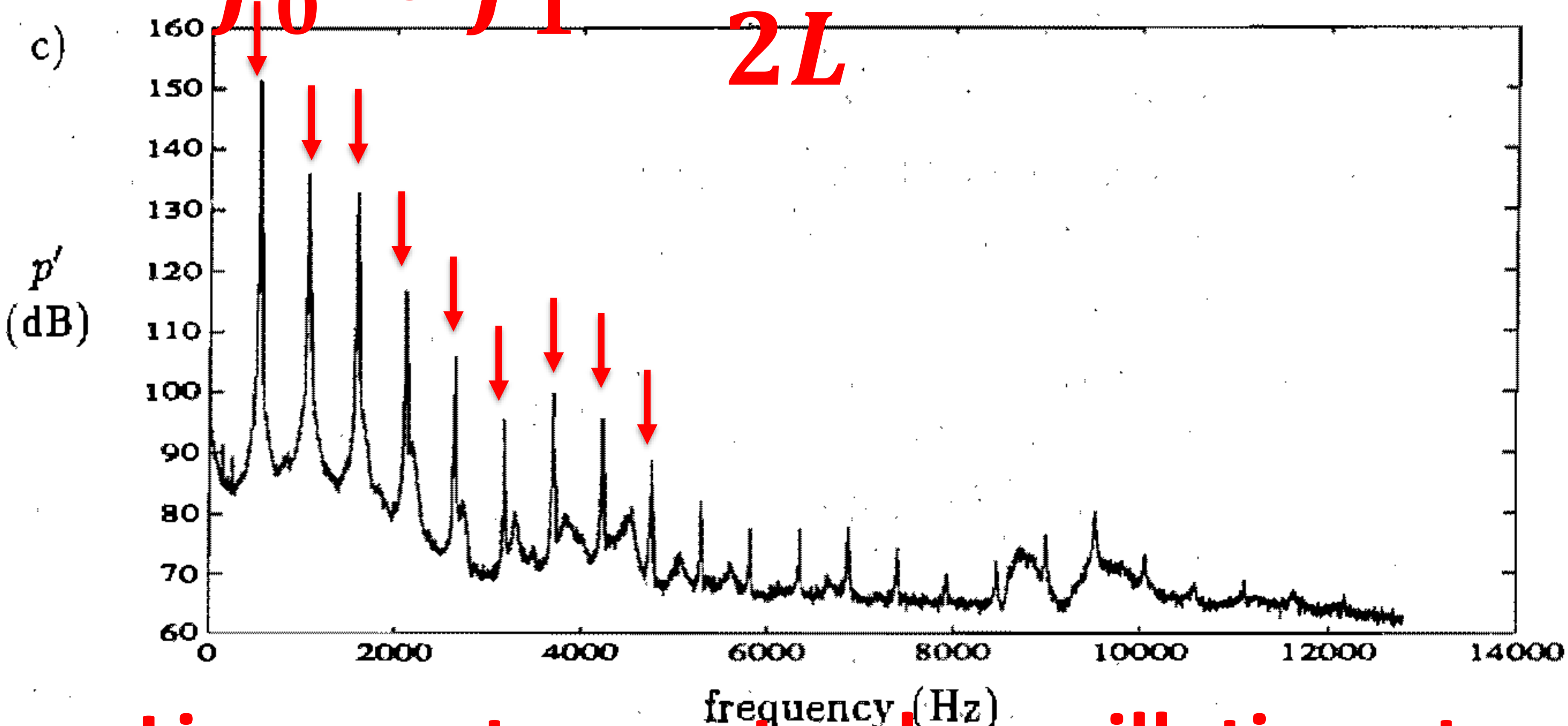


Non-linearity generates higher harmonics

$$T_0 = \frac{1}{f_0}$$

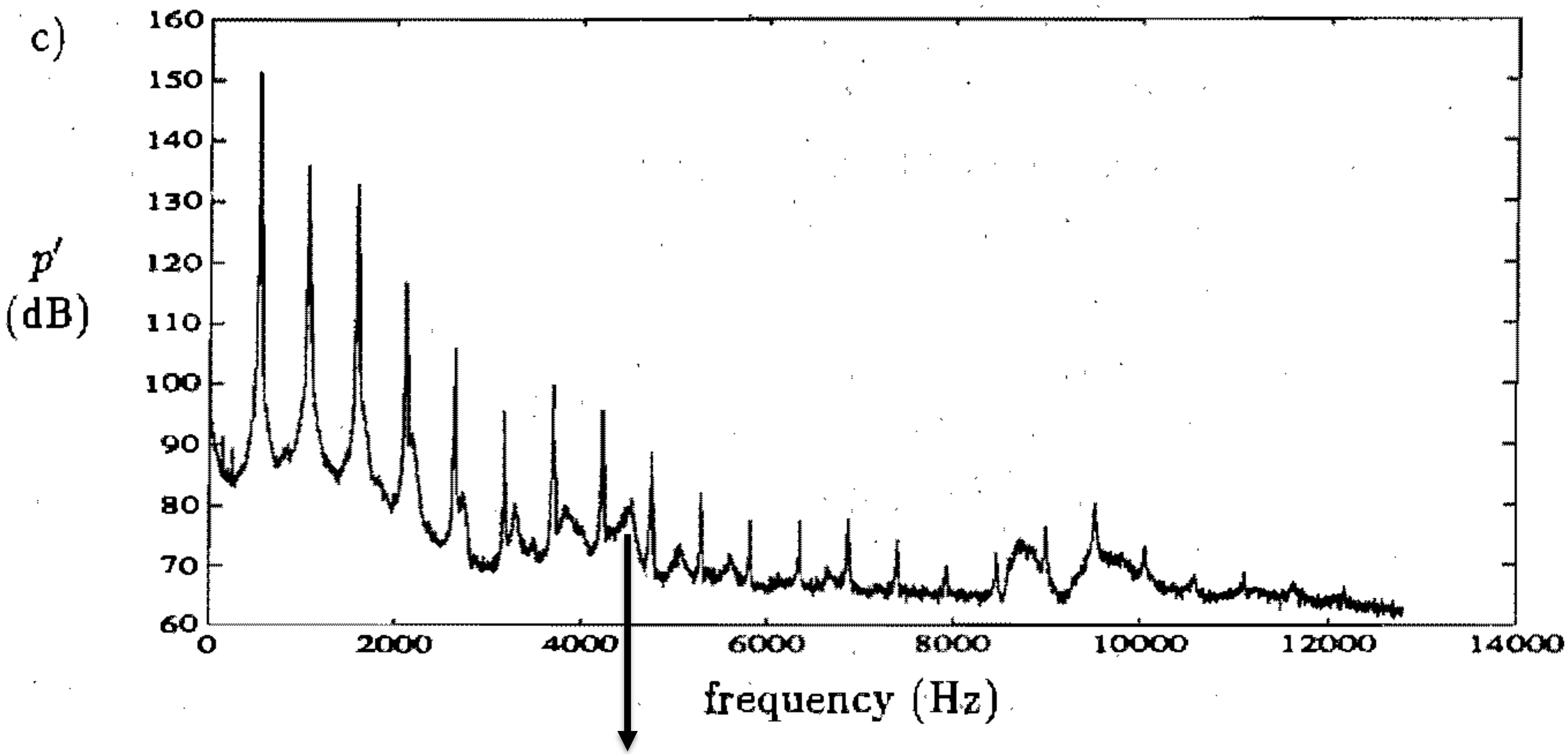


$$f_0 \approx f_1 = \frac{c}{2L}$$

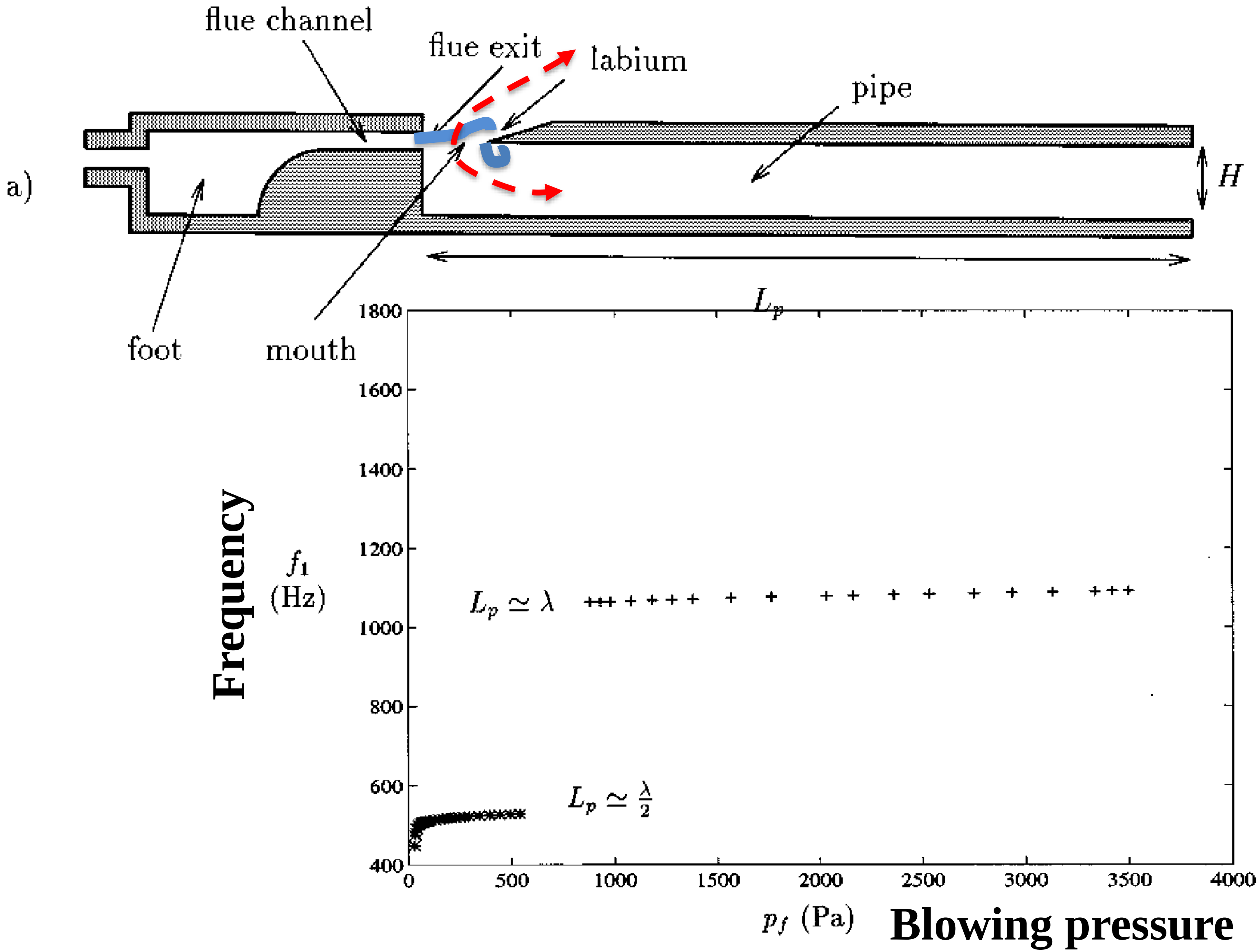


Line spectrum: steady oscillation at frequency f_0 with harmonics at nf_0

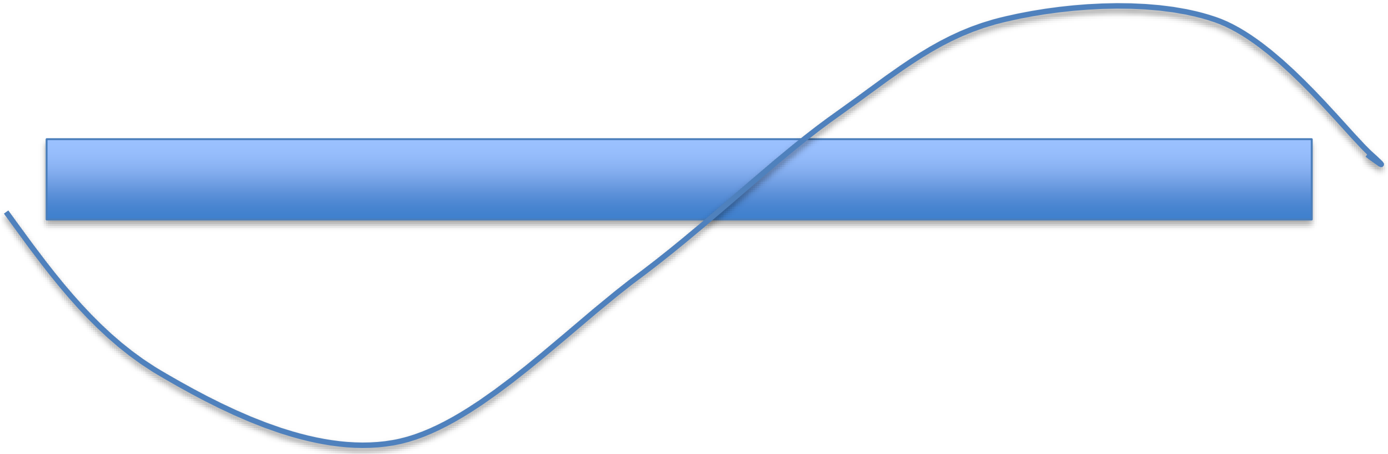
The higher harmonics are essential for the perception of musical sound (quality).



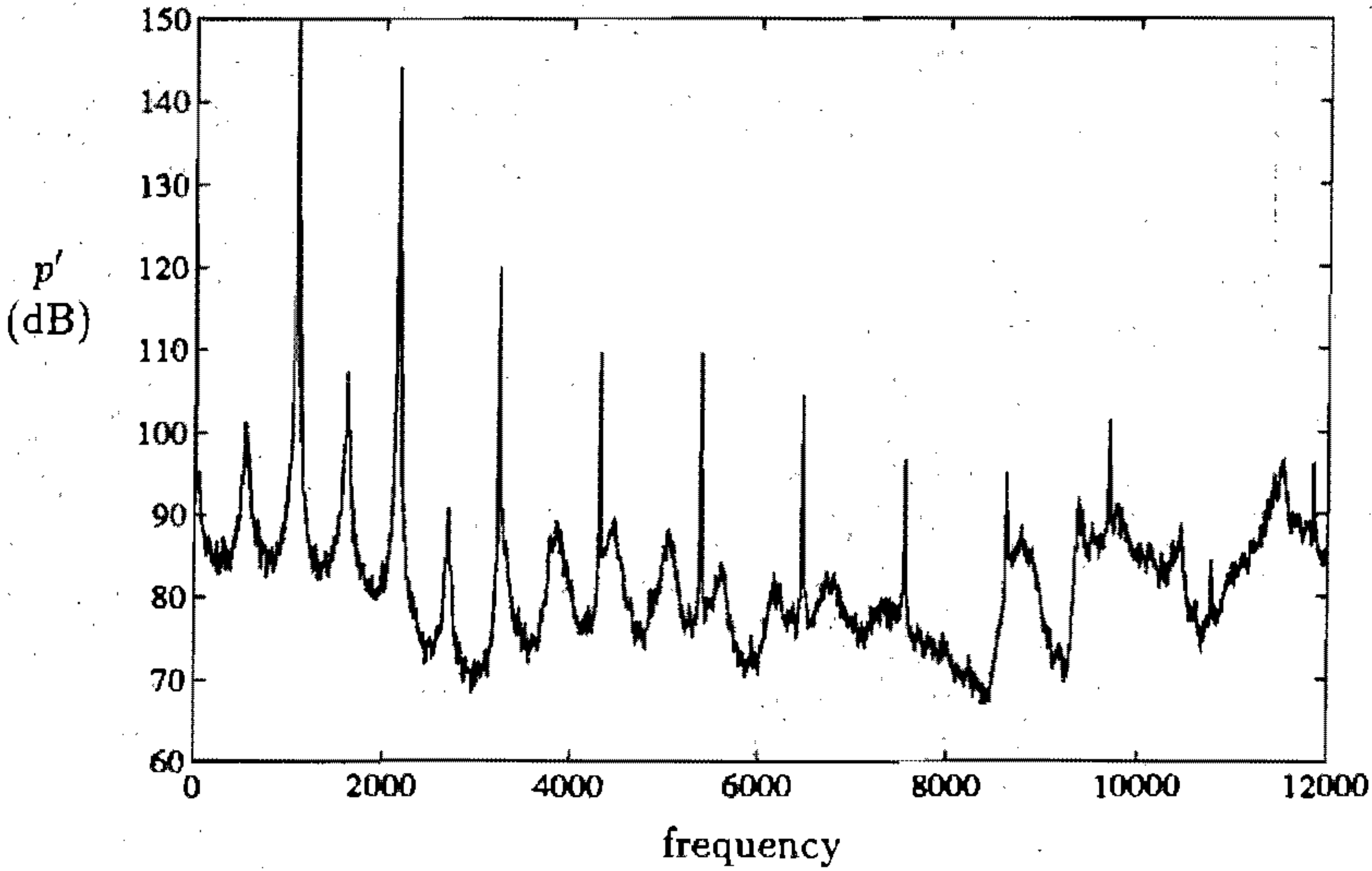
Broadband noise spectrum due to turbulence



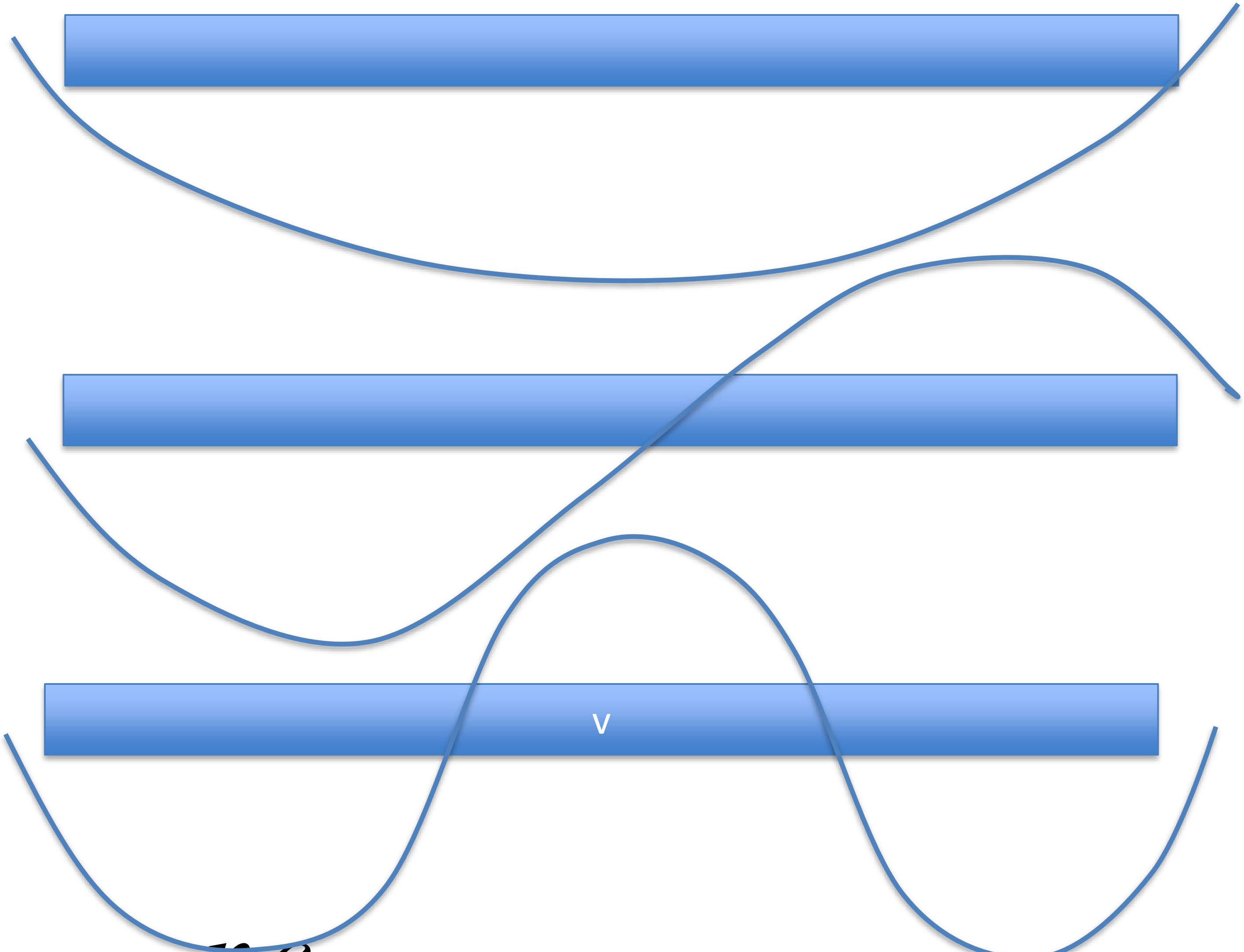
Blowing pressure



$$f_0 \approx f_2 = \frac{c}{L}$$

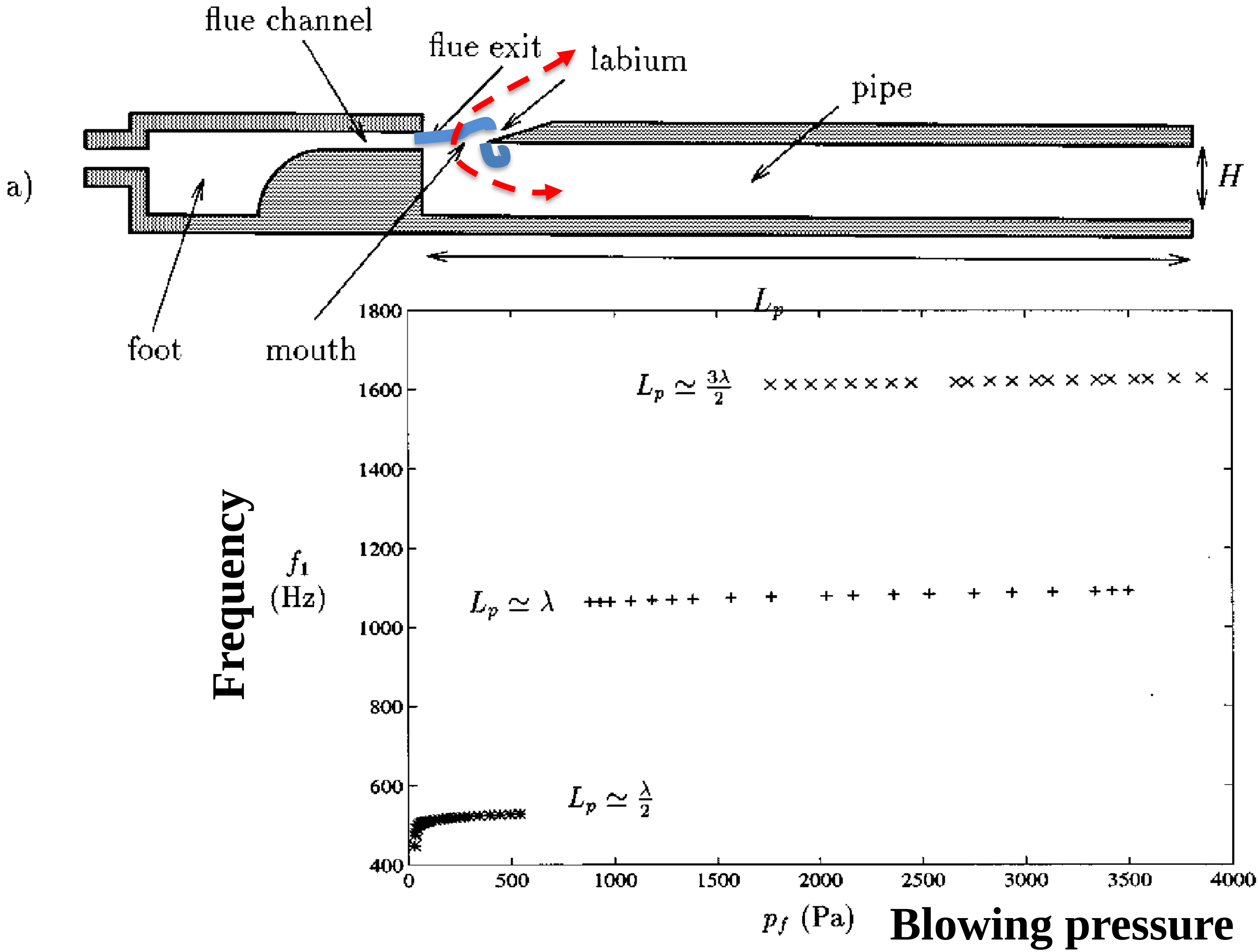


150
140
130
120
110
100
90
80
70
60
p'
(dB)
0
2000
4000
6000
8000
10000
12000
frequency

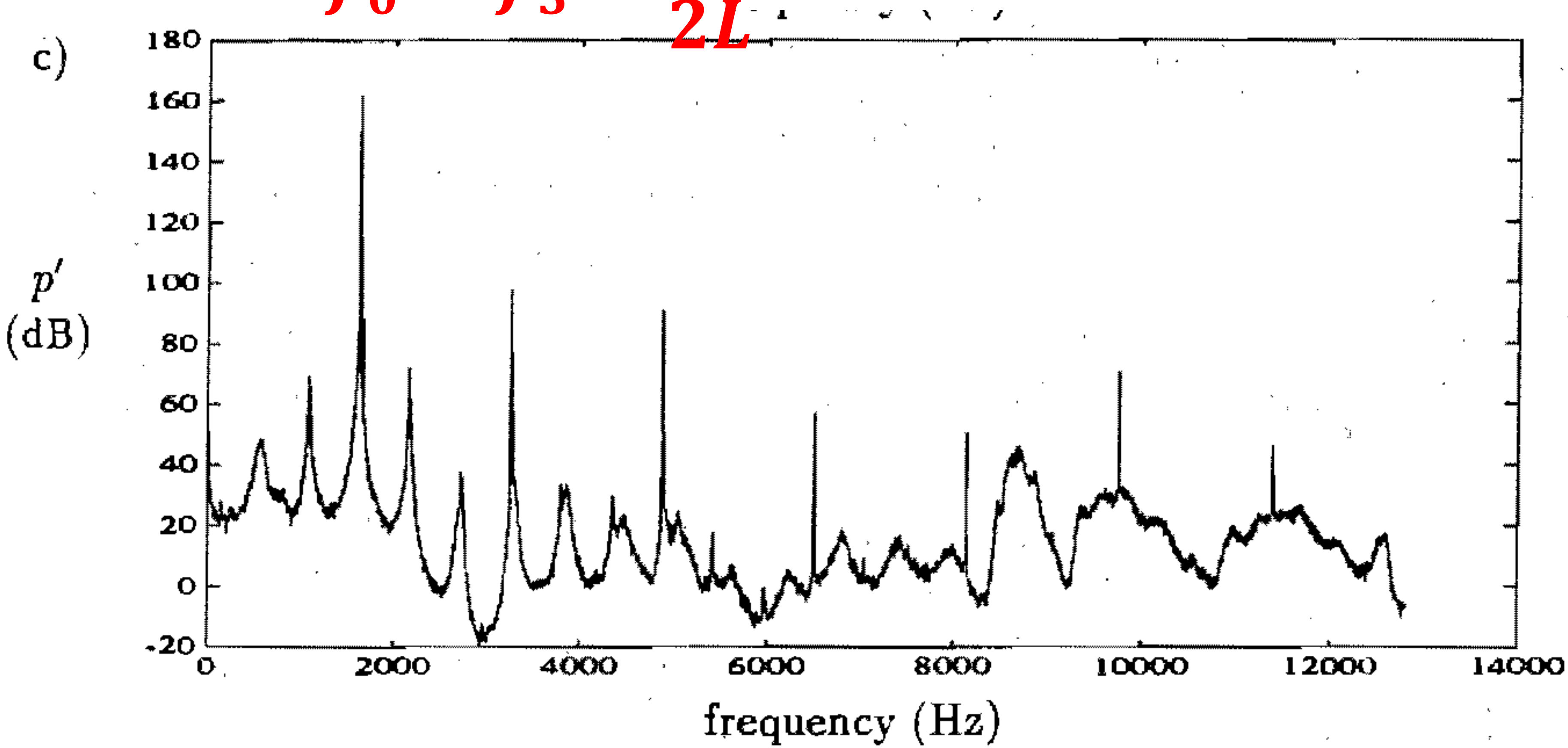


$$f_n \approx \frac{nc}{2(L+2d)} \;;\; n = 1,2,3\ldots$$

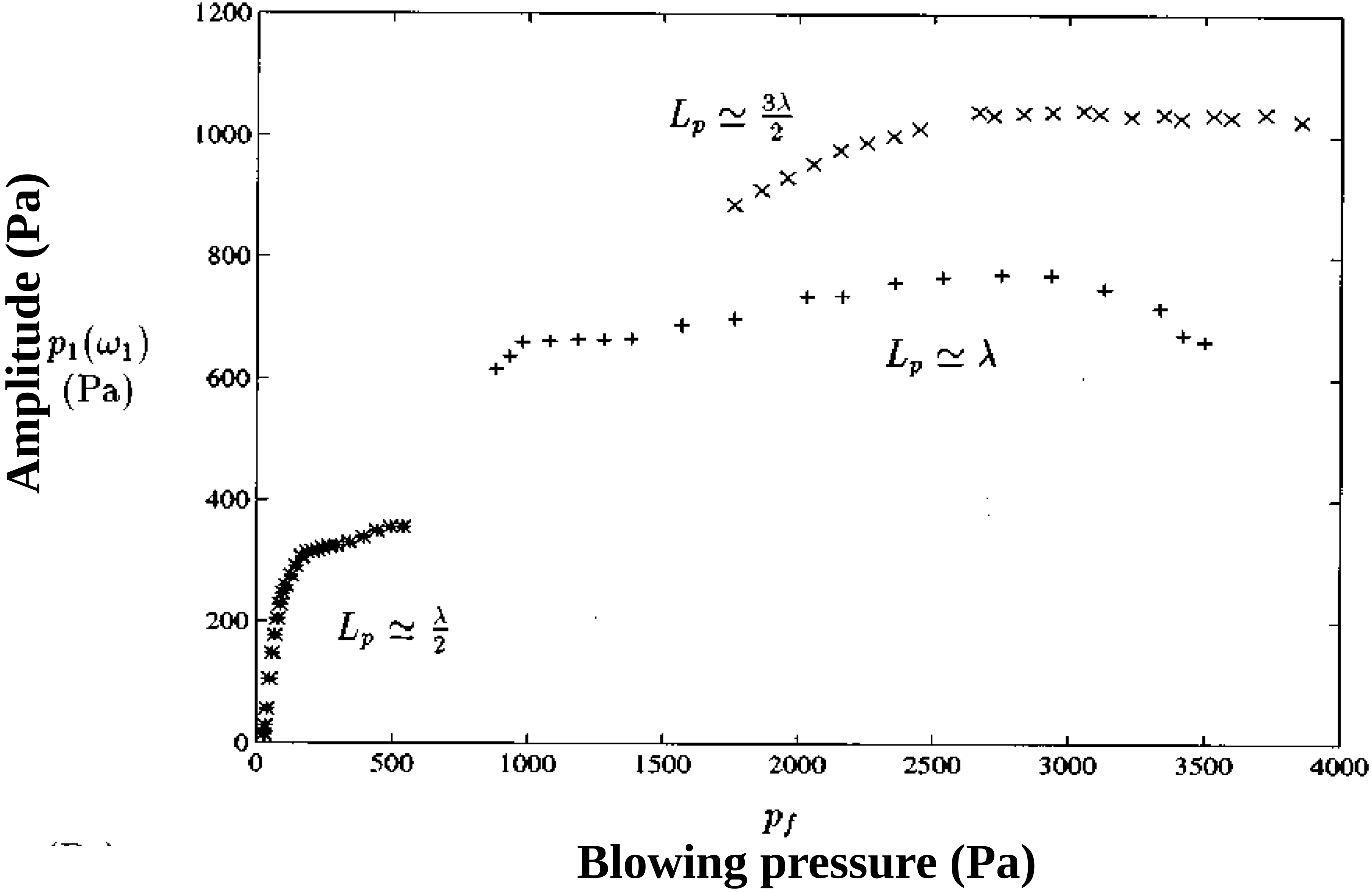
(open-open) pipe


flue channel
flue exit
labium
pipe
a)
H
foot
mouth
L_p
Frequency
f_1 (Hz)
1800
1600
1400
1200
1000
800
600
400
$L_p \simeq \frac{3\lambda}{2}$
$L_p \simeq \lambda$
$L_p \simeq \frac{\lambda}{2}$
0
500
1000
1500
2000
2500
3000
3500
4000
p_f (Pa)
Blowing pressure

$$f_0 \approx f_3 = \frac{3c}{2L}$$

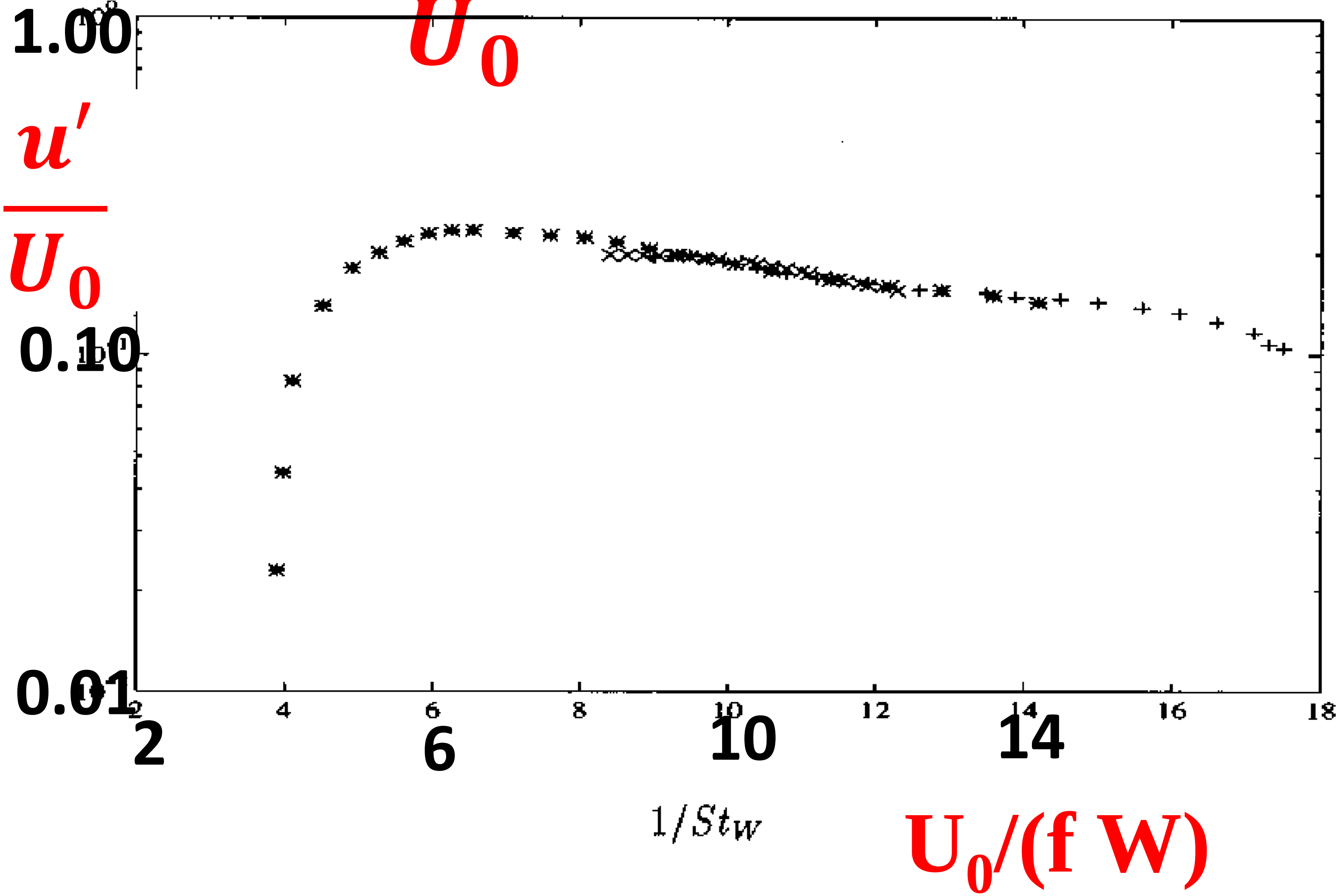


Acoustic pressure amplitude *p'* increases with blowing pressure

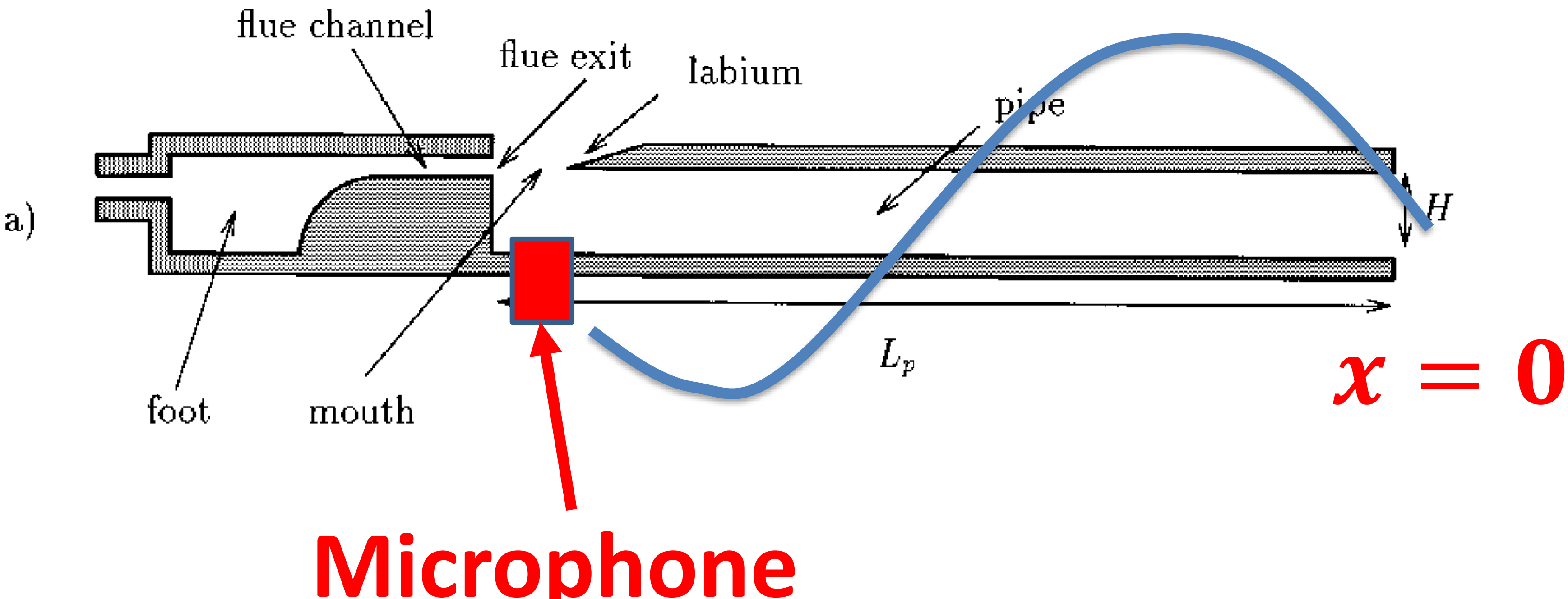


Amplitude (Pa)
$p_1(\omega_1)$ (Pa)
$L_p \simeq \frac{3\lambda}{2}$
$L_p \simeq \lambda$
$L_p \simeq \frac{\lambda}{2}$
0
200
400
600
800
1000
1200
0
500
1000
1500
2000
2500
3000
3500
4000
p_f
Blowing pressure (Pa)

$$\frac{u'}{U_0} \approx 0.25$$

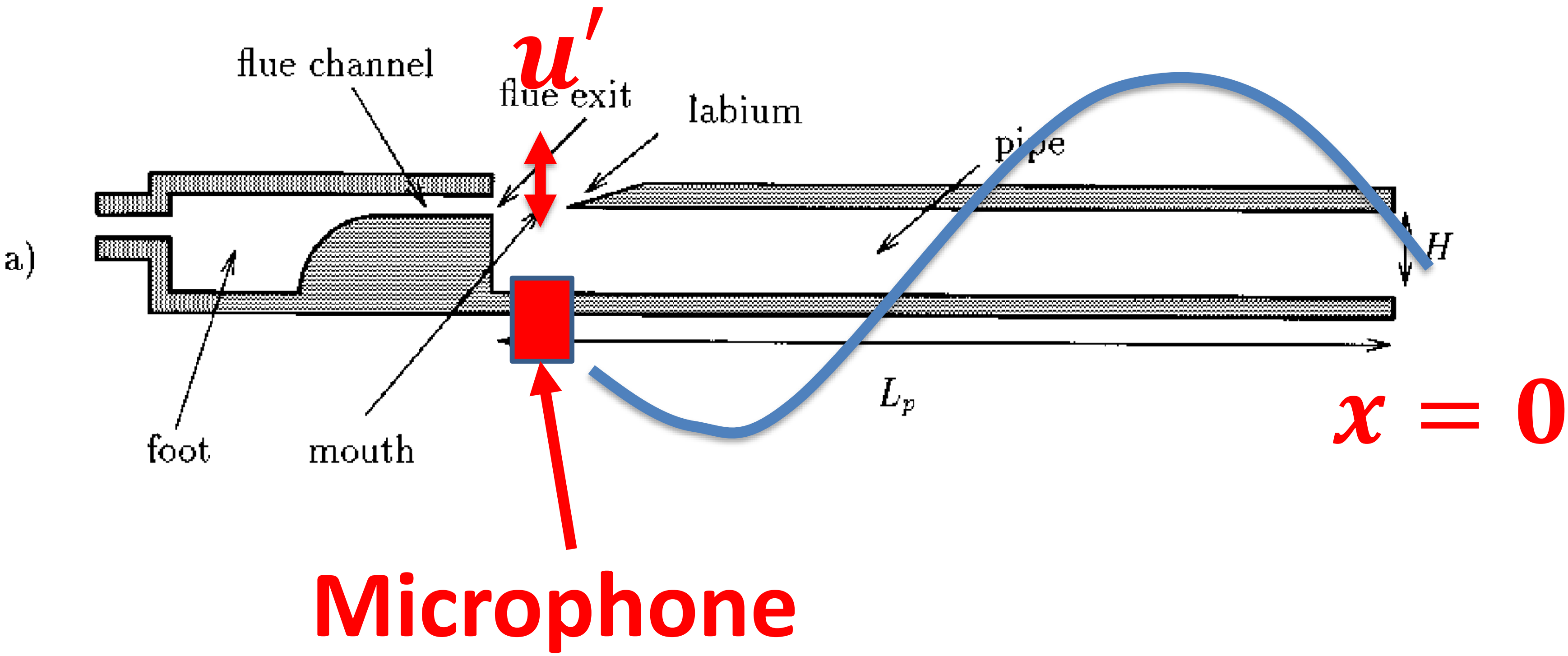


$$p' = \alpha \cos(2\pi f t) \sin\left(\frac{2\pi f x}{c}\right)$$



Plane standing wave model

$$p' = \alpha \cos(2\pi f t) \sin\left(\frac{2\pi f x}{c}\right)$$



$$p' = \alpha \cos(\omega t) \sin\left(\frac{\omega x}{c}\right)$$

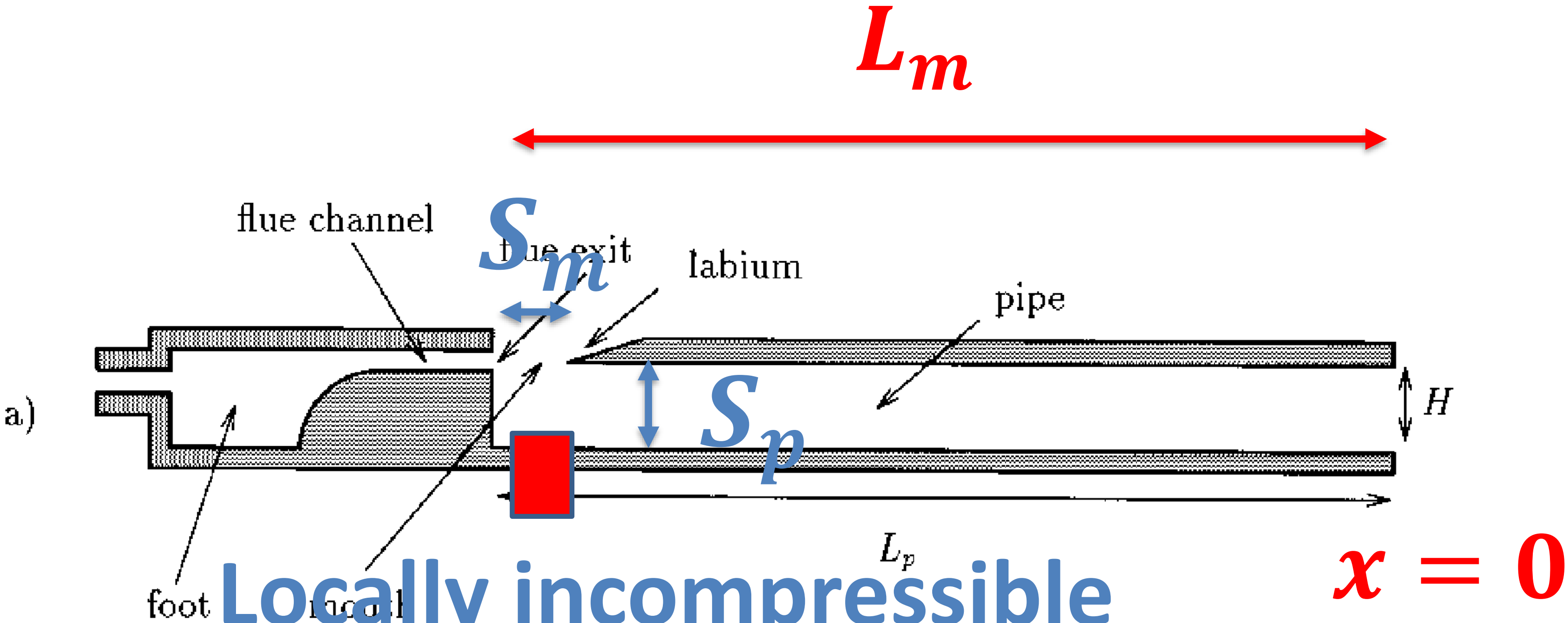
$$\rho \frac{\partial u'_p}{\partial t} = - \frac{\partial p'}{\partial x}$$

$$p' = \alpha \cos(\omega t) \sin\left(\frac{\omega x}{c}\right)$$

$$\rho \frac{\partial u_p'}{\partial t} = -\frac{\partial p'}{\partial x}$$

$$u_p' = -\frac{\alpha}{\rho c} \sin(\omega t) \cos\left(\frac{\omega x}{c}\right)$$

In pipe at the microphone position



Locally incompressible acoustic flow

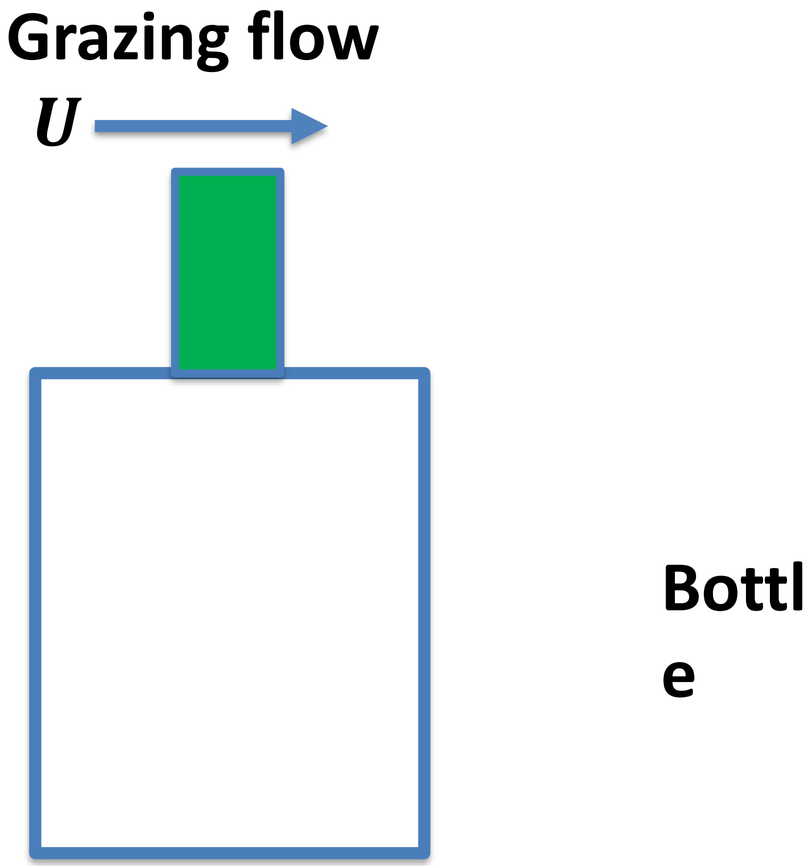
$$S_p u'_p = S_m u'$$

Dimensionless flow velocity (1/Strouhal)

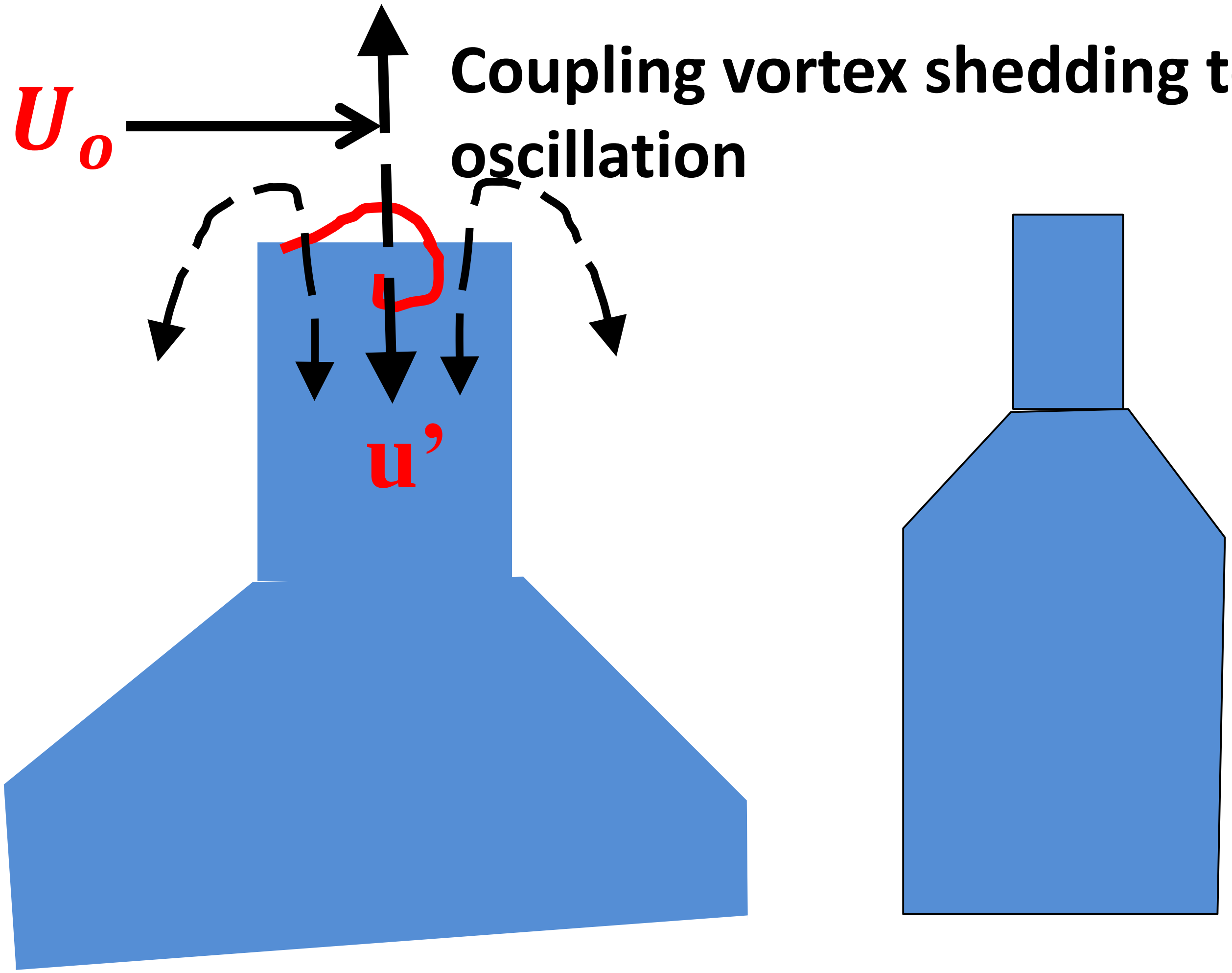
$$\frac{1}{St} = \frac{U_0}{f\,W} = \frac{\sqrt{\frac{2\,P_{mouth}}{r}}}{f\,W}; \quad r = 1.2\ kg\,/\,m^3$$

Dimensionless amplitude (amplitude acoustic velocity/jet velocity)

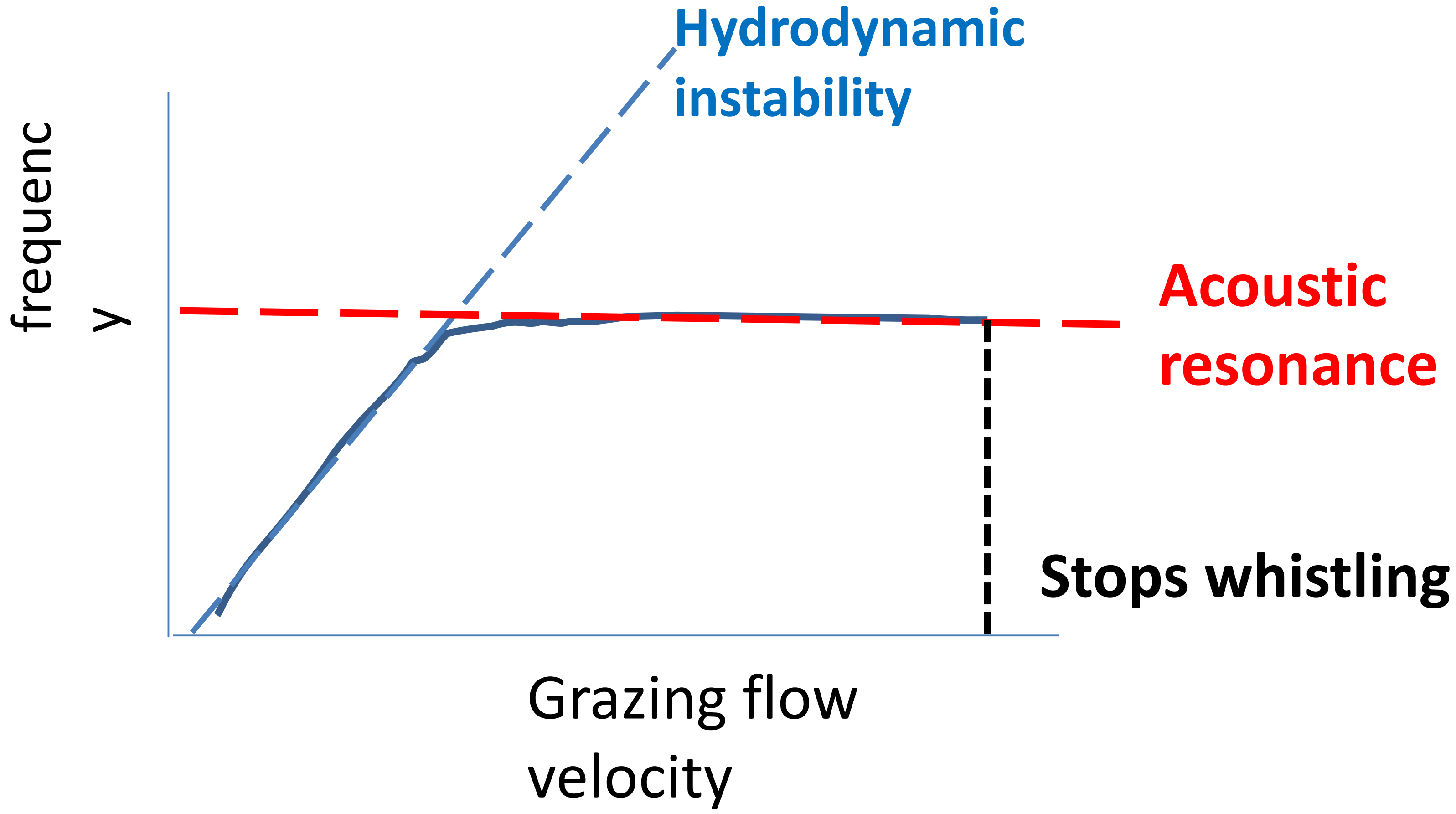
$$\frac{u'}{U_0} = \frac{a}{r\,c\,U_0}\left|\cos\left(\frac{wL_m}{c}\right)\right|\frac{S_p}{S_m}$$


Grazing flow
U
Bottl
e

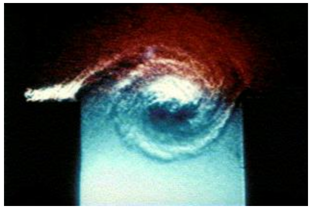
Coupling vortex shedding to acoustic oscillation

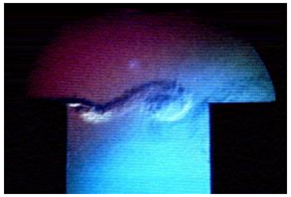


Oscillation frequency



Hydrodynamic modes



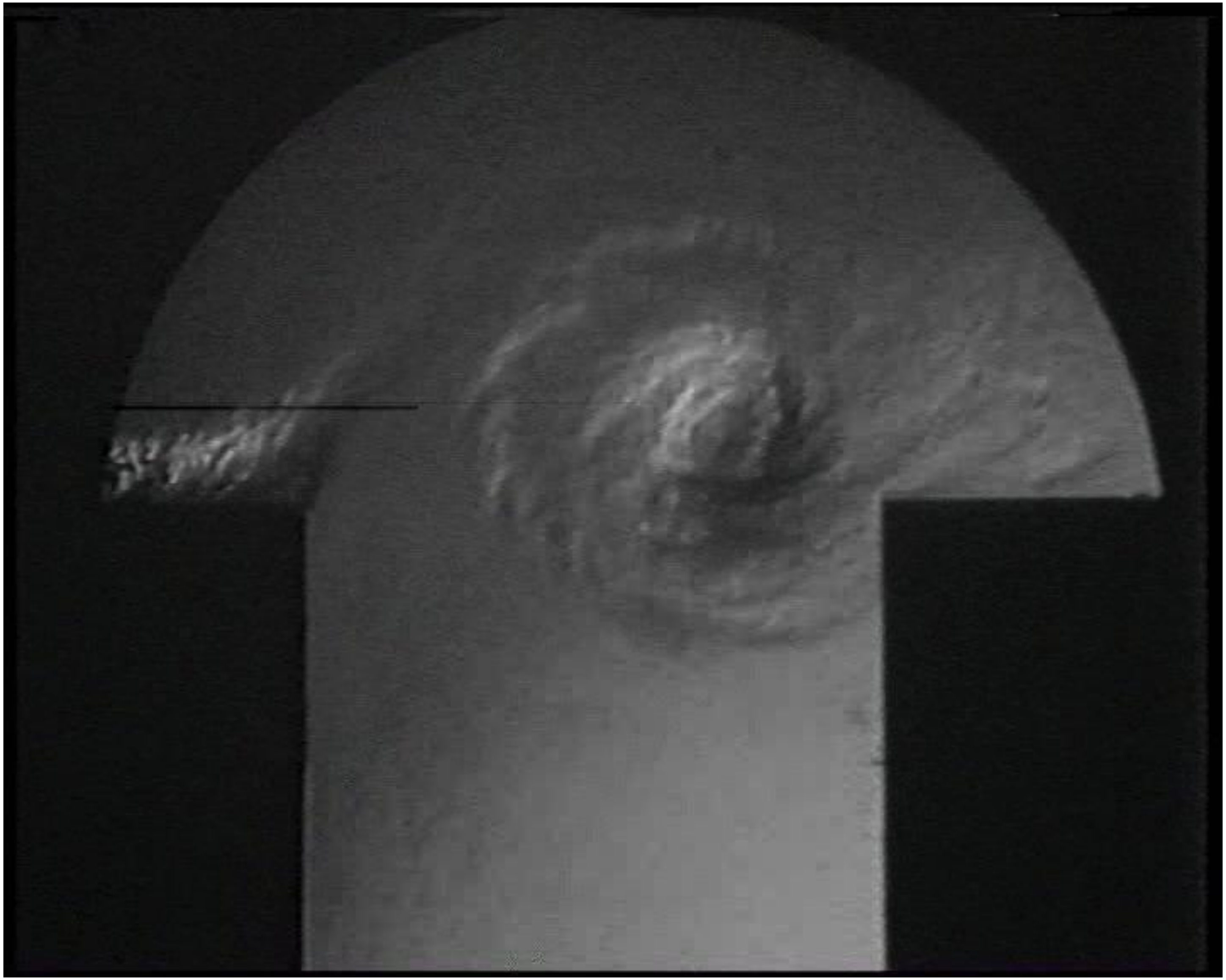


Hydrodynamic instability
(Amplifier)

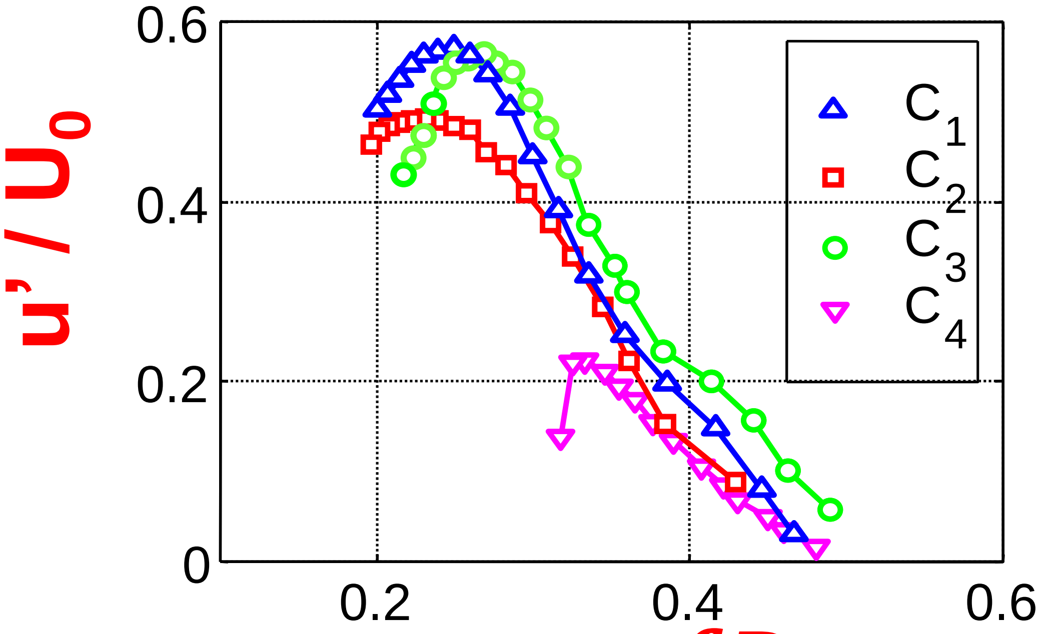
Perturbation of shear layer (acoustic feedback)

Unsteady force on wall (sound source)

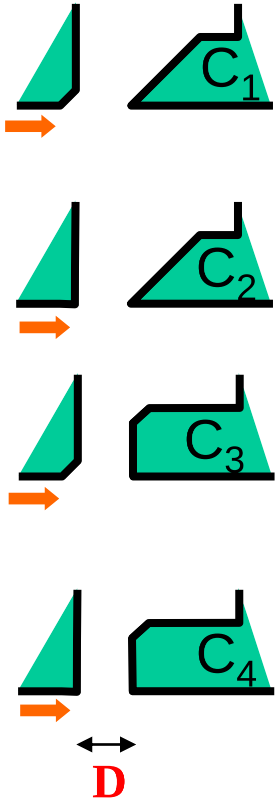
Bottle resonance
(Filter)

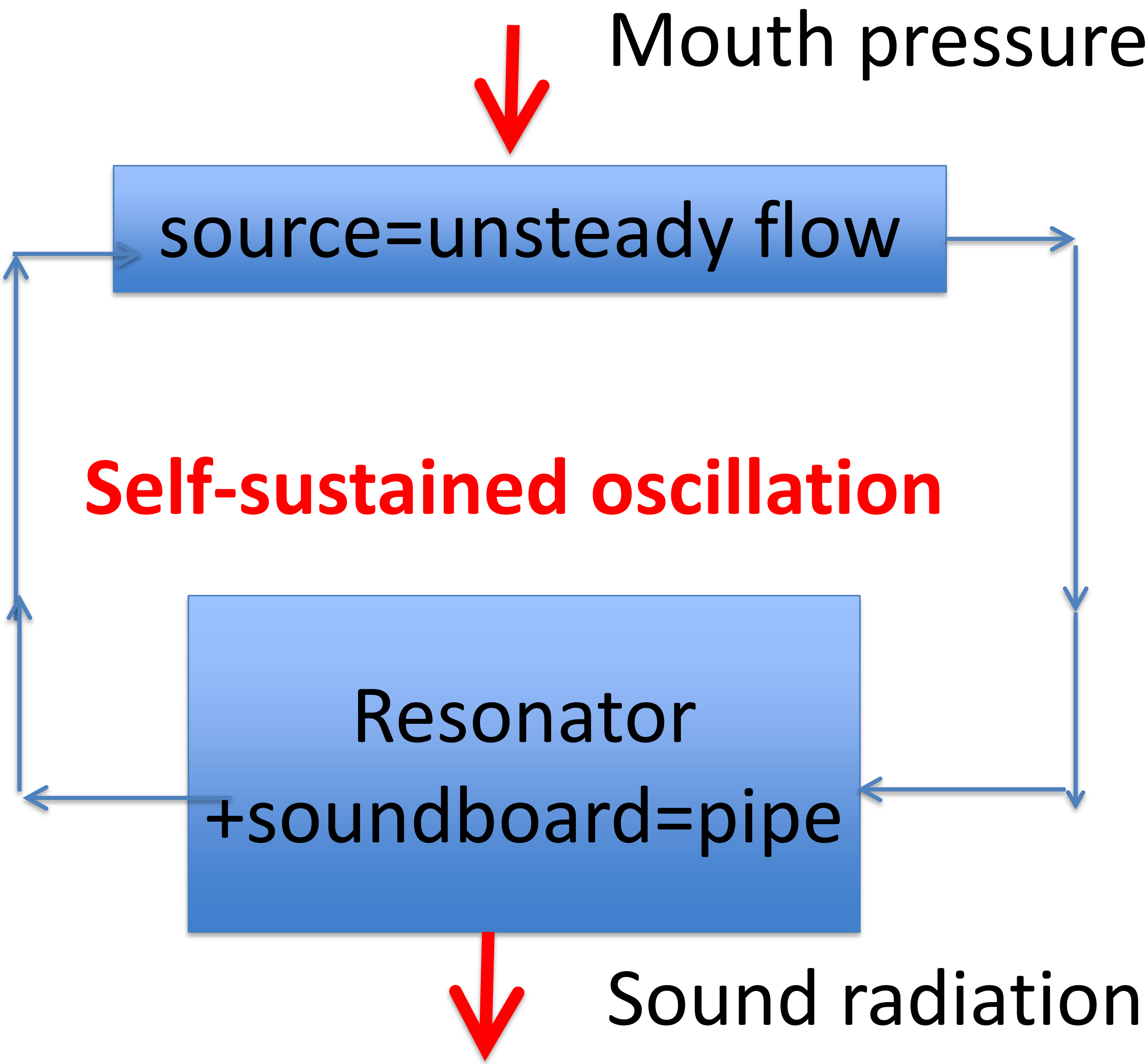


Ratio acoustic velocity in neck / grazing flow velocity



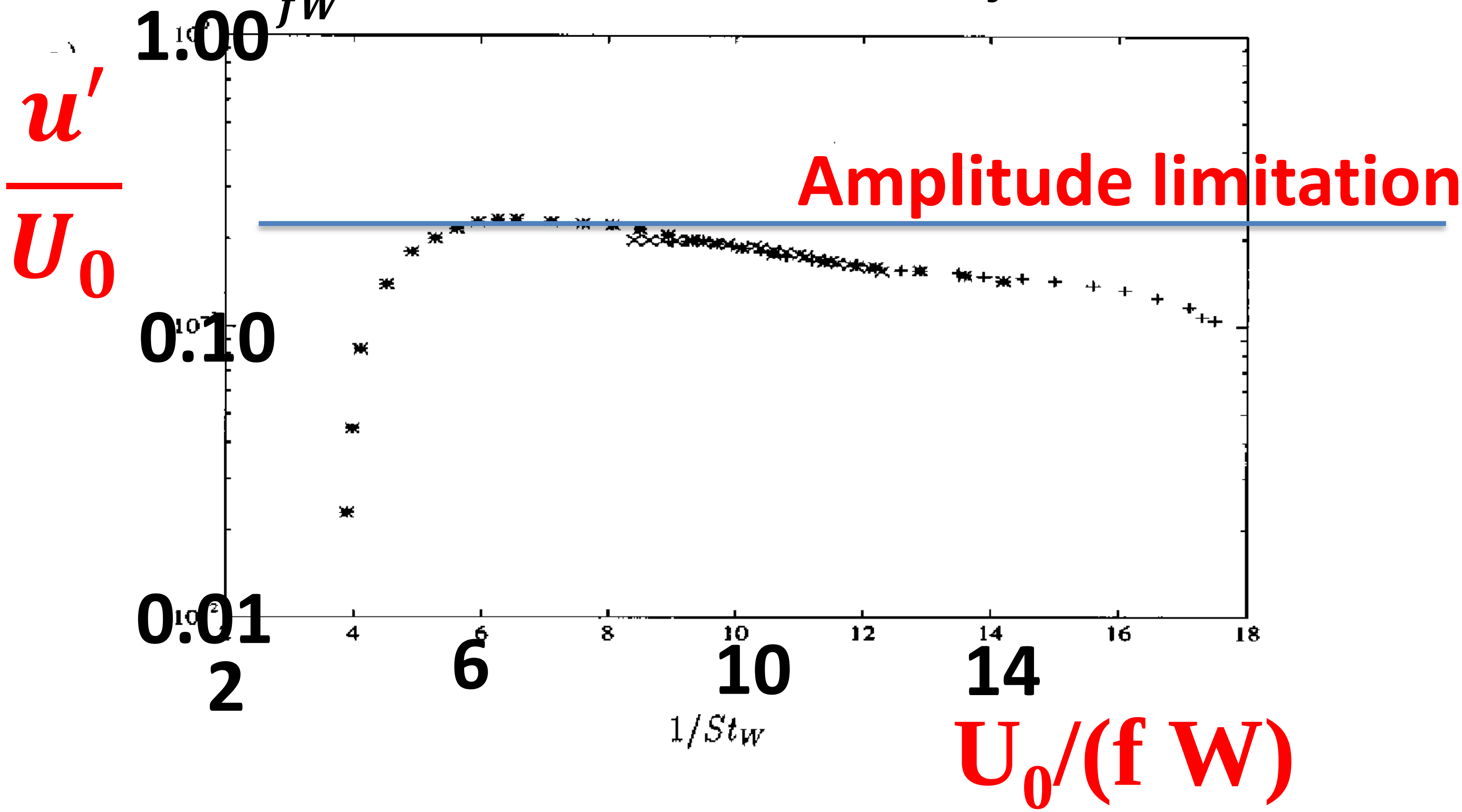
$$Sr = \frac{fD}{U_0}$$



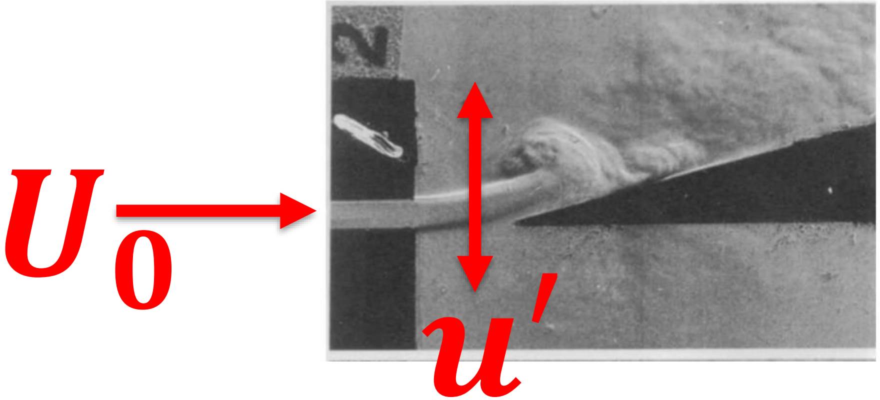

Mouth pressure
source=unsteady flow
Self-sustained oscillation
Resonator
+soundboard=pipe
Sound radiation

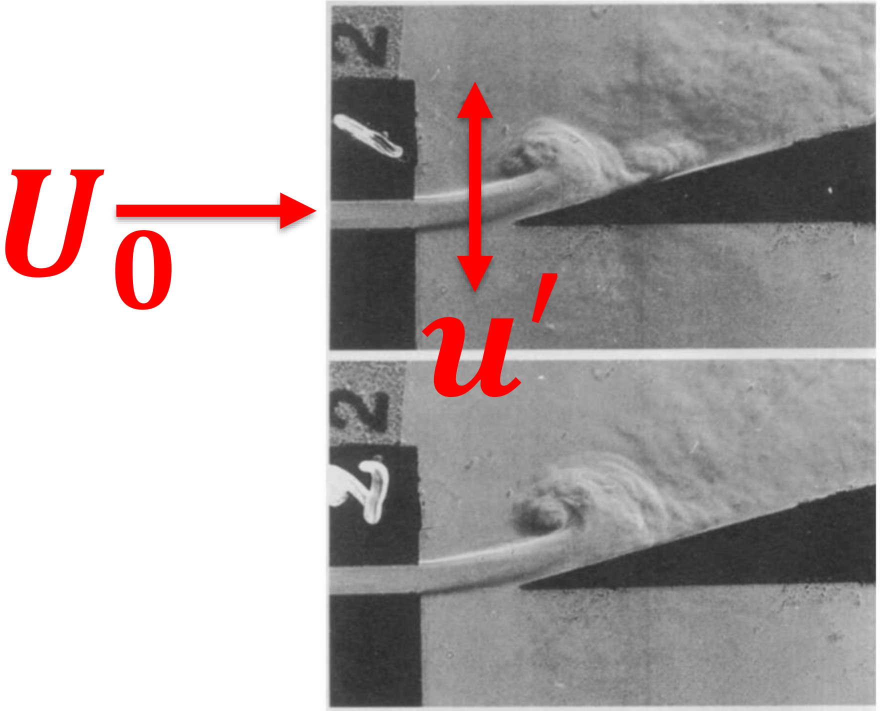
u_{ac}/U_0 **dimensionless amplitude**

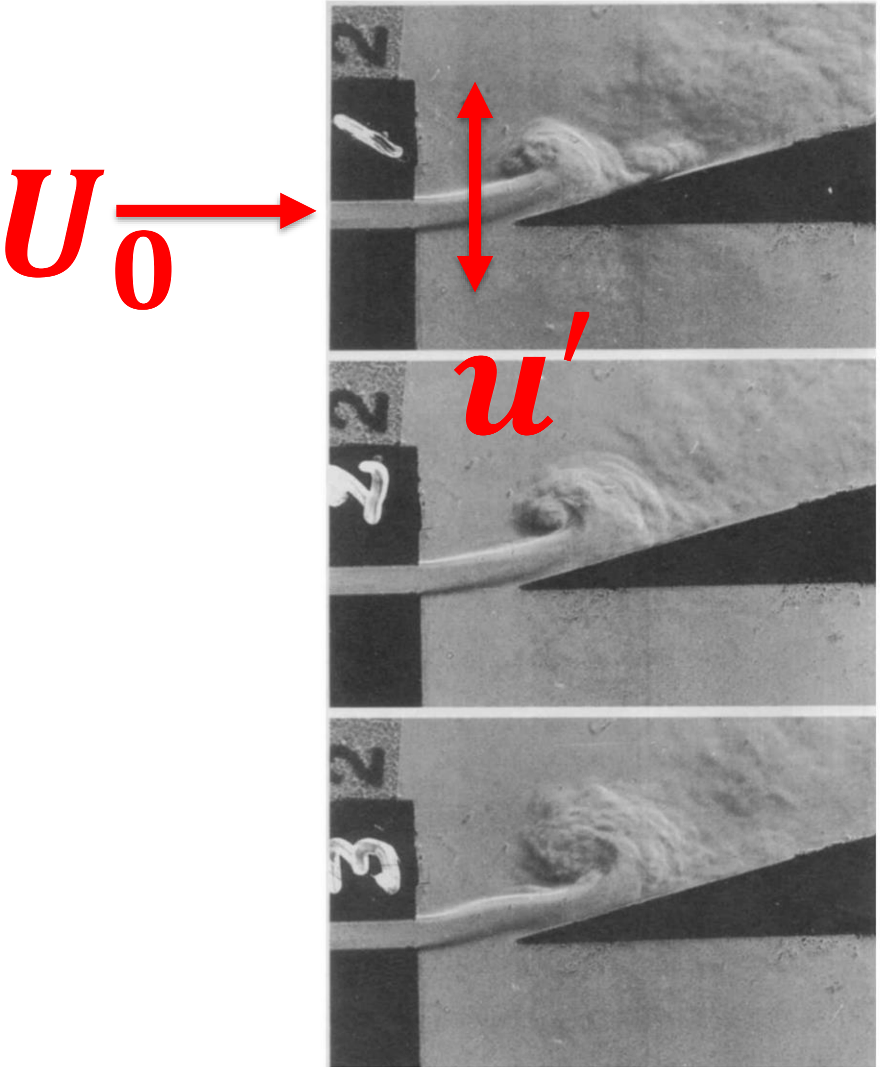
$\frac{U_0}{fW}$ **dimensionless velocity**

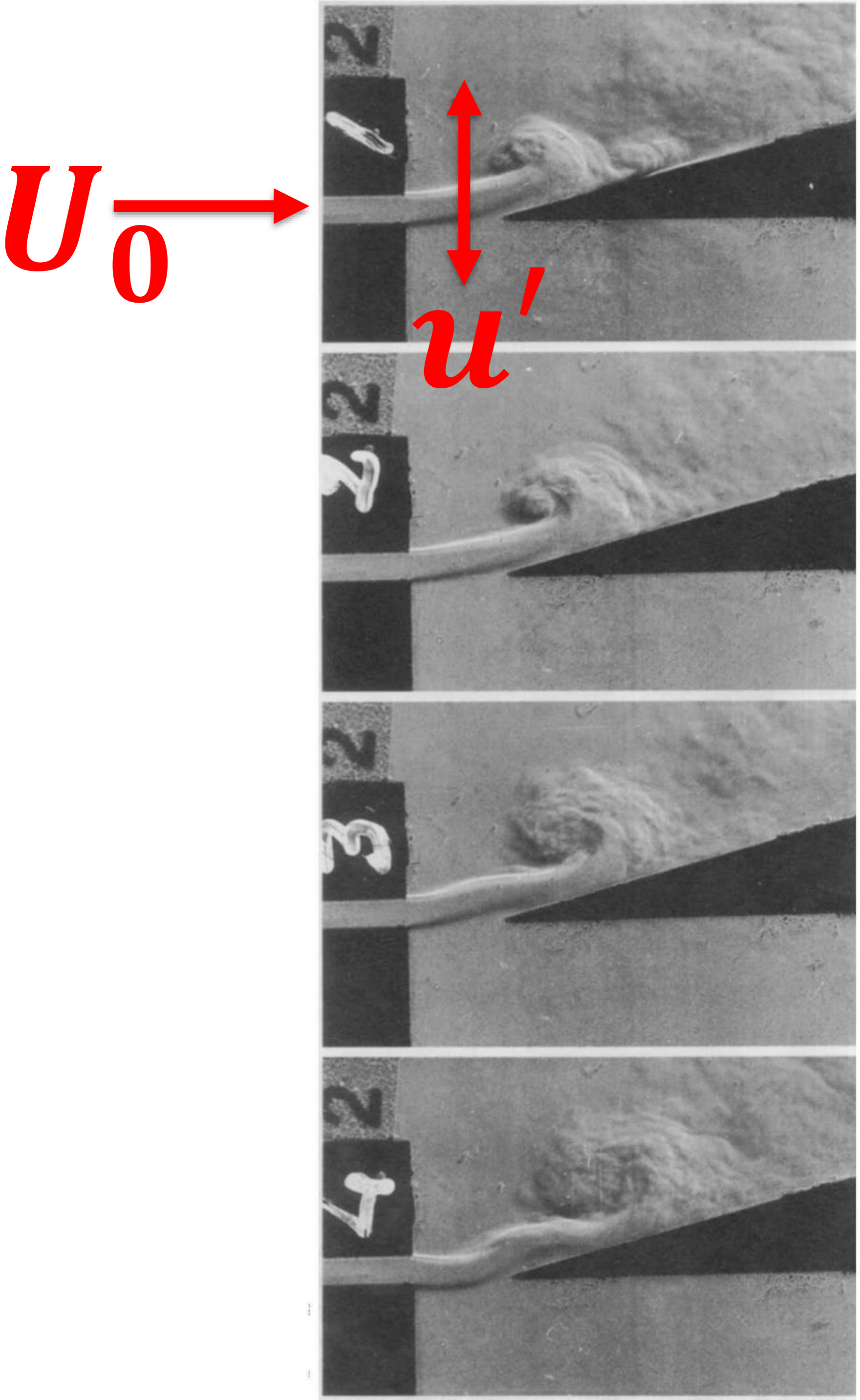


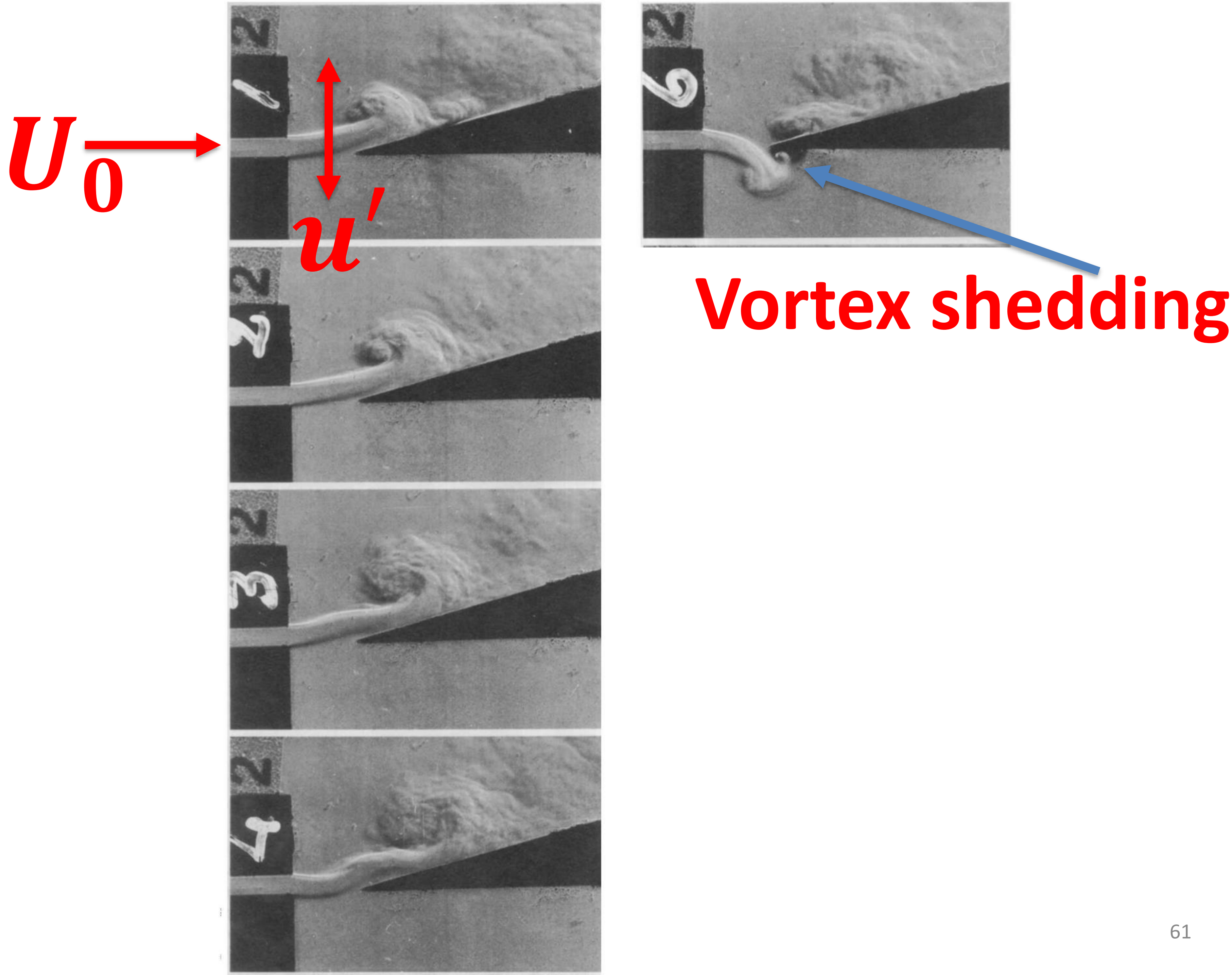
Amplitude limiting non-linearity ?

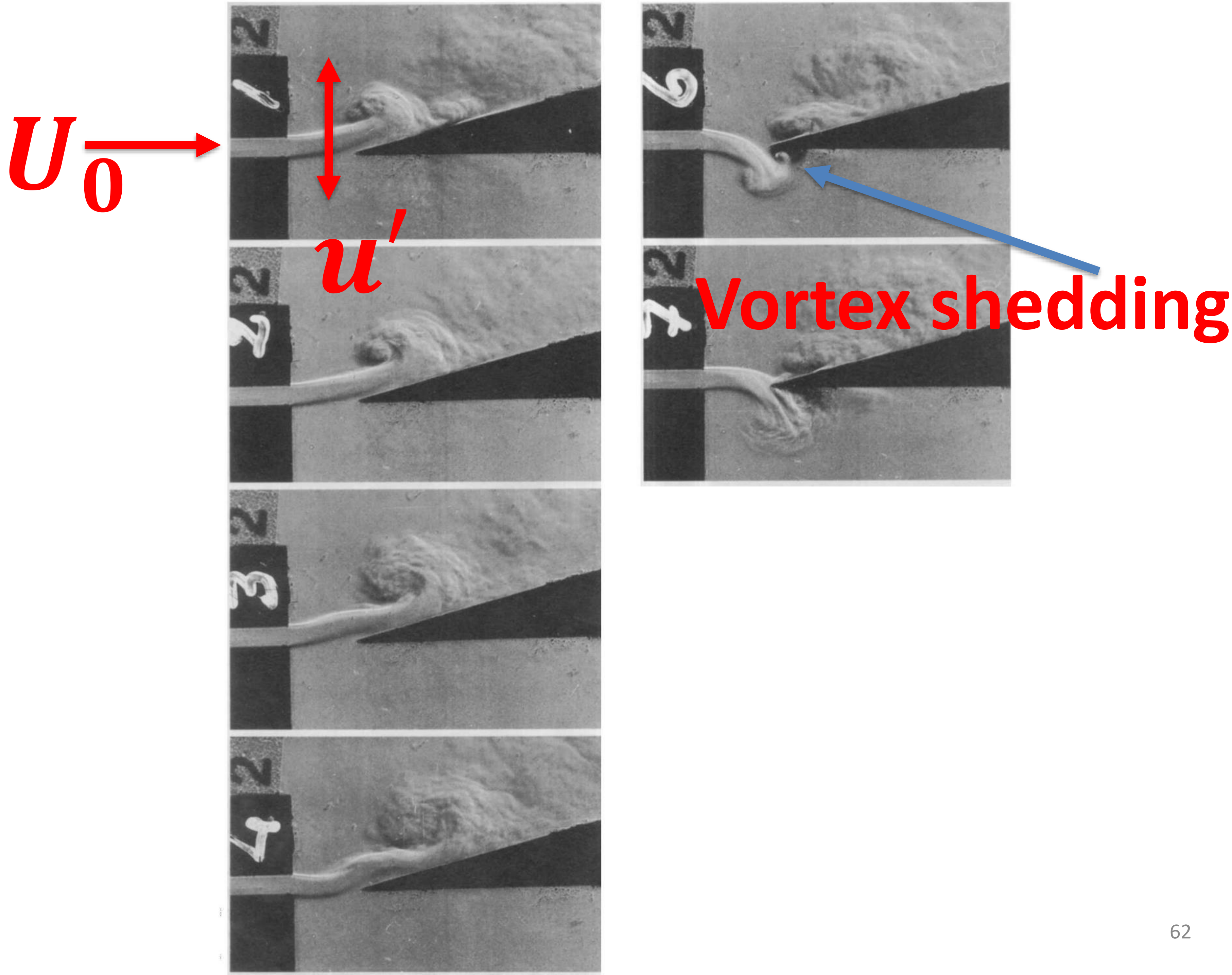

U_0
u'


U_0
u'

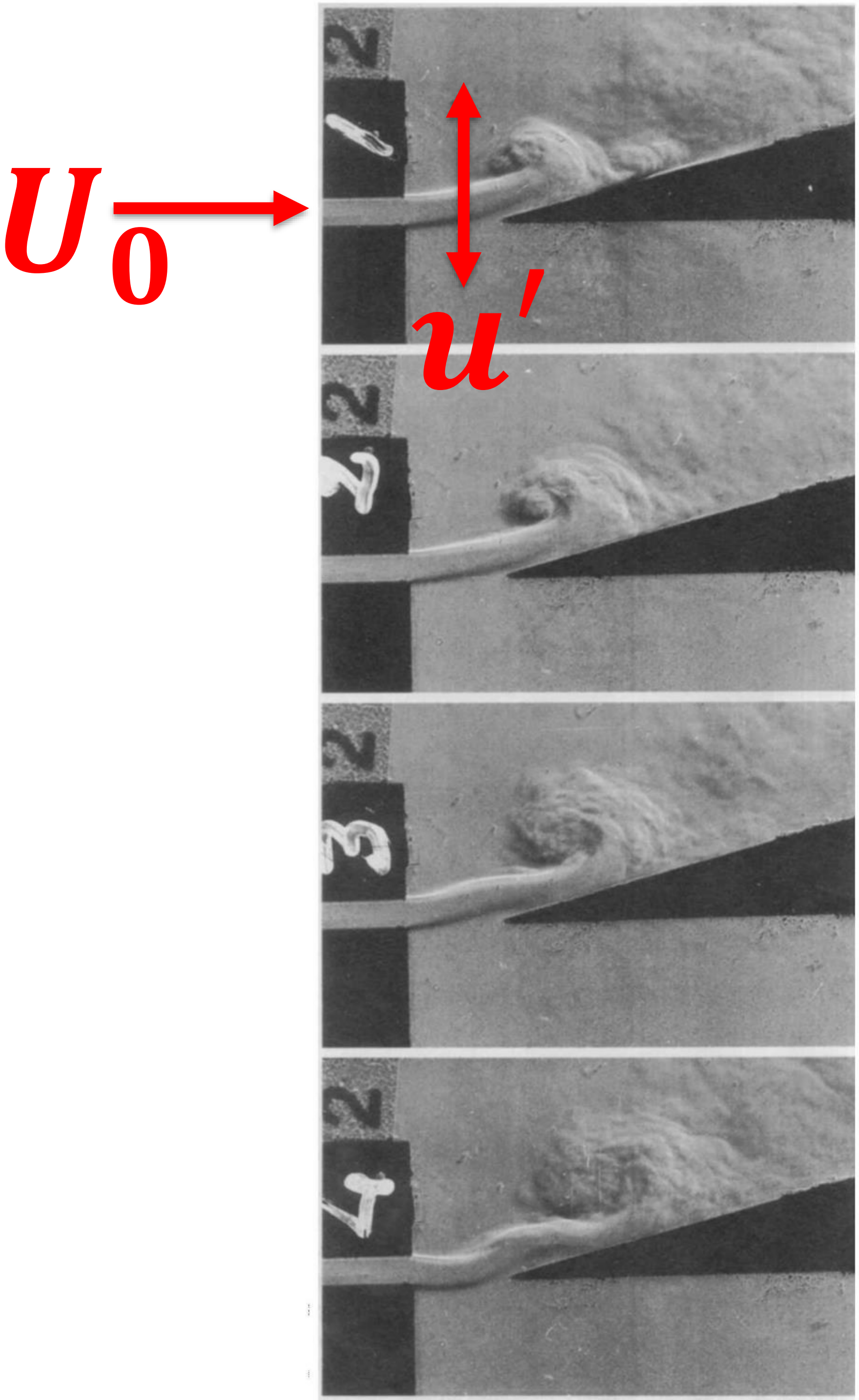

U_0
u'
2
1
2
2
2
3

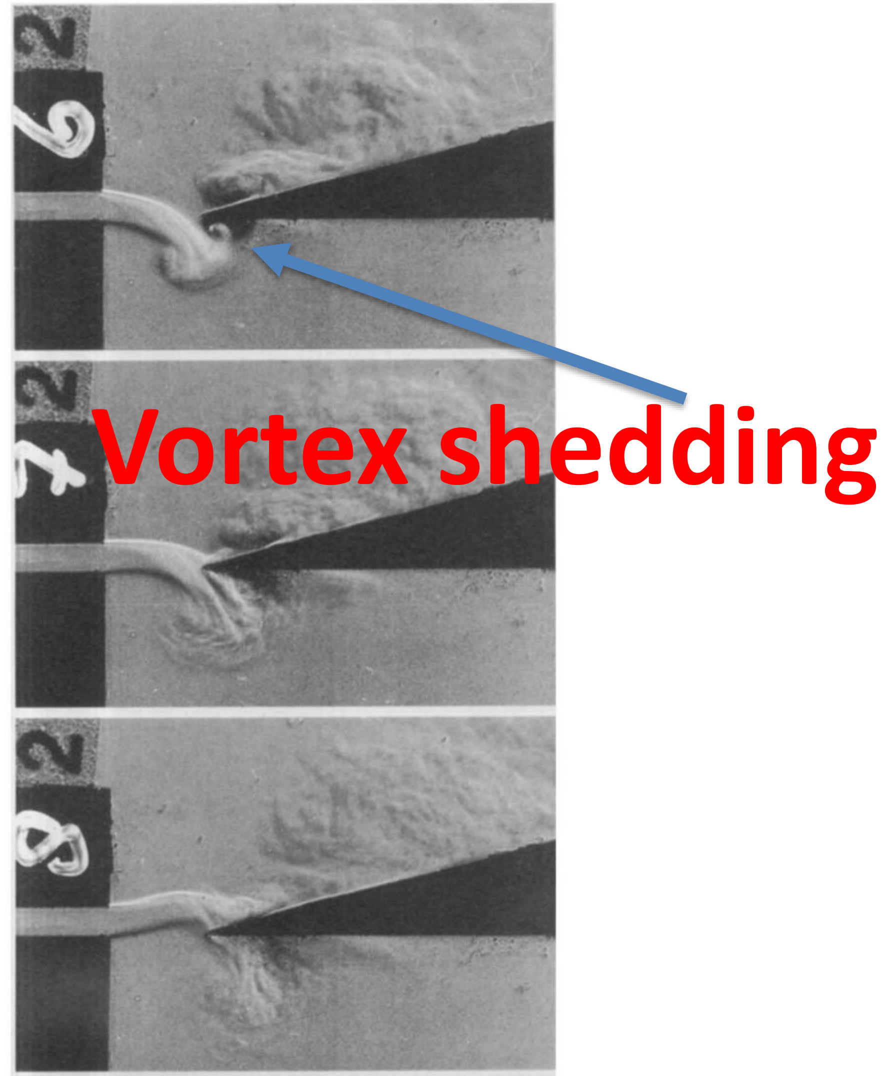

U_0
u'


U_0
u'
Vortex shedding

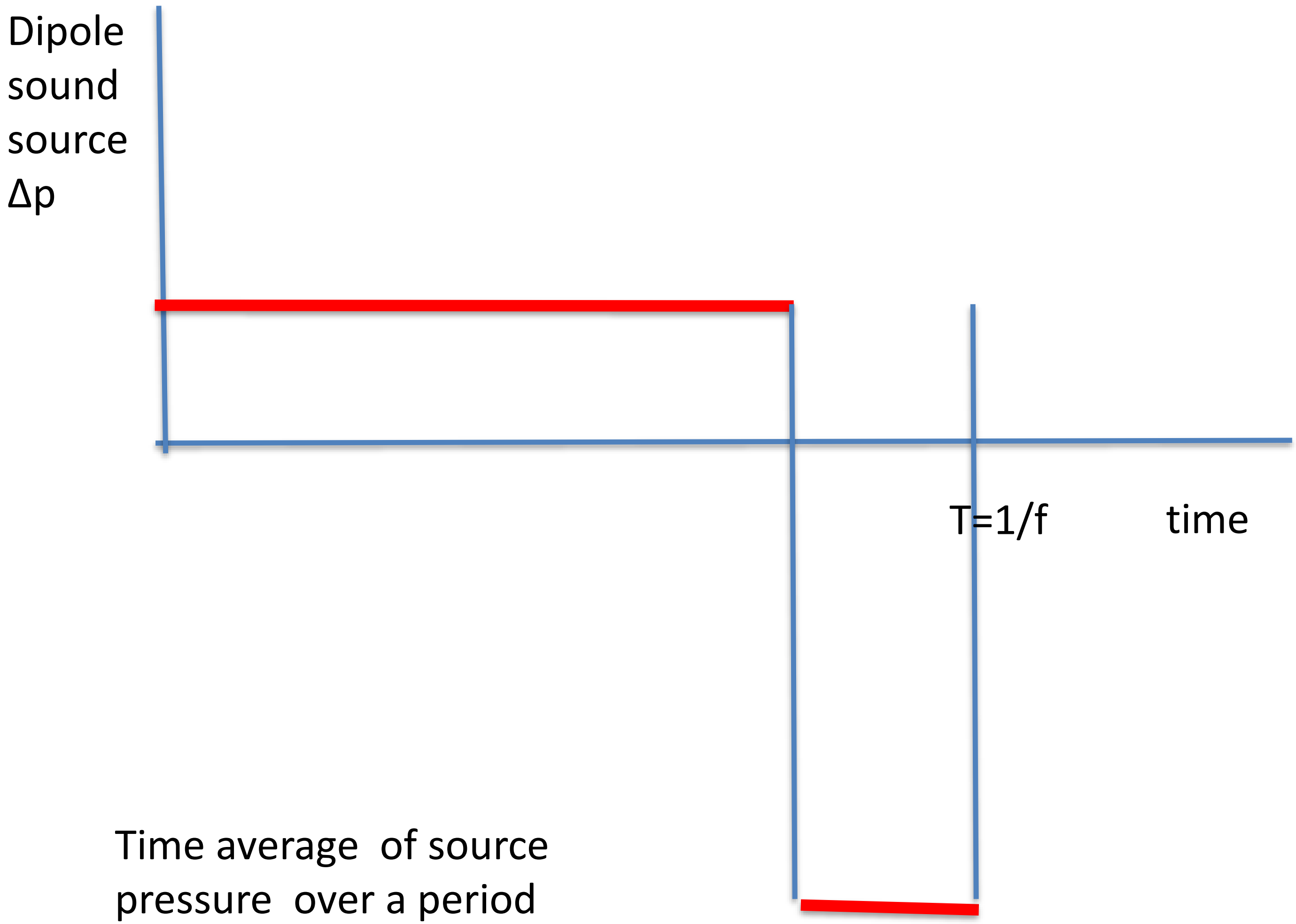


U_0
u'
Vortex shedding

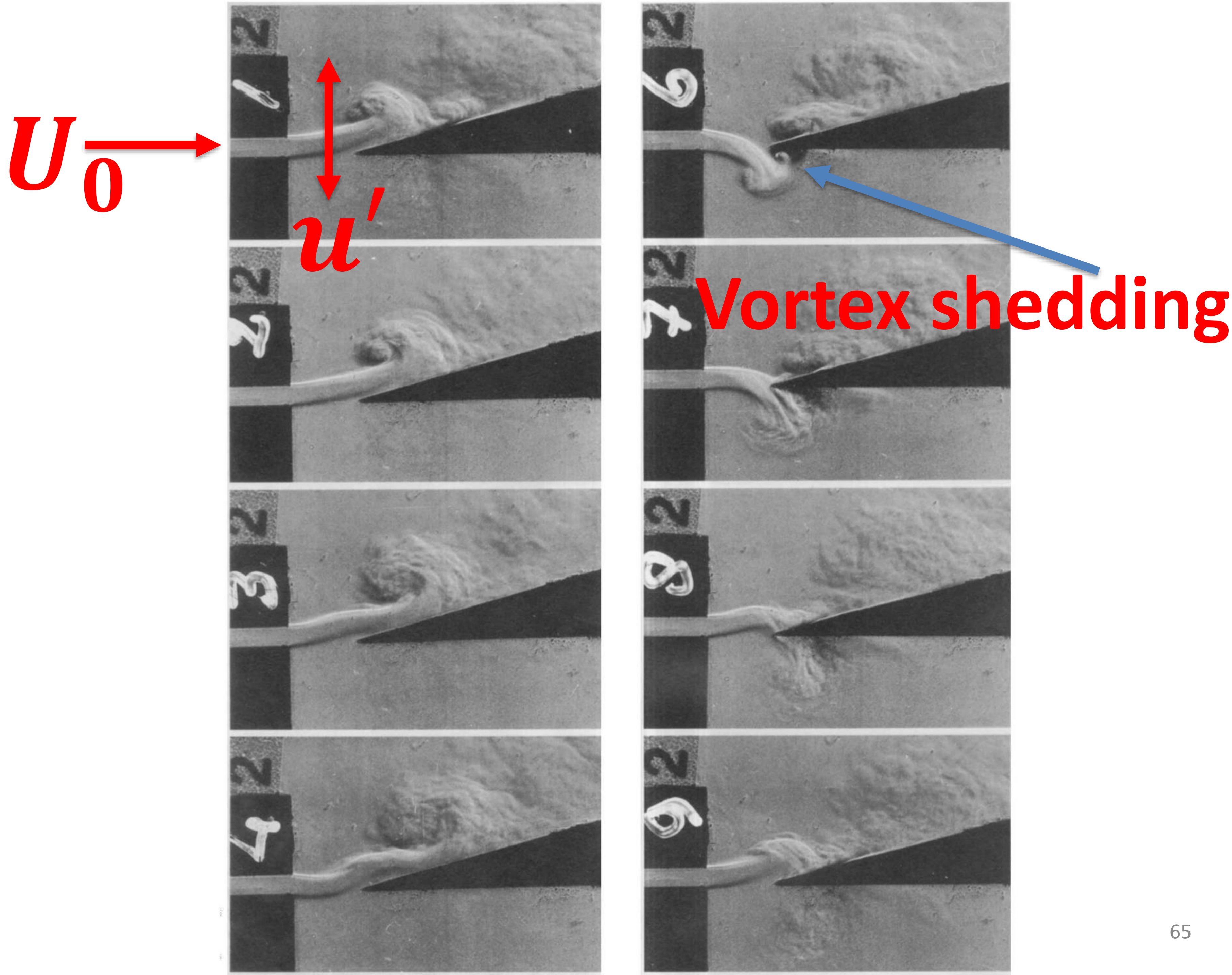




Mention that the jet remains 70% of the oscillation period above the labium. Hence the interaction results in a sort pulse.

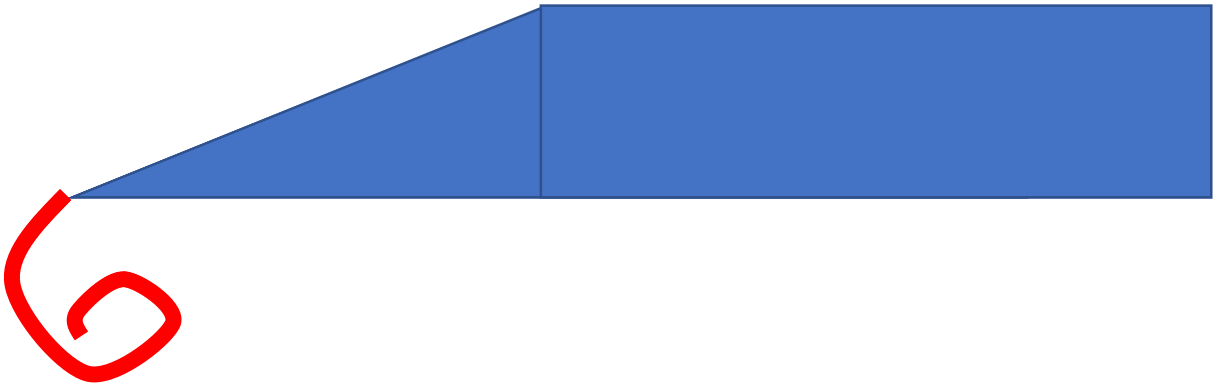


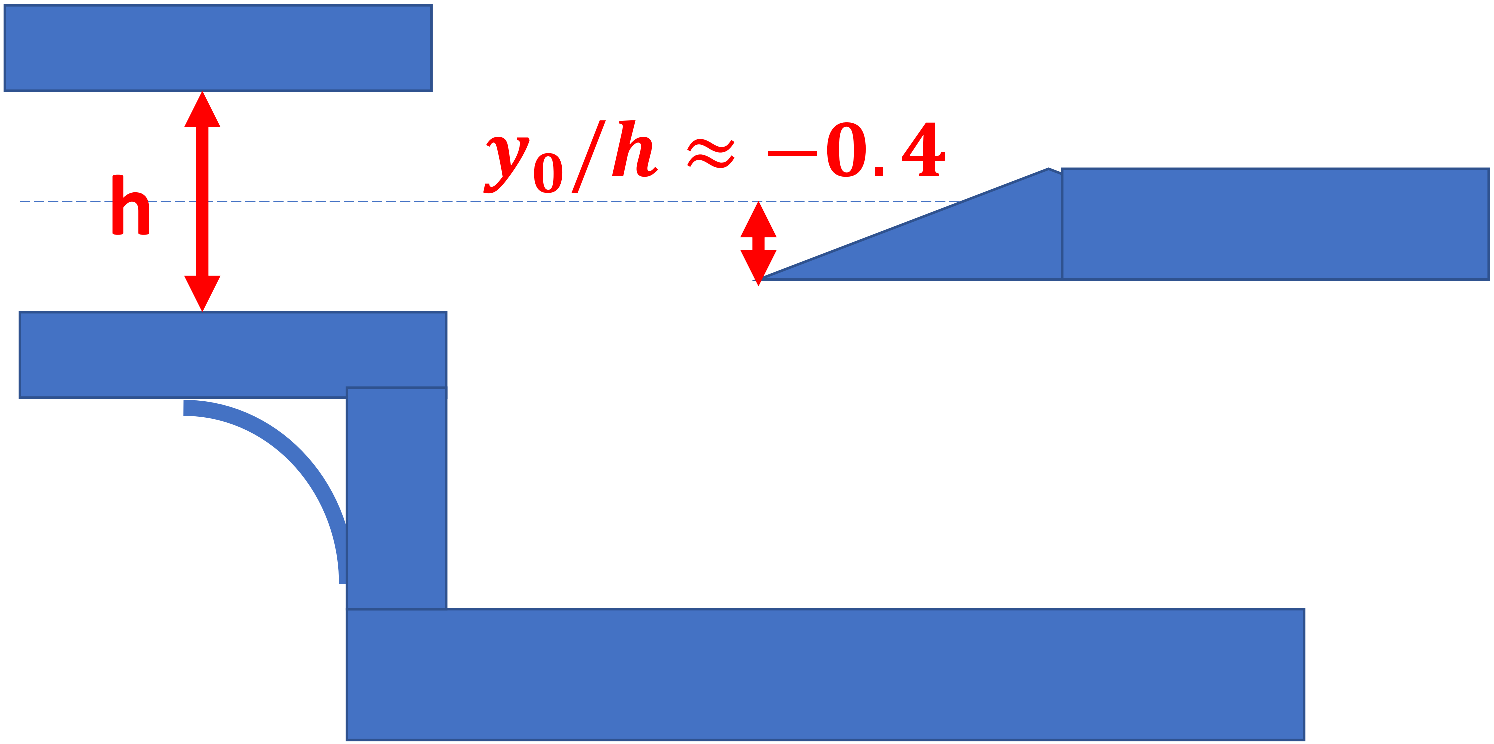
Time average of source pressure over a period of oscillation T is zero.



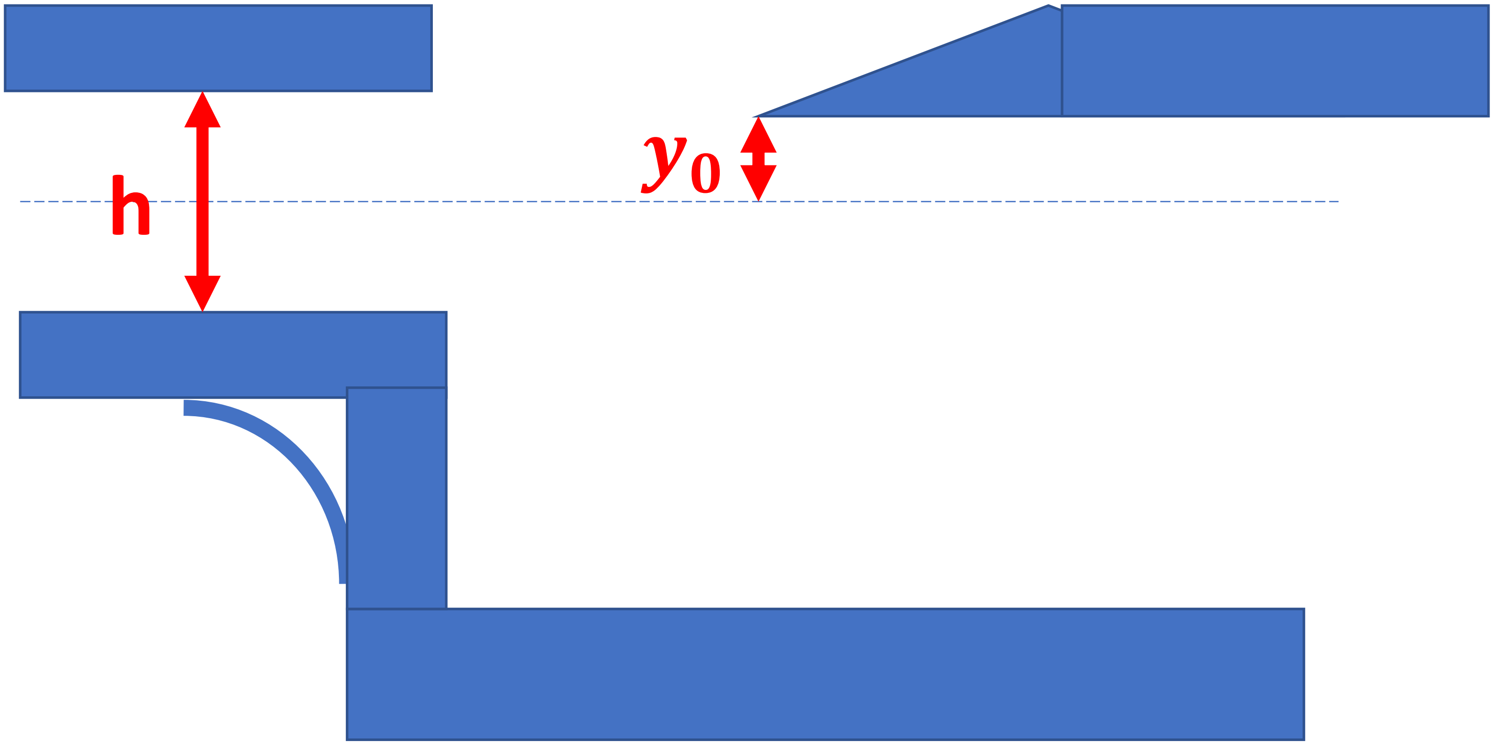
U_0
u'
Vortex shedding

Vortex shedding at the labium is the amplitude limiting mechanism



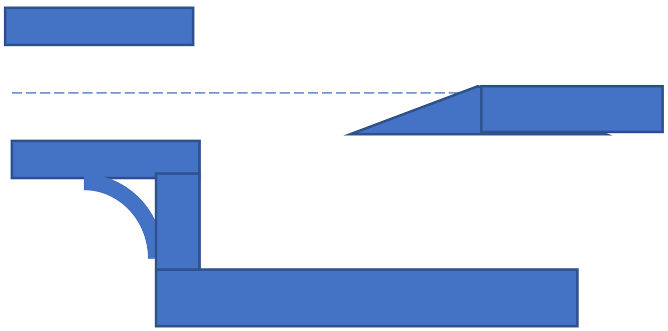


Typical recorder flute geometry



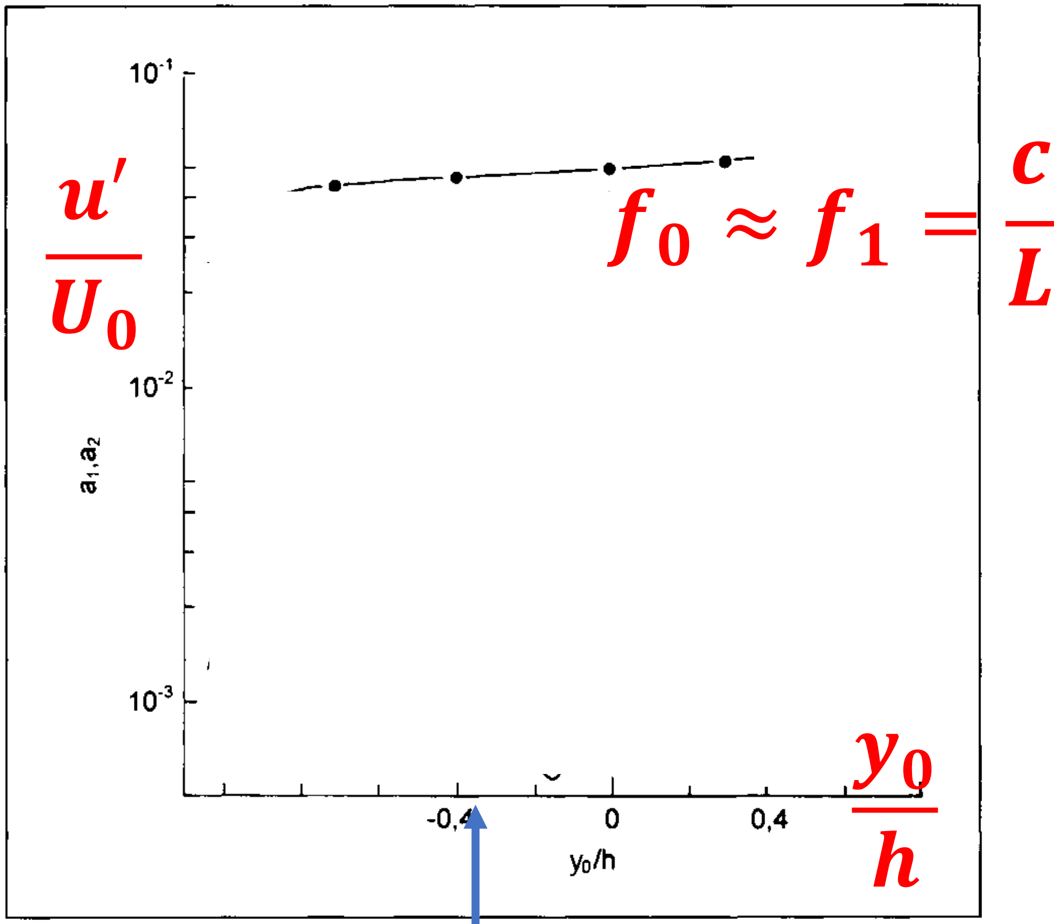
Influence offset of labium

Recorder-like geometry

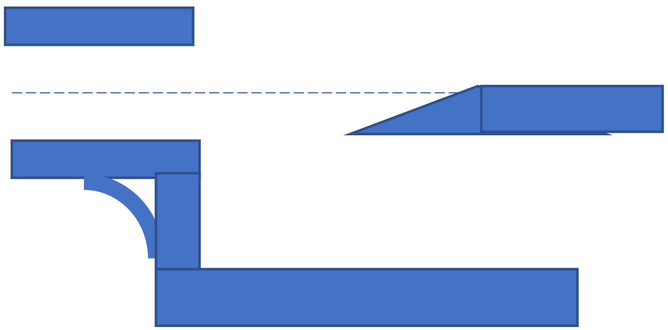


Fundamental f_0

Harmonic $2f_0$

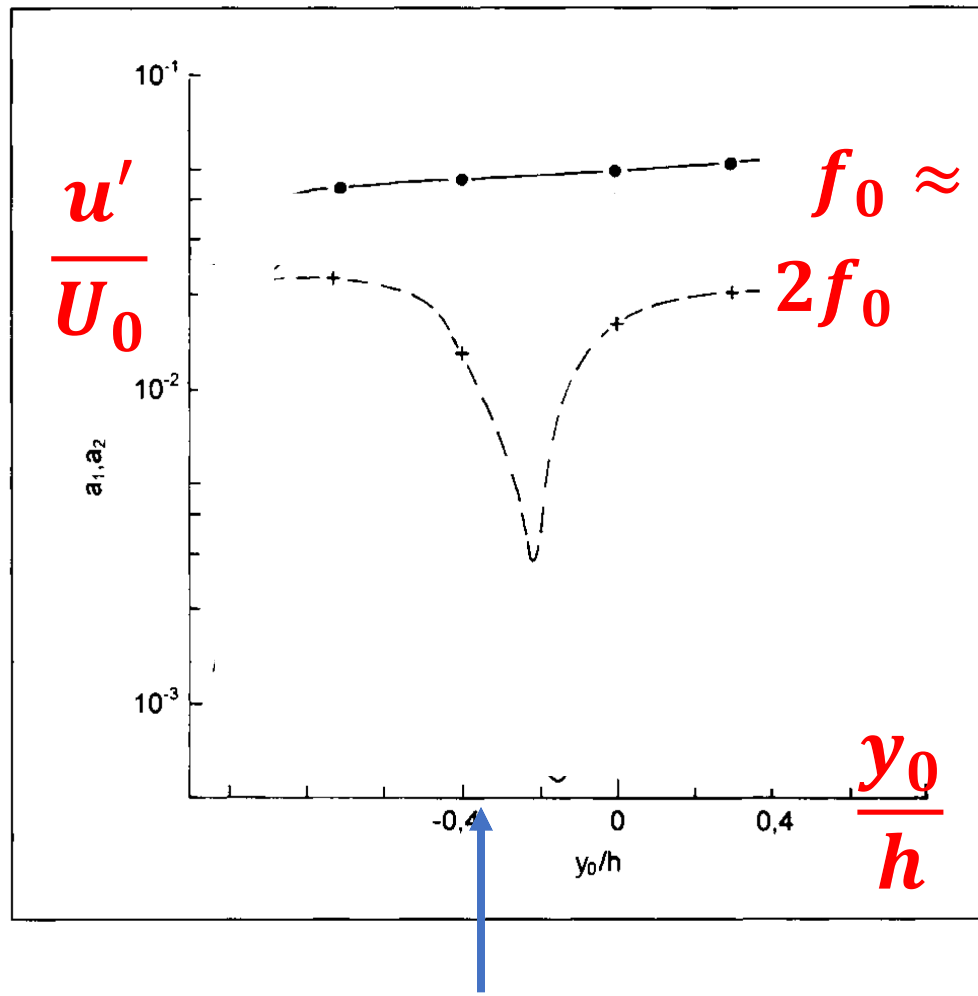


Recorder flute



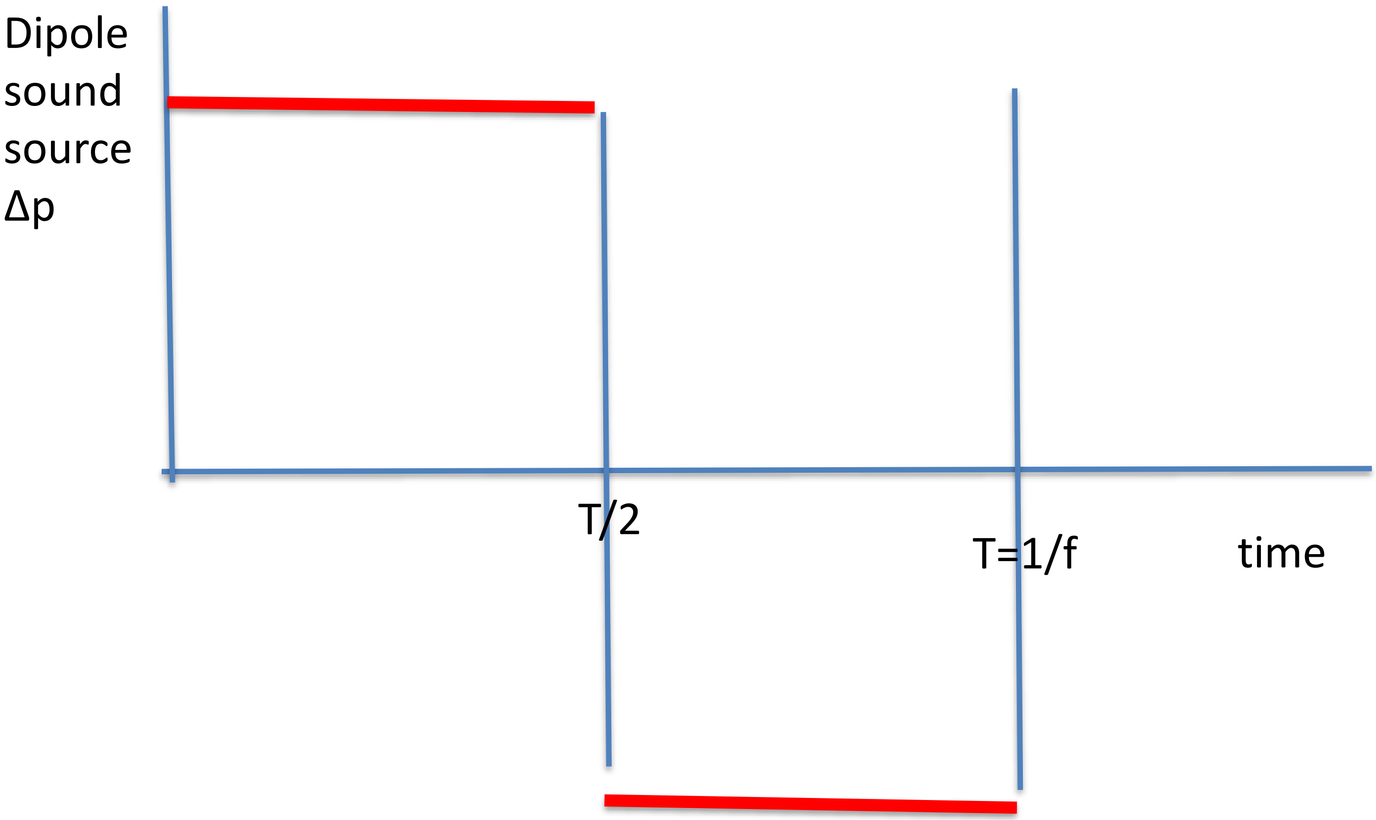
Fundamental f_0

Harmonic $2f_0$



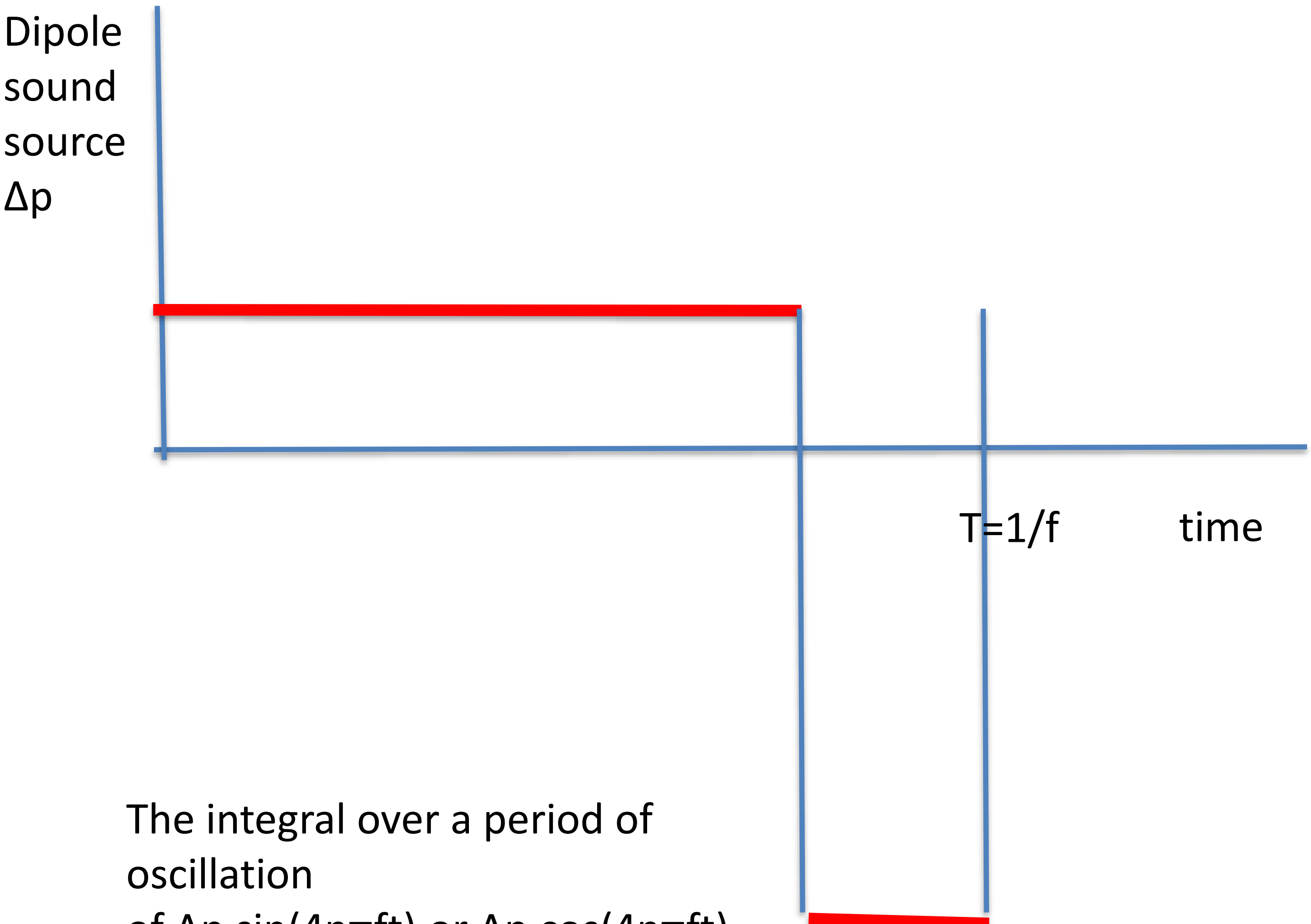
Recorder flute

A symmetric labium position suppresses even harmonics

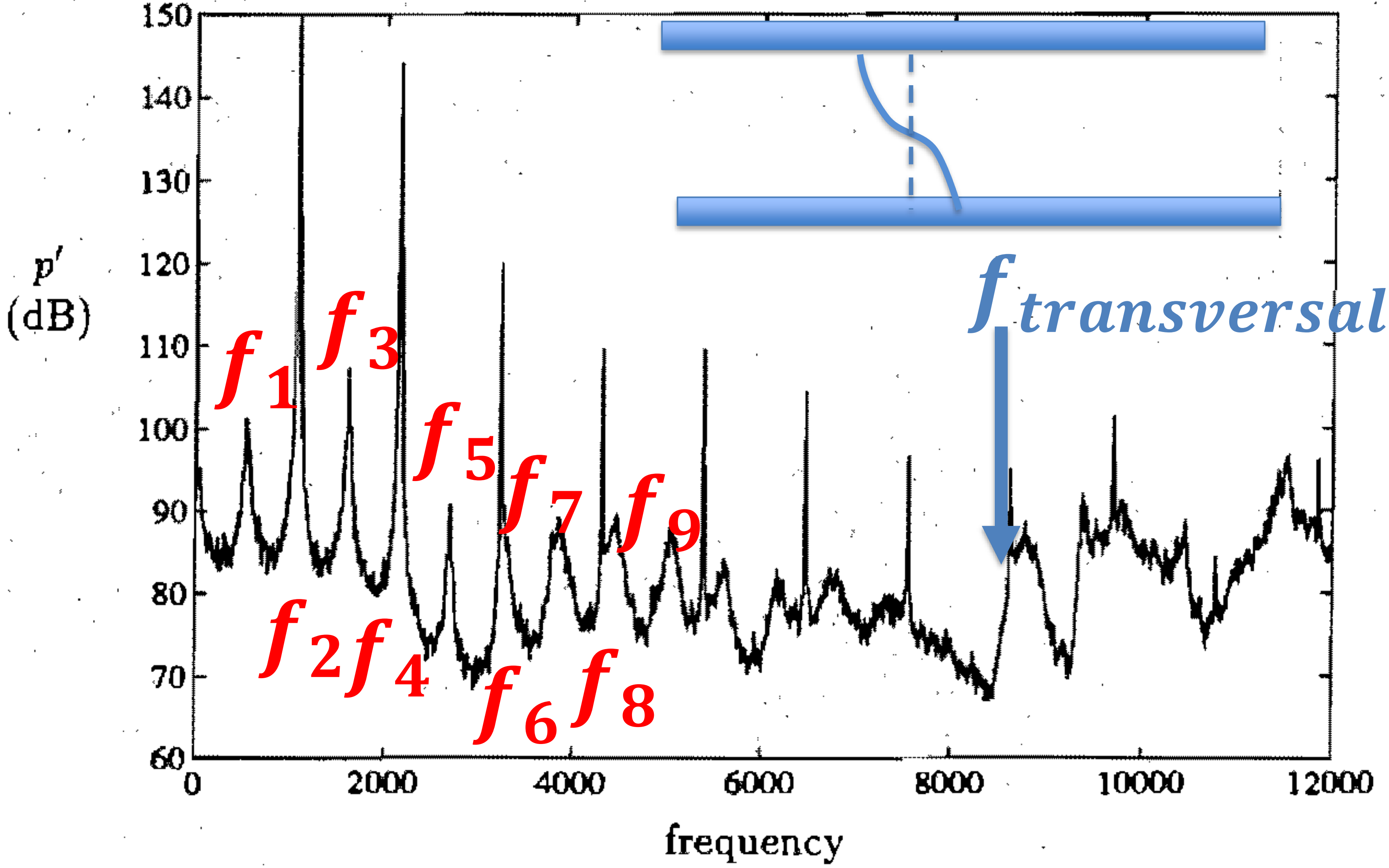


A symmetric signal does not produce even harmonics (the integral over a period of oscillation of Δp sin(4nπft) or Δp cos(4nπft) (with n=1,2,3...) vanishes.

An asymmetric labium position generates even harmonics



The integral over a period of oscillation
of $\Delta p \sin(4n\pi ft)$ or $\Delta p \cos(4n\pi ft)$
(with n=1,2,3...)

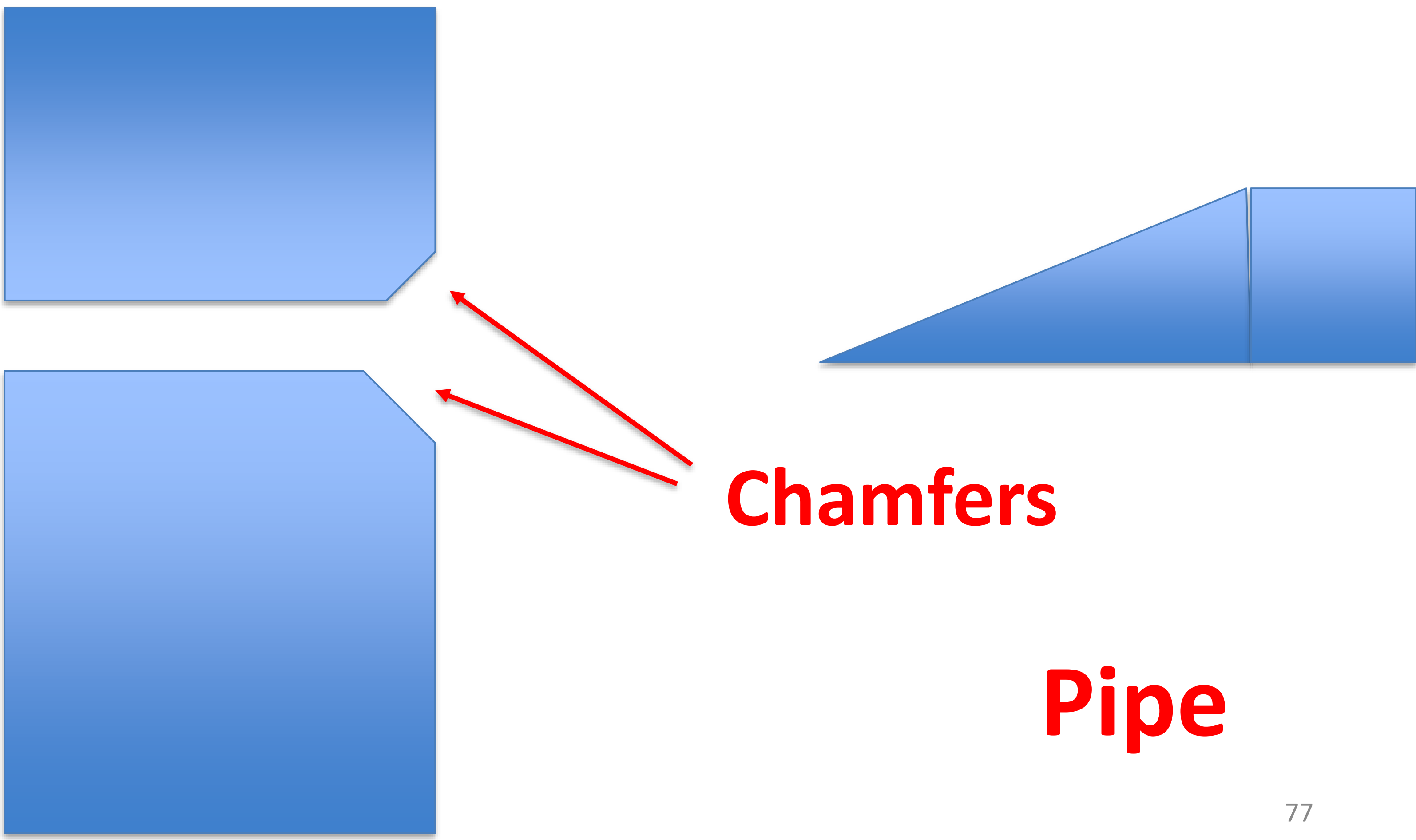


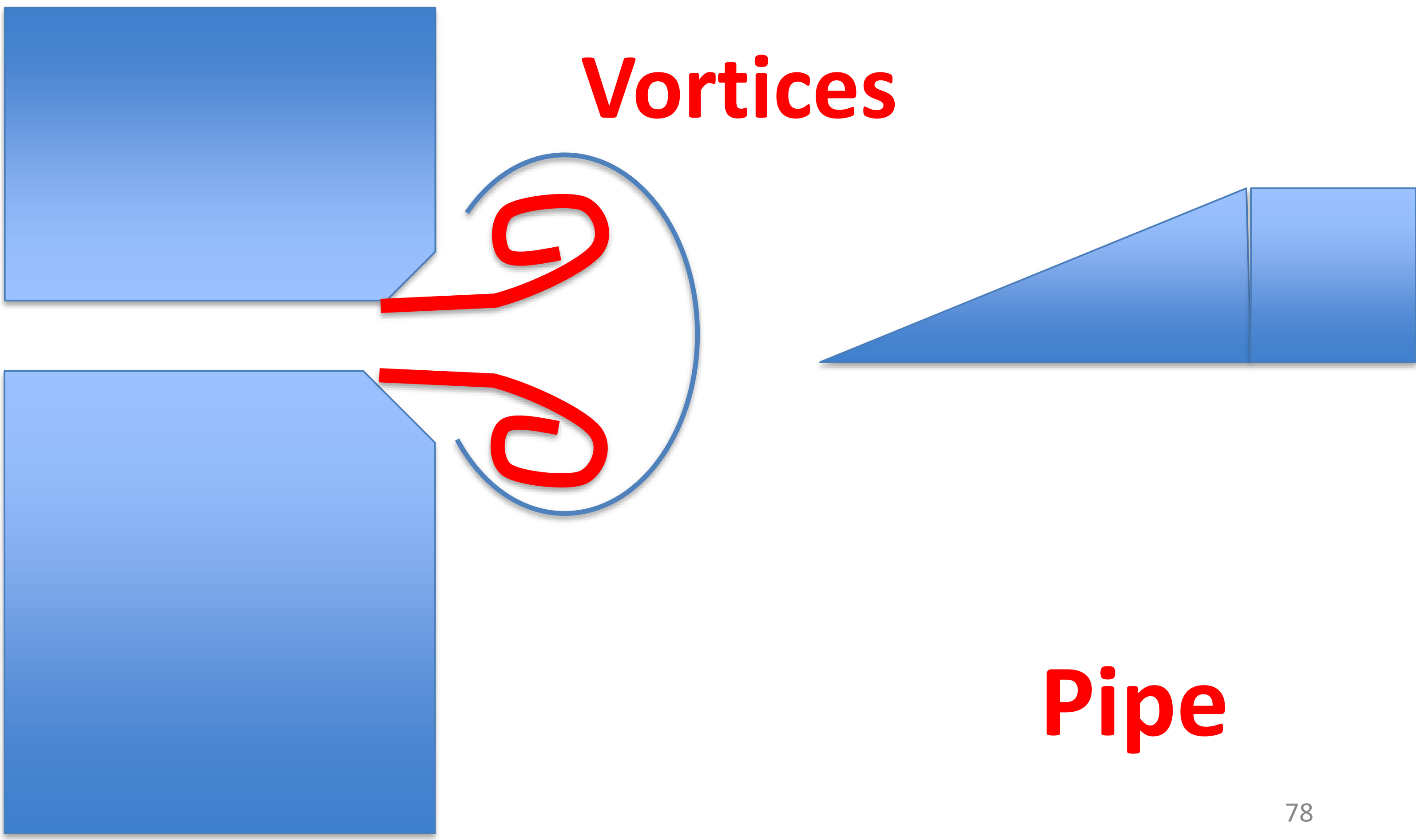
f_1
f_2
f_3
f_4
f_5
f_6
f_7
f_8
f_9
$f_{transversal}$
p' (dB)
150
140
130
120
110
100
90
80
70
60
0
2000
4000
6000
8000
10000
12000
frequency

Break

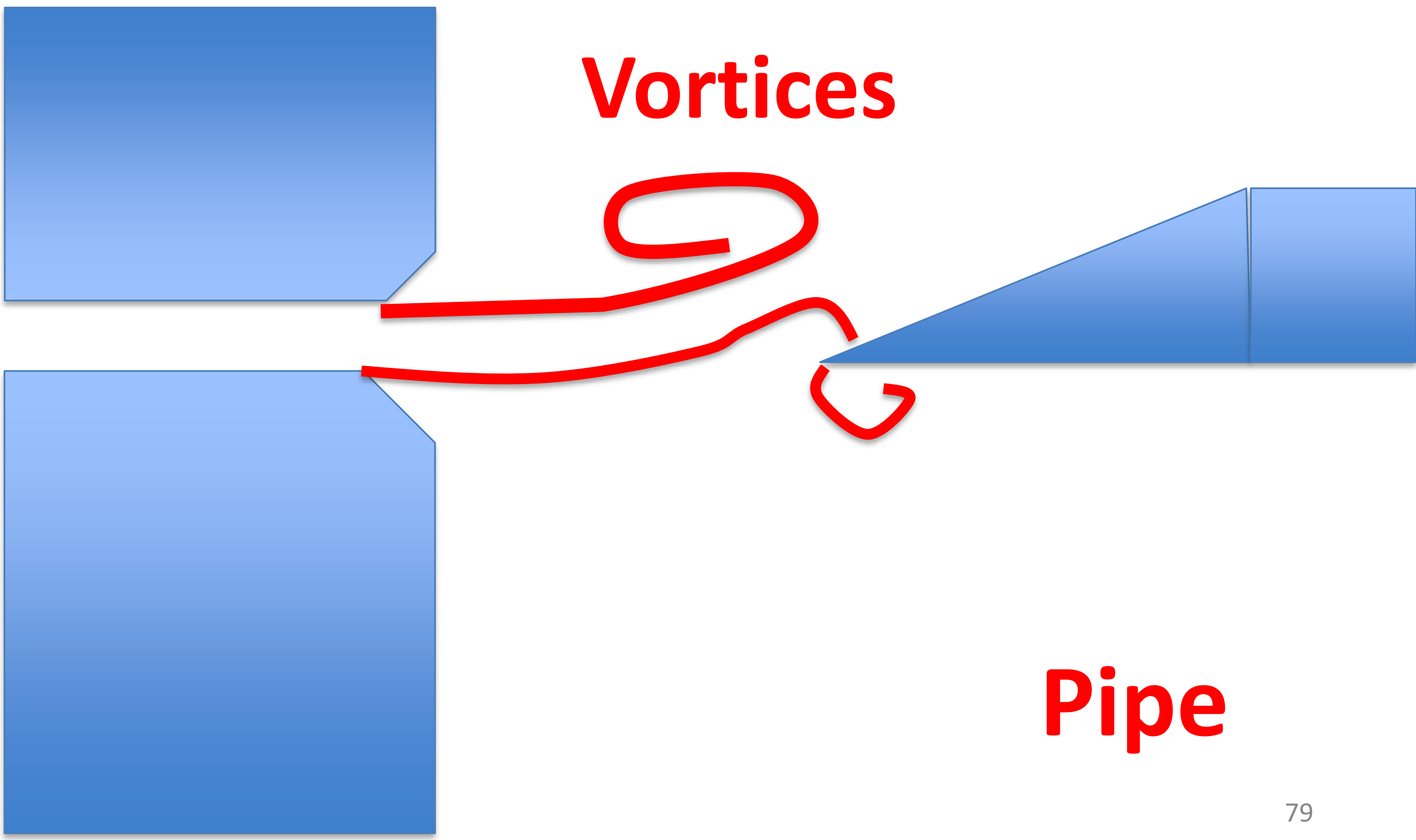
Attack transient is essential for musical sound perception

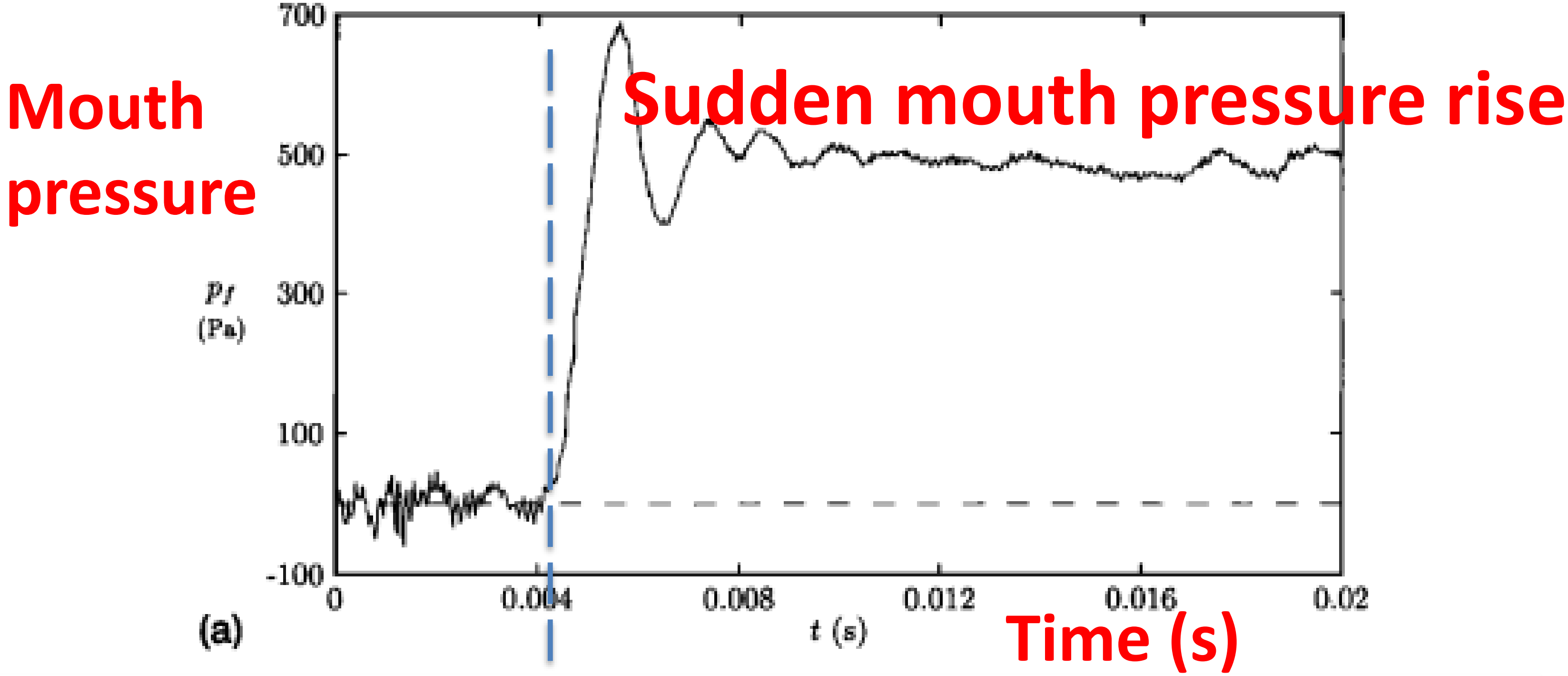
Attack transient in a recorder-like organ pipe
Flow visualization Benoit Fabre (2013)

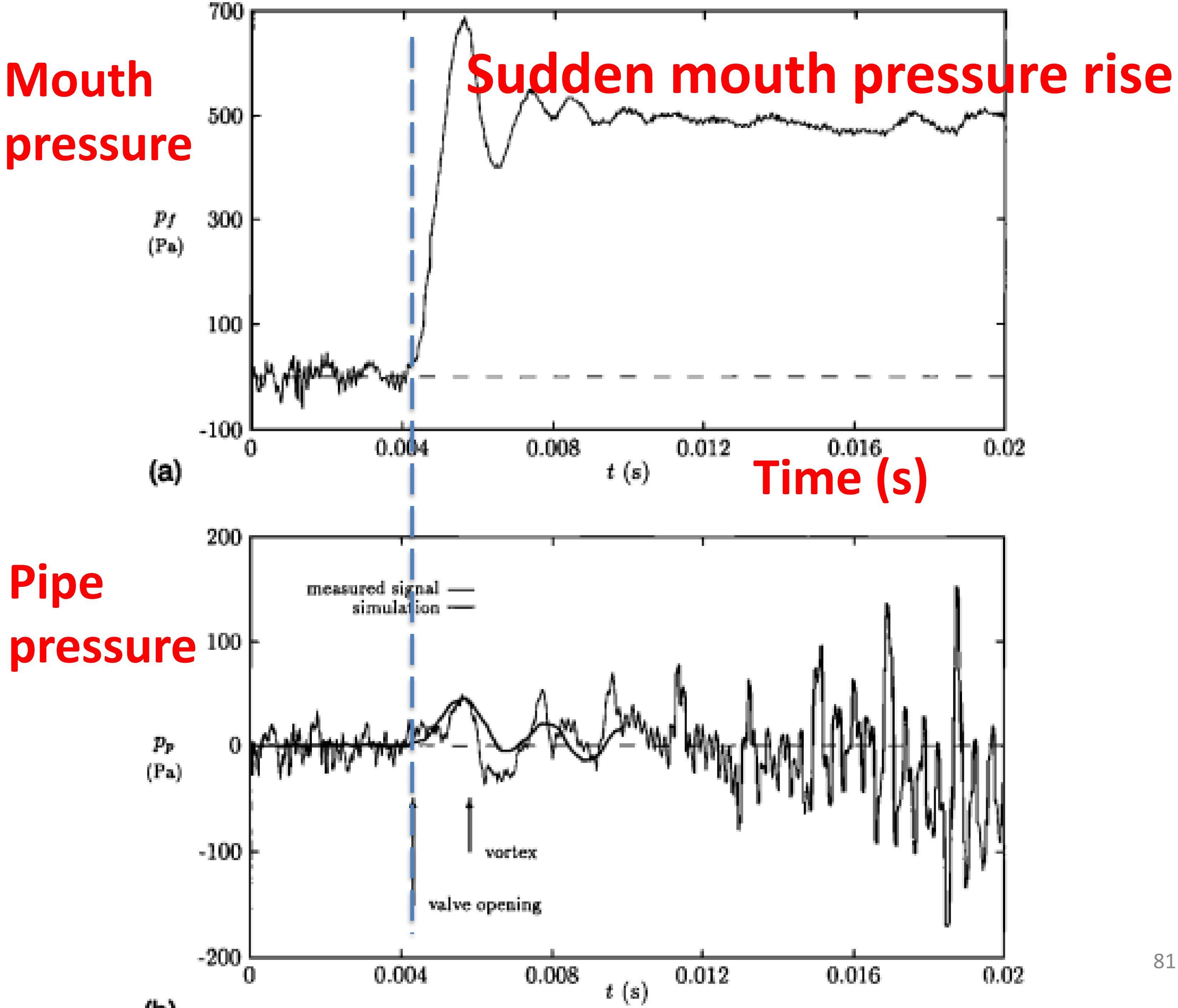

Chamfers
Pipe


Vortices
Pipe

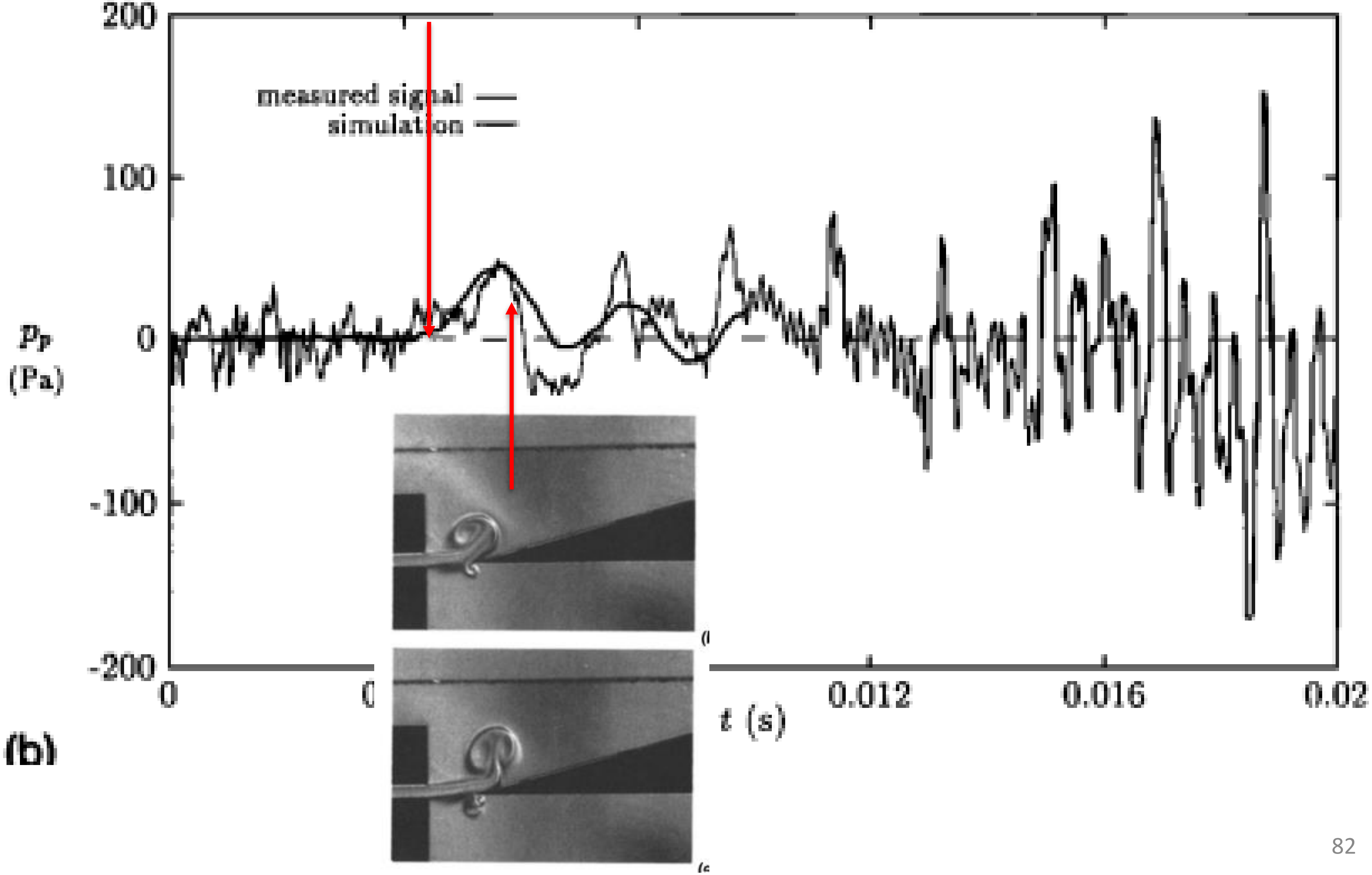
Interaction of jet with labium

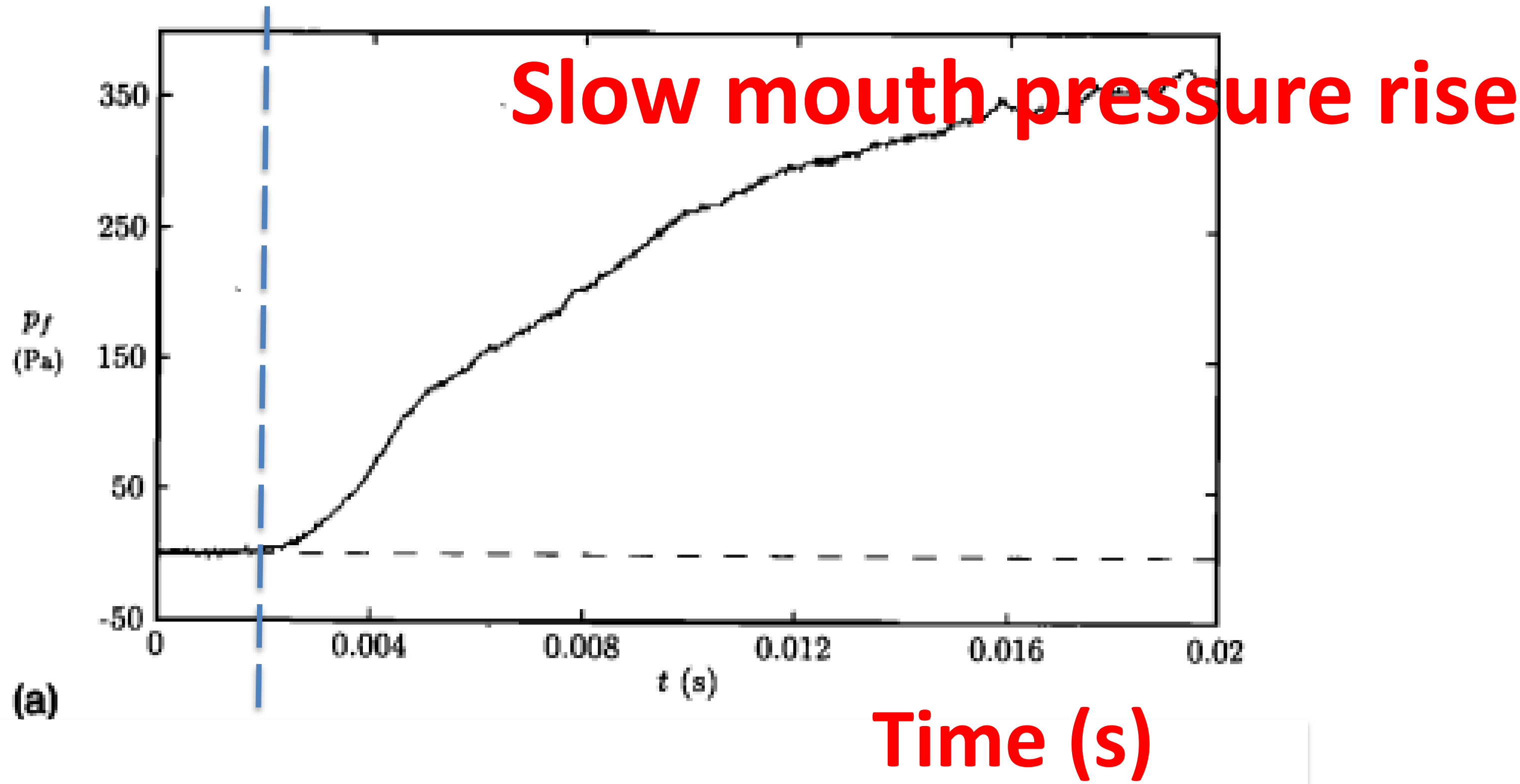



Mouth pressure
Sudden mouth pressure rise
700
500
300
100
-100
p_f (Pa)
0
0.004
0.008
0.012
0.016
0.02
t (s)
Time (s)
(a)

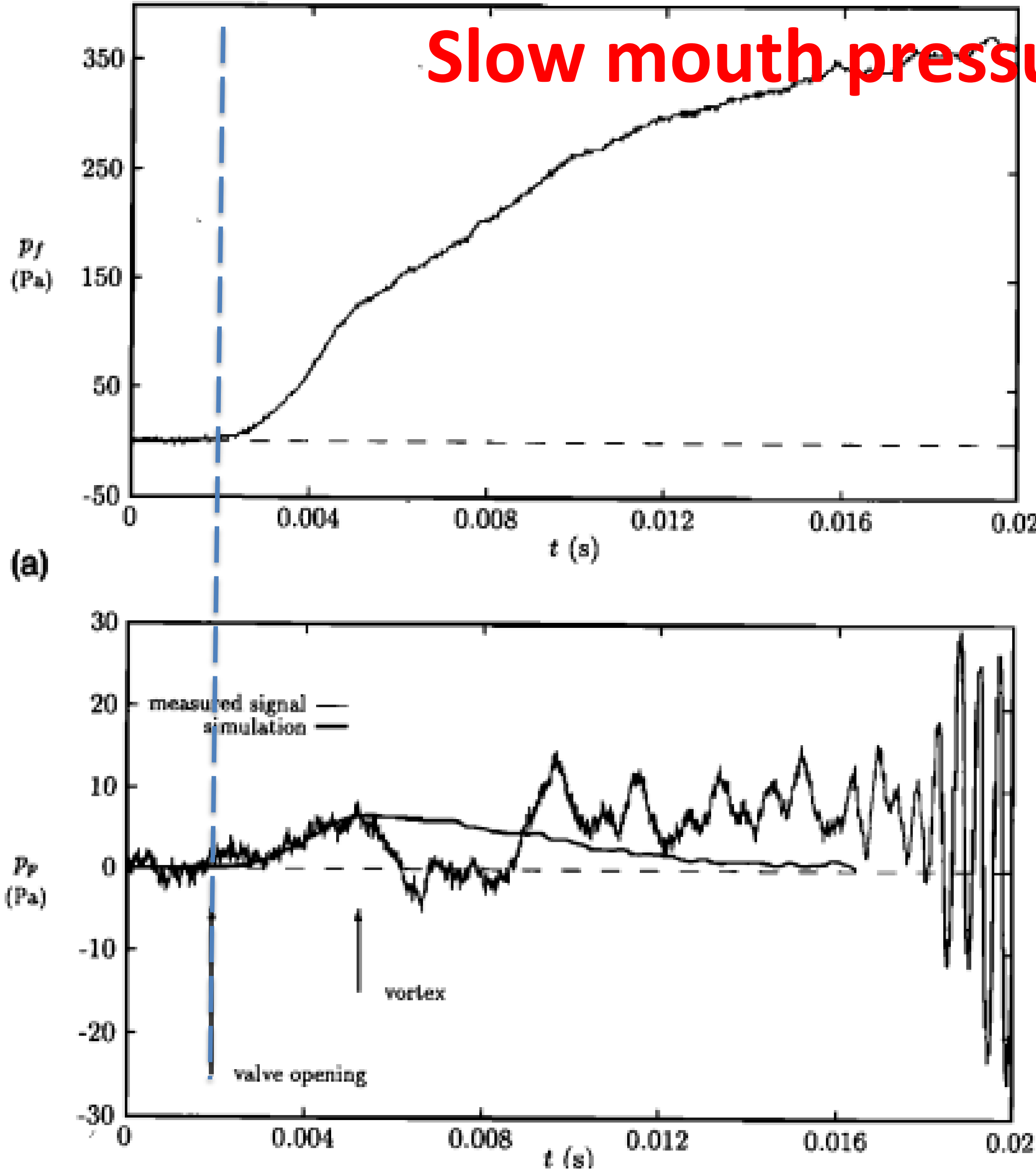

Mouth pressure
Sudden mouth pressure rise
Time (s)
Pipe pressure
700
500
300
100
-100
p_f (Pa)
0
0.004
0.008
0.012
0.016
0.02
t (s)
(a)
200
100
0
-100
-200
p_p (Pa)
measured signal
simulation
vortex
valve opening

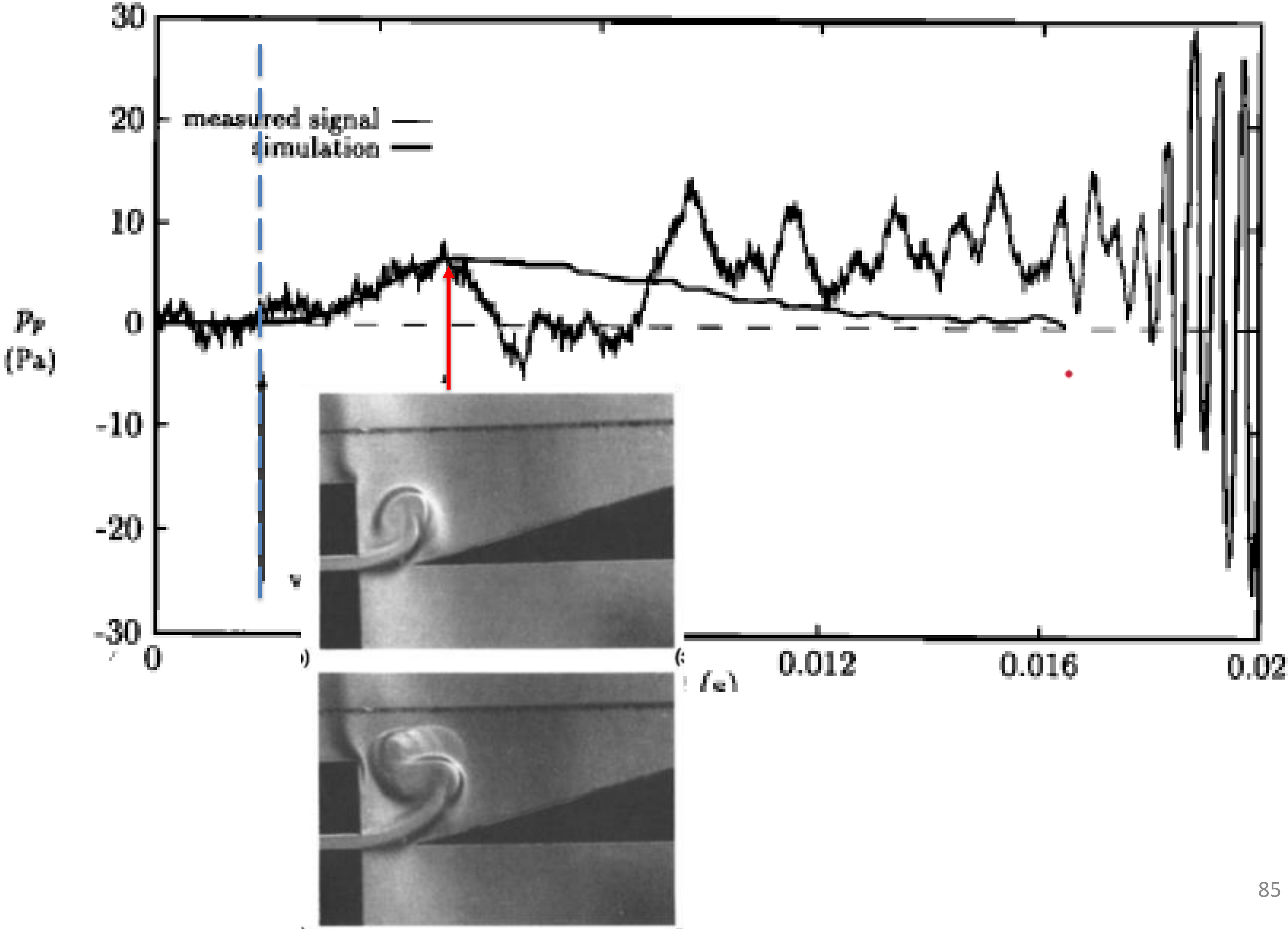
Sudden mouth pressure rise

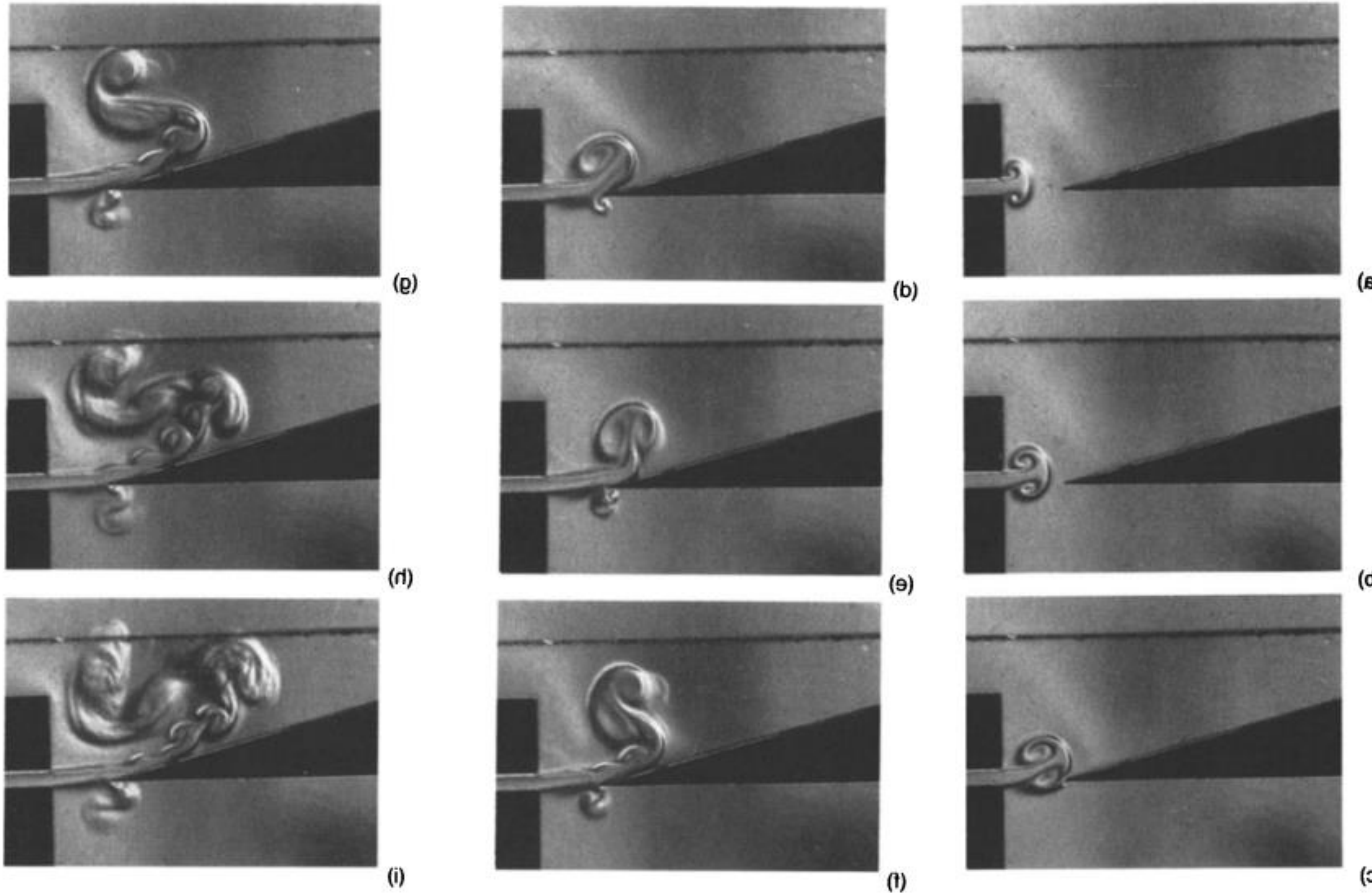



Slow mouth pressure rise
350
250
p_f (Pa)
150
50
-50
0
0.004
0.008
0.012
0.016
0.02
t (s)
(a)
Time (s)

Slow mouth pressure rise



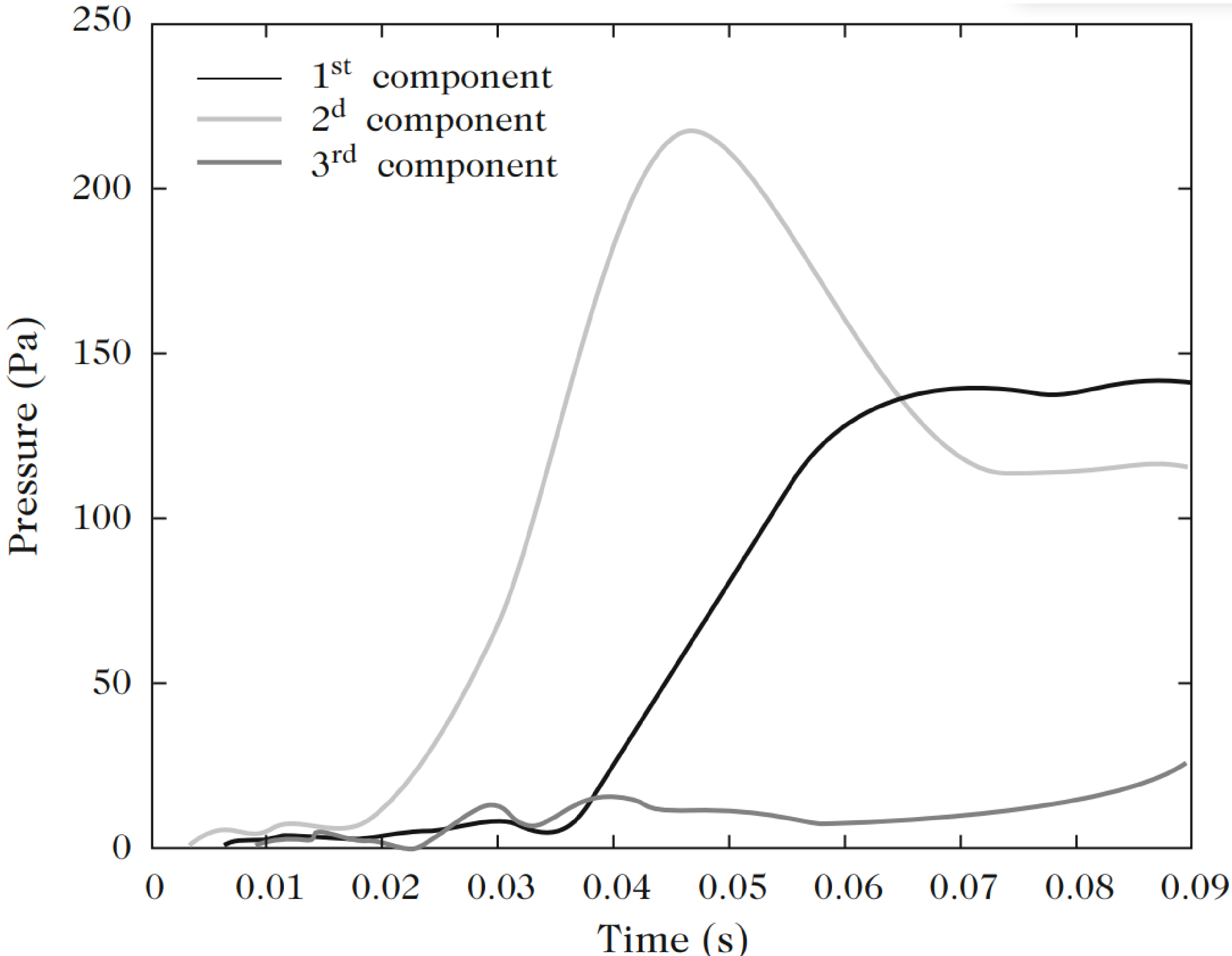

30
20
10
0
-10
-20
-30
measured signal
simulation
p_p
(Pa)
0
0.012
0.016
0.02



Attack transient in a recorder-like organ pipe
Flow visualization Benoit Fabre (2013)

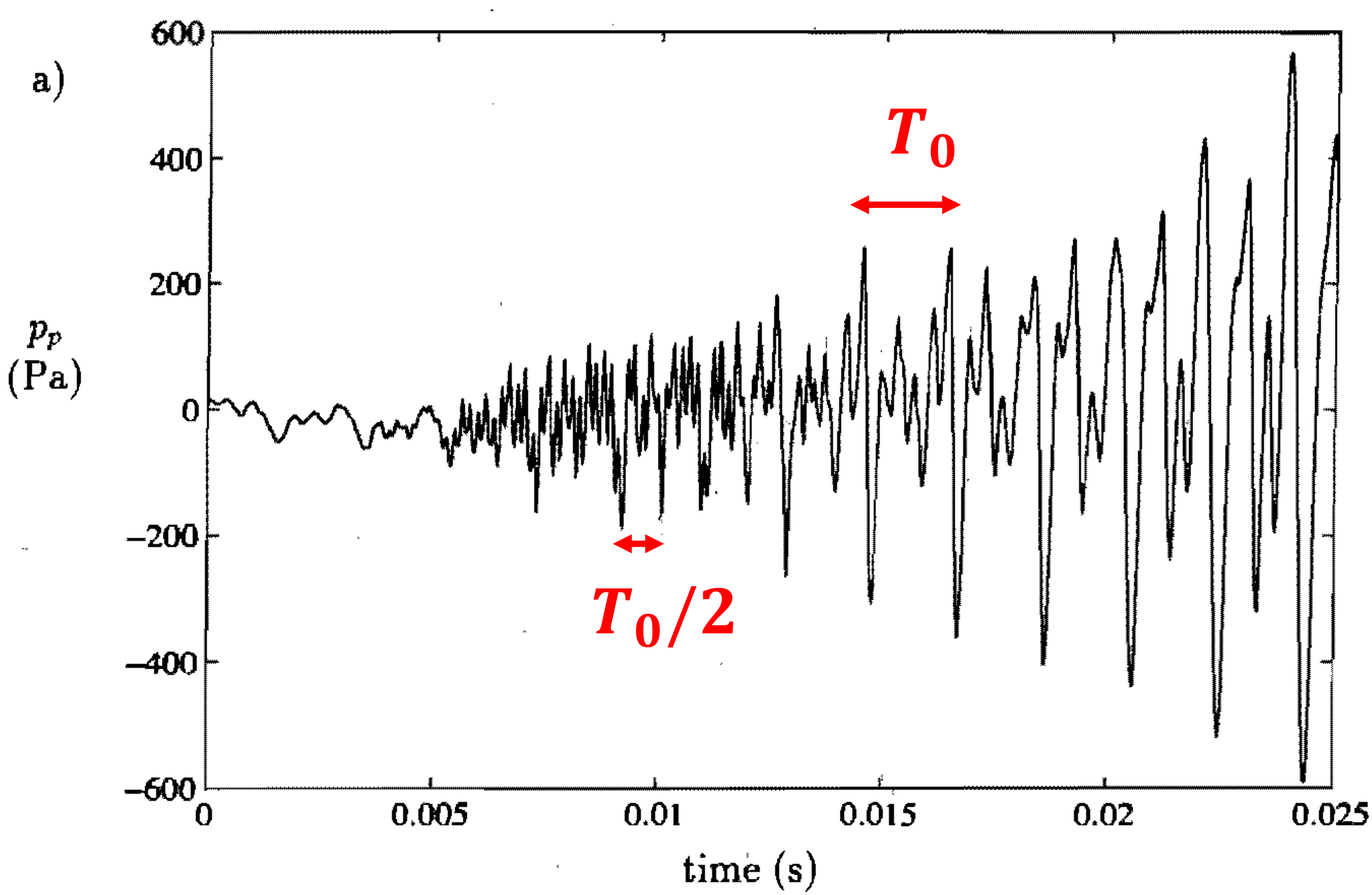
Oscillation starts as an “edge-tone” mixed with acoustic pipe oscillation on higher mode.

Castellengo (1999)



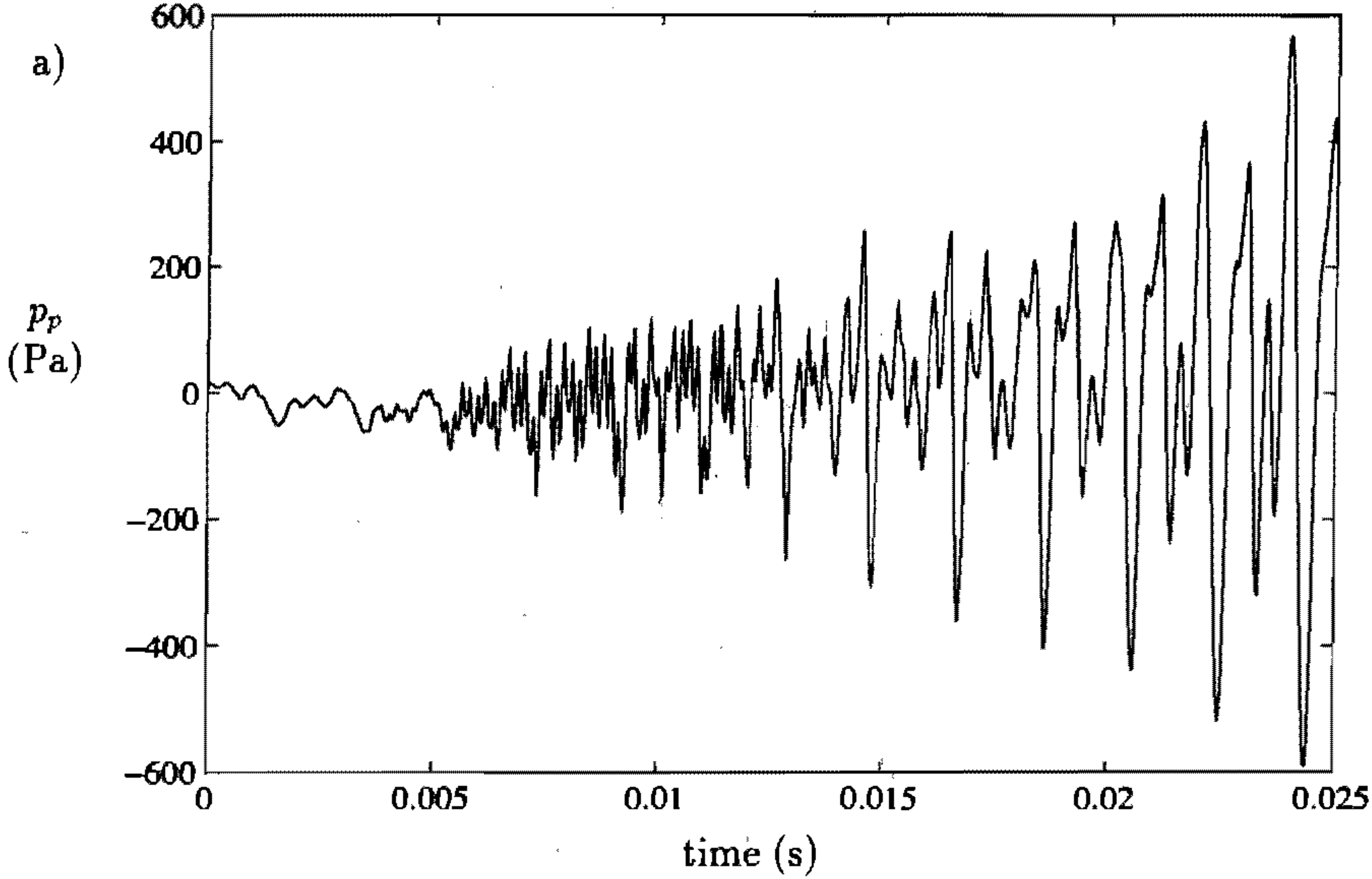
Ségoufin (2000)

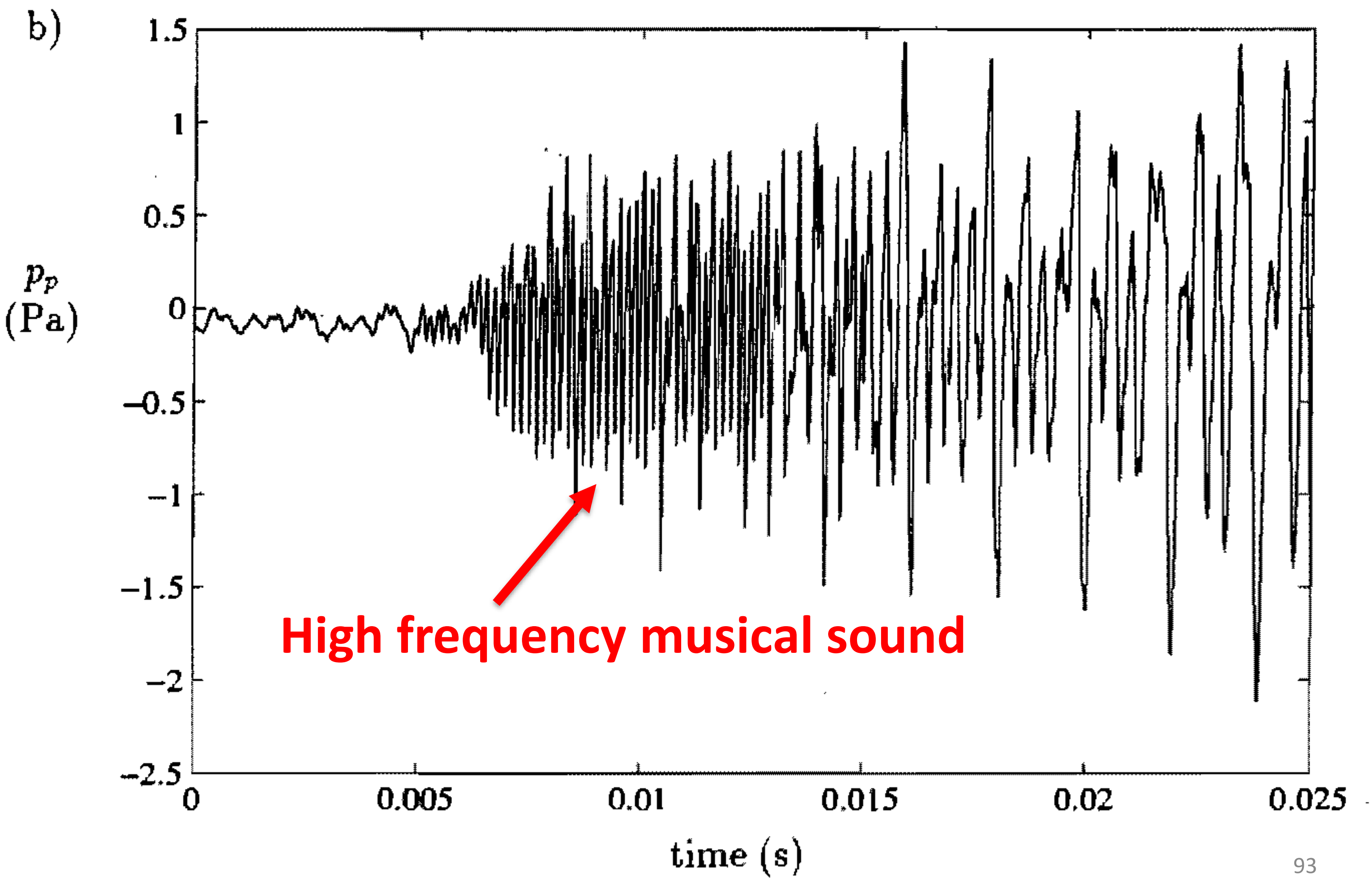
Attack transient (internal signal)



Attack transient in a recorder-like organ pipe
Flow visualization Benoit Fabre (2013)

Attack transient (internal signal)

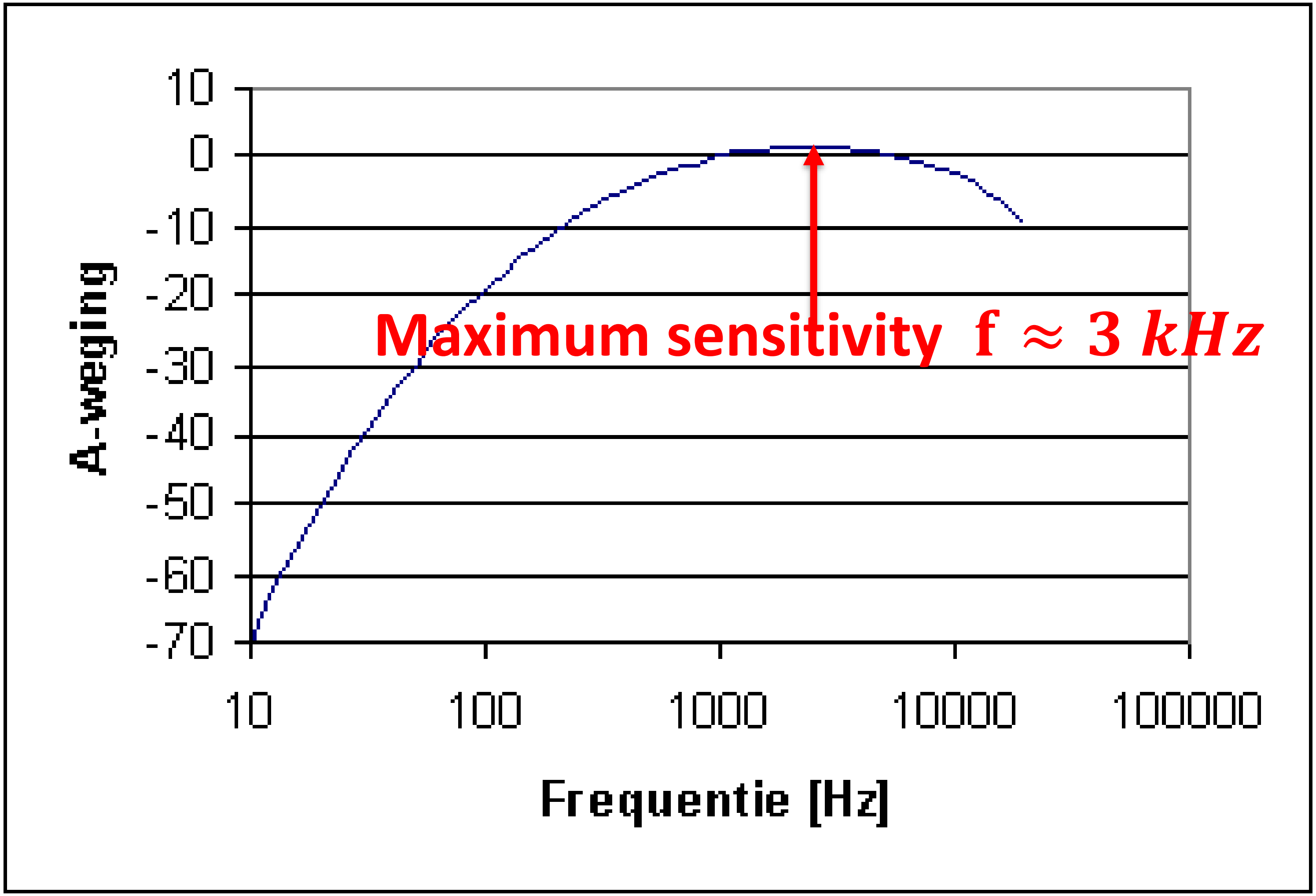



b)
1.5
1
0.5
0
−0.5
−1
−1.5
−2
−2.5
p_p
(Pa)
0
0.005
0.01
0.015
0.02
0.025
time (s)
High frequency musical sound

Radiated power increases with frequency:

$$\boldsymbol{I = \langle p'u' \rangle \propto (ka_0)^4 = \left(\frac{2\pi f a_0}{c}\right)^4}$$

Sensitivity of human hearing (dBA)

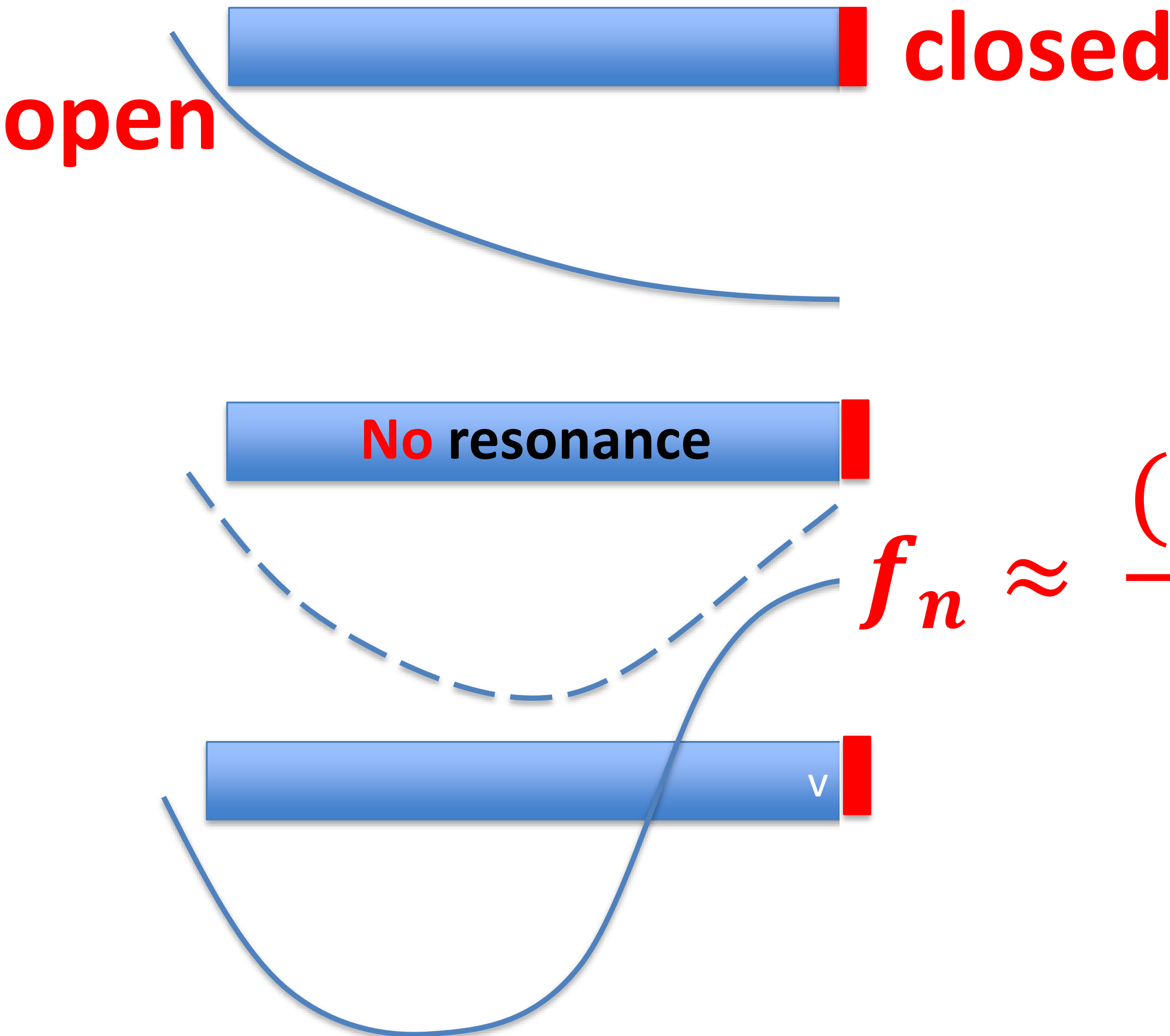


wikipedia

For low pitch the radiated sound of the fundamental is below the hearing threshold for pure tones.
The low pitch "fundamental" is "constructed" by our brains using the higher harmonics.

Sound source

Acoustics



$$f_n \approx \frac{(2\,n-1)c}{4(L+\delta)}$$

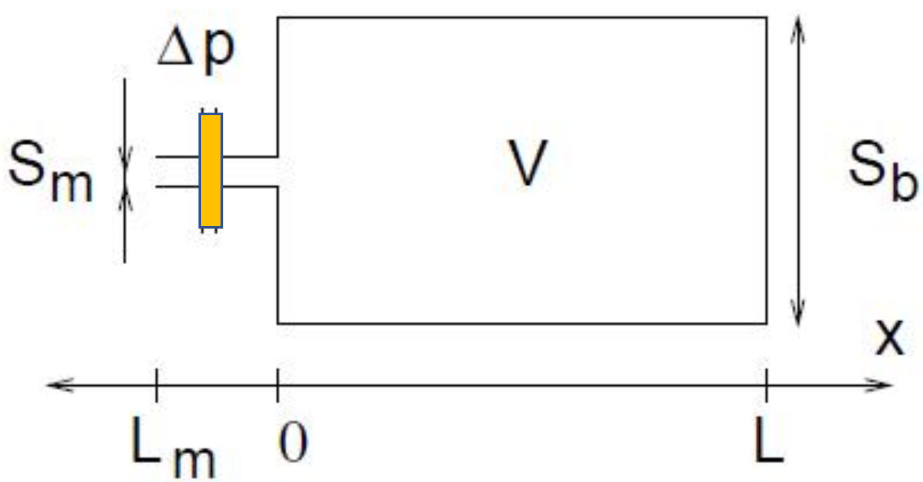
Open end

$$p \approx' 0$$

Closed end

$$\frac{\partial p'}{\partial x} = 0$$

Uneven harmonics dominate spectrum open-closed pipe instruments with cylindrical pipes (organ pipes, clarinet…)


Δp
Sm
V
Sb
x
Lm
0
L

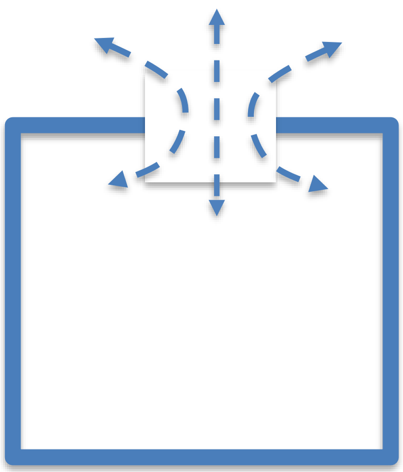
Resonance frequency of a tone hole

$$\omega = 2\pi f = \sqrt{\frac{m}{K}}$$

$$m = \rho S_n \delta_n$$

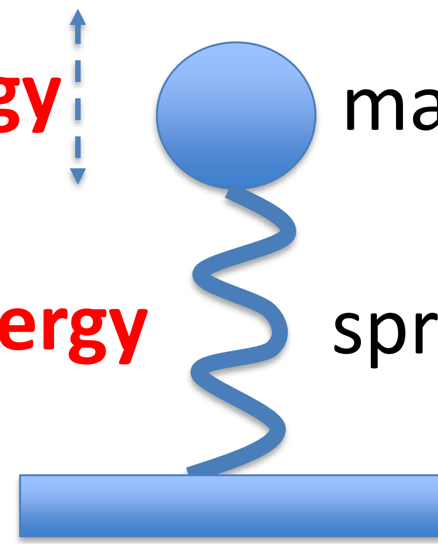
neck

volume



Kinetic energy

Potential energy



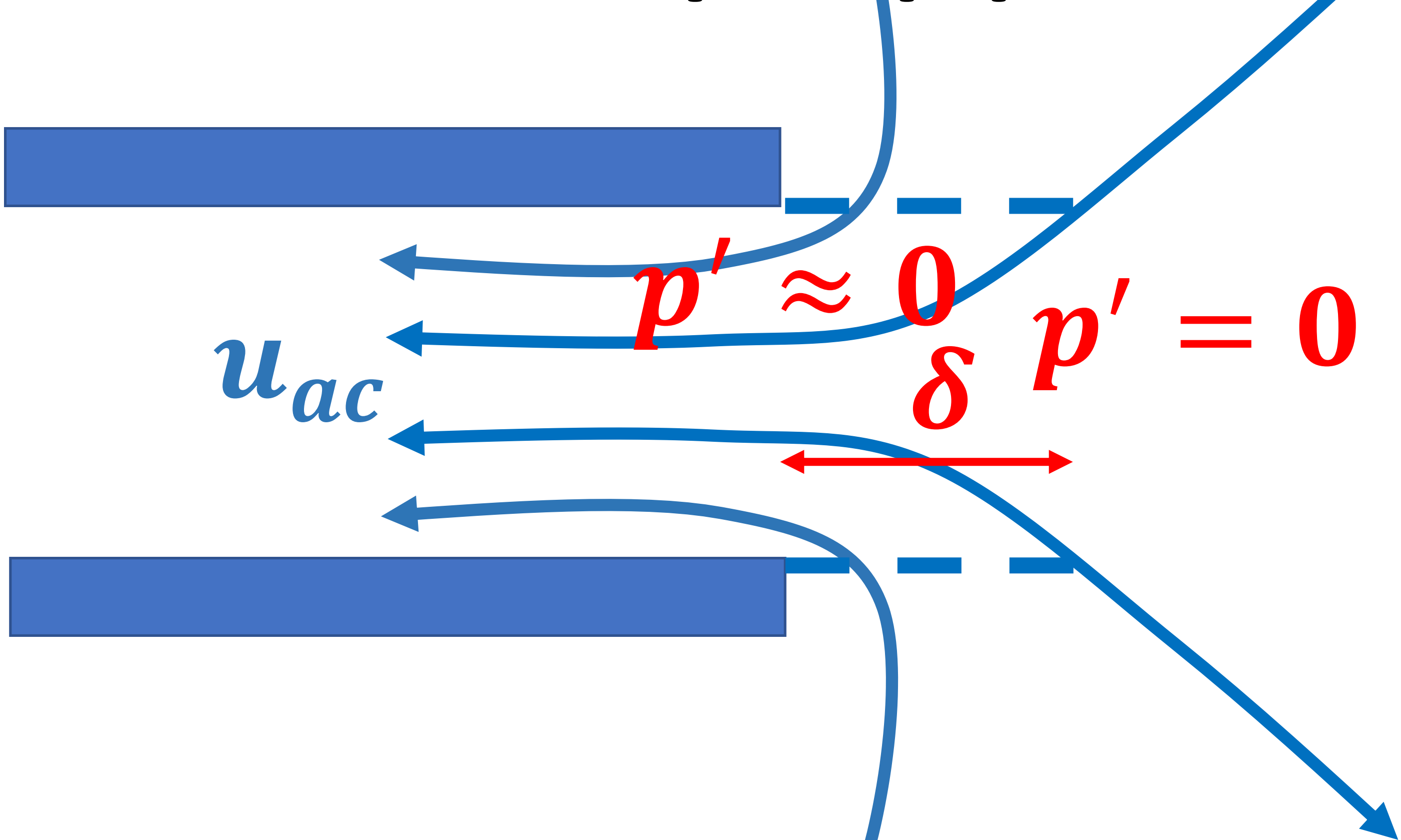
mass

spring

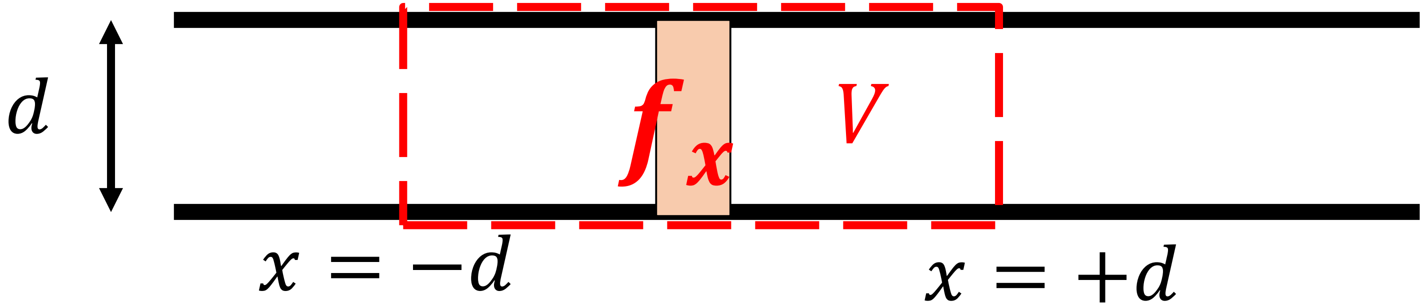
$$K = -\frac{F}{\Delta x} = \frac{\gamma p S_n^2}{V}$$

Effective neck length: δ_n

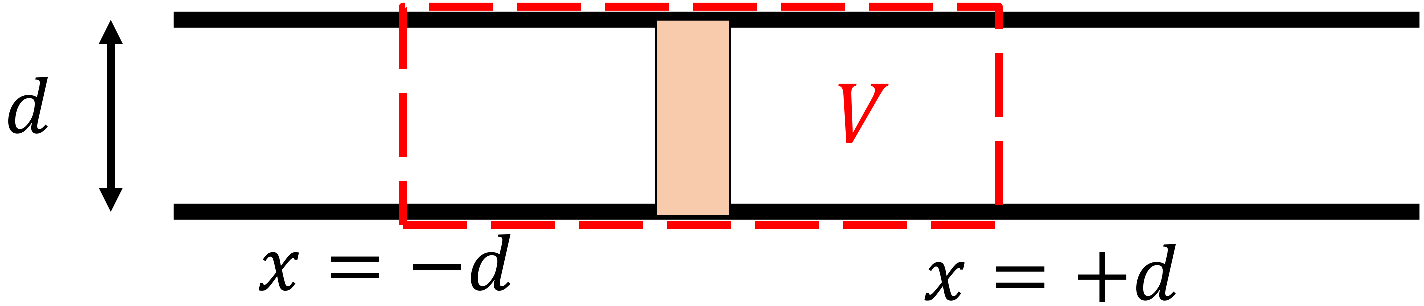
Just outside an open pipe termination



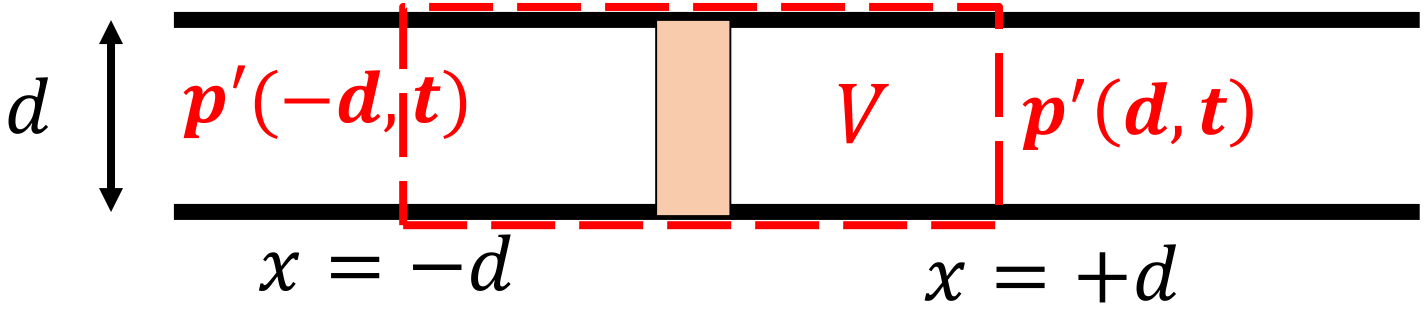
Mass of air in end correction takes kinetic energy of flow into account



Low frequency $\left(\left(\frac{\omega d}{c}\right)^2 \ll 1\right) \Rightarrow$ **Plane waves** $p'(x,t)$

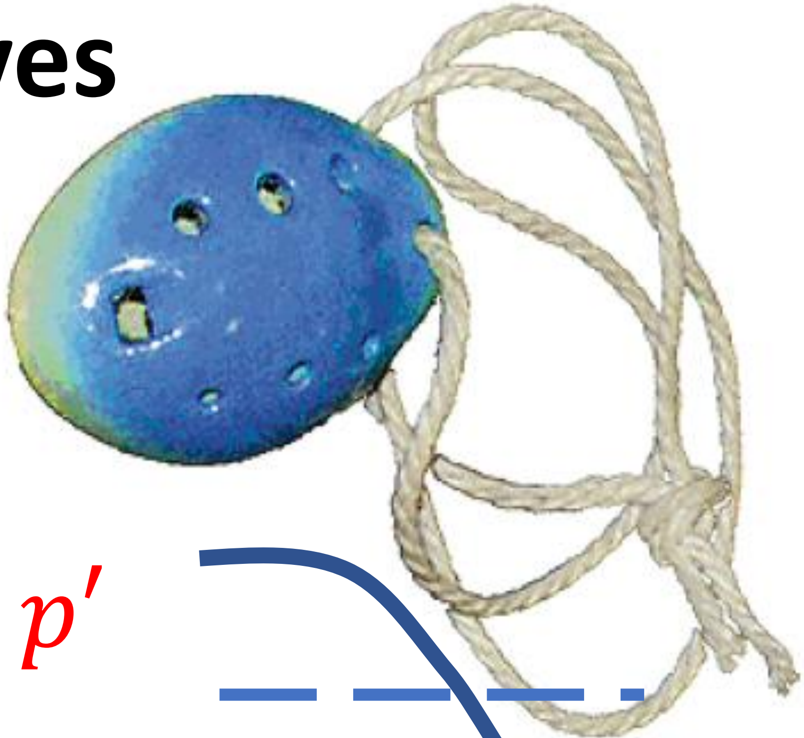


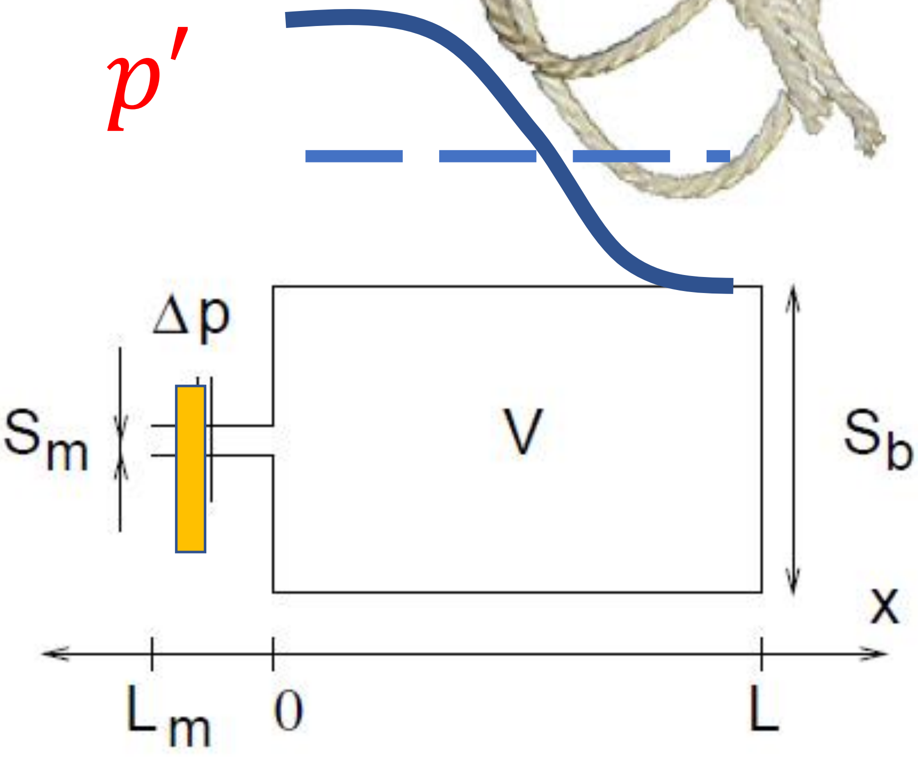
$$\iiint_V \nabla p' dV = \frac{\pi d^2}{4}\left(p'(d,t) - p'(-d,t)\right) \approx F_x(t) \equiv \iiint_V f_x dV$$



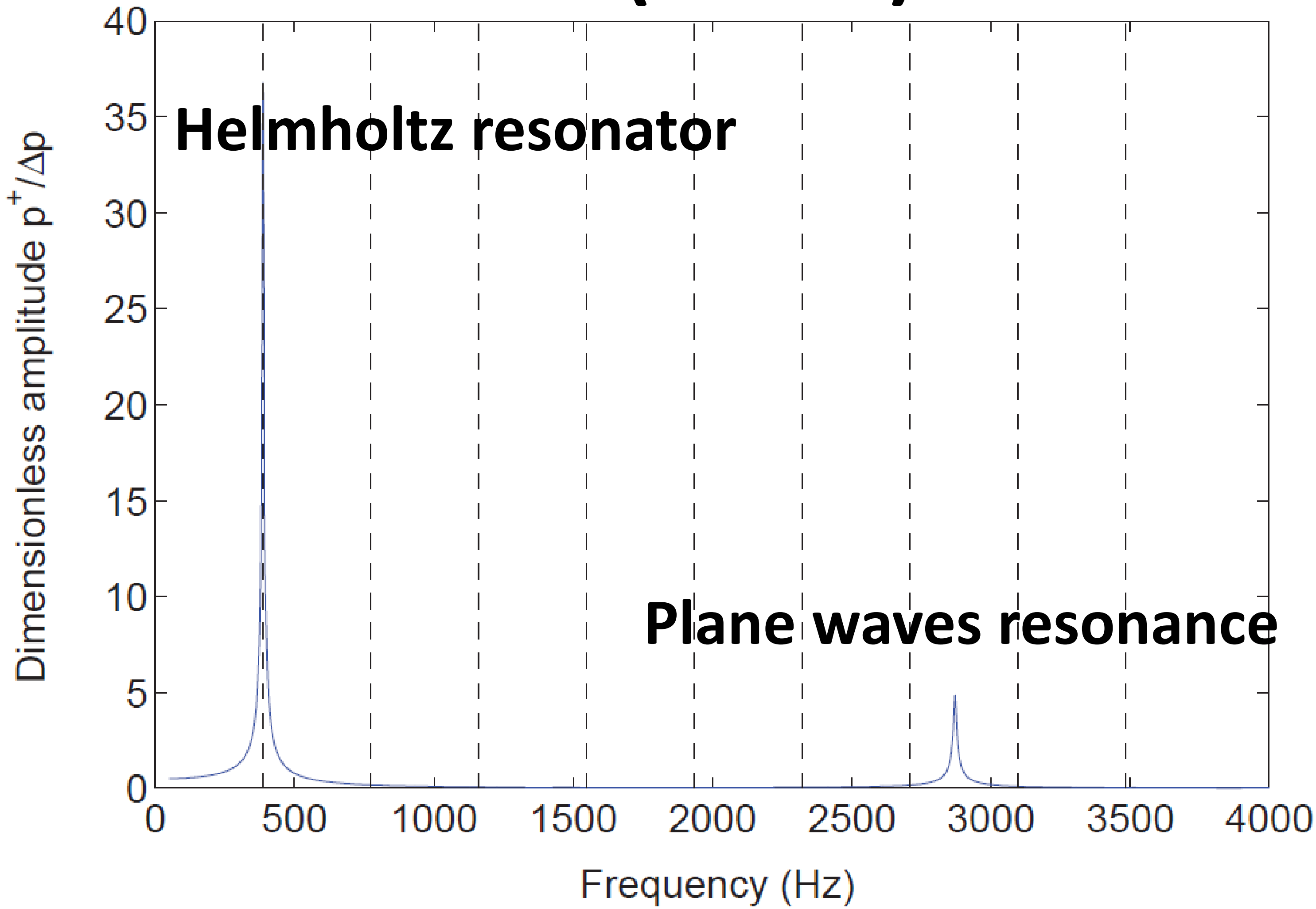
$$\Delta p = \left(p'(d,t) - p'(-d,t)\right) \approx \frac{F_x(t)}{\left(\frac{\pi d^2}{4}\right)}$$

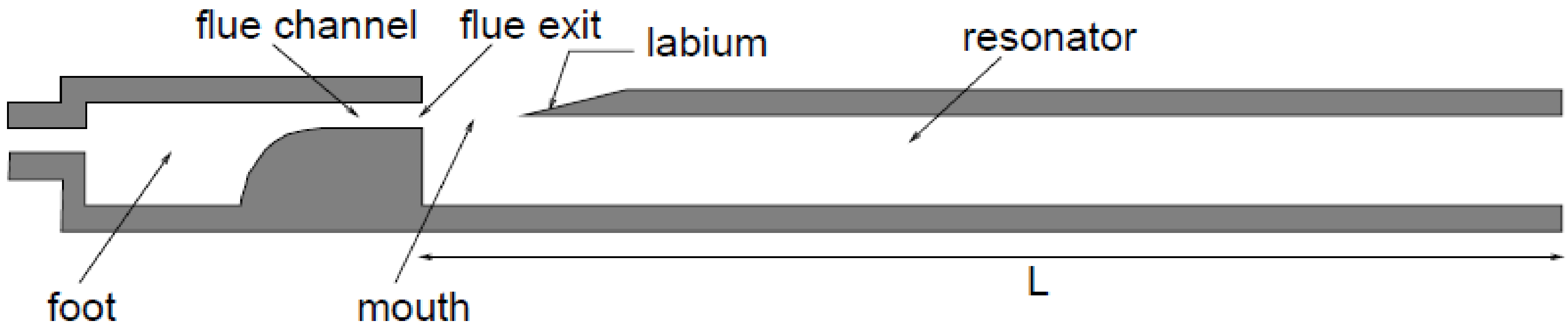
Plane waves

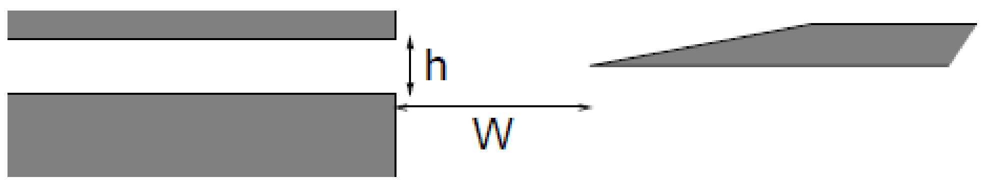


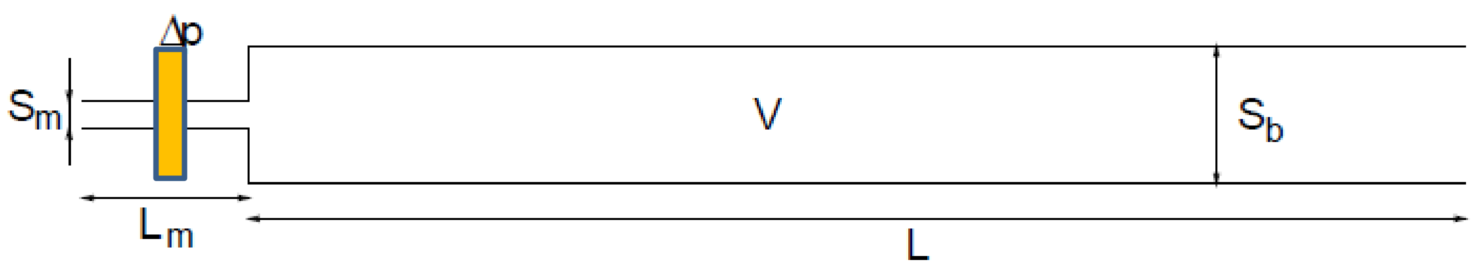


Ocarina (bottle)

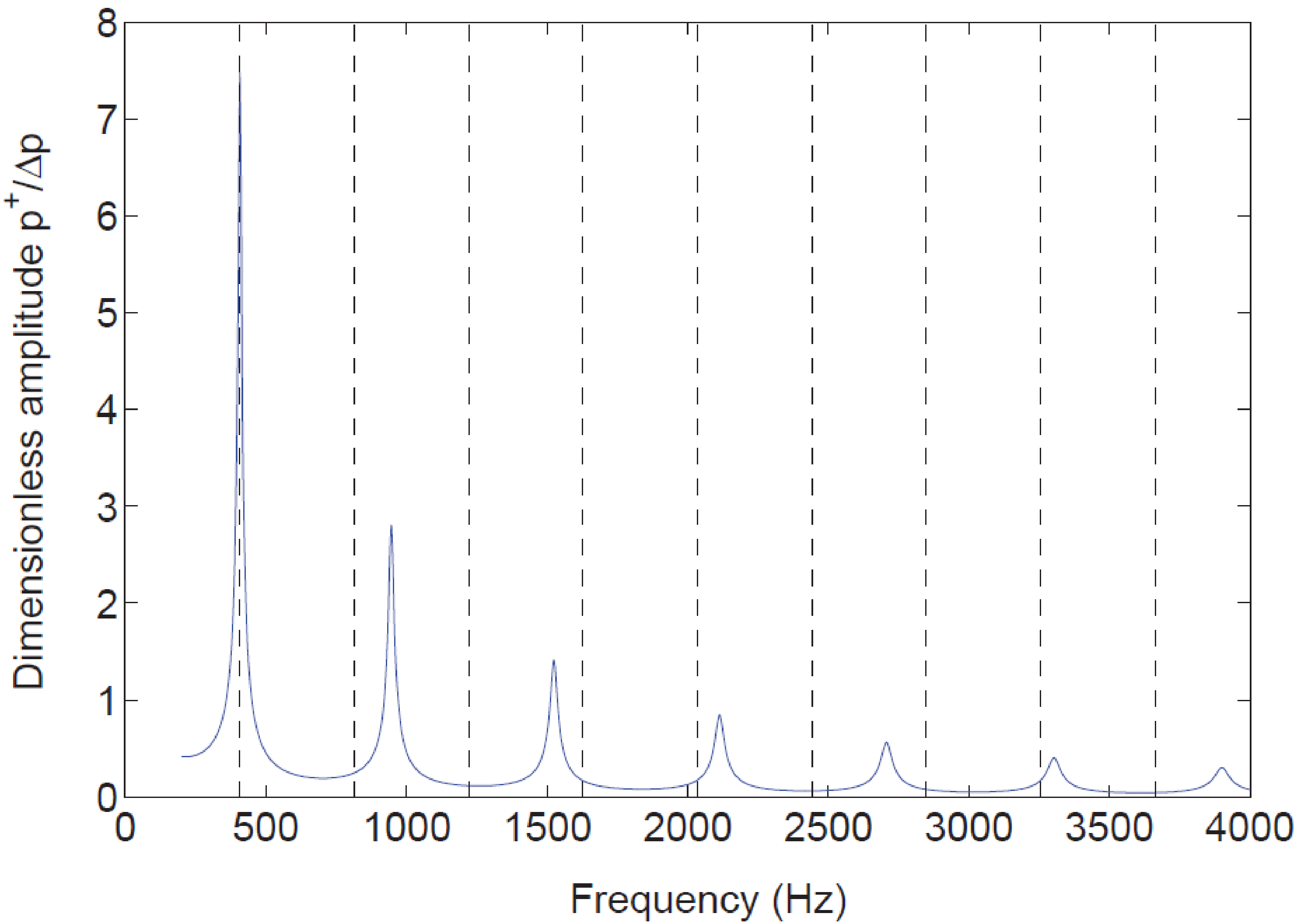



flue channel
flue exit
labium
resonator
foot
mouth
L


h
W

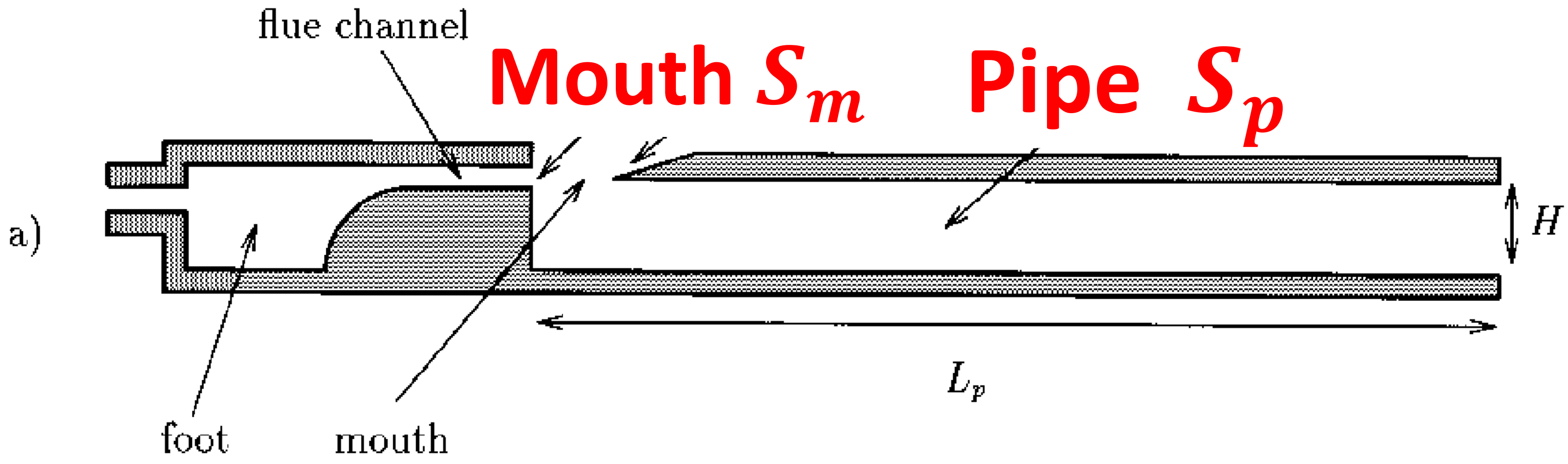

Δp
Sm
V
Sb
Lm
L

Organ pipe



8
7
6
5
4
3
2
1
0
Dimensionless amplitude $p^+/\Delta p$
0
500
1000
1500
2000
2500
3000
3500
4000
Frequency (Hz)

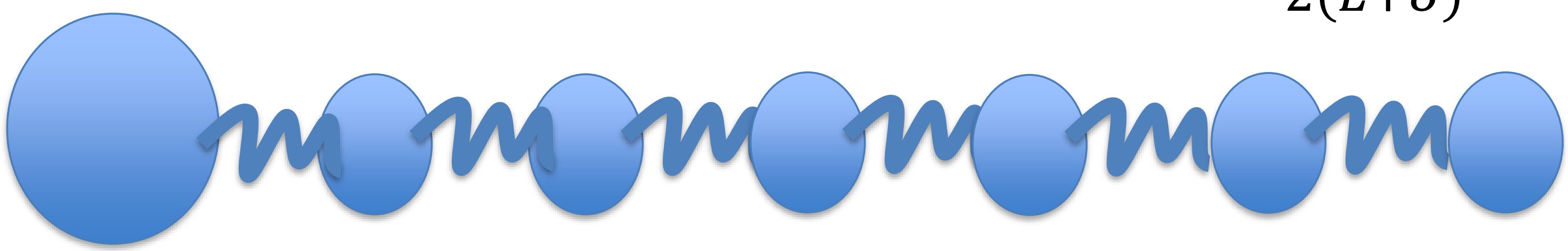
$$\frac{S_p}{S_m} > 1$$



Ideal open-open pipe: $f_n = nf_1 = \frac{n\,c}{2\,L}$

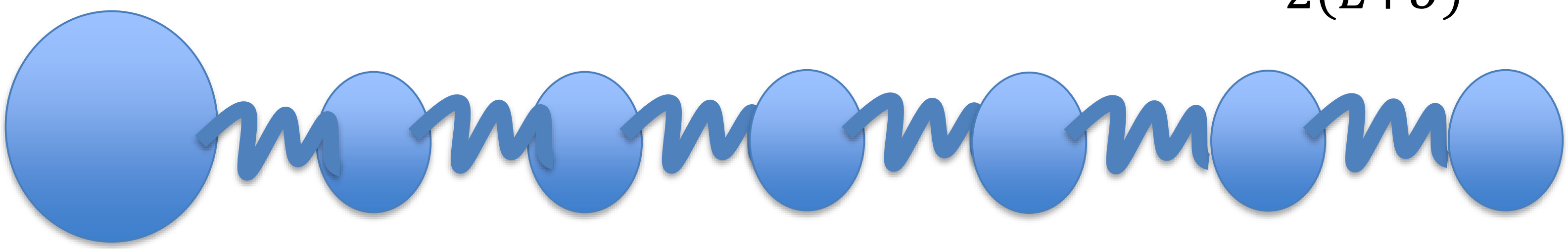
Ideal open-open pipe: $\boldsymbol{f_n = nf_1 = \frac{n\,c}{2\,L}}$

Recorder flute $f_n = nf_1 \sim \frac{n\,c}{2(L+\delta)}$

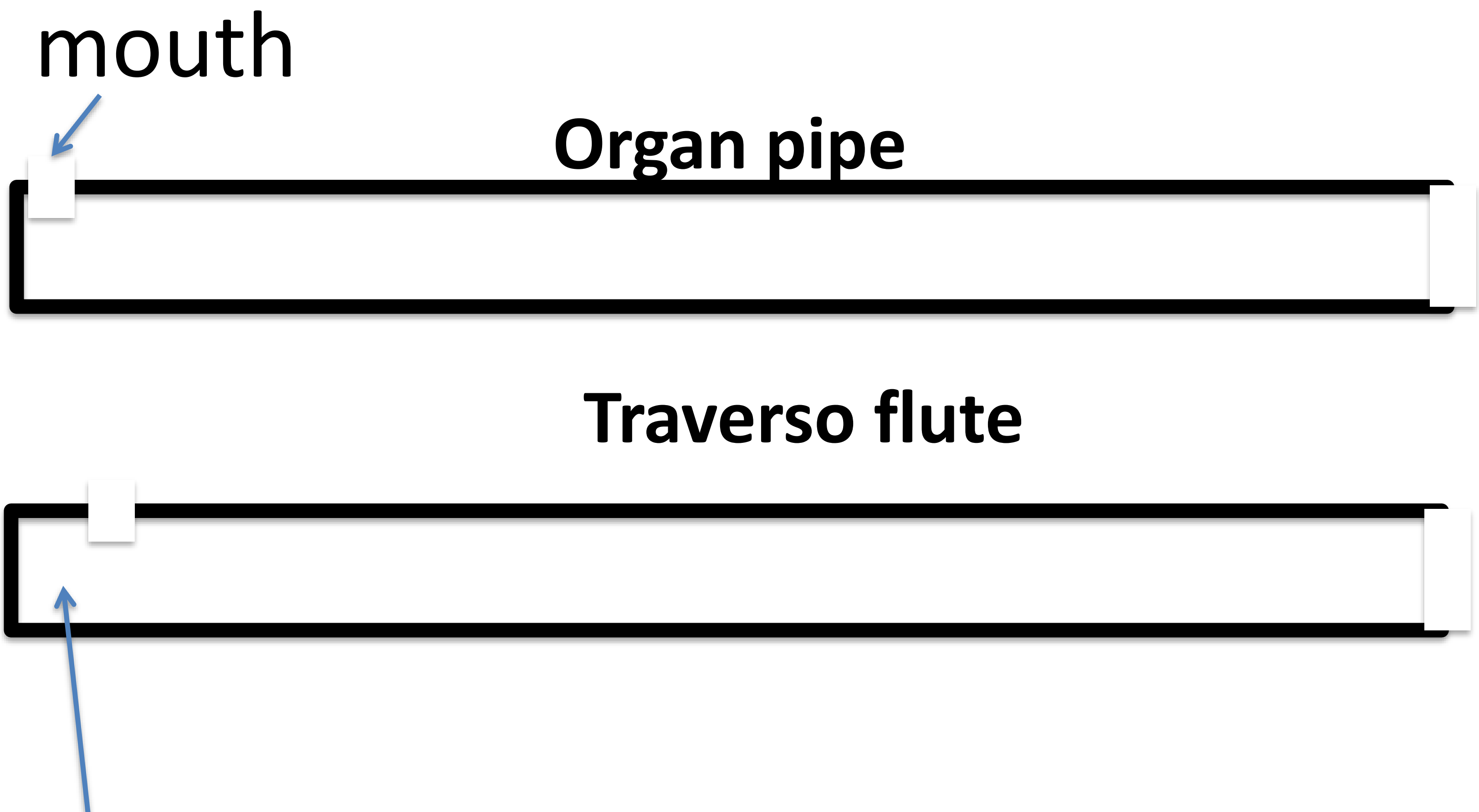


Ideal open-open pipe: $f_n = nf_1 = \frac{n\,c}{2\,L}$

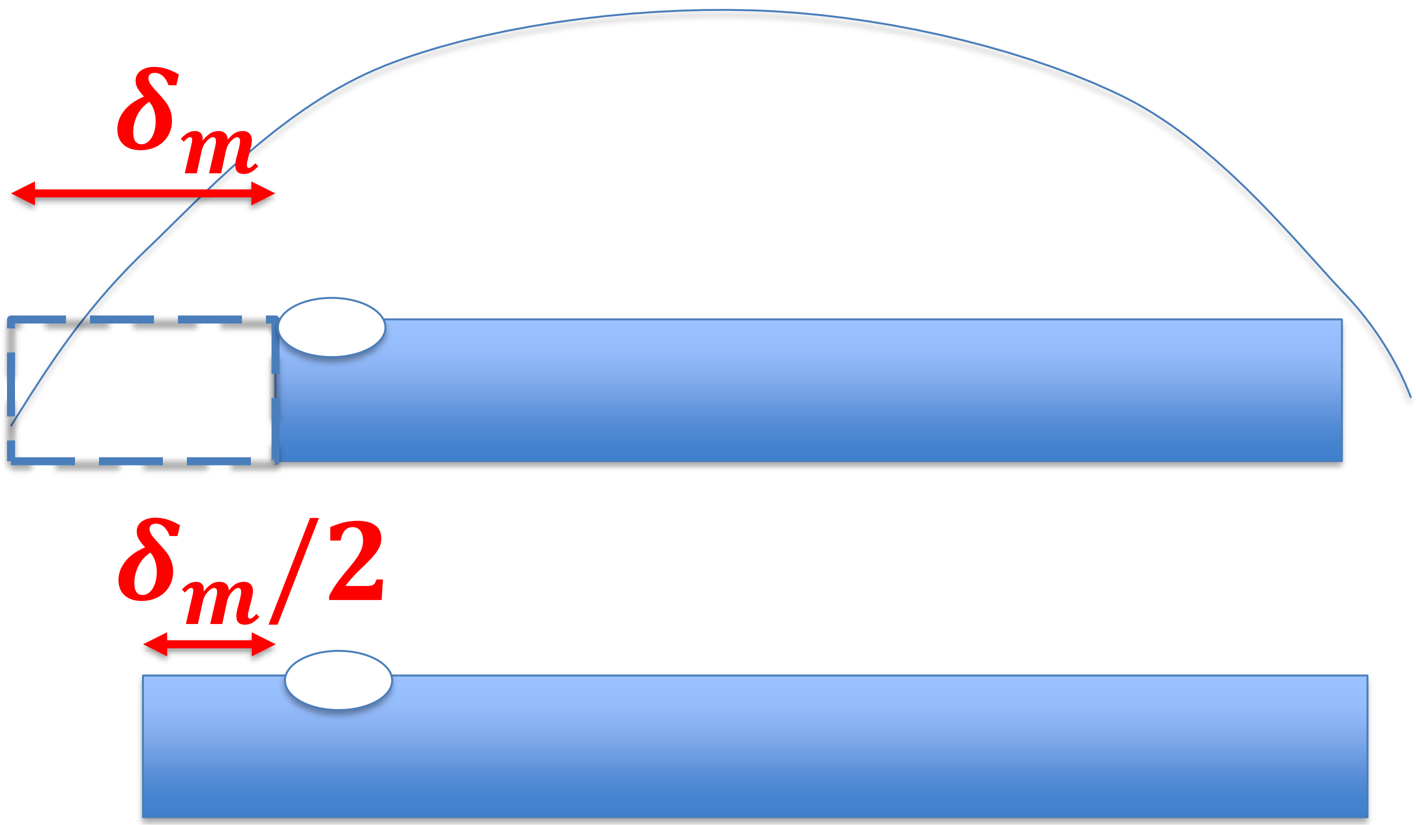
Recorder flute $f_n = nf_1 \sim \frac{n\,c}{2(L+\delta)}$



Traverso flute $f_n = nf_1 = \frac{n\,c}{2(L+\delta)}$

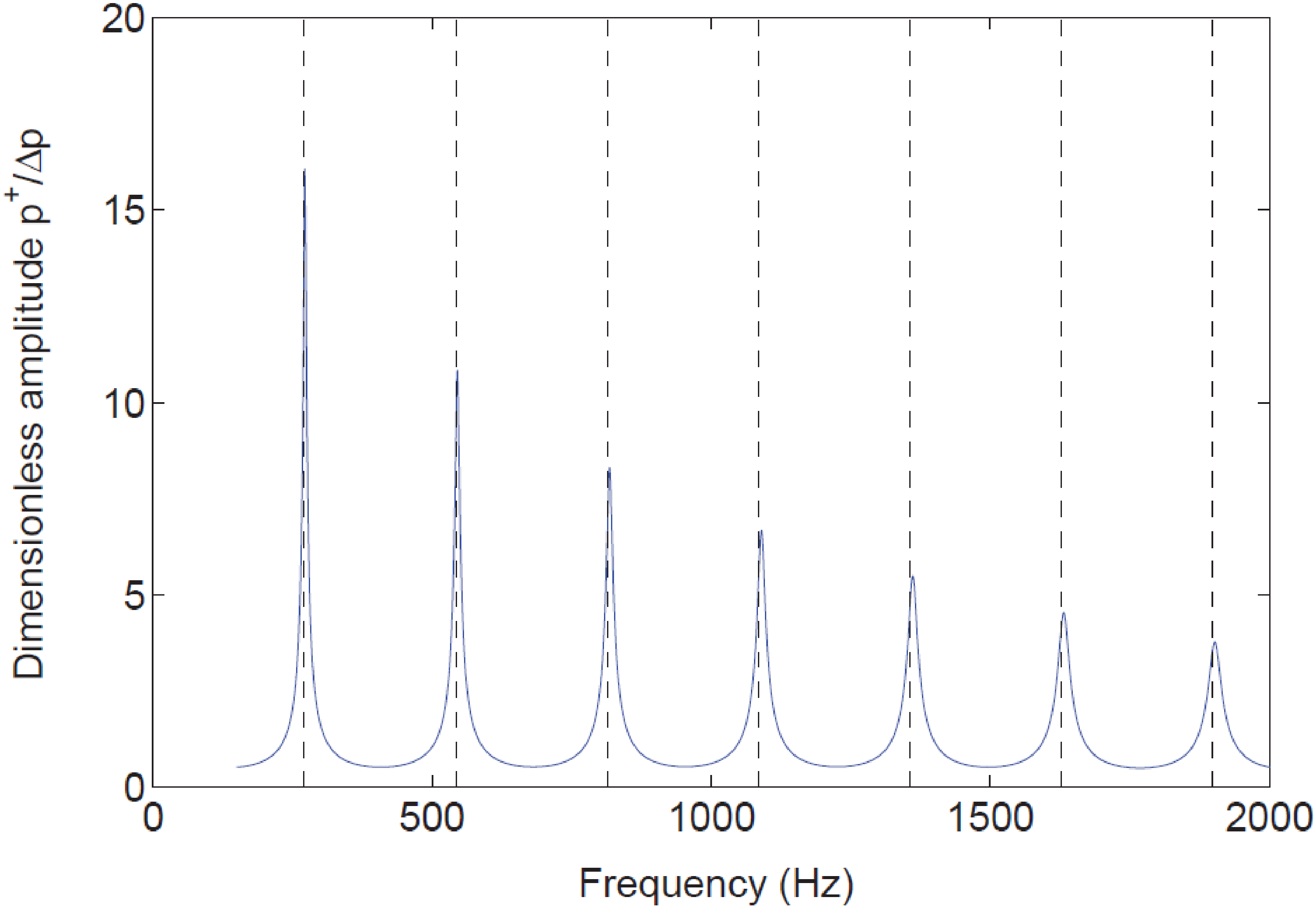


Extra compliance to compensate for inertia in mouth



In the baroque flute the head joint is cylindrical, this provides a good response for the lowest notes. The head joint of the modern Boehm flute is not cylindrical to obtain an optimal acoustic response for all the notes.

Flute



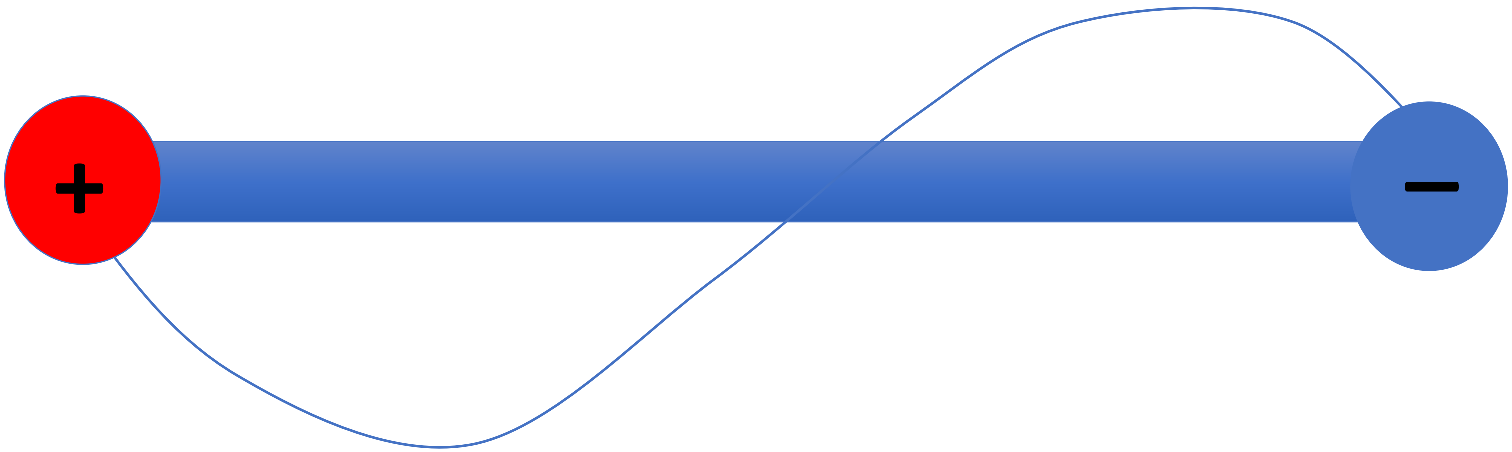
20
15
10
5
0
0
500
1000
1500
2000
Dimensionless amplitude $p^+/\Delta p$
Frequency (Hz)

Modes multiple of first mode implies:
Sound is rich in higher harmonics
Bright sound

$$f_n \approx n\, f_1 \approx n\, f_0$$

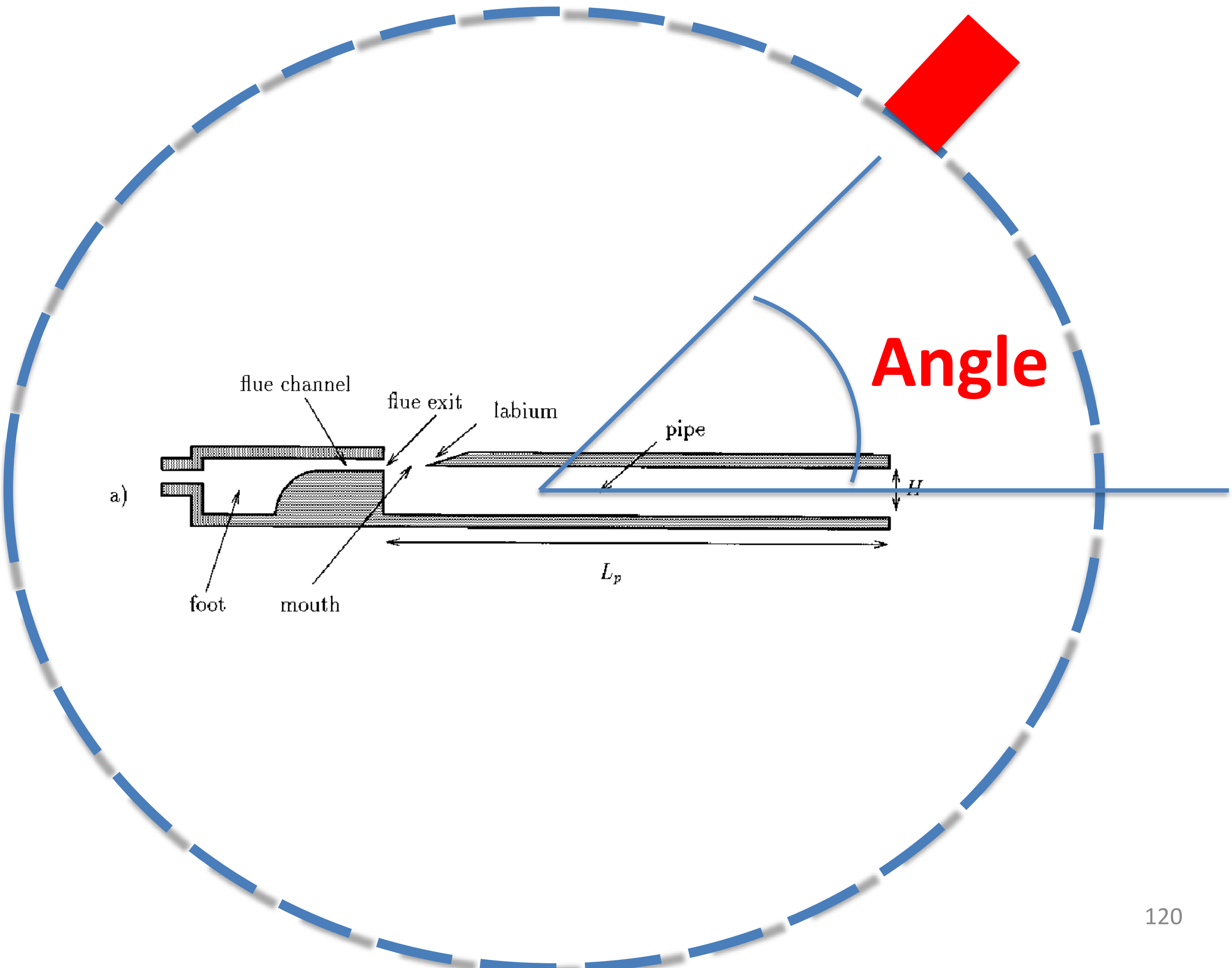
Directivity: fundamental mode

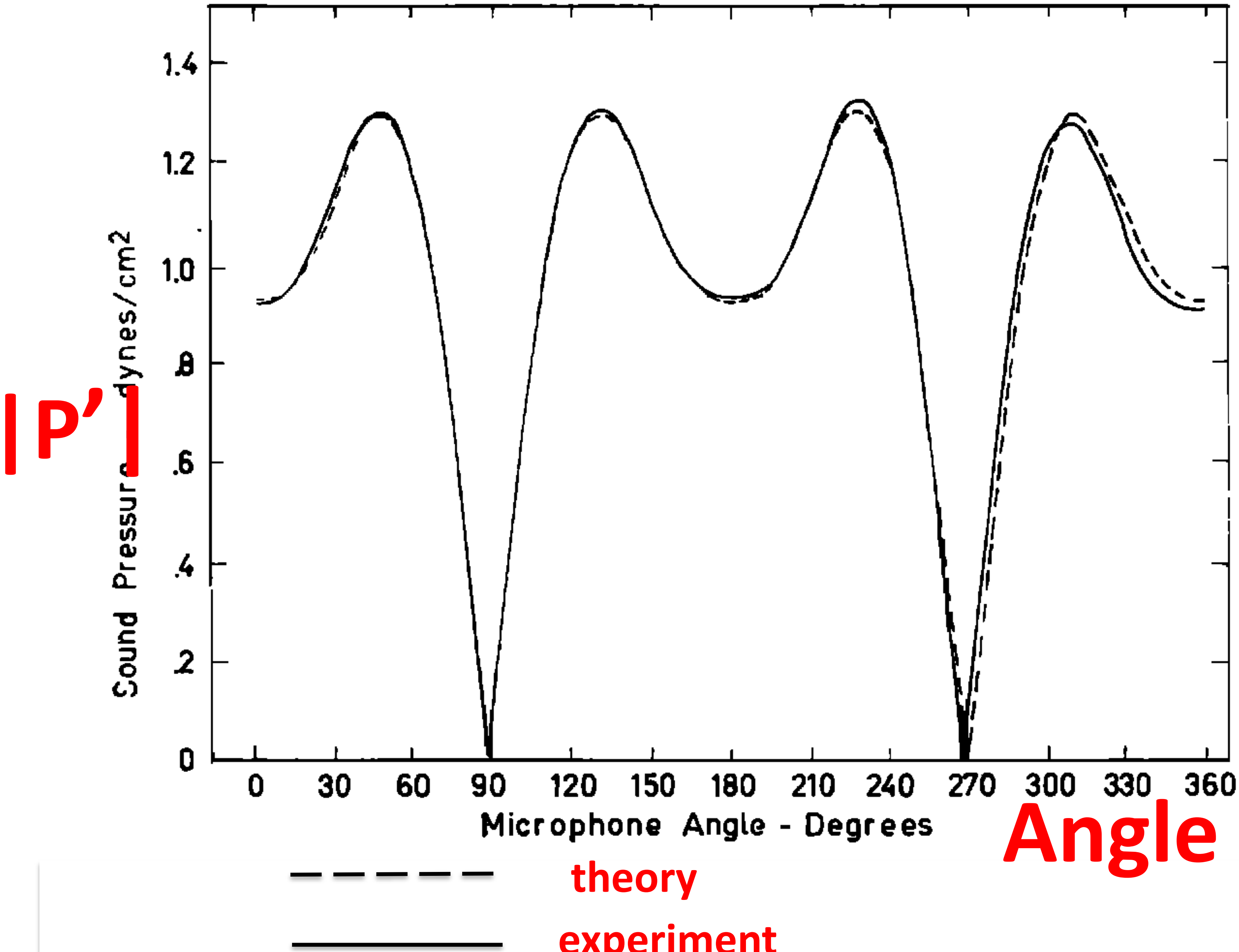
Directivity second mode



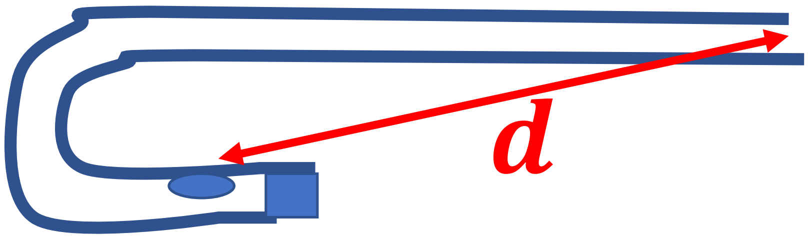
Equal sound strength of sources?
Coltman (1977)

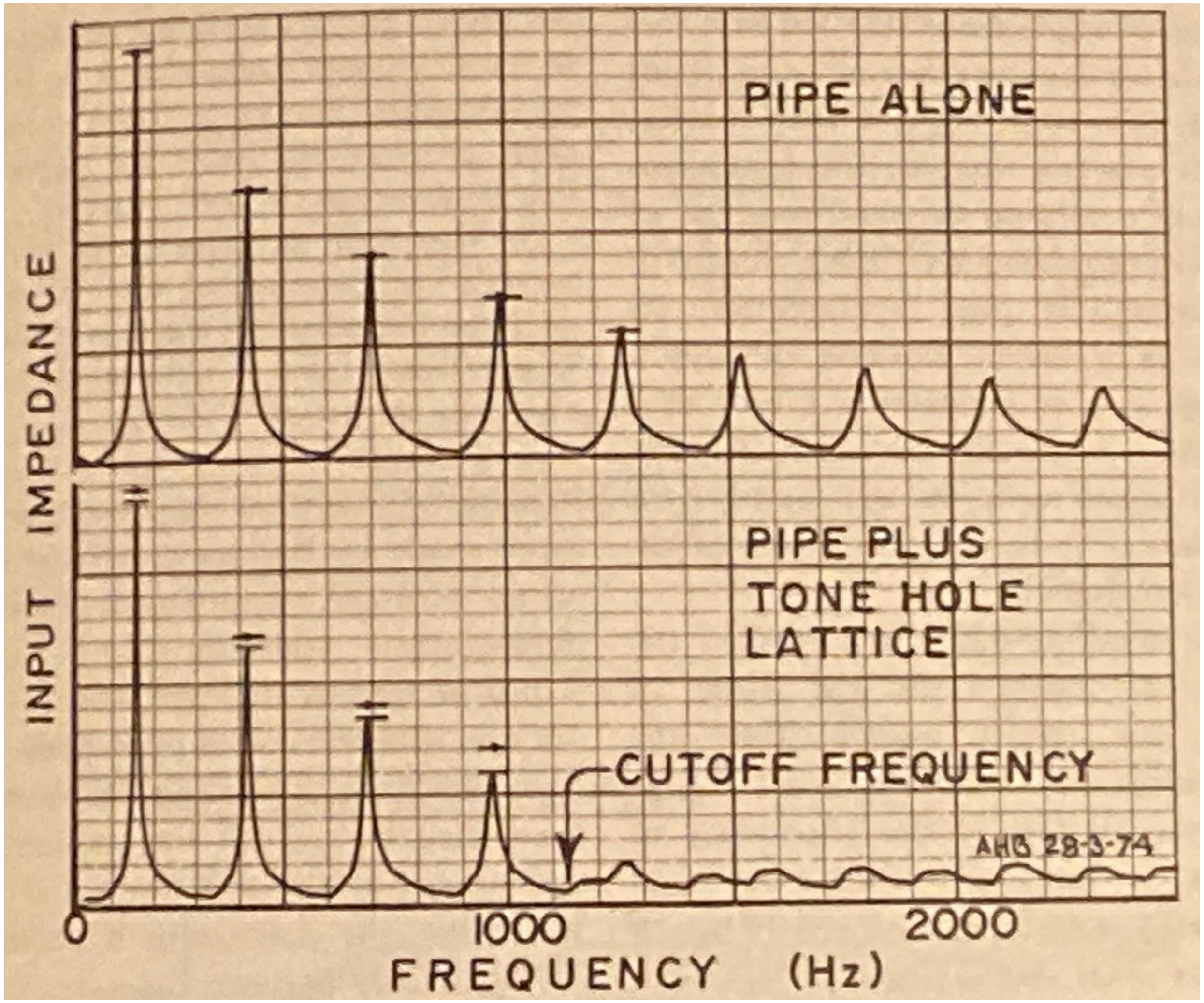
Distant microphone




|P'|
Sound Pressur
dynes/cm2
1.4
1.2
1.0
.8
.6
.4
.2
0
0
30
60
90
120
150
180
210
240
270
300
330
360
Microphone Angle - Degrees
Angle
theory
experiment

Curved pipe effect (Coltman 1984)

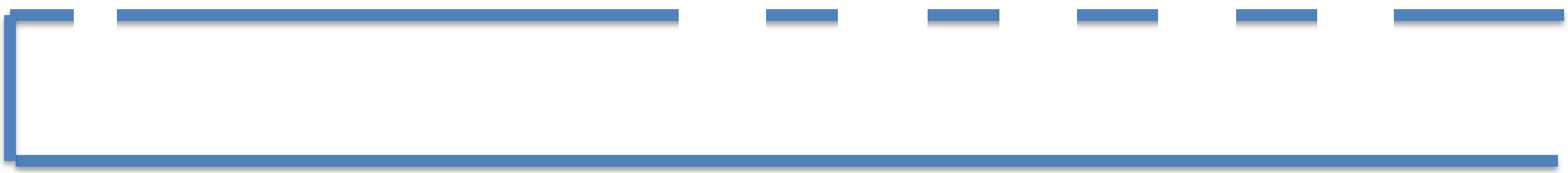




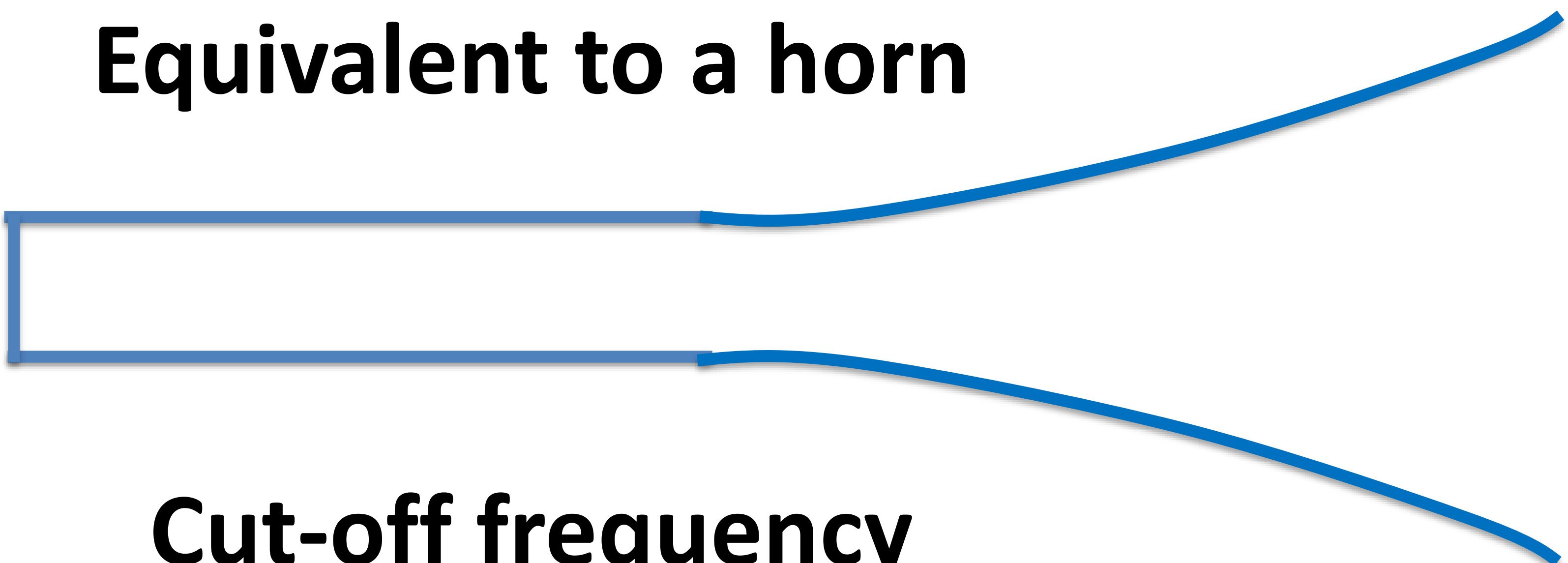
PIPE ALONE
PIPE PLUS
TONE HOLE
LATTICE
CUTOFF FREQUENCY
AHB 28-3-74
INPUT IMPEDANCE
0
1000
2000
FREQUENCY (Hz)

Benade (1976)

Tone-hole lattice helps radiation high frequencies



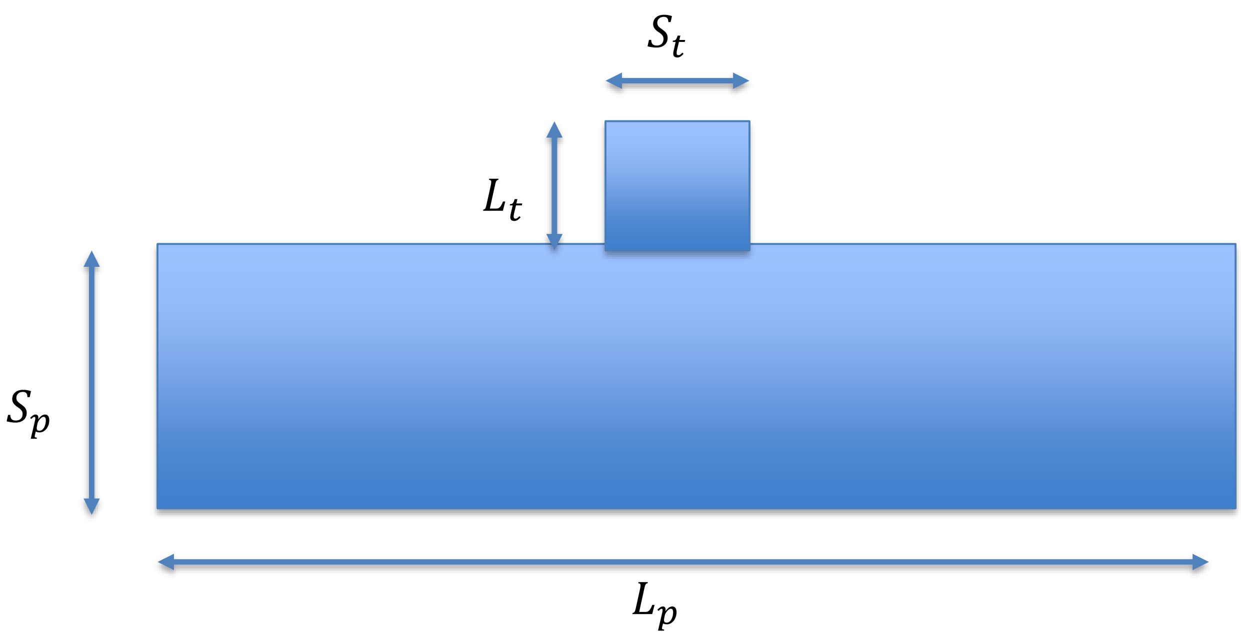
Equivalent to a horn



Cut-off frequency

Helmholtz resonance frequency cell:

$$\omega_c = c_o\sqrt{\frac{S_t}{S_p L_p L_t}}$$



Prandtl:

VORTICES ARE THE MUSCLES OF FLOW

Müller & Obermeir (Fluid Dyn. Res. 3, (1988) 43 – 51)**:**

VORTICES ARE THE VOICE OF FLOWS

The acoustics of musical instruments is subtle.

But the musician is even more important.

https://youtu.be/Ve6PTrlLGOU

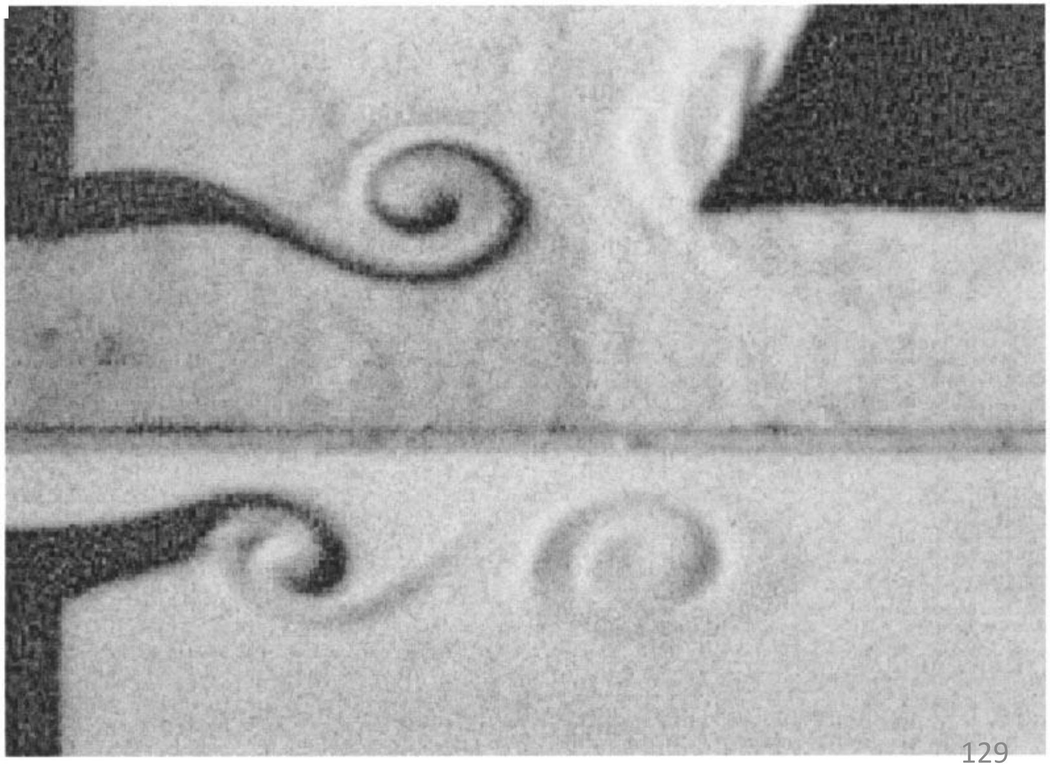
https://youtu.be/__YdjypIZ_o

Windorgel op de Nolledijk, te Vlissingen – YouTube

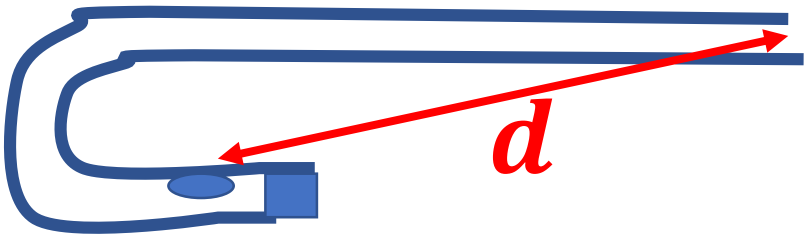
(1) Chakra Windorgel met prachtig geluid - YouTube

Most Aeolian organs have a very poor acoustical design.

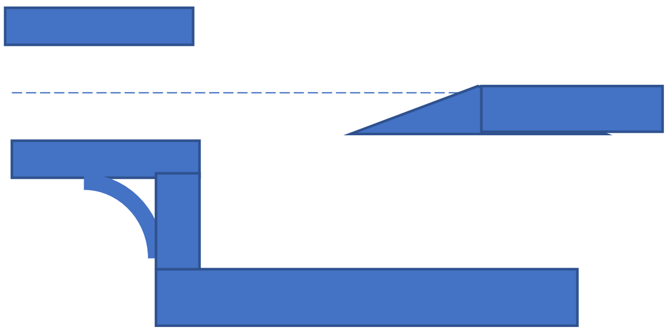
Thank you for your attention



Curved pipe effect (Coltman 1984)

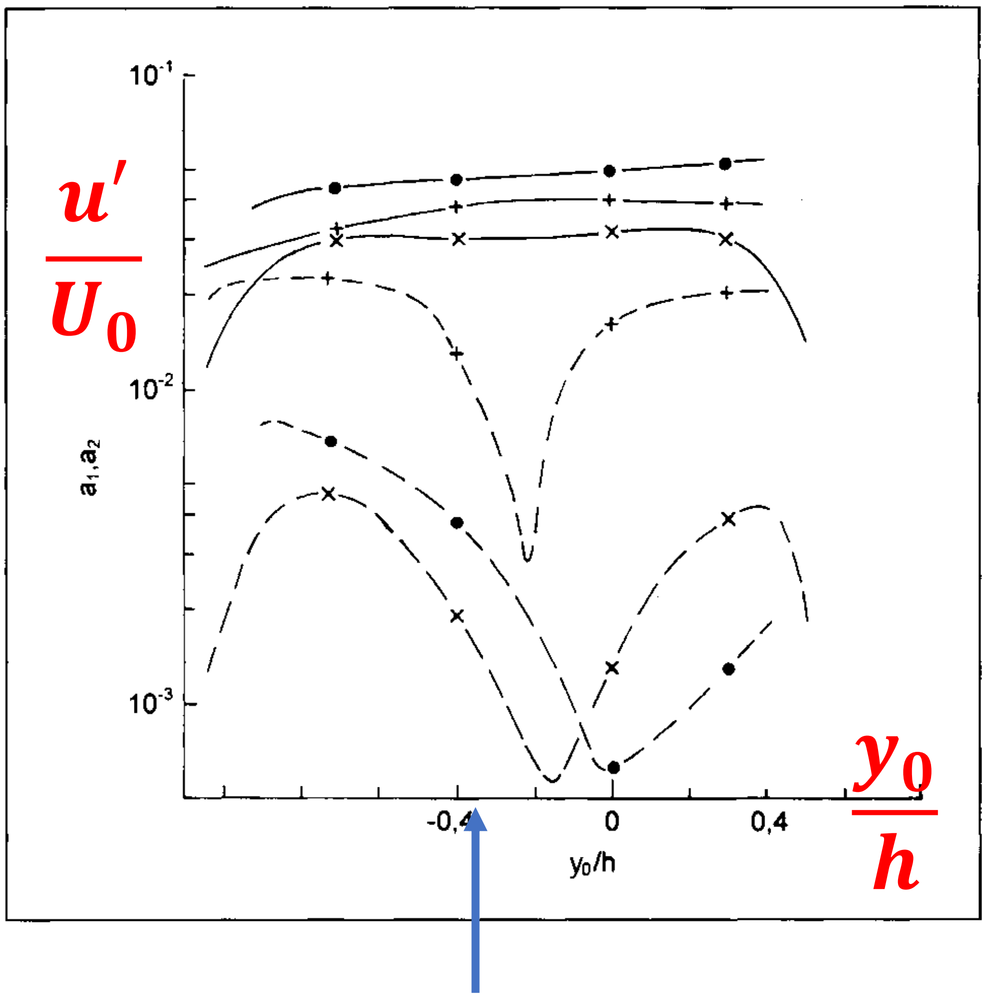


$$\frac{W}{W_0} = 1 \pm \frac{2\, i_1 i_2}{i_1^2 + i_2^2}\, \frac{\sin k\, d}{kd}$$



Fundamental f_0

Harmonic $2f_0$



Recorder flute

$$\frac{1}{2}(m + m_{added})u_{ac}^2$$

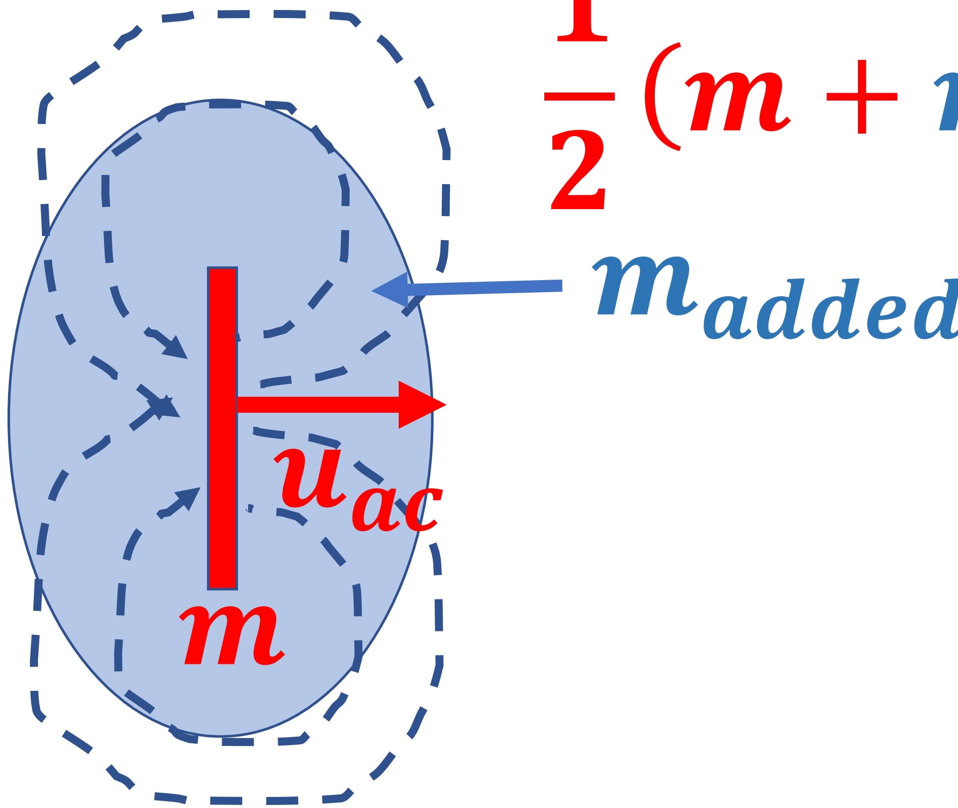


Plate in fluid: The added mass takes the kinetic energy of the fluid into account

Differences between small and large instruments？

-In large instruments transversal pipe Oscillation are in audible sound range.

-Higher Reynolds numbers: more turbulence (broadband noise)