ASSA
AUTUMN SCHOOL SERIES IN ACOUSTICS

Aeroacoustics:
whistling buildings

Avraham Hirschberg= Avraha(mico)= Mico

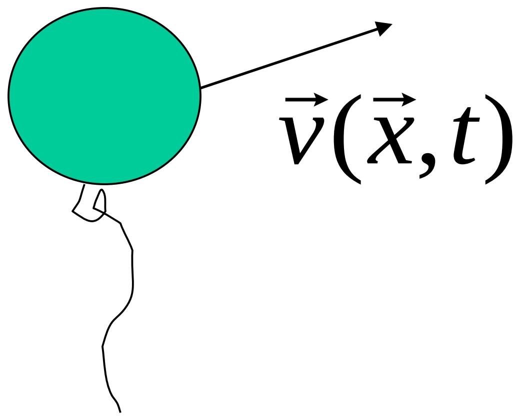
Beetham Tower Manchester

Study of sound production by flows and influence of flow on acoustic propagation.

-General theoretical background
-Whistling
-Some applications to building acoustics

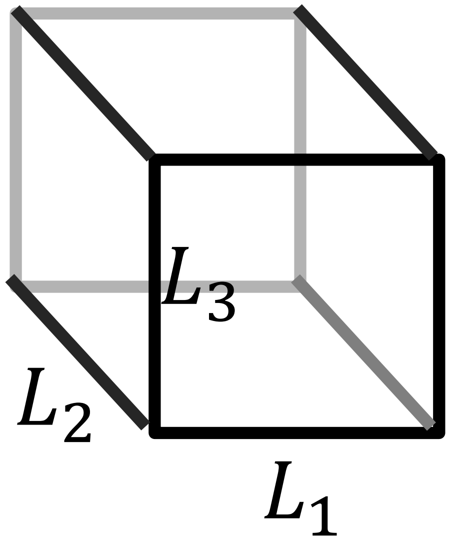
Mass conservation

$$m = \rho V$$



$$\frac{1}{m}\frac{Dm}{Dt} = \frac{1}{\rho}\frac{D\rho}{Dt} + \frac{1}{V}\frac{DV}{Dt} = 0$$

Rate of relative increase of volume: divergence

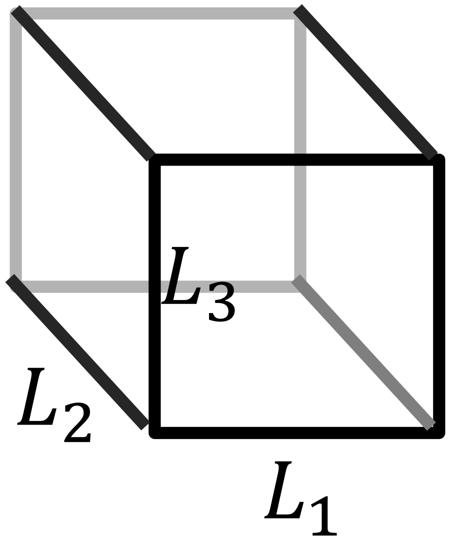


$$\frac{1}{\rho}\frac{D\rho}{Dt} = -\frac{1}{V}\frac{DV}{Dt}; \qquad V = L_1 L_2 L_3$$

$$\frac{1}{V}\frac{DV}{Dt} = \frac{1}{L_1}\frac{DL_1}{Dt} + \frac{1}{L_2}\frac{DL_2}{Dt} + \frac{1}{L_3}\frac{DL_3}{Dt}$$

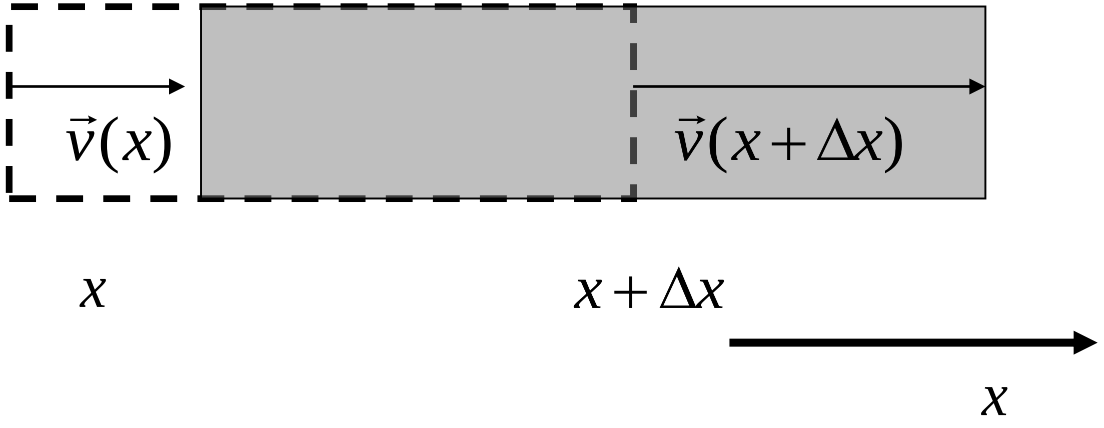
Rate of relative increase of volume: divergence

$$\frac{1}{\rho}\frac{D\rho}{Dt} = -\frac{1}{V}\frac{DV}{Dt};\qquad V = L_1 L_2 L_3$$



$$\frac{1}{V}\frac{DV}{Dt} = \frac{1}{L_1}\frac{DL_1}{Dt} + \frac{1}{L_2}\frac{DL_2}{Dt} + \frac{1}{L_3}\frac{DL_3}{Dt}$$

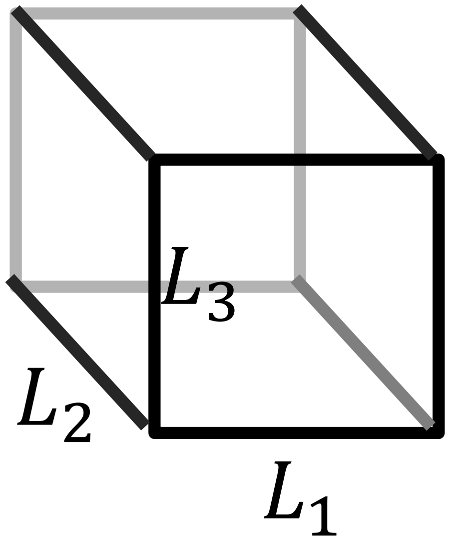
$$\vec{v} = (u_1, u_2, u_3)$$



Rate of relative increase of volume: divergence

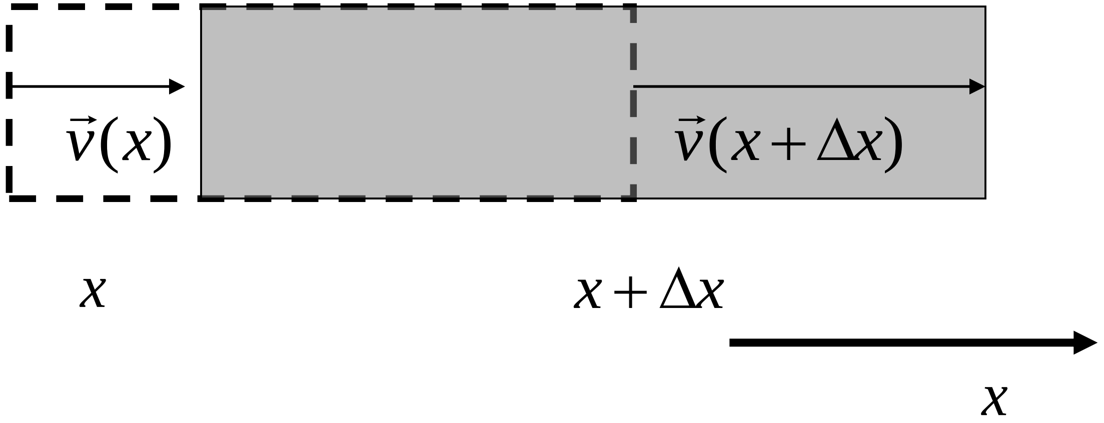
$$\frac{1}{\rho}\frac{D\rho}{Dt} = -\frac{1}{V}\frac{DV}{Dt};$$

$$V = L_1 L_2 L_3$$



$$\frac{1}{V}\frac{DV}{Dt} = \frac{1}{L_1}\frac{DL_1}{Dt} + \frac{1}{L_2}\frac{DL_2}{Dt} + \frac{1}{L_3}\frac{DL_3}{Dt} = \frac{\partial u_1}{\partial x_1} + \frac{\partial u_2}{\partial x_2} + \frac{\partial u_3}{\partial x_3} = \nabla \cdot \vec{v}$$

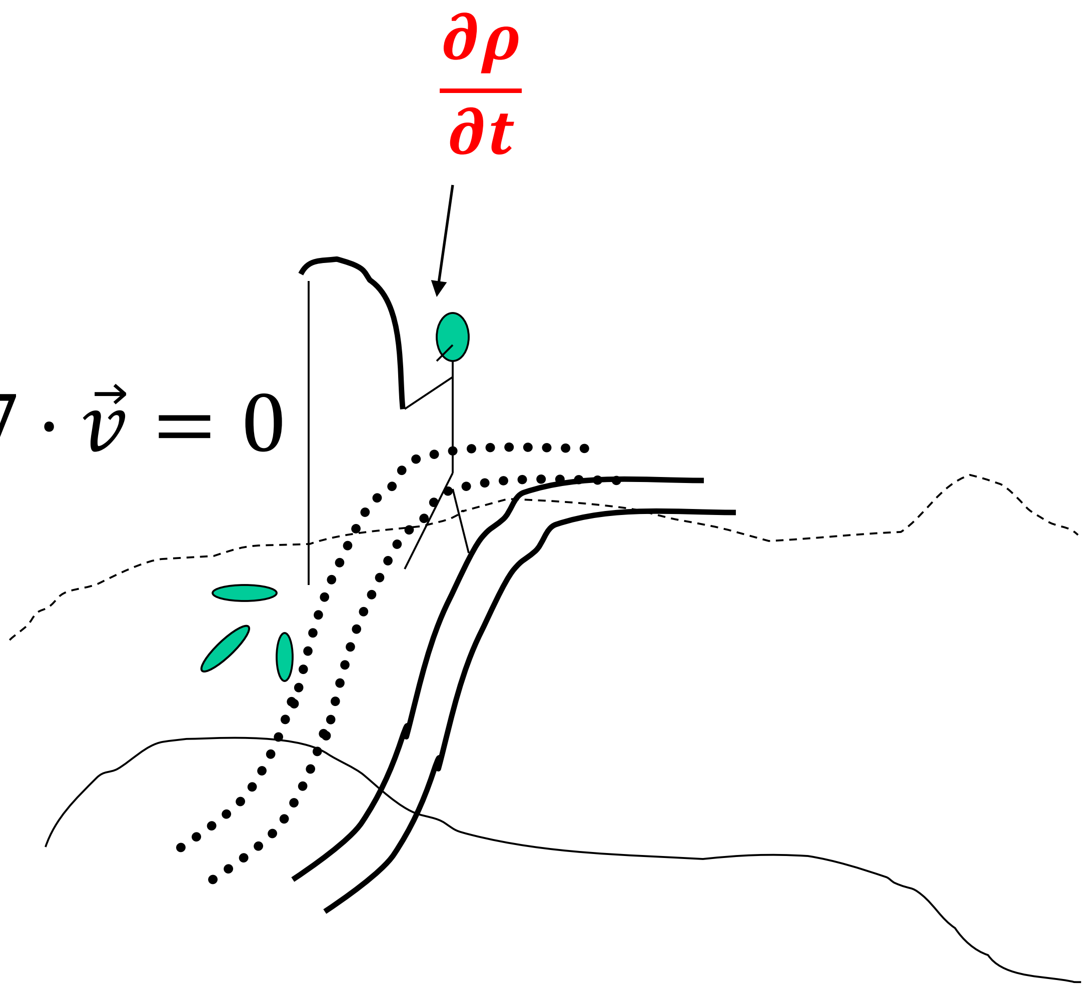
$$\vec{v} = (u_1, u_2, u_3)$$



Convective effects

$$\frac{1}{\rho}\frac{D\rho}{Dt} + \nabla \cdot \vec{v} = 0$$

$$\frac{1}{\rho}\left(\frac{\partial \rho}{\partial t} + (\vec{v} \cdot \nabla)\rho\right) + \nabla \cdot \vec{v} = 0$$



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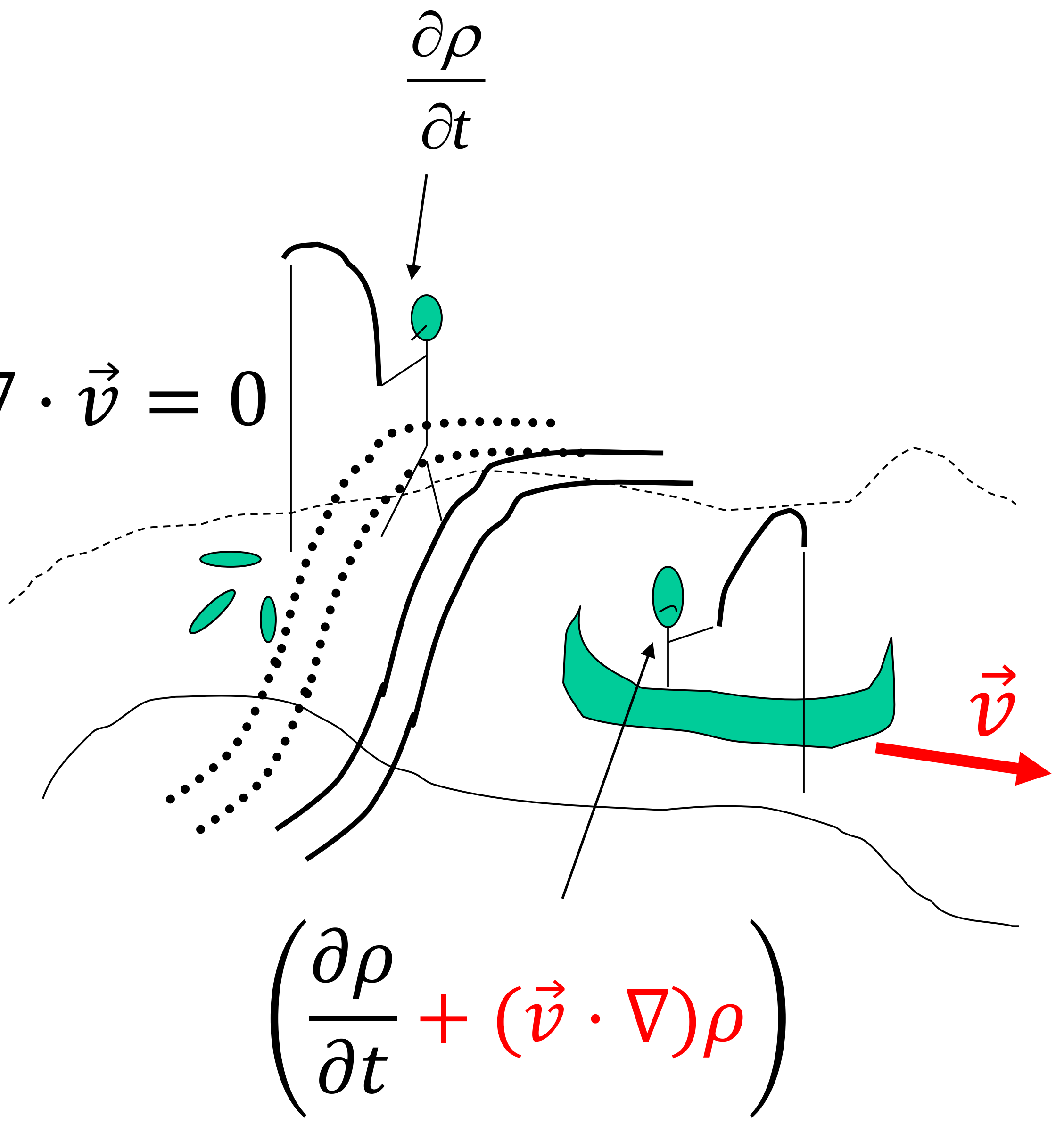
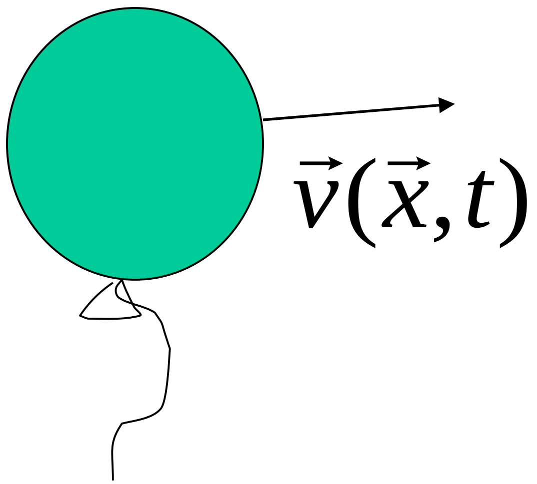




Newton

$$\rho \frac{D\vec{v}}{Dt} = -\nabla p + \nabla \cdot \vec{\vec{\sigma}} + \vec{f}$$

Mass

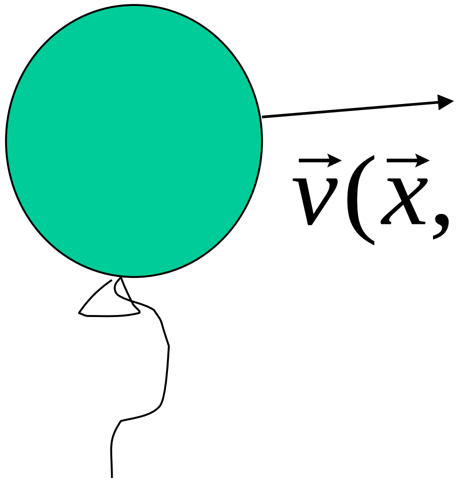
Acceleration

Surface forces

Volume forces

$$\frac{\partial \vec{v}}{\partial t} + \vec{v} \cdot \nabla \vec{v}$$

Non-linear (complex behaviour, turbulence…)



$\vec{v}(\vec{x},t)$

Newton

$$\rho \frac{D\vec{v}}{Dt} = -\nabla p + \nabla \cdot \vec{\vec{\sigma}} + \vec{f}$$

Mass

Acceleration

Surface forces

Volume forces

$$\frac{\partial \vec{v}}{\partial t} + \vec{v} \cdot \nabla \vec{v}$$

Non-linear (complex behaviour, turbulence…)

$$\frac{1}{\rho}\frac{D\rho}{Dt} + \nabla \cdot \vec{v} = 0$$

$$\rho \frac{D\vec{v}}{Dt} = -\nabla p + \nabla \cdot \vec{\vec{\sigma}} + \vec{f}$$

Linear perturbations of a uniform stagnant fluid:

$$\rho = \rho_0 + \rho'$$

$$p = p_0 + p'$$

Quiescent fluid

$$\vec{v} = \vec{v}_0 + \vec{v}' = \vec{v}'$$

Linearized

$$\frac{\rho'}{\rho_0} << 1$$

$$\frac{\partial \rho'}{\partial t} + \rho_0 \nabla \cdot \vec{v}' = 0$$

$$\rho_0 \frac{\partial \vec{v}'}{\partial t} = -\nabla p' + \nabla \cdot \vec{\vec{\sigma}}' + \vec{f}$$

Viscous effects negligible in most cases (high Reynolds).

$$\frac{\partial}{\partial t}\left(\frac{\partial \rho'}{\partial t} + \rho_0 \nabla \cdot \vec{v}' = 0\right)$$

Eliminate $\vec{v}'$

$$-\nabla \cdot \left(\rho_0 \frac{\partial \vec{v}'}{\partial t} + \nabla p' = \vec{f}\right)$$

$$\frac{\partial^2 \rho'}{\partial t^2} - \nabla^2 p' = -\nabla \cdot \vec{f}$$

More unknowns than equations!

Assume local thermodynamical equilibrium:

$\boldsymbol{p = p(\rho, s)}$ **Equation of state**

$$p' = \left(\frac{\partial p}{\partial \rho}\right)_s \rho' + \left(\frac{\partial p}{\partial s}\right)_\rho s'$$

$$c^2 = \left(\frac{\partial p}{\partial \rho}\right)_s$$

Definition speed of sound

Linearized

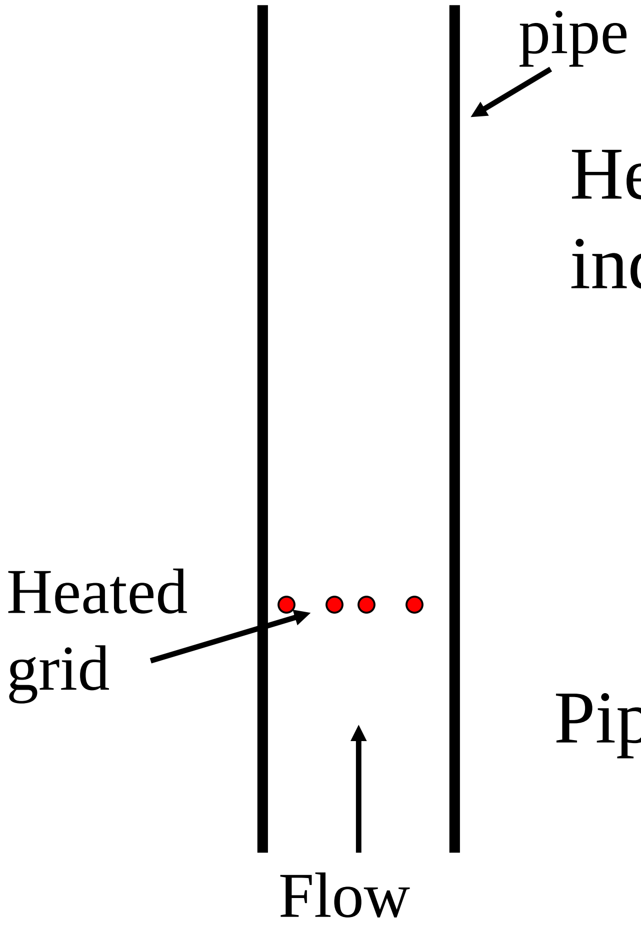
$$\frac{1}{{c_0}^2}\frac{\partial^2 p'}{\partial t^2} - \nabla^2 p' = -\nabla \cdot \vec{f} + \frac{1}{{c_0}^2}\left(\frac{\partial p}{\partial s}\right)_\rho \frac{\partial^2 s'}{\partial t^2}$$

Non uniform force field

Entropy production
(heat transfer, combustion)

Scalar wave equation with source term

Rijke tube (unsteady heat transfer)

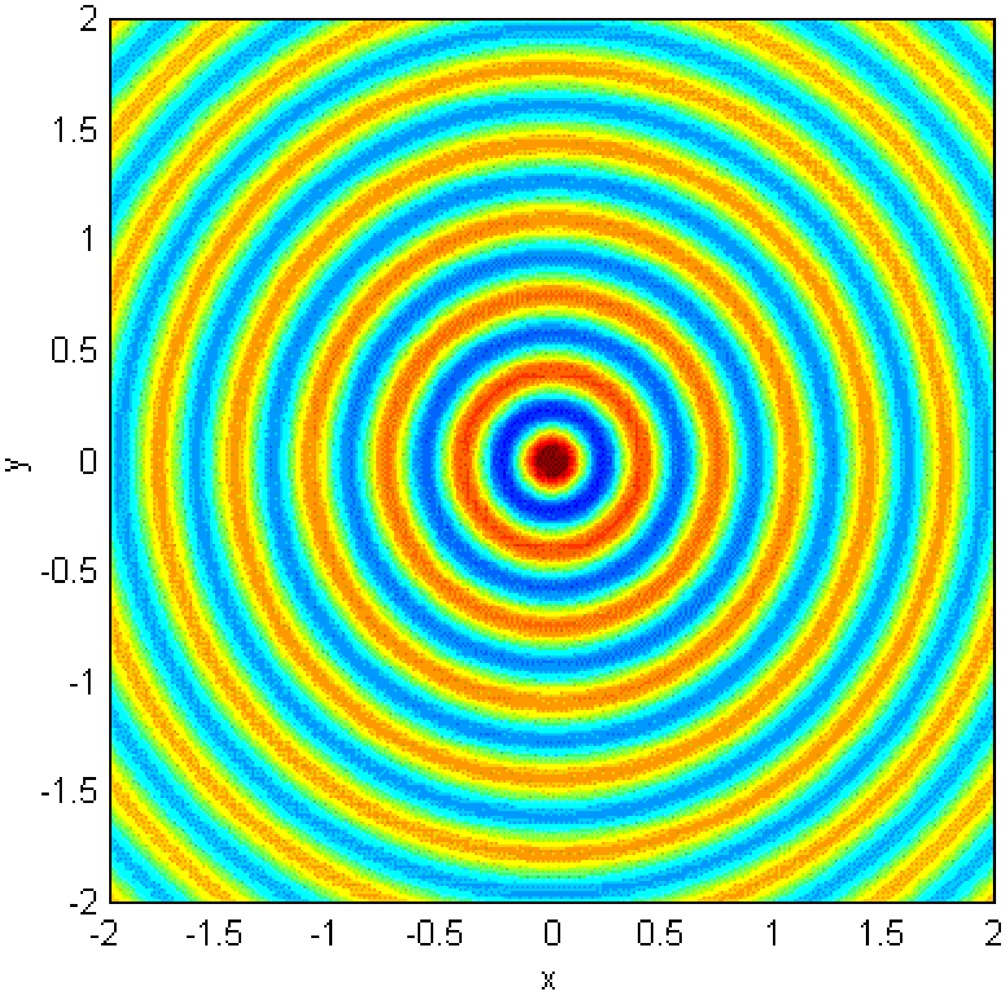


Heat transfer q'_w induces dilatation → $$\boxed{\frac{dV}{dt} \propto q'_w}$$

Pipe is acoustical mass-spring system

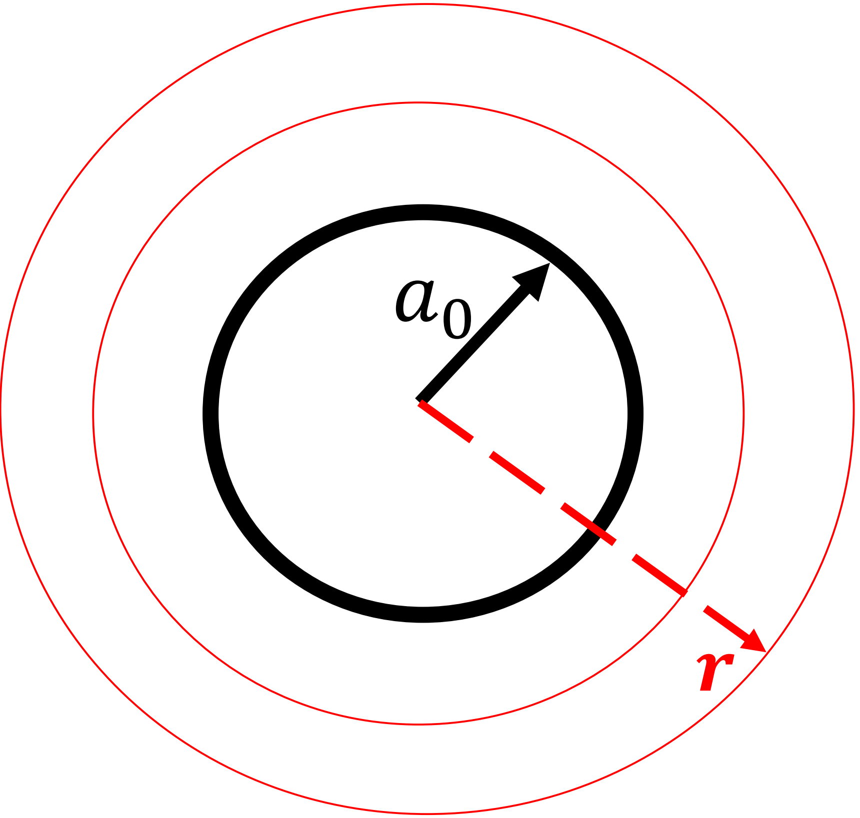
Small pulsating sphere in free space

Monopole (wiki)



Small pulsating sphere:

$$p' = \hat{p}e^{i\omega t} = \frac{A}{r}e^{i\omega\left(t-\frac{r}{c}\right)}$$



Small pulsating sphere:

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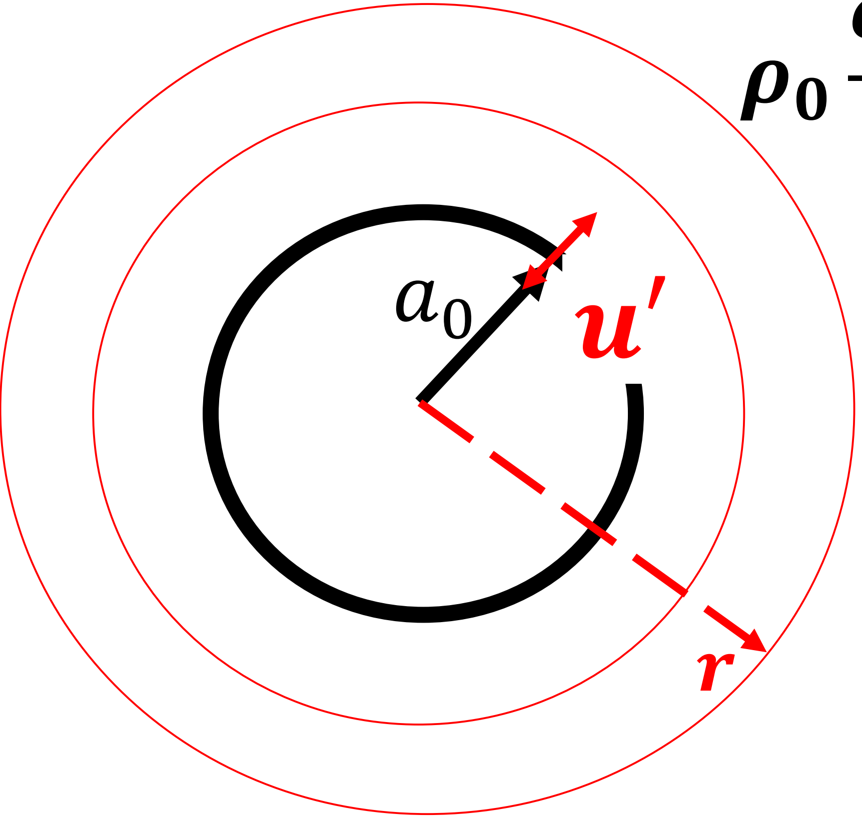
$$\rho_0\frac{\partial u'}{\partial t} = -\frac{\partial p'}{\partial r} = \frac{A}{r}\left(\frac{1}{r} + i\frac{\omega}{c}\right)e^{i\omega\left(t-\frac{r}{c}\right)}$$



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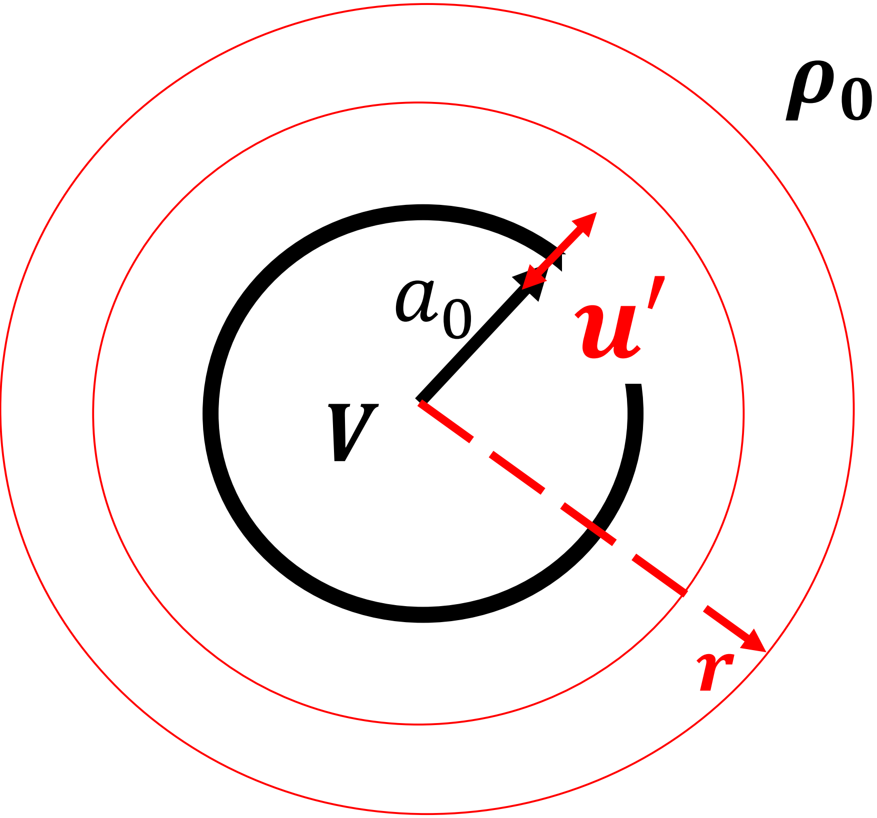


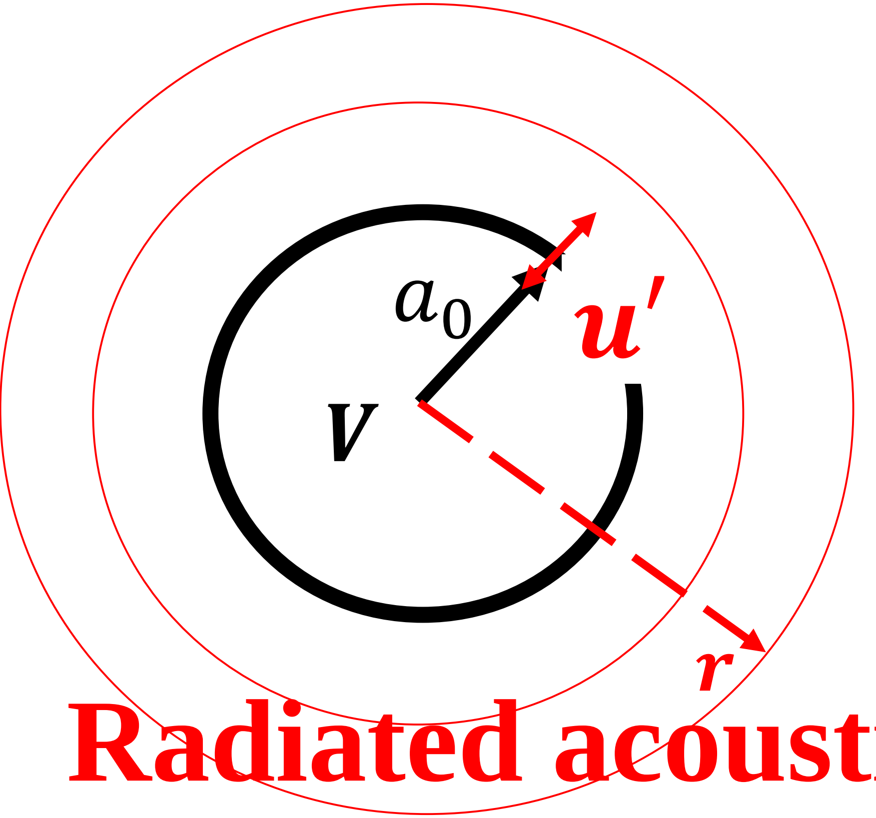
$$\rho_0 \frac{\partial u'}{\partial t} = -\frac{\partial p'}{\partial r} = \frac{A}{r}\left(\frac{1}{r} + i\frac{\omega}{c}\right)e^{i\omega\left(t-\frac{r}{c}\right)}$$

$$\frac{p'(a_0)}{\rho_0 c u'(a_0)} = \frac{ika_0 + (ka_0)^2}{1 + (ka_0)^2}$$

$$\frac{a_0\omega}{c} = ka_0 \ll 1$$

Small pulsating sphere:

Radiated power proportional to real part of impedance.



$$\frac{p'(a_0)}{\rho_0 c u'(a_0)} = \frac{ika_0 + (ka_0)^2}{1 + (ka_0)^2}$$

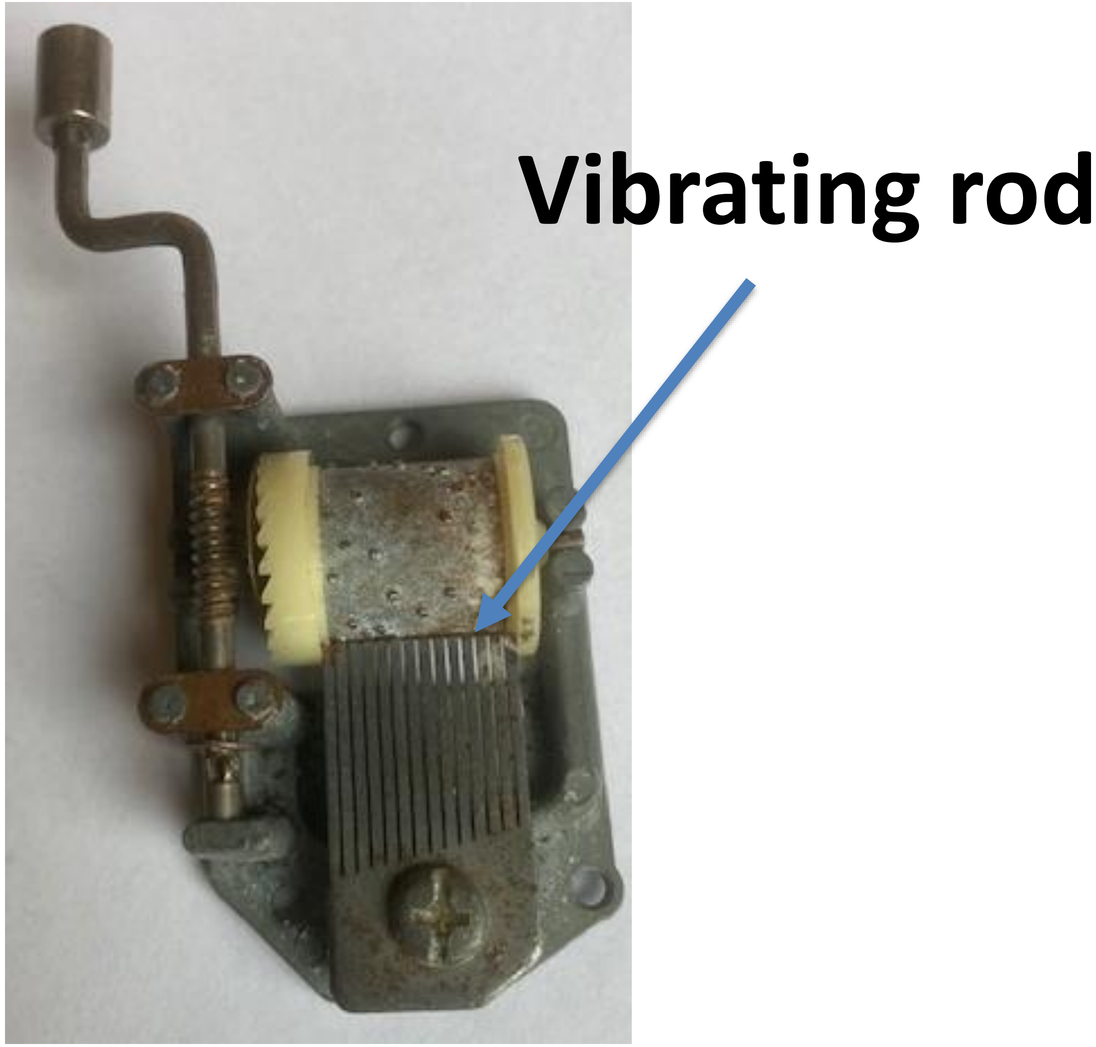
$$\frac{a_0\omega}{c} = ka_0 \ll 1$$

Radiated acoustic power proportional to

$$I = \langle p'\ u' \rangle \propto (ka_0)^4$$

Source of sound

-Sound source
in musical box

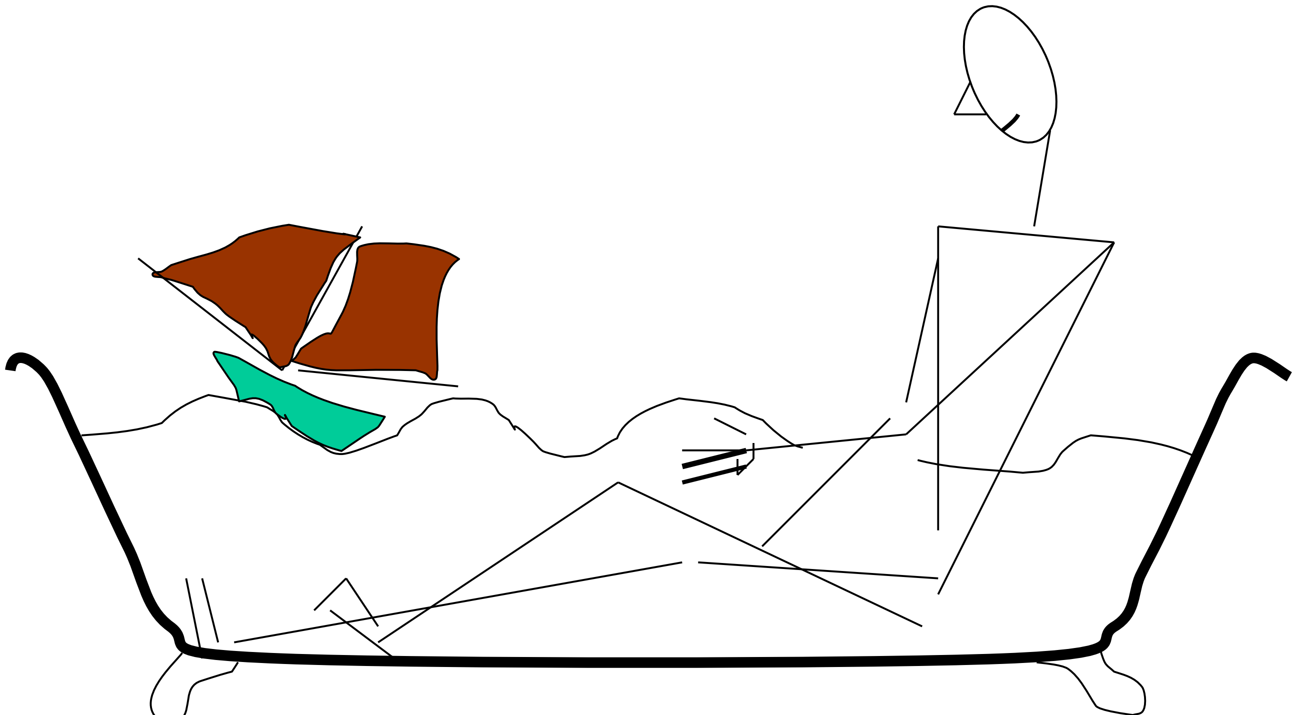


Source of sound (Wall vibration)

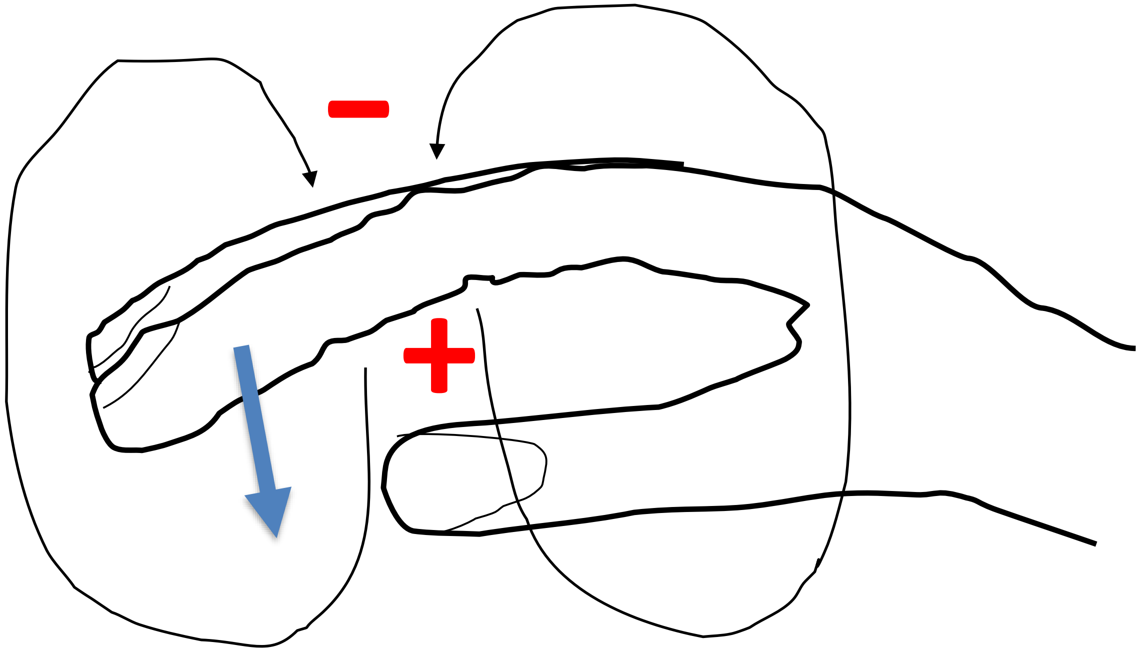
-Sound source
 in musical box is very
inefficient.

-Why?

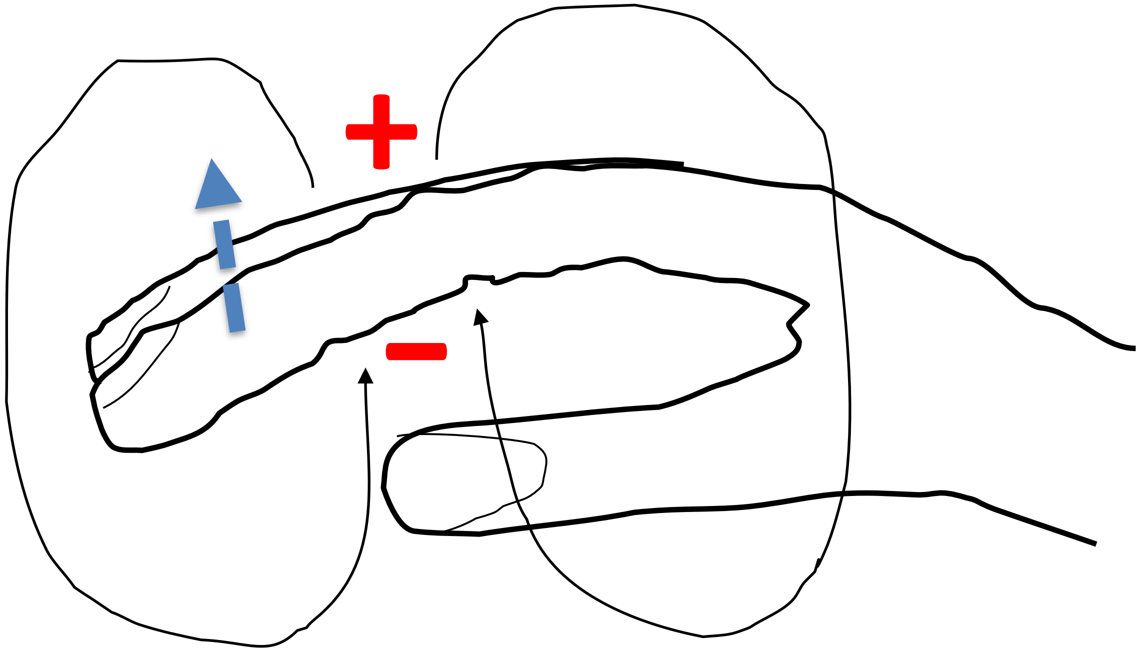
Making waves



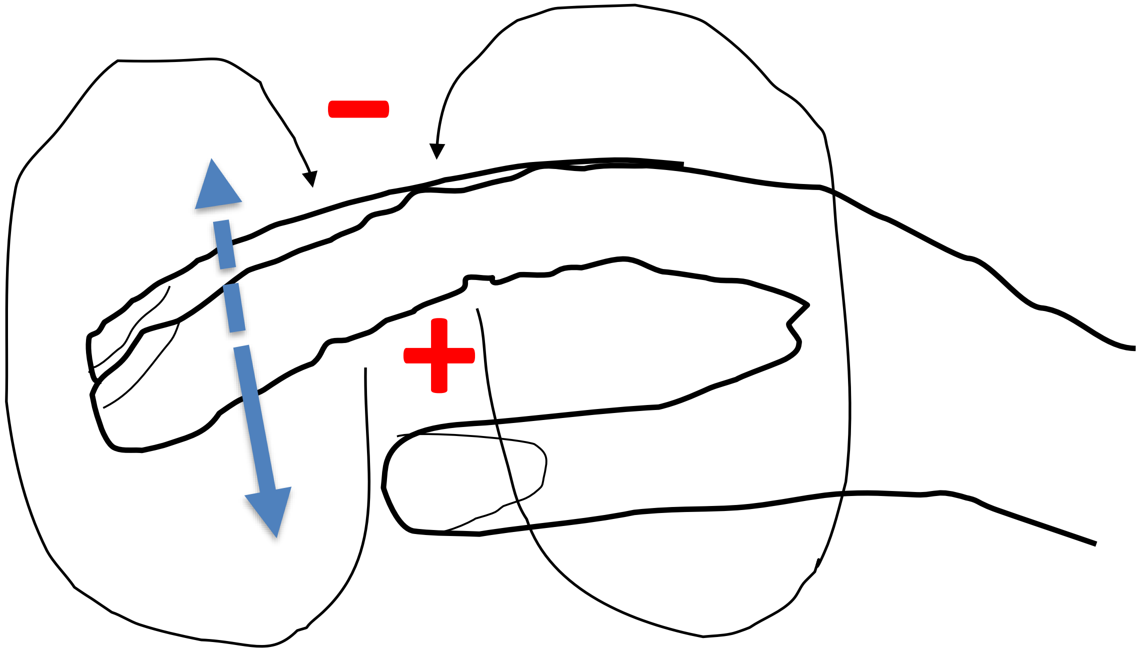
Making waves



Making waves

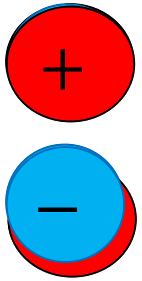


Making waves

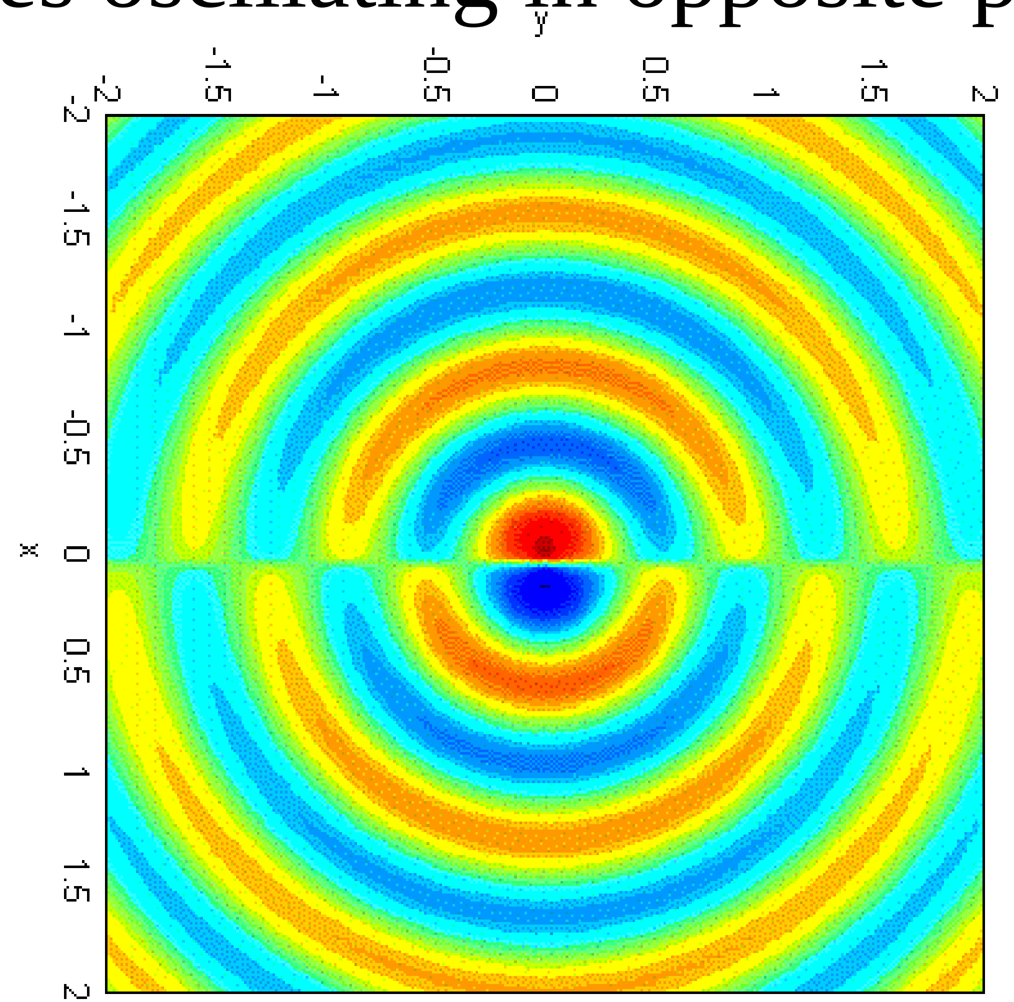


Dipole sound source:

Two monopoles in proximity oscillating in opposite phase



Two monopoles oscillating in opposite phase => Dipole (wiki)



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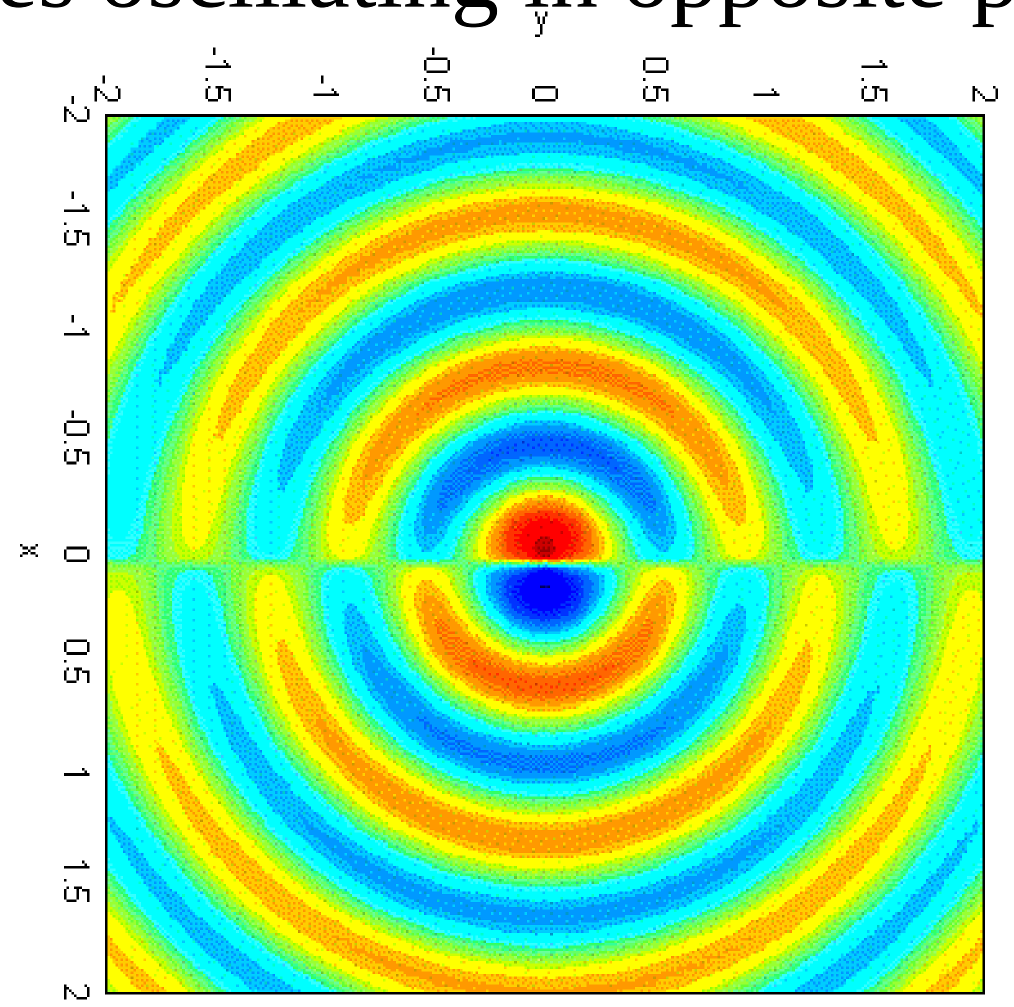

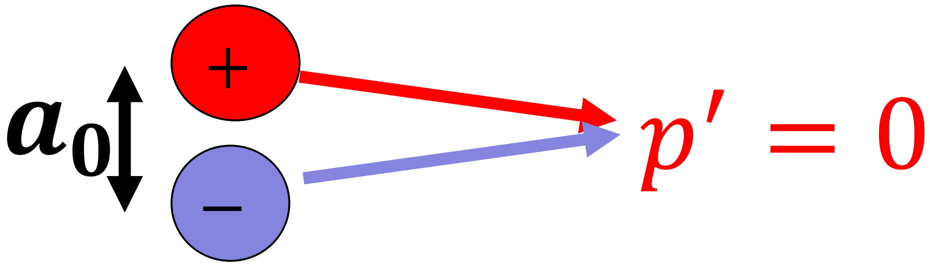

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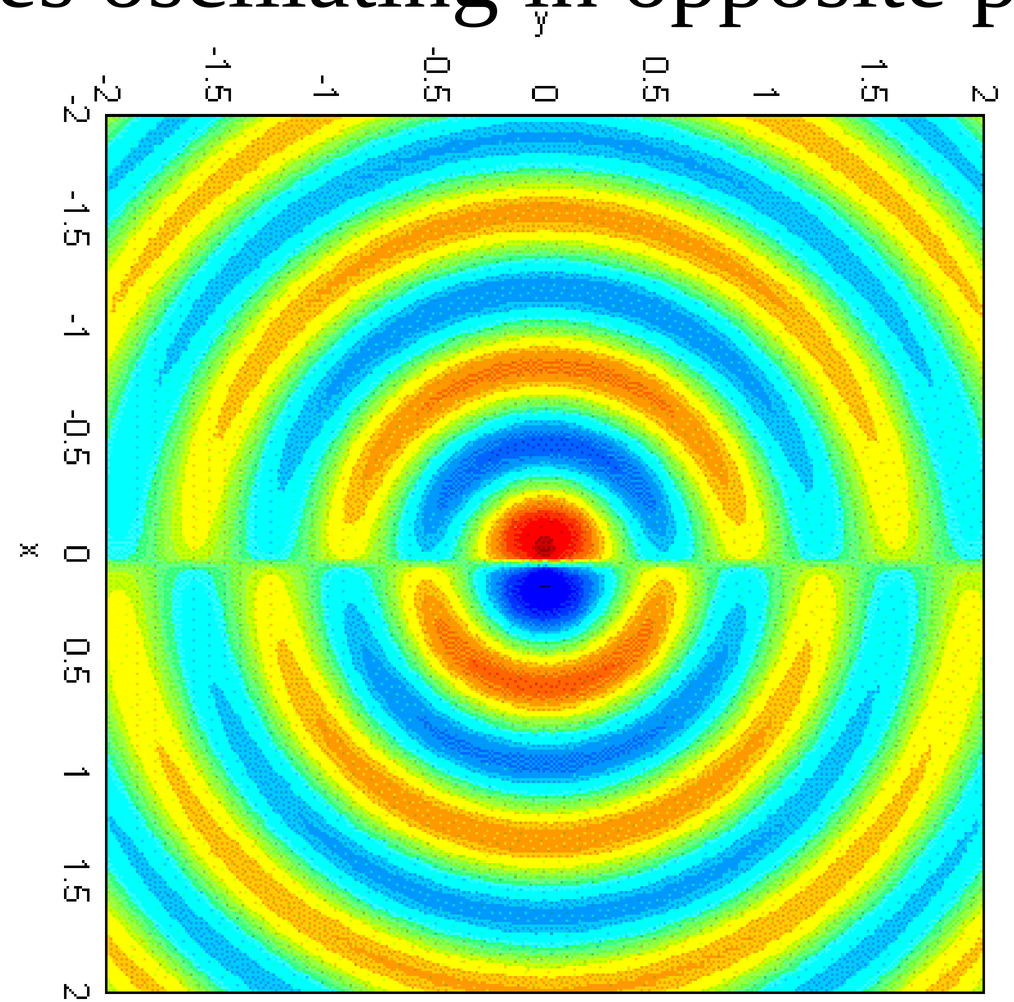
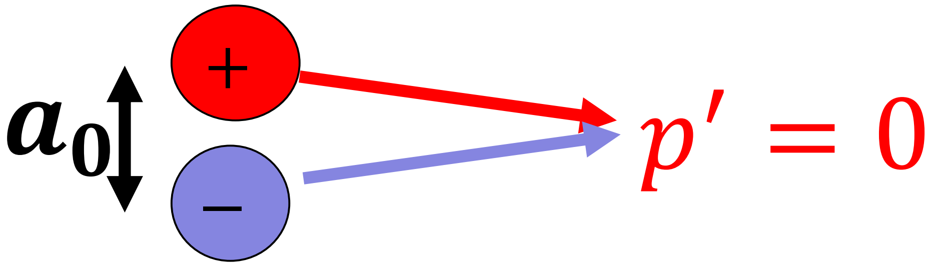
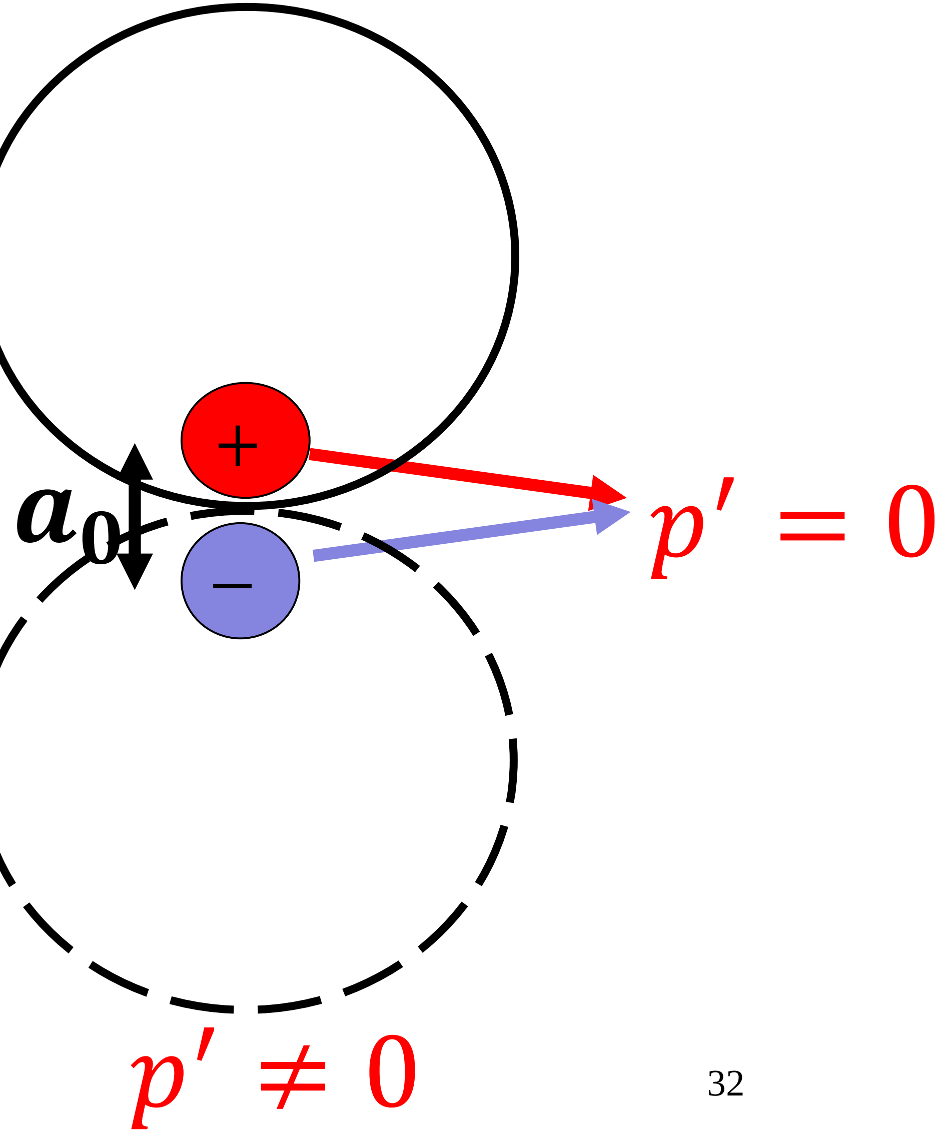


$p' \neq 0$



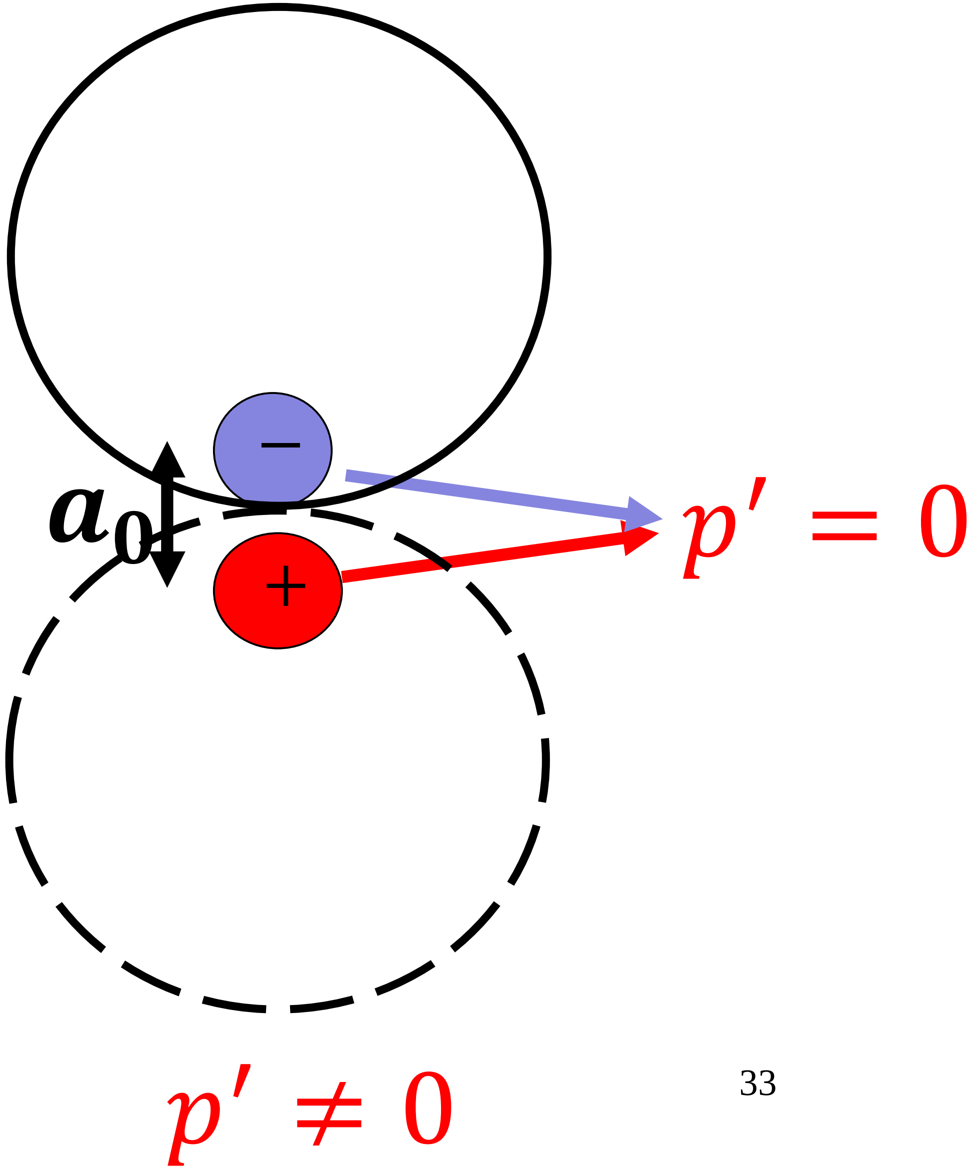
Two monopoles oscillating in opposite phase => Dipole (wiki)

Directivity of amplitude



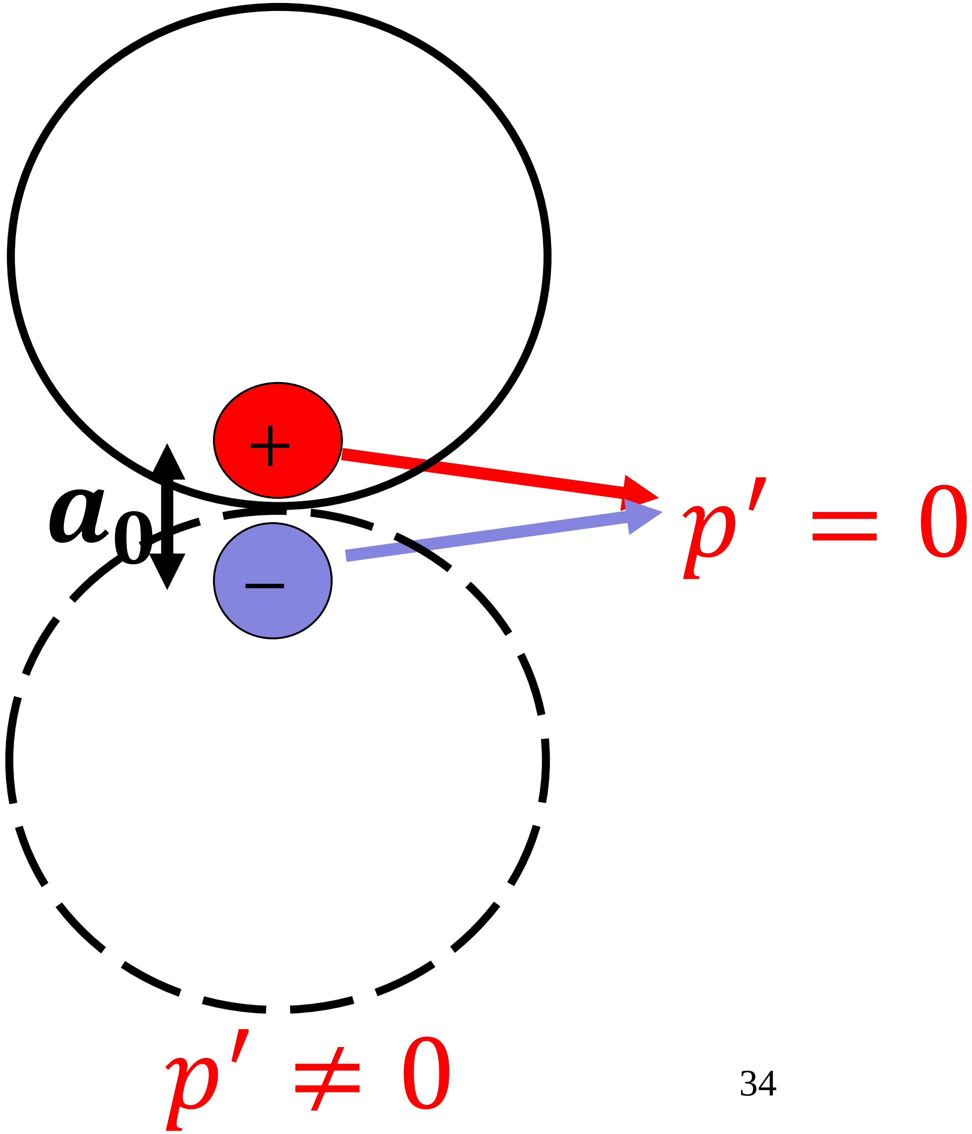
Two monopoles oscillating in opposite phase => Dipole (wiki)

Directivity of amplitude



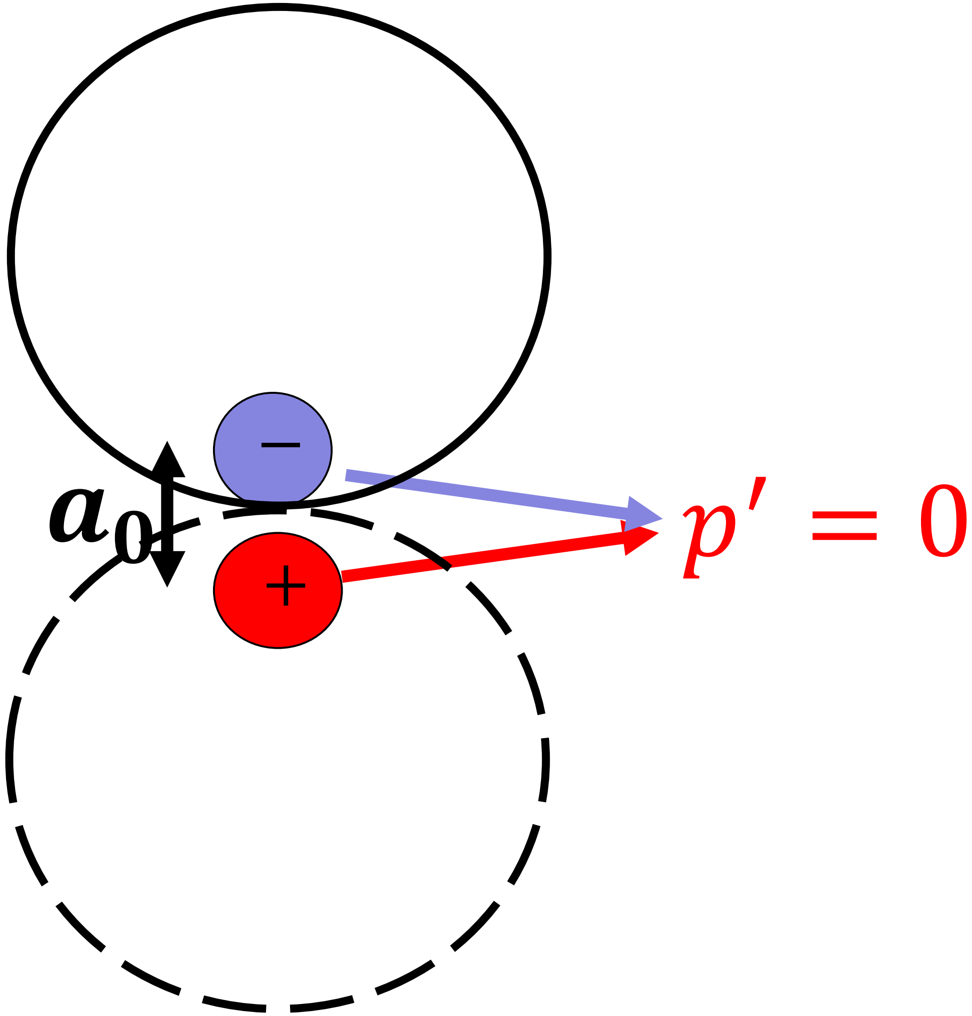
Two monopoles oscillating in opposite phase => Dipole (wiki)

Directivity of amplitude



Two monopoles oscillating in opposite phase => Dipole (wiki)

Radiated acoustic power in free space proportional to $(ka_0)^6$.



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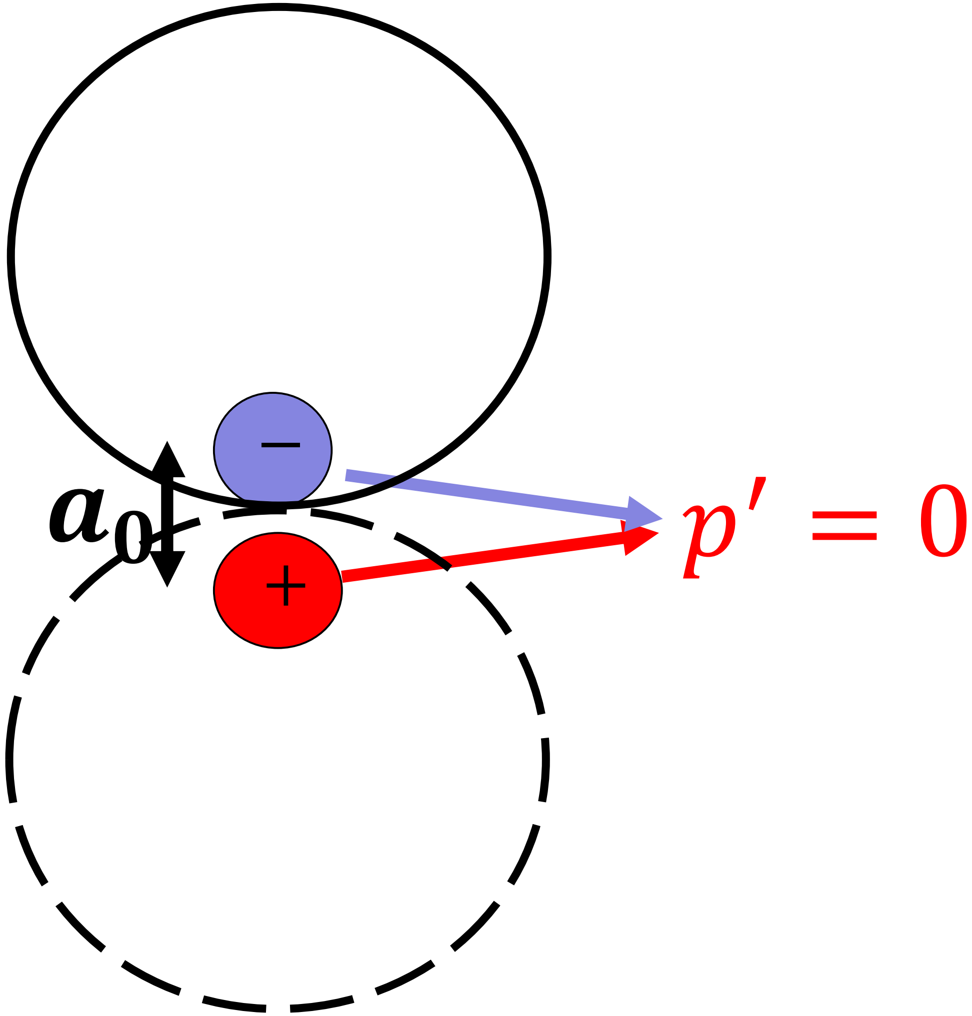
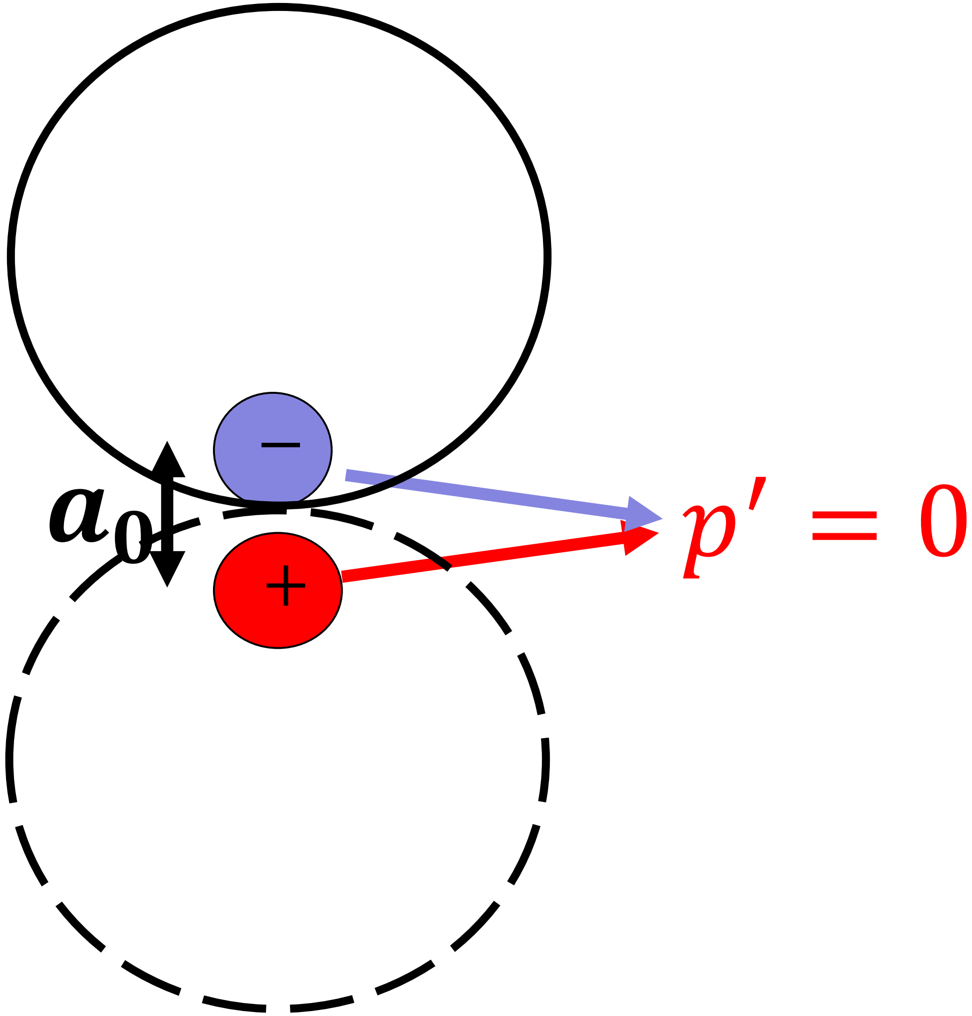
Radiated acoustic power in free space proportional to $(ka_0)^6$



Two monopoles oscillating in opposite phase => Dipole (wiki)

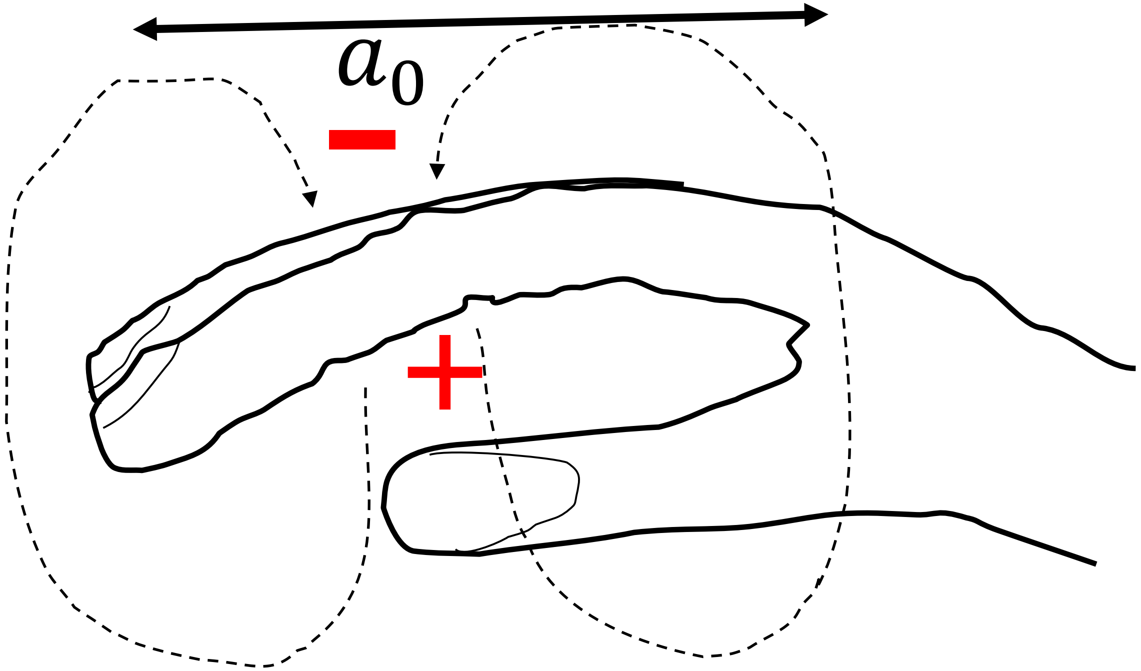
Radiated acoustic power in free space proportional to $(ka_0)^6$.

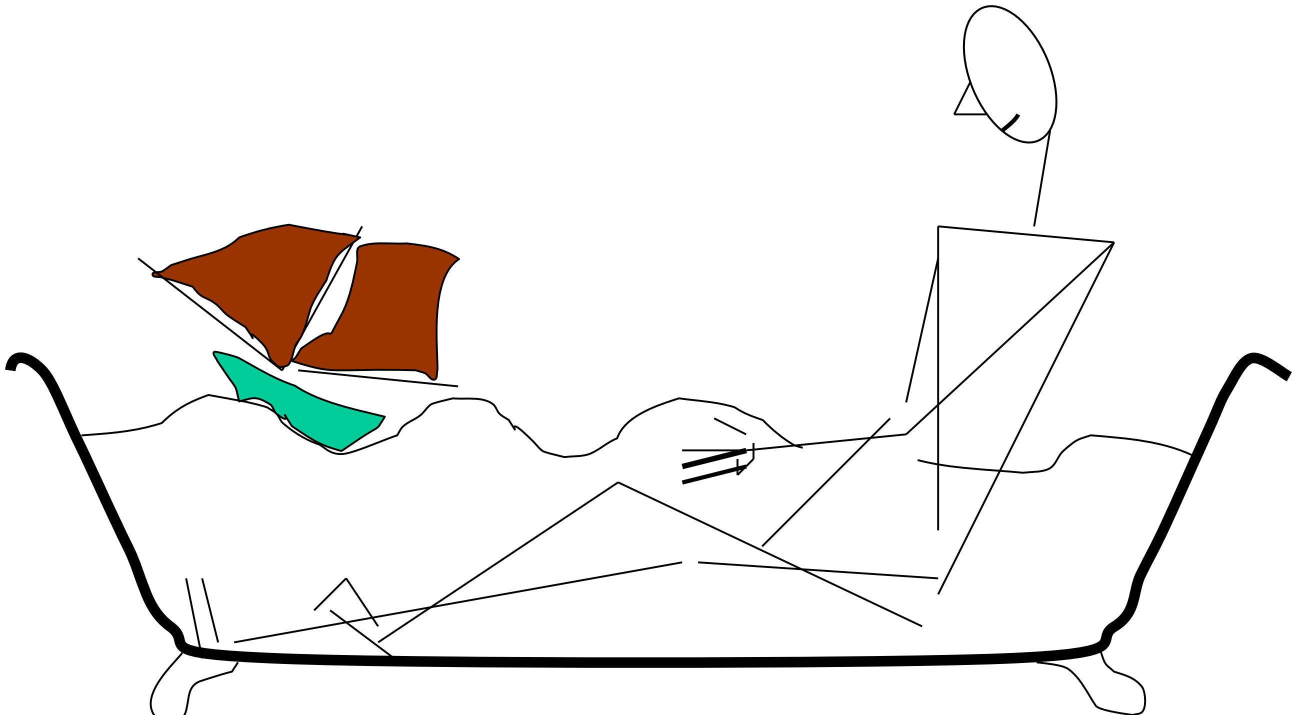
$$\boldsymbol{a_0 = 1\,mm, \frac{c}{f} = 300\,mm}$$



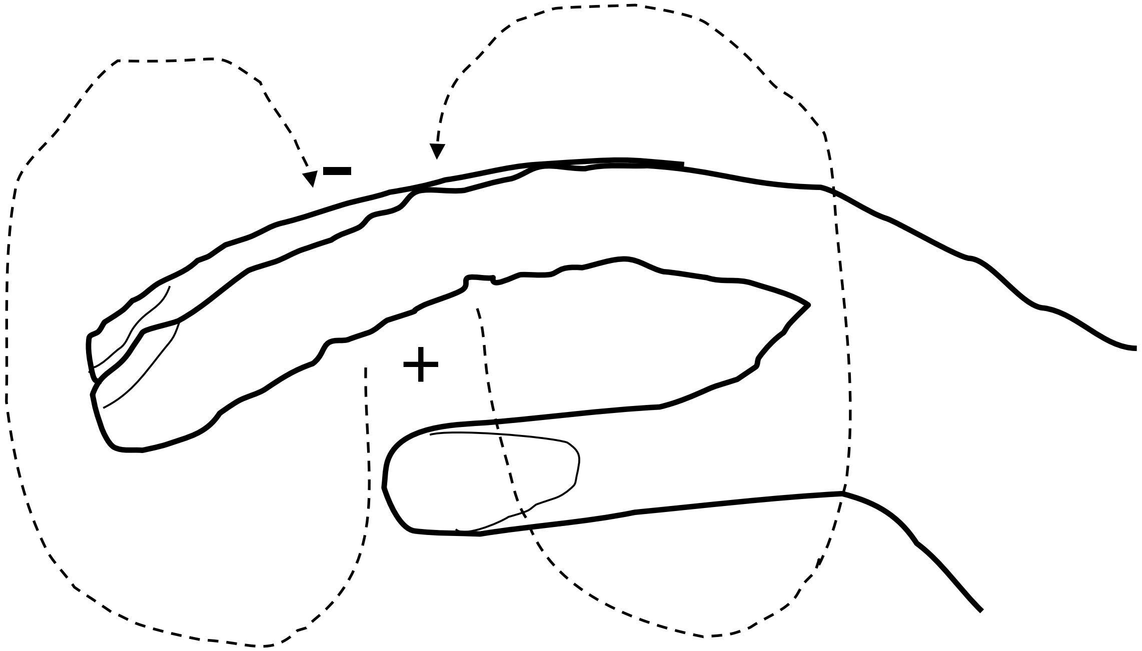
$$\left(\frac{2\pi f\, a_0}{c}\right)^6 \sim 10^{-10}$$ **Difficult in free space!**

Making waves



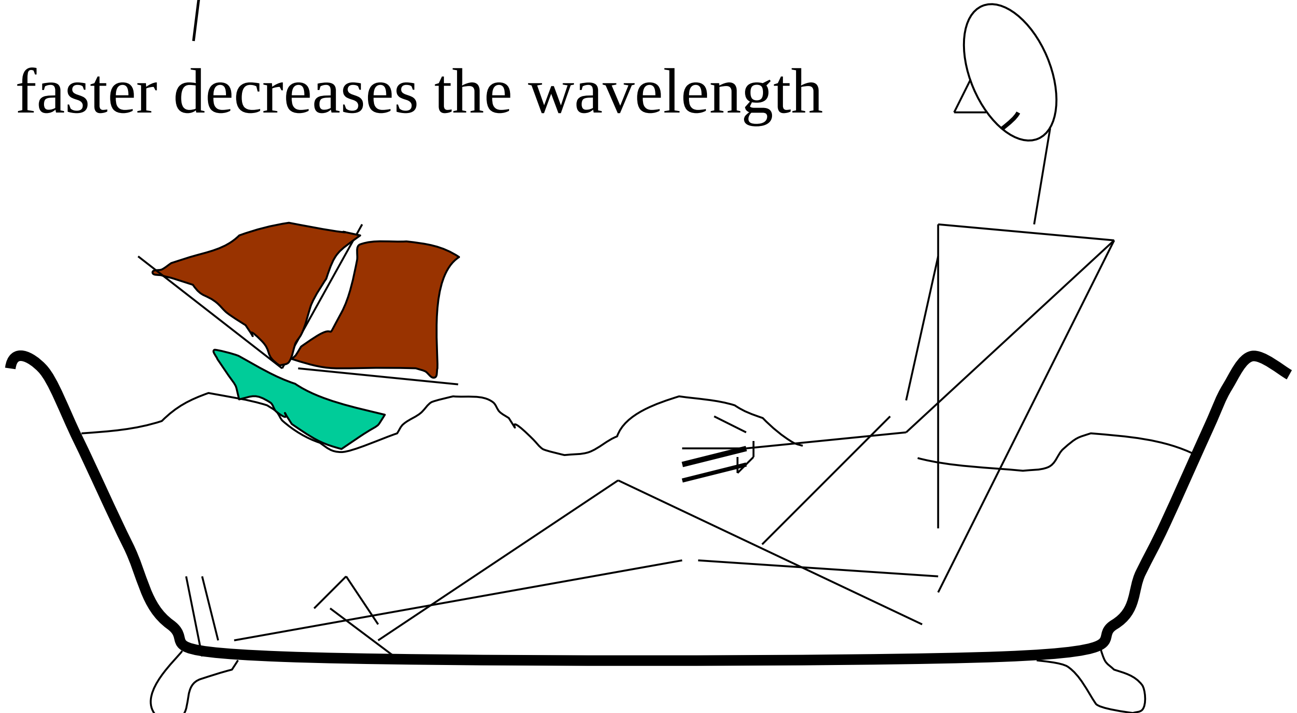


Making waves



$$ka_0 = \frac{2\pi a_0}{\lambda}$$

Moving faster decreases the wavelength

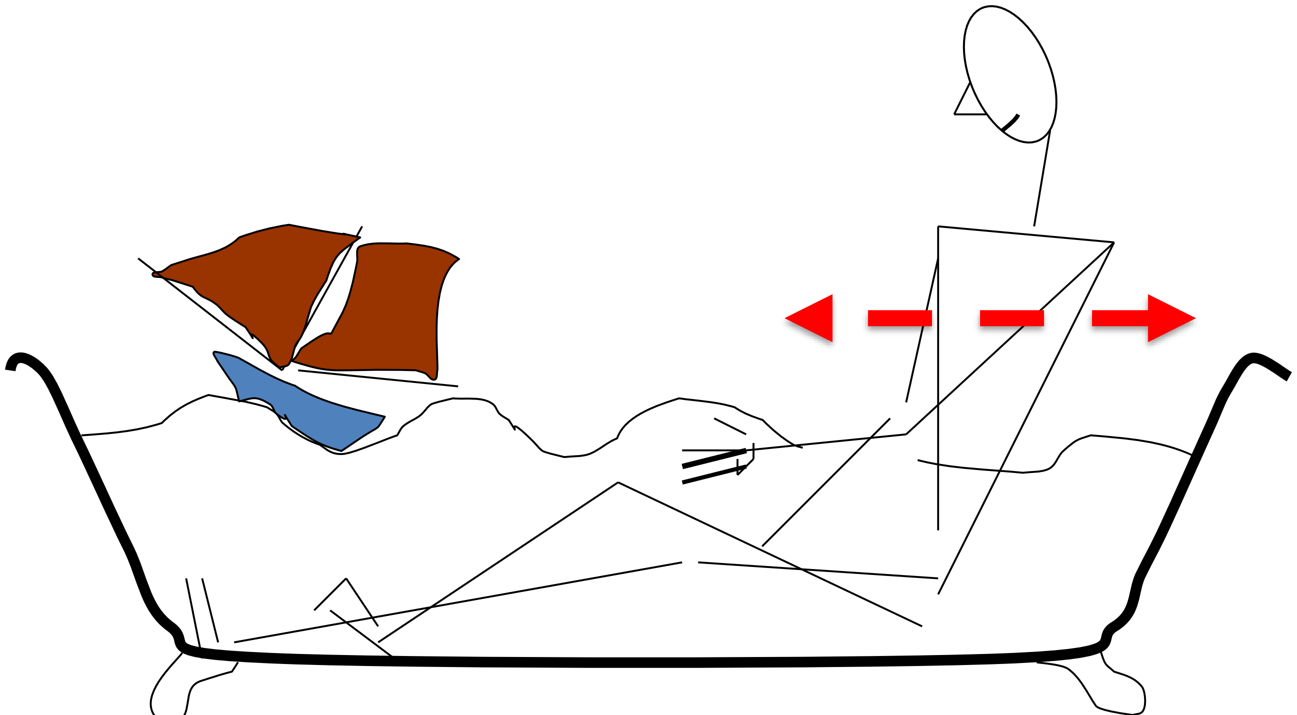


Making waves

Use your body to make strong waves

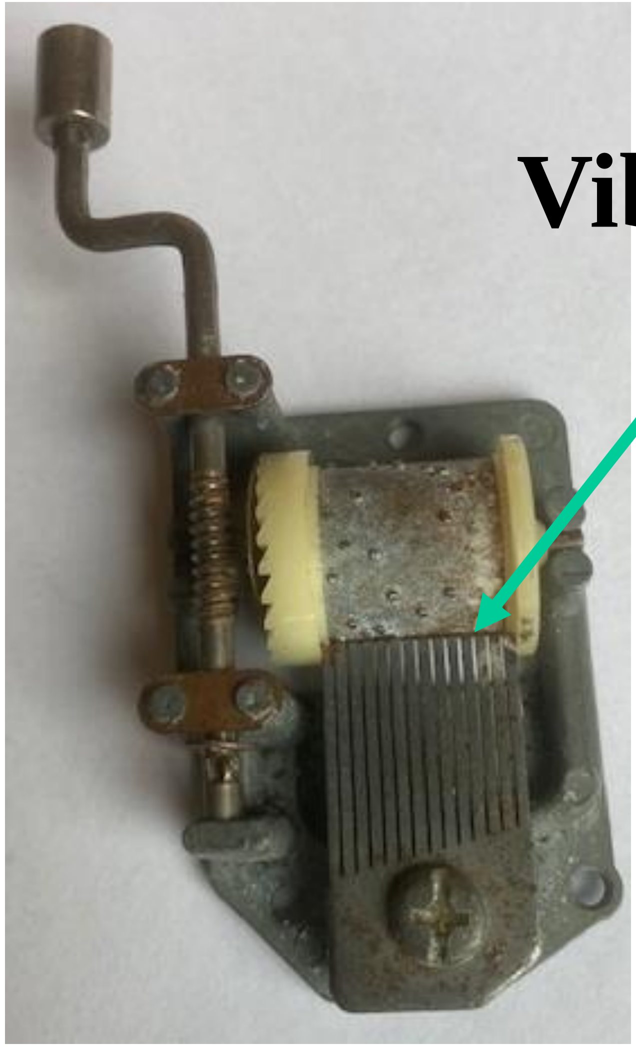
make a_0 large

$$ka_0 = \frac{2\pi a_0}{\lambda}$$



Source of sound

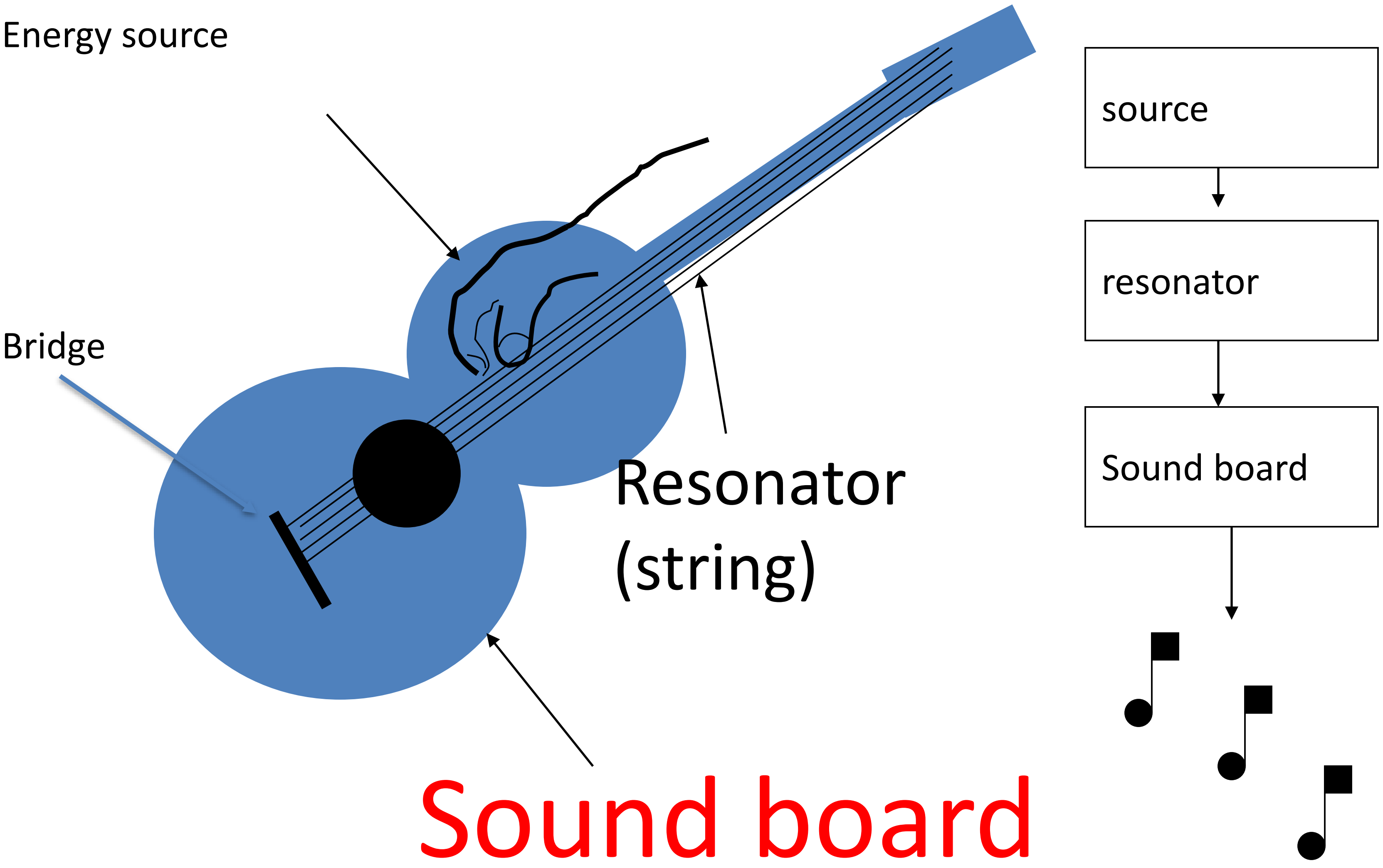
-Sound source
 in musical box



Vibrating rod

SOUNDBOARD

Musical Instrument (wavelength order 0.3 m)



$$\frac{1}{{c_0}^2}\frac{\partial^2 p'}{\partial t^2} - \nabla^2 p' = -\nabla \cdot \vec{f} + \frac{1}{{c_0}^2}\left(\frac{\partial p}{\partial s}\right)_\rho \frac{\partial^2 s'}{\partial t^2}$$

Non uniform force field.

$\vec{f}$ force density (per unit volume) exerted on fluid

Entropy production
(heat transfer, combustion)

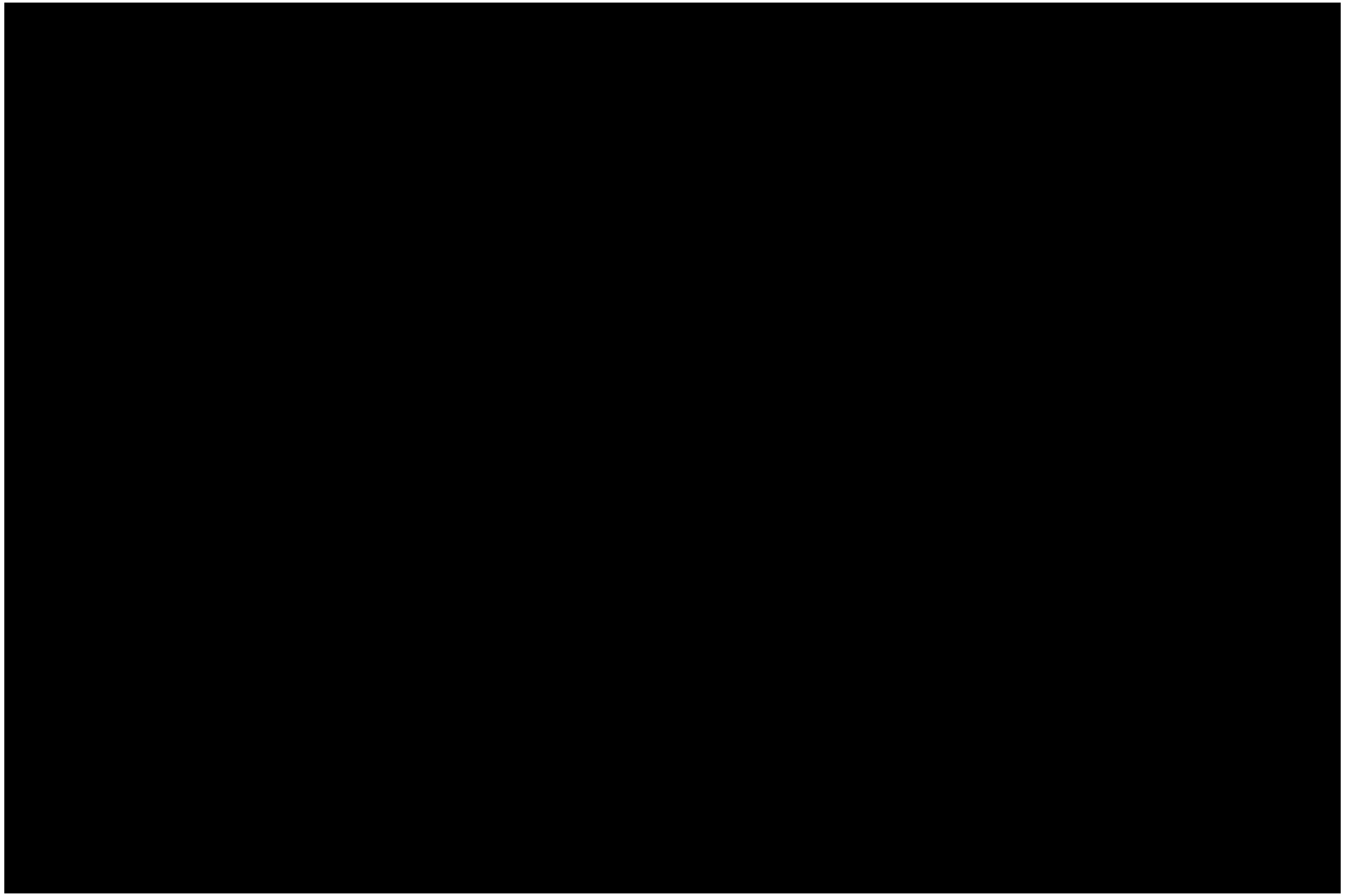
Study of sound production by flows and influence of flow on acoustic propagation.

-General theoretical background

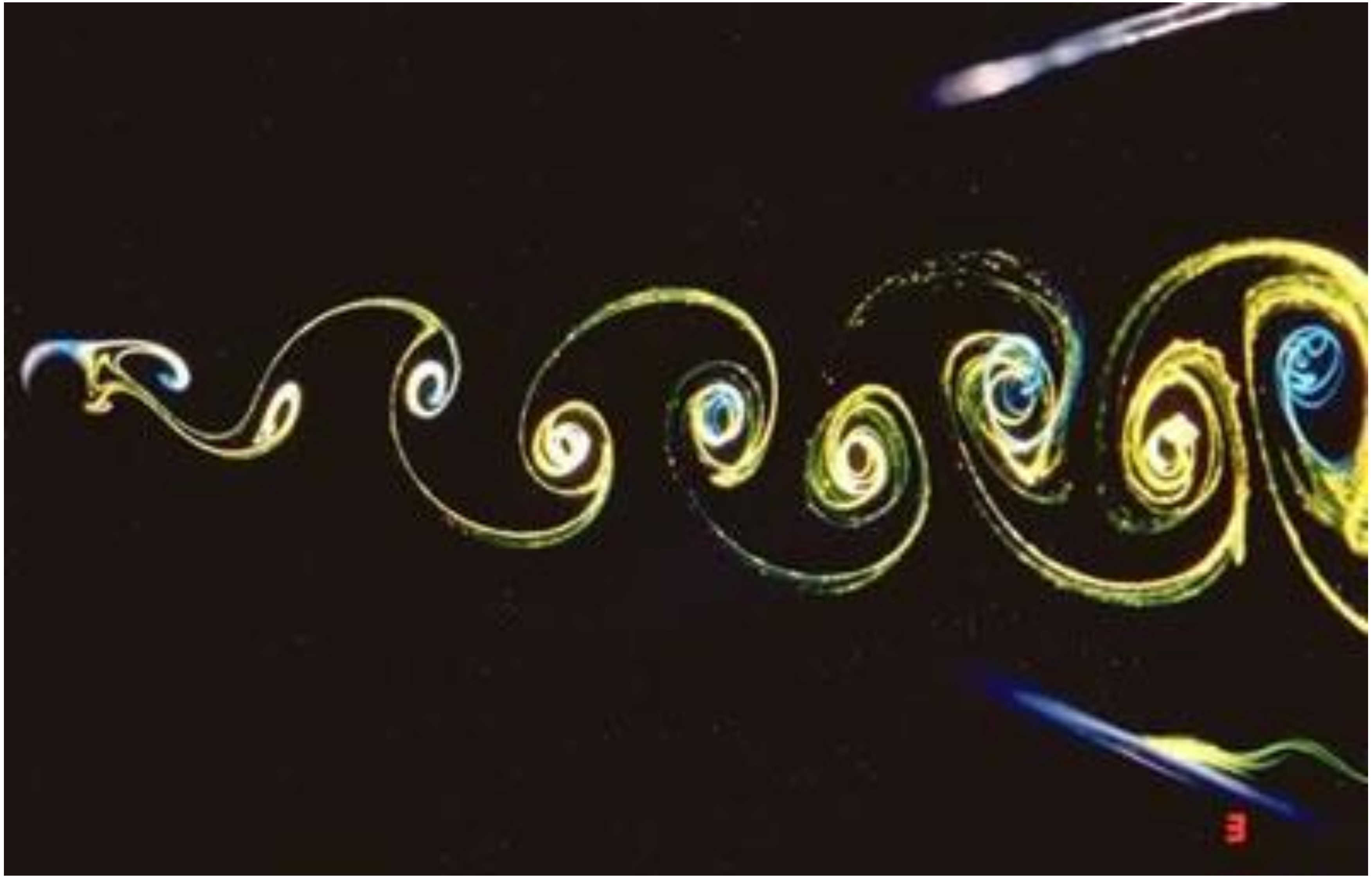
-Whistling

-Some applications to building acoustics

Hydrodynamic instability of wake of a cylinder in cross flow

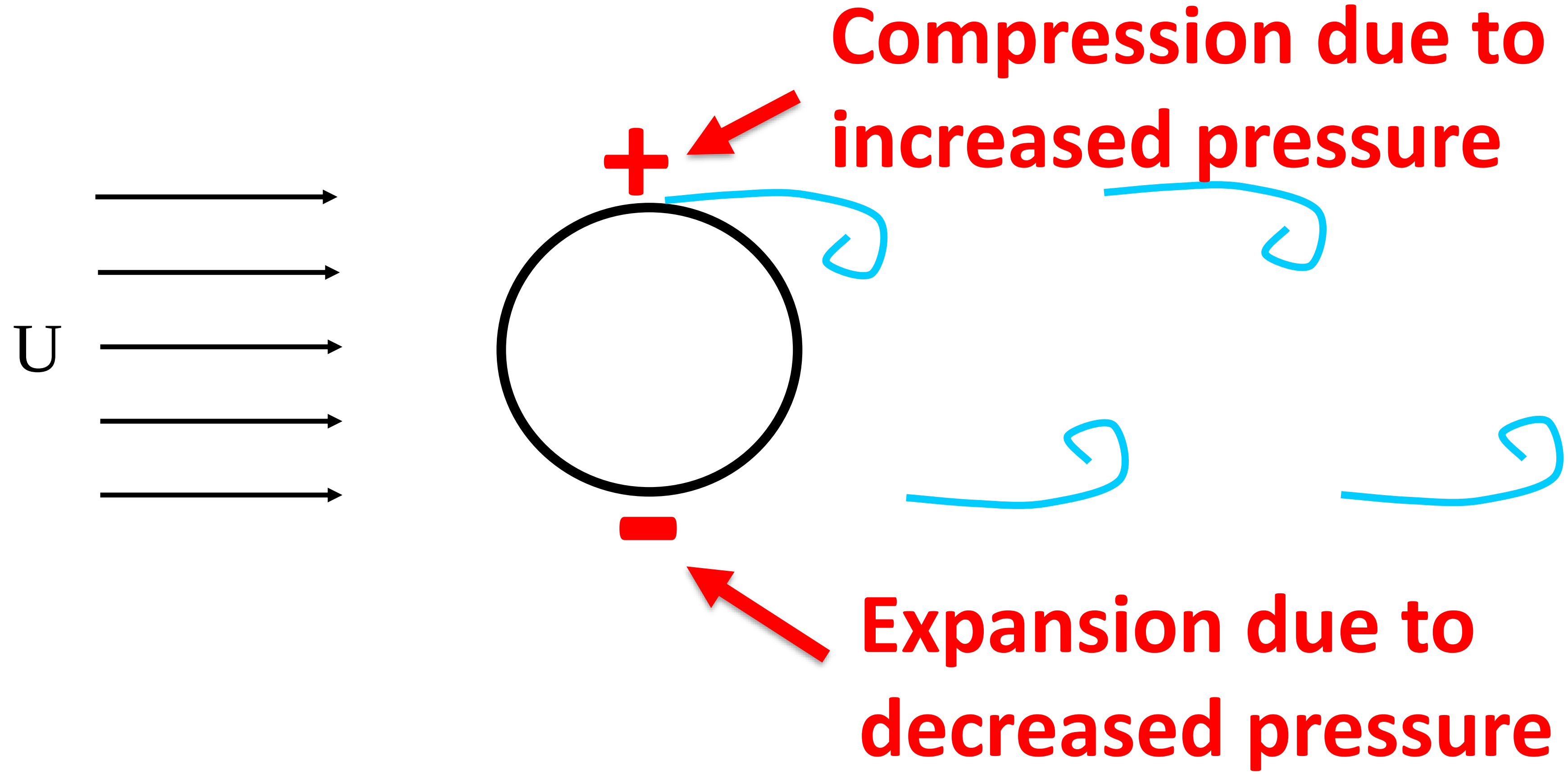


Lift force: $\vec{L} = -\rho\,(\vec{\Omega} \times \vec{v})$



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

Dipole Source of Sound



$$\frac{1}{{c_0}^2}\frac{\partial^2 p'}{\partial t^2} - \nabla^2 p' = -\nabla \cdot \vec{f} + \frac{1}{{c_0}^2}\left(\frac{\partial p}{\partial s}\right)_\rho \frac{\partial^2 s'}{\partial t^2}$$

Non uniform force field: walls!

Without walls:

no dipole sound sources

Entropy production
(heat transfer, combustion)

Aeolian sound sources: Voice of the wind

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

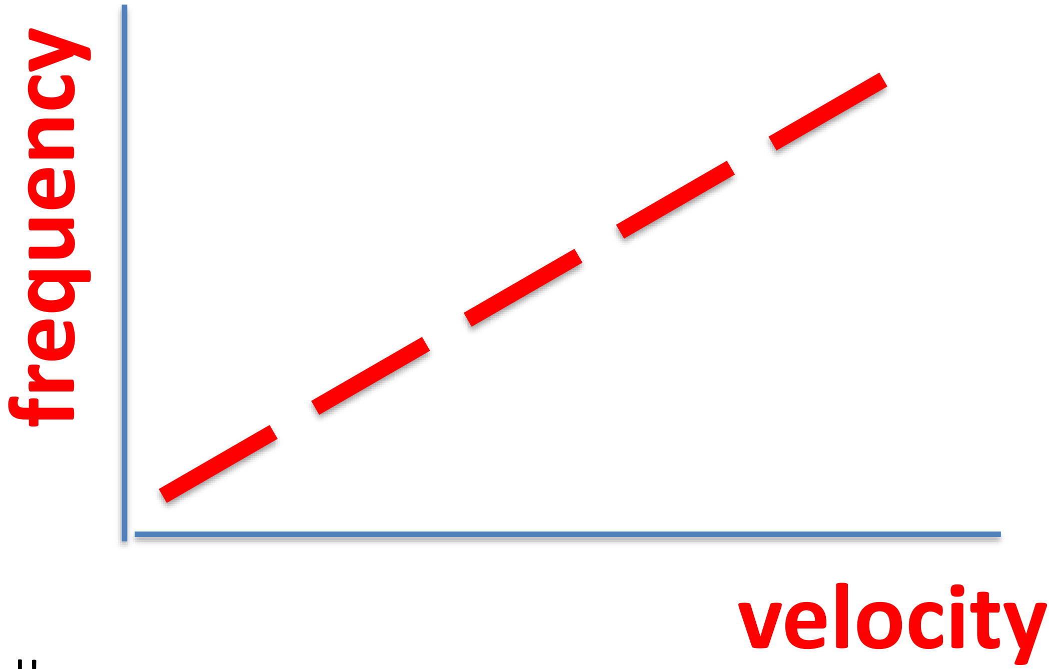
-Sound of wind in a forest…

Whistling threes

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

Strouhal number

$$St = \frac{fD}{U} \approx 0.2$$



Estimate wind speed!

Hybrid approach

1) Calculate/estimate hydrodynamic force on object (ignoring the sound production)

2) Use hydrodynamic force to calculate the radiate sound field (ignoring the hydrodynamic flow)

Break

Hybrid approach and analogy

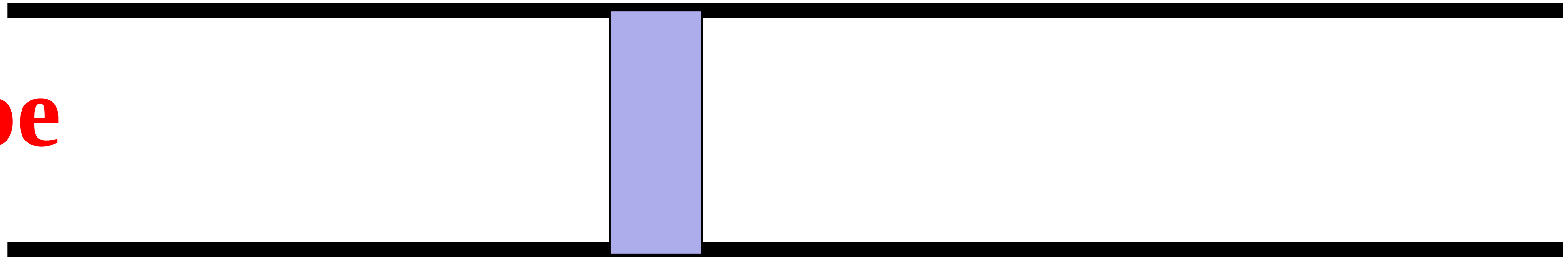
1) Calculate/estimate hydrodynamic force on object (ignoring the sound production)

2) Use hydrodynamic force to calculate the radiate sound field (ignoring the hydrodynamic flow)

Wave equation with sound source determined by force: Aeroacoustic analogy (Gutin 1936, Curle 1955)

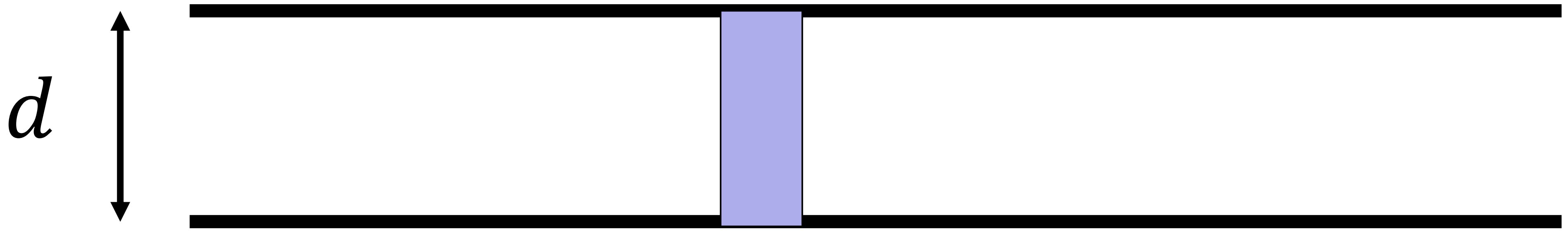
Predicting sound radiation:
The most simple case

pipe



$$\frac{1}{{c_0}^2}\frac{\partial^2 p'}{\partial t^2} - \nabla^2 p' = -\nabla \cdot \vec{f} + \frac{1}{{c_0}^2}\left(\frac{\partial p}{\partial s}\right)_\rho \frac{\partial^2 s'}{\partial t^2}$$

$\vec{f}$ force per unit volume

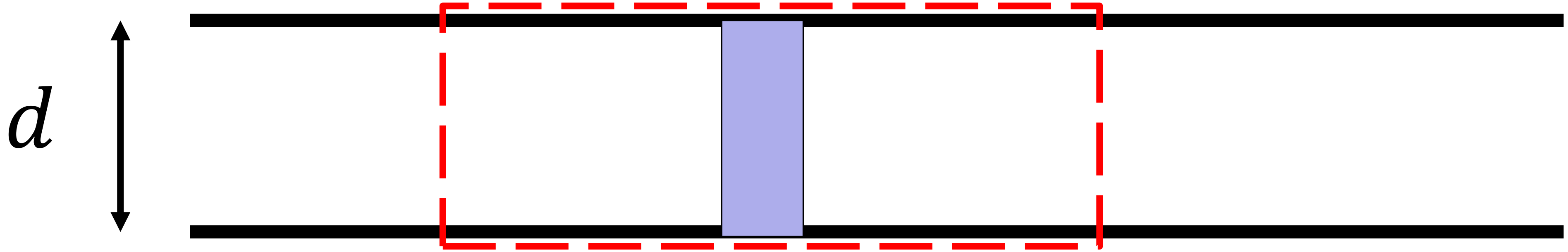


$$\frac{1}{{c_0}^2}\frac{\partial^2 p'}{\partial t^2} - \nabla^2 p' = -\boldsymbol{\nabla}\cdot\vec{\boldsymbol{f}} + \frac{1}{{c_0}^2}\left(\frac{\partial p}{\partial s}\right)_\rho \frac{\partial^2 s'}{\partial t^2}$$

Low frequency $\left(\left(\frac{\omega d}{c}\right)^2 \ll 1\right)$:

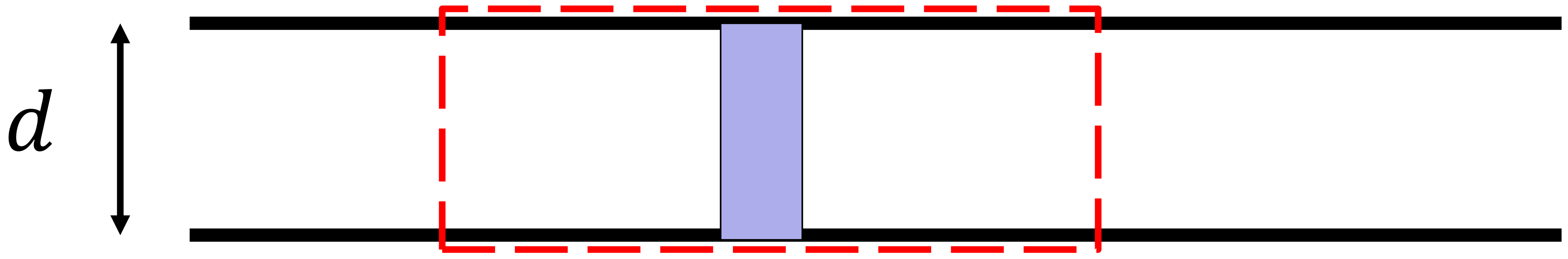
-far field plane waves

-in source region $\left(\frac{1}{{c_0}^2}\frac{\partial^2 p'}{\partial t^2} \ll \nabla^2 p'\right)$



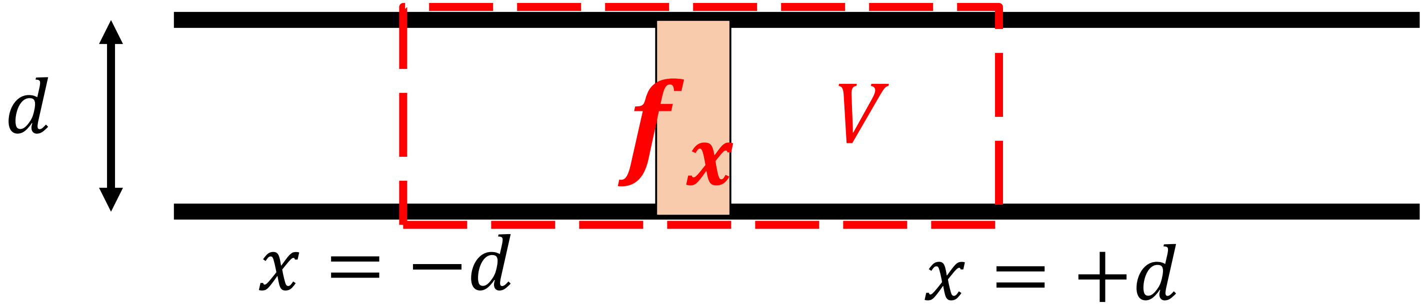
$$\nabla^2 p' = \nabla \cdot \nabla p' \approx \boldsymbol{\nabla} \cdot \vec{\boldsymbol{f}}$$

$$\text{Low frequency} \left(\left(\frac{\omega d}{c} \right)^2 \ll 1 \right):$$

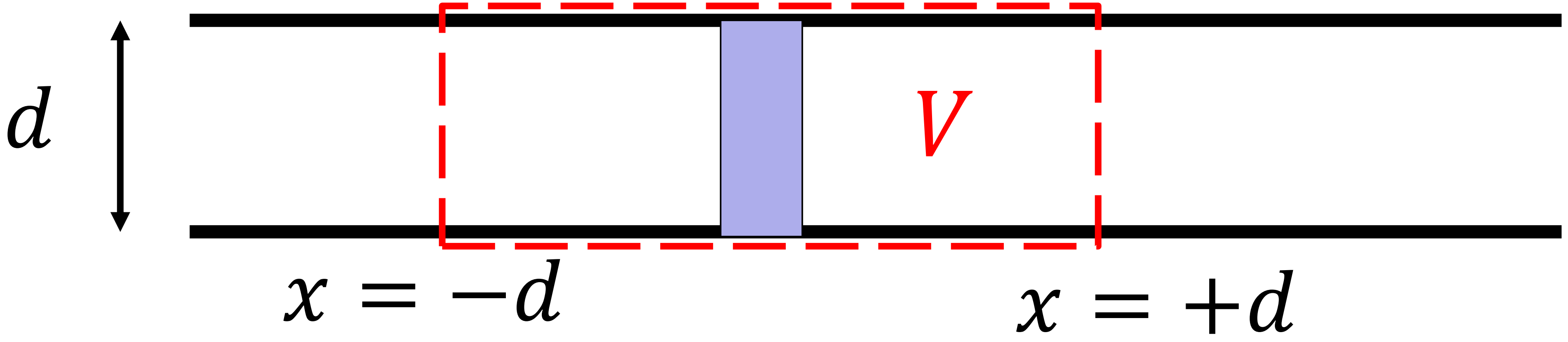


$$\nabla p' \approx \vec{\boldsymbol{f}}$$

Low frequency $\left(\left(\frac{\omega d}{c}\right)^2 \ll 1\right)$:

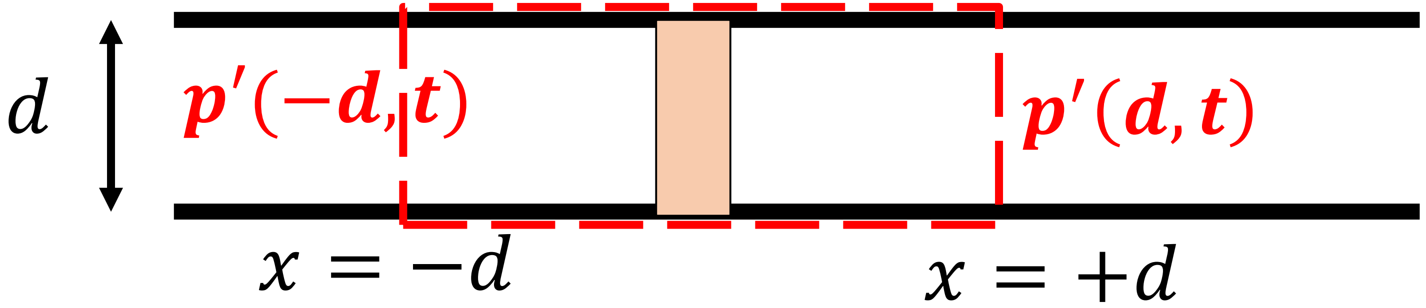


Low frequency $\left(\left(\frac{\omega d}{c}\right)^2 \ll 1\right) \Rightarrow$ **Plane waves** $p'(x,t)$



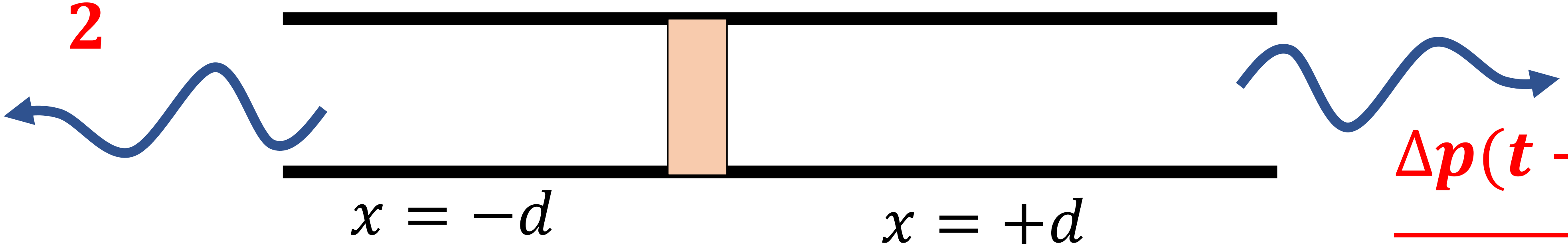
$$\iiint_V \nabla p' dV = \frac{\pi d^2}{4}\left(p'(d,t) - p'(-d,t)\right) \approx F_x(t) \equiv \iiint_V f_x dV$$

Low frequency $\left(\left(\frac{\omega d}{c}\right)^2 \ll 1\right)$



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

$$-\frac{\Delta p\left(t+\frac{x}{c_0}\right)}{2}$$



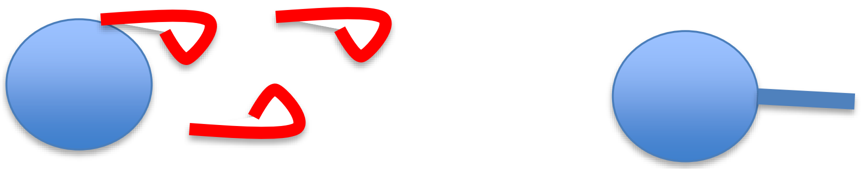
$$\frac{\Delta p\left(t-\frac{x}{c_0}\right)}{2}$$

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

Coherence of vortex shedding

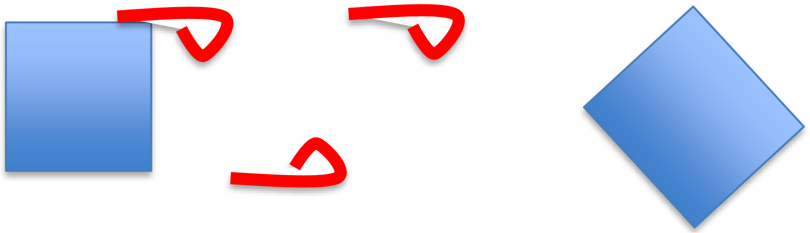
Sound generated by cylinder fairly weak:
-dipole sound source
-limited coherence of vortex shedding
-effect of finite length…

Effect of shape of cylinder/rod

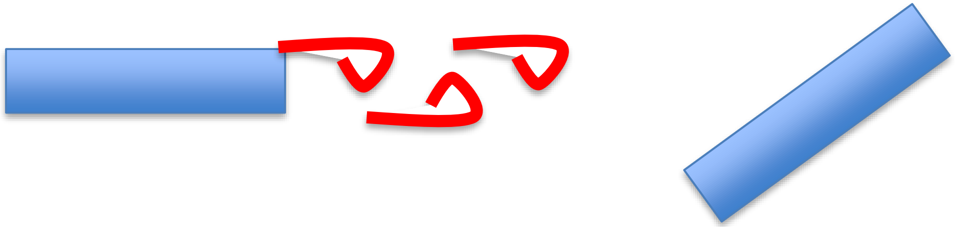


Supression of wake instability

Cylinder, square rod
and plate at normal incidence
all display a von Kármán vortex street in the wake



Square rod under 45^o has a stable wake or
A von `Kármán vortex street depending on
Initial flow conditions (upstream or downstream
Perturbation)



Complex vortex shedding depending
on the angle of attack

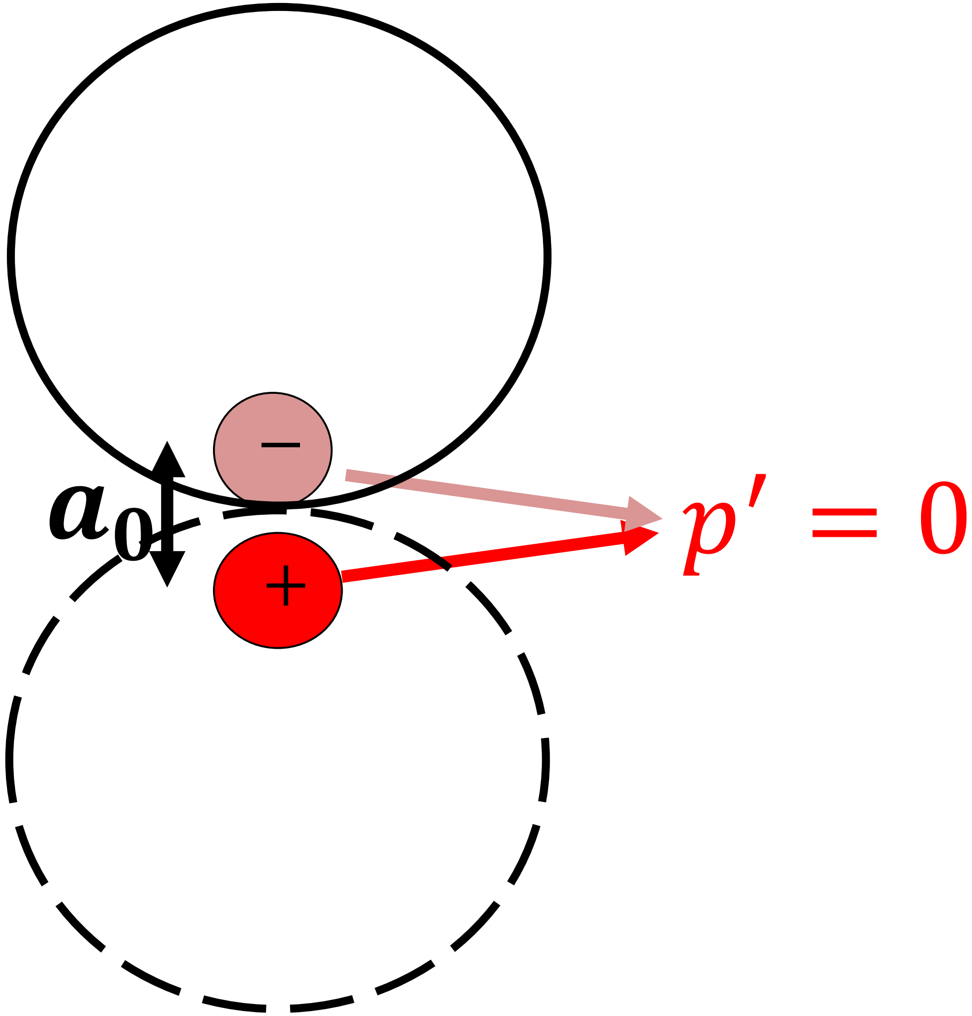
For some geometries multiple wave structures are possible
(stable/unstable)

Predicting low frequency broadband noise (air-conditioning duct):

Often scaling laws are useful for design. These scaling laws are based on aeroacoustic theory.

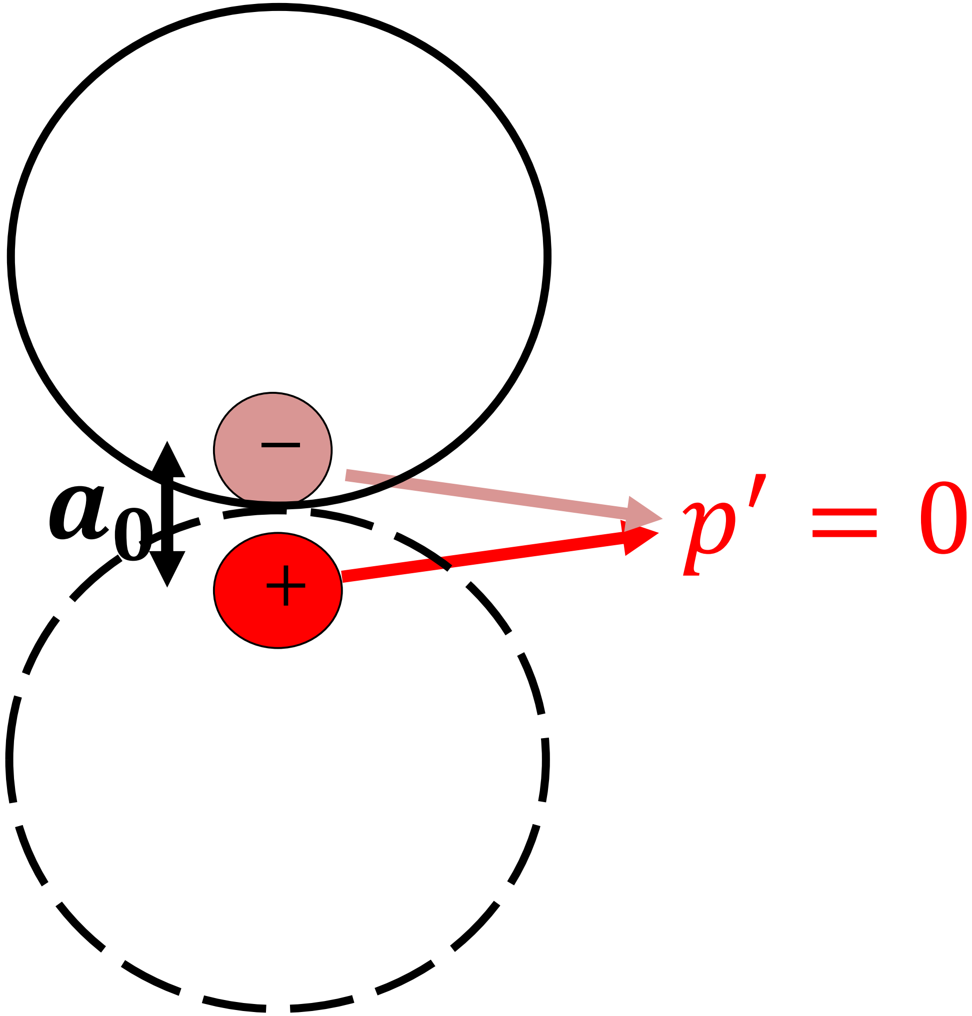
Two monopoles oscillating in opposite phase

Radiated acoustic power in free space proportional to $(ka_0)^6$.

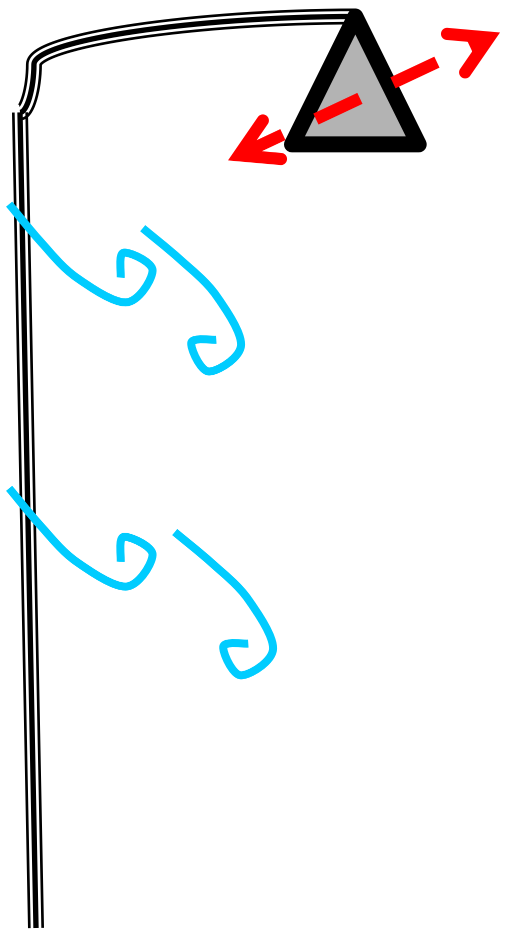


Radiated acoustic power in free space proportional to $(ka_0)^6 \propto M^6$.

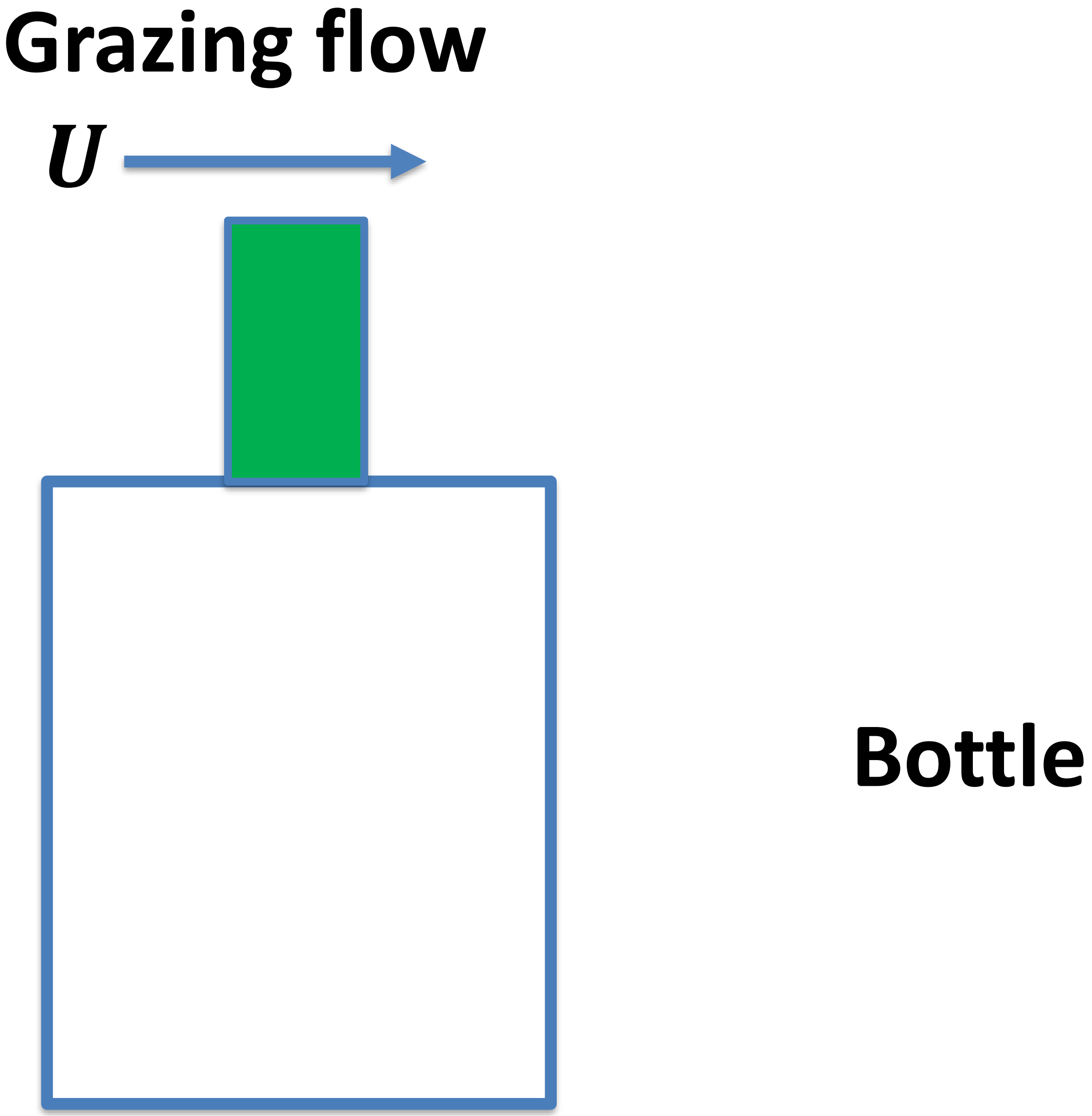
$$k = \frac{2\pi}{\lambda} = \frac{2\pi f}{c} = 2\pi \left(\frac{St}{D}\right)\frac{U}{c}$$



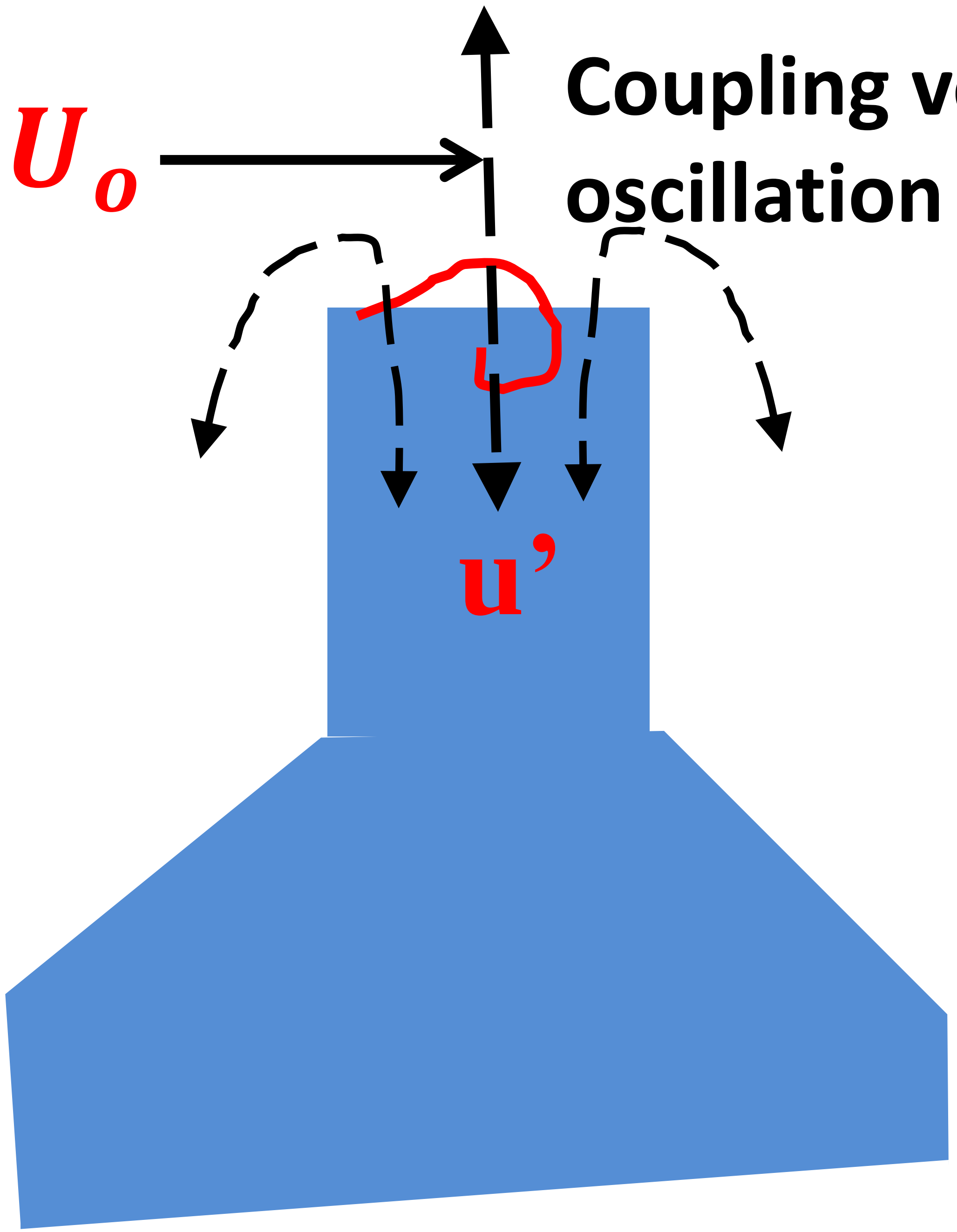
Failure of the two-step procedure

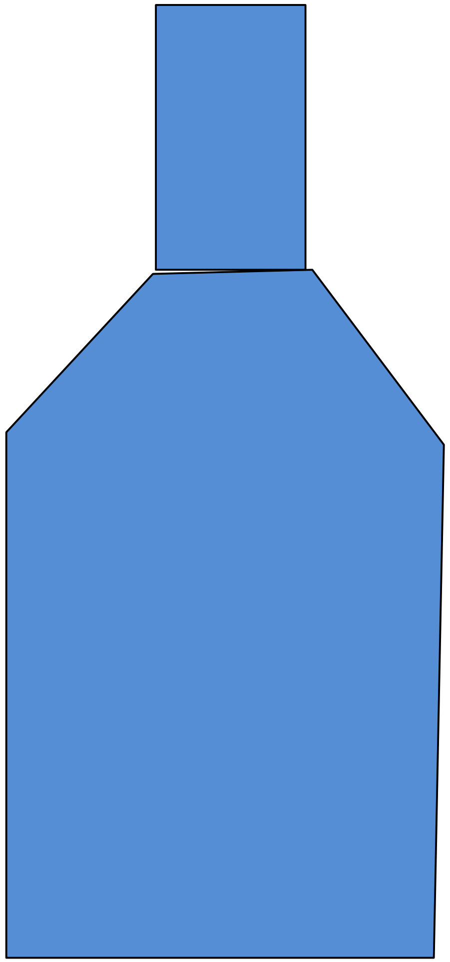


Coupling with mechanical vibration
(Aeolian harp legend of David)

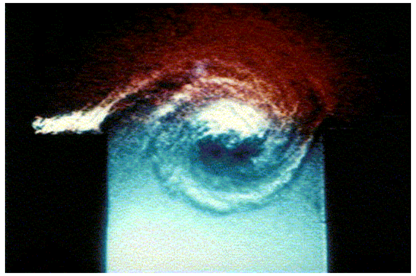

Grazing flow
U
Bottle

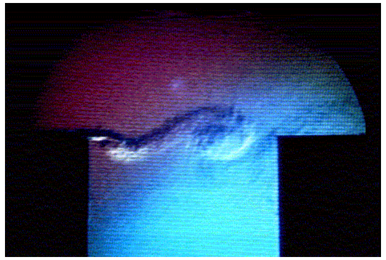
Coupling vortex shedding to acoustic oscillation





Hydrodynamic modes





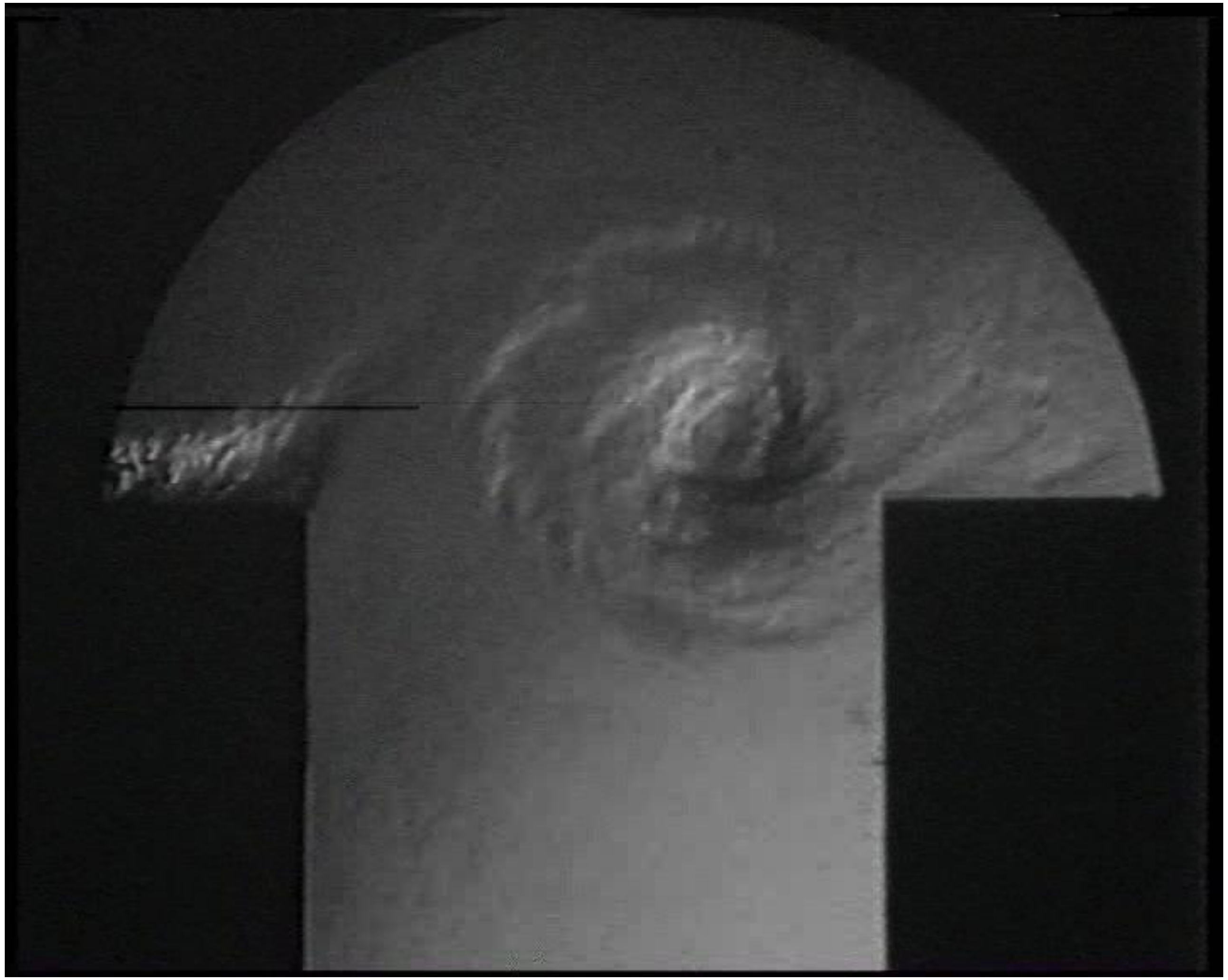
Hydrodynamic instability
(Amplifier)

Unsteady force
on wall
(sound source)

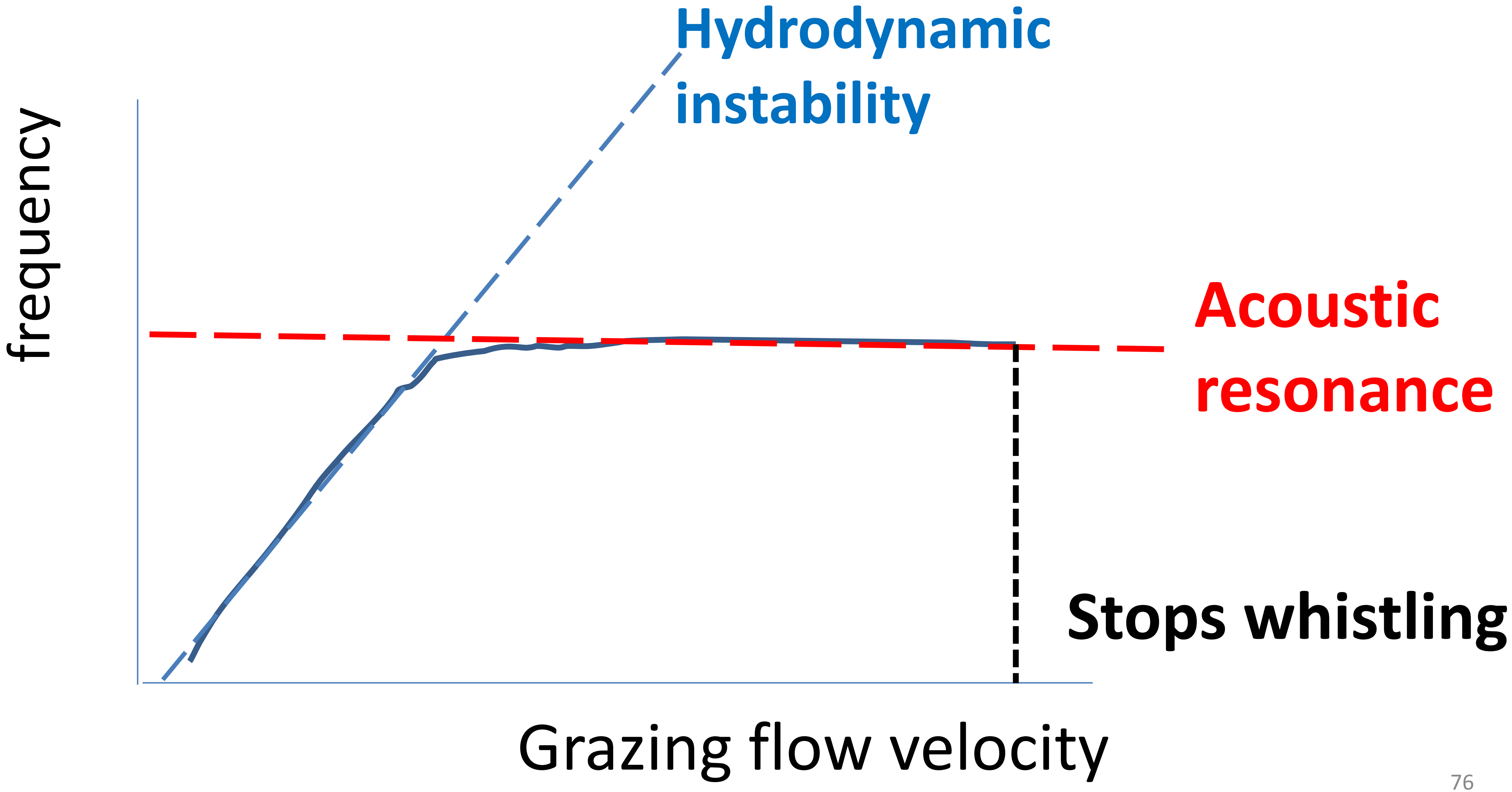
Bottle resonance
(Filter)

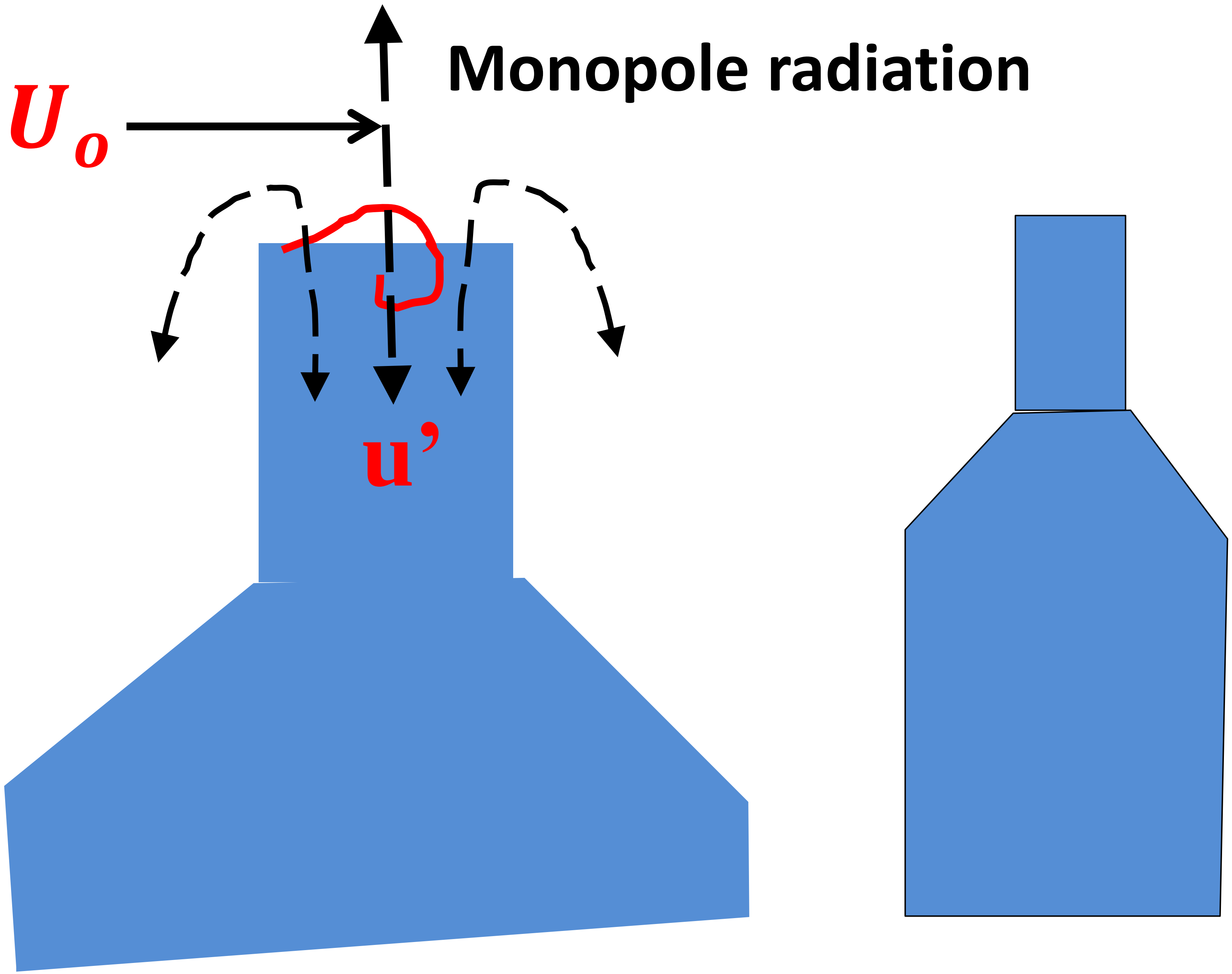
Perturbation
of shear layer
(acoustic feedback)

Unsteady flow



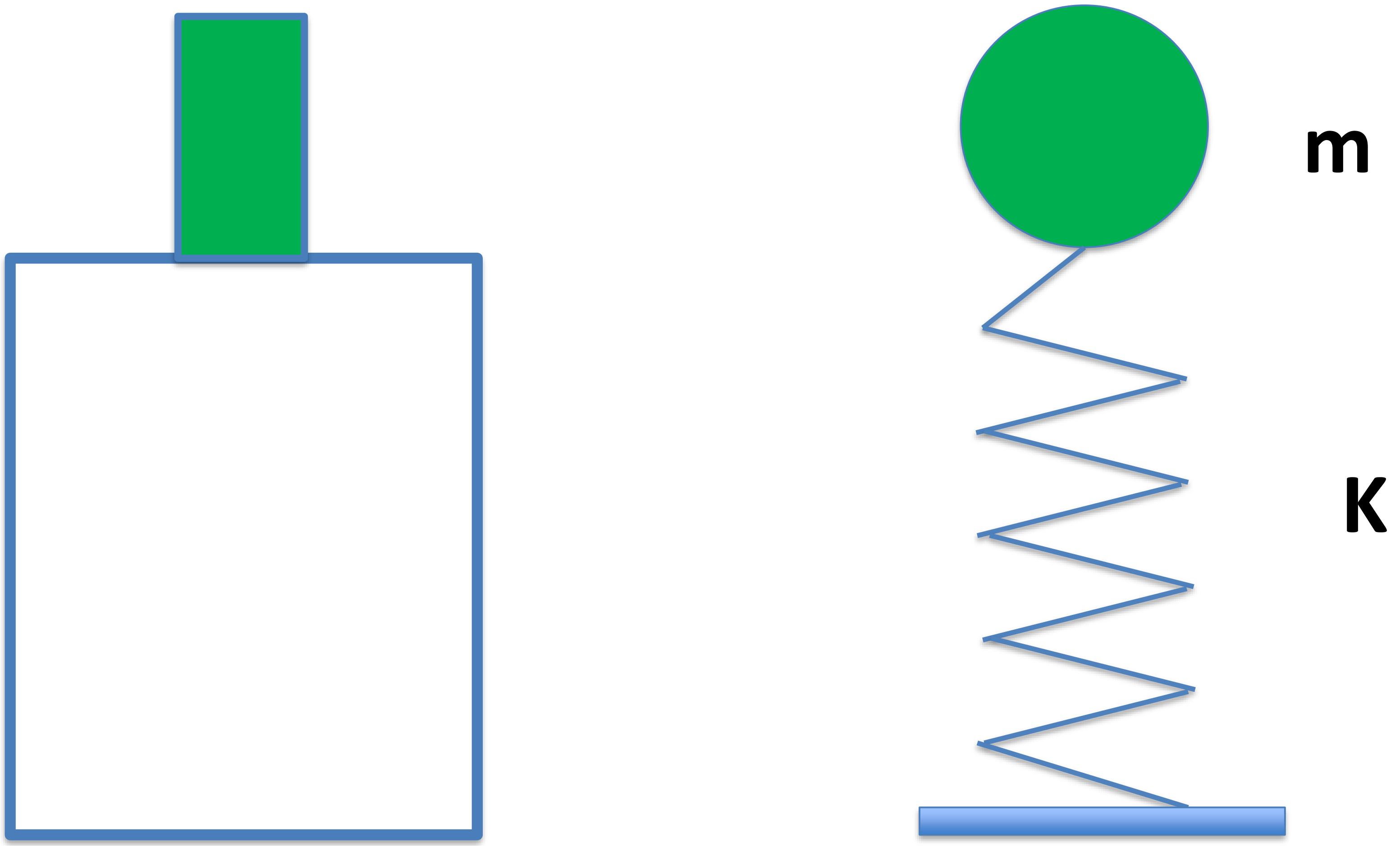
Oscillation frequency



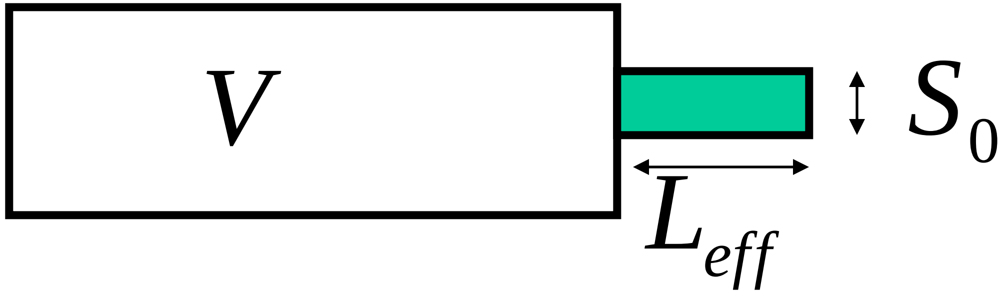


Monopole radiation
U_o
u'

Bottle Is acoustic mass-spring system

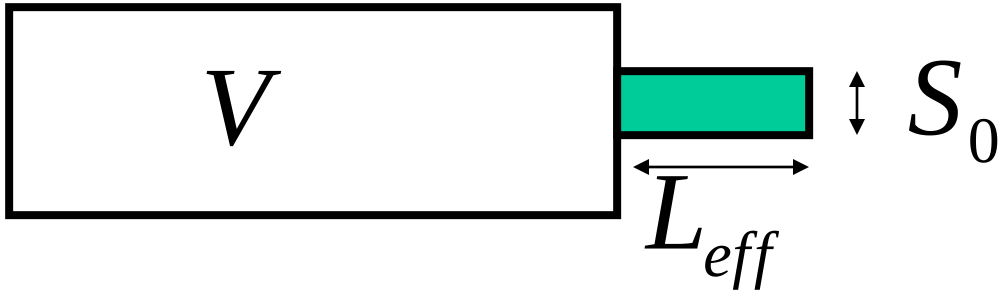


Mass-spring system



$$m = \rho_0 L_{eff} S_0$$

Mass-spring system



$$m = \rho_0 L_{eff} S_0$$

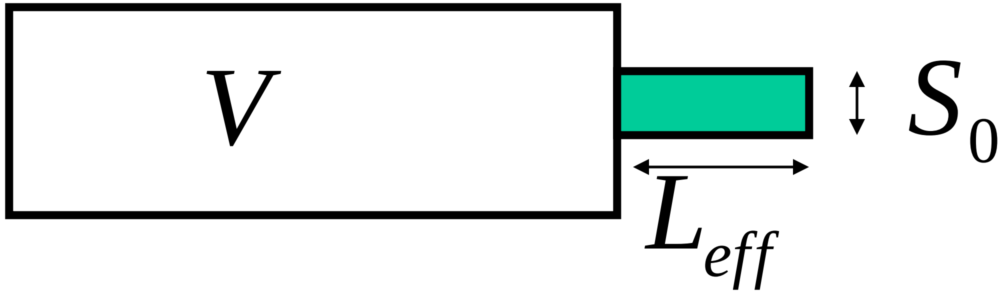
Kinetic energy outside the neck not negligible

L_{eff} takes inertia outside the neck into account

Effective resonator-pipe length
is larger than neck length (Bernoulli).

The acoustic flow does not stop at the end of the pipe !

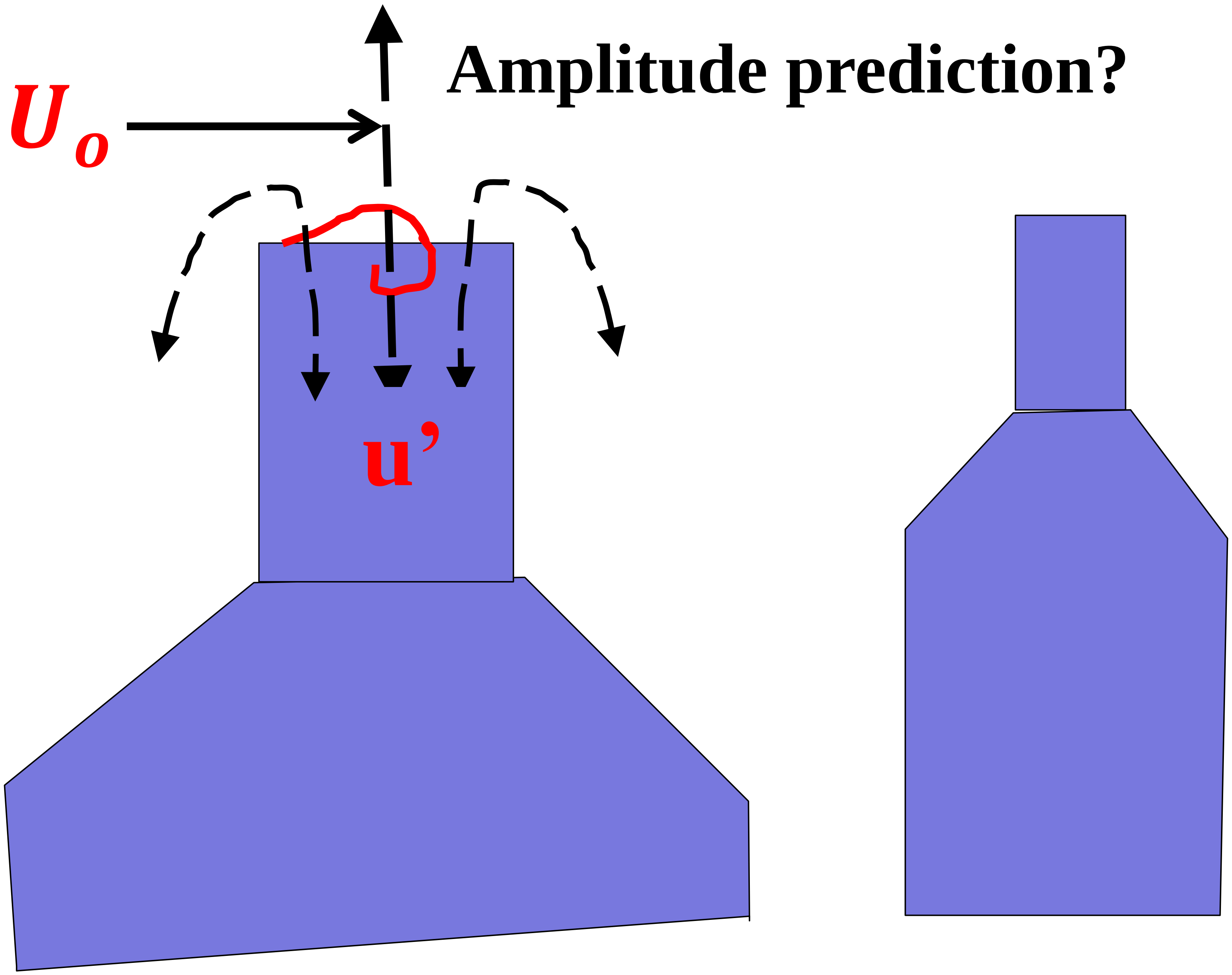
Mass-spring system



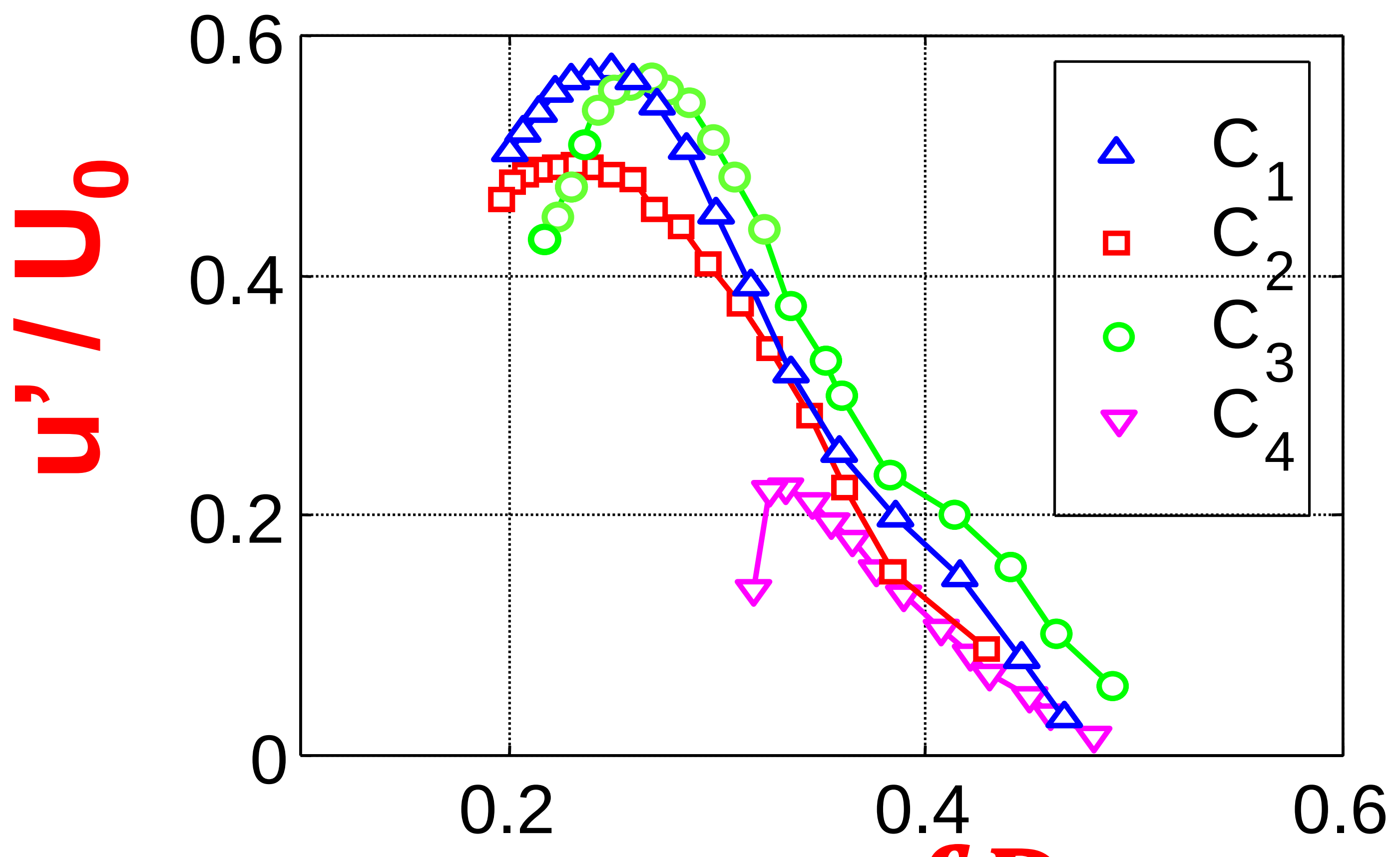
$$m = \rho_0 L_{eff} S_0$$

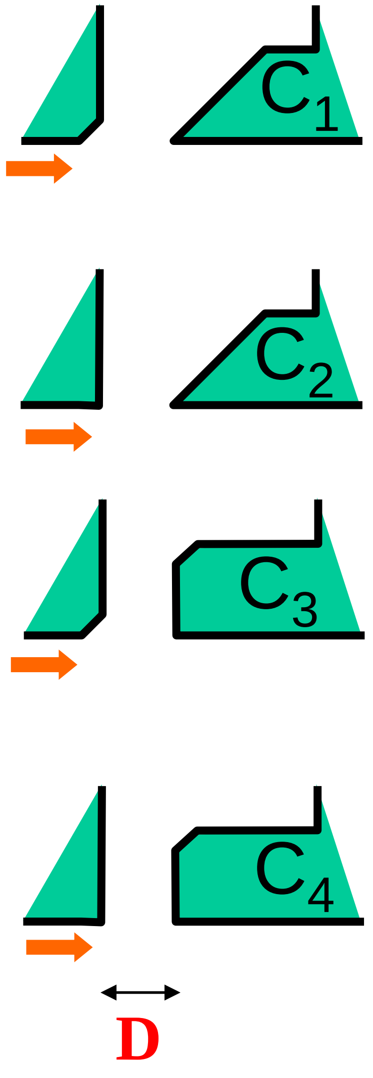
$$K = \rho_0 {c_0}^2 \frac{{S_0}^2}{V}$$

$$\boldsymbol{\omega = 2\pi f = \sqrt{\frac{K}{m}} = c_0 \sqrt{\frac{S_0}{V L_{eff}}}}$$


U_o
Amplitude prediction?
u'

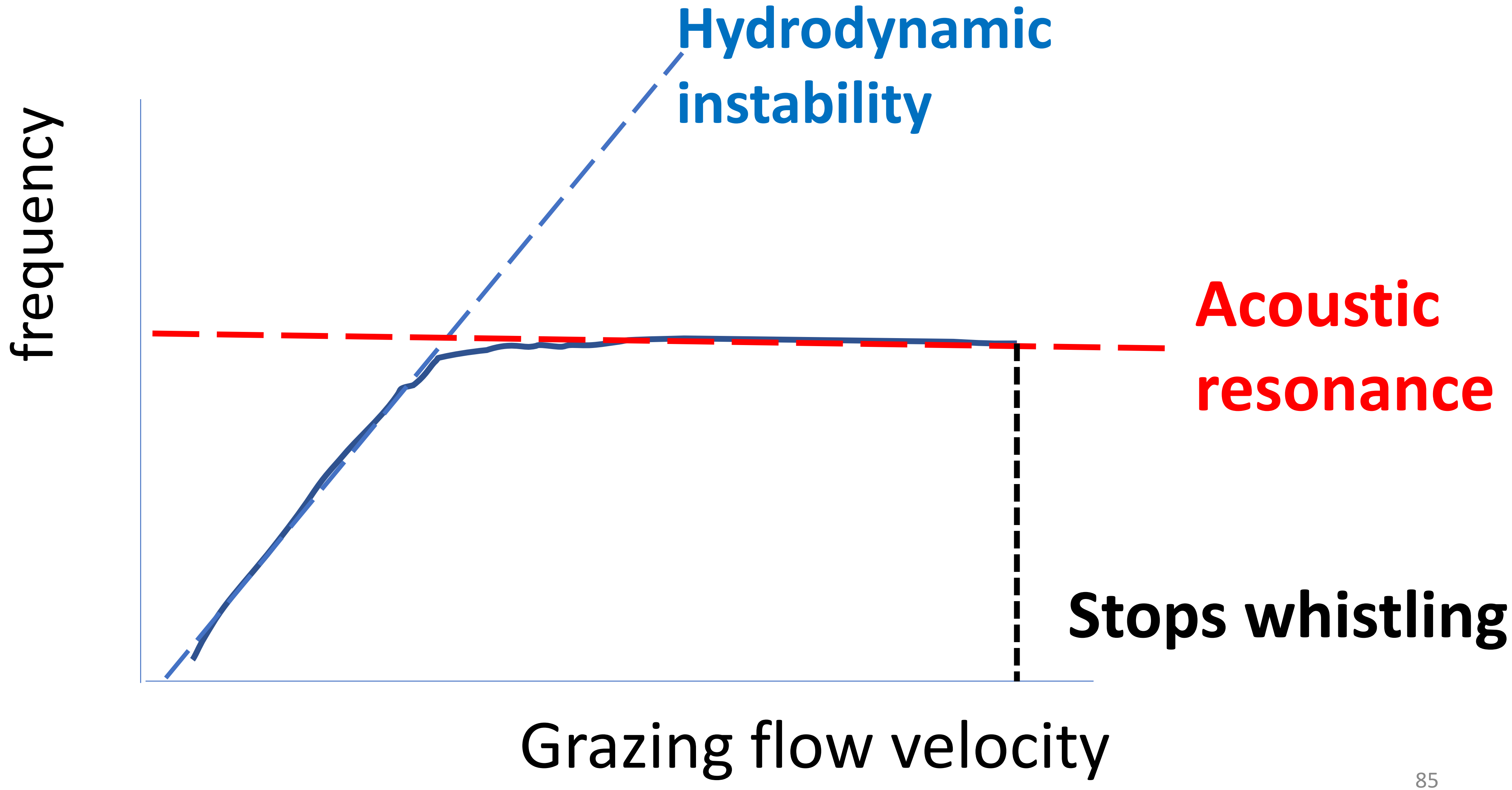
Ratio acoustic velocity in neck / grazing flow velocity



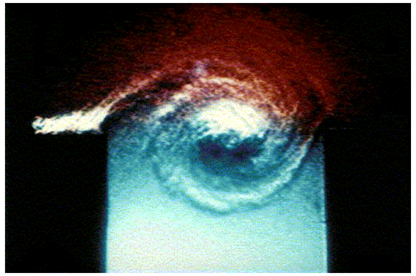


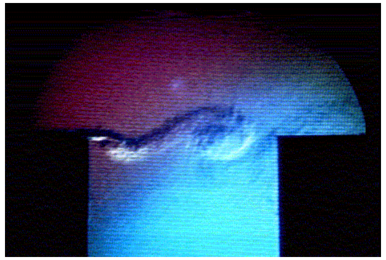
$$Sr = \frac{fD}{U_0}$$

Oscillation frequency



Hydrodynamic modes





Hydrodynamic instability
(Amplifier)

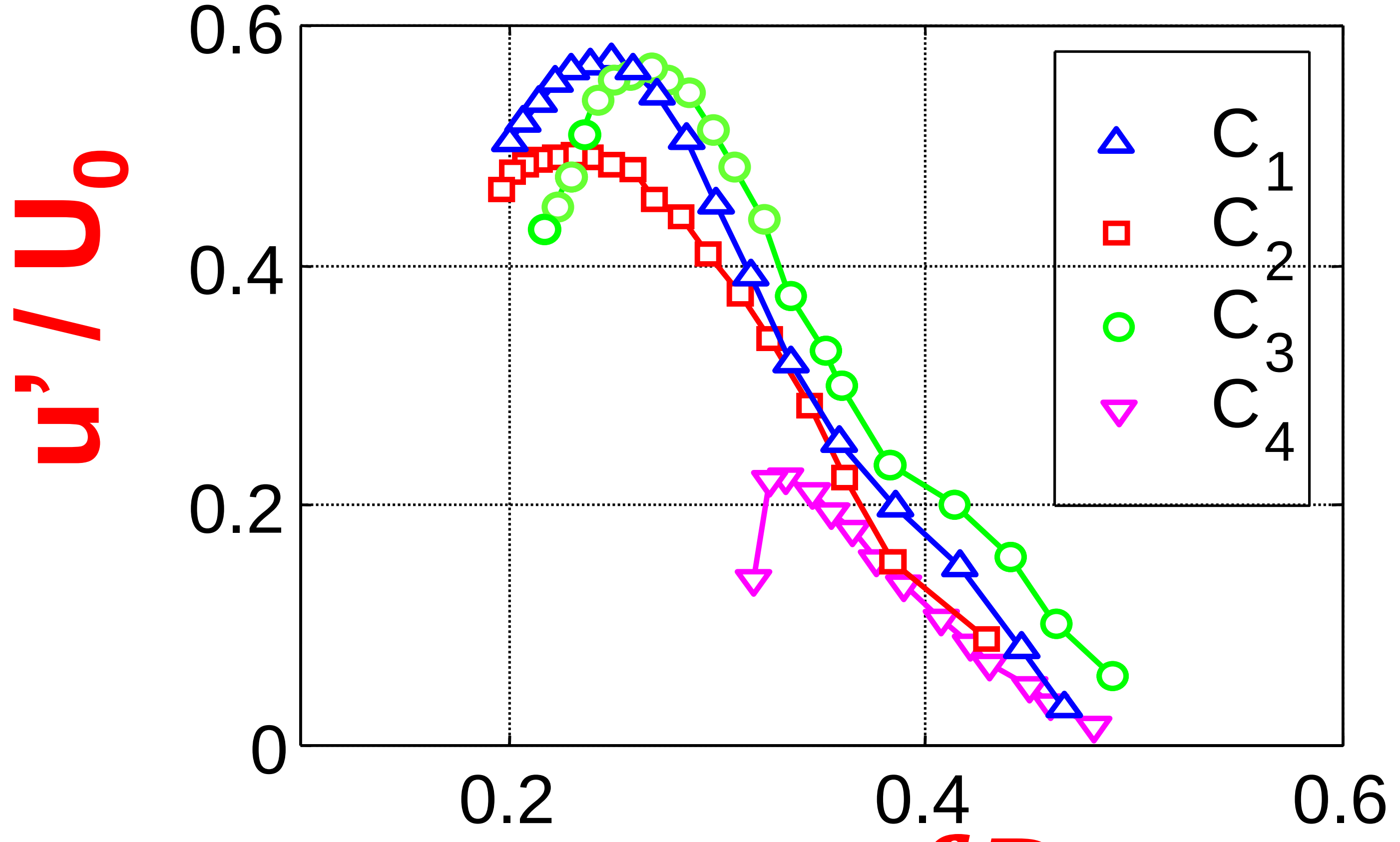
Perturbation
of shear layer
(acoustic feedback)

Unsteady force
on wall
(sound source)

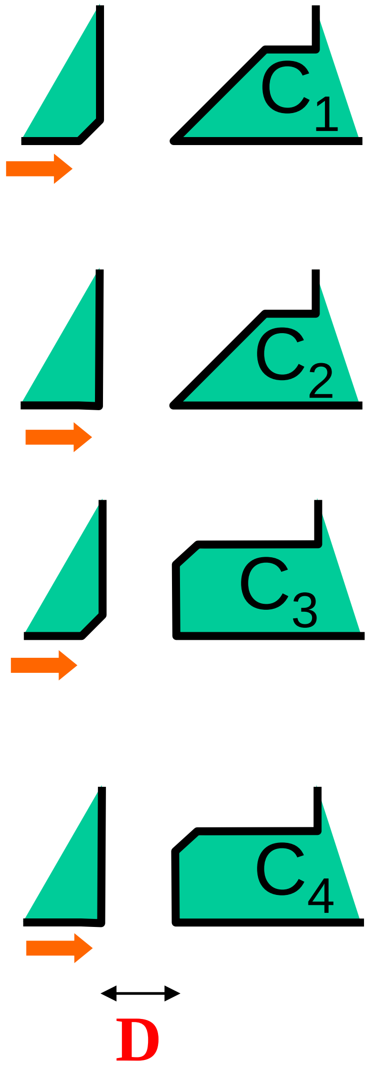
Bottle resonance
(Filter)

NON-LINEAR AMPLITUDE SATURATION

Ratio acoustic velocity in neck / grazing flow velocity



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



Wind organ pipes

Study of sound production by flows and influence of flow on acoustic propagation.

-General theoretical background

-Whistling

-Some applications to building acoustics

Corrugated pipes

➔ Usefulness:

Global flexibility & Local rigidity

➔ Applications

natural gas production

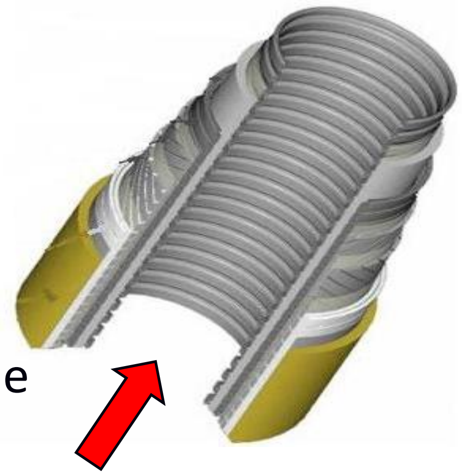
vacuum cleaners

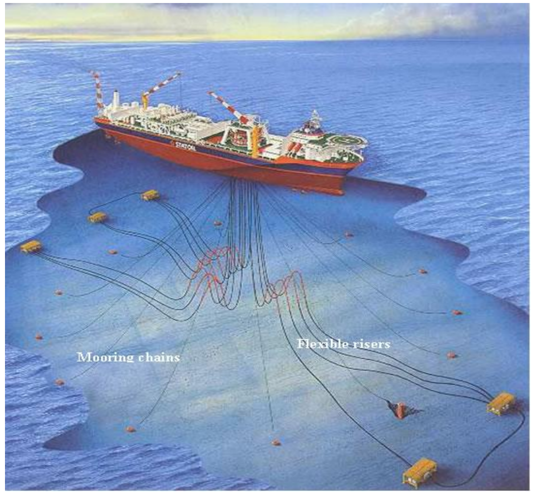
ventilation systems

heat exchangers

➔ Problems:

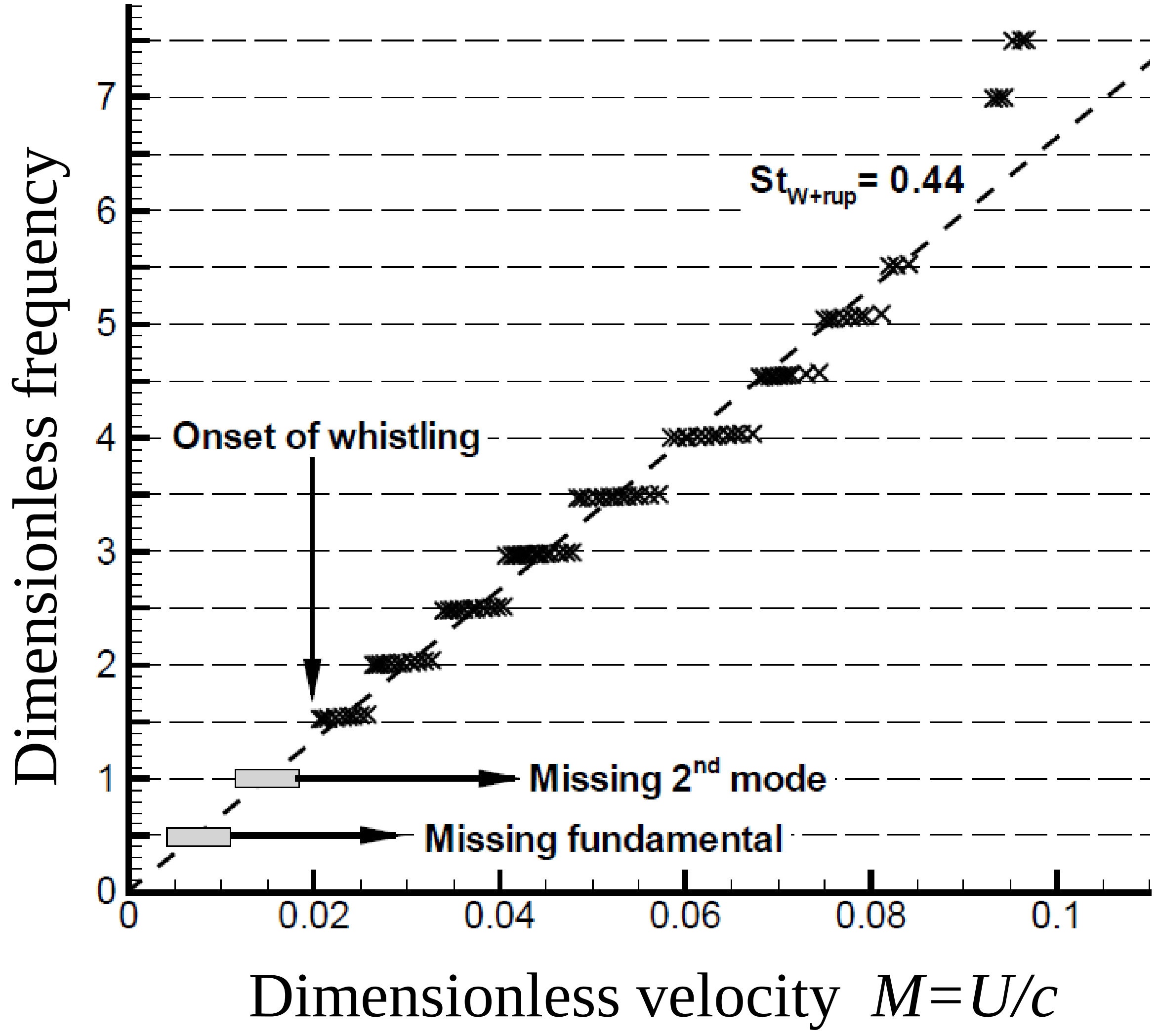
Noise | Environmental issue
Vibration | Structural problem

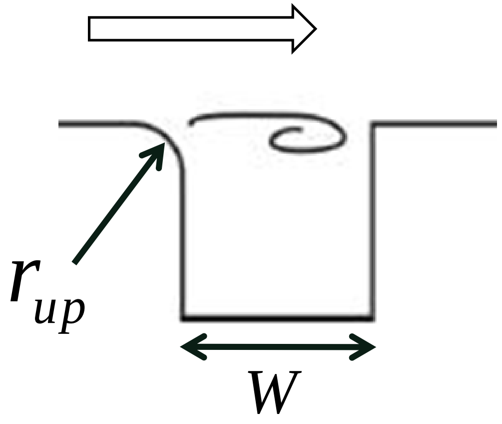




Strouhal Number

$$L/(cT) = fL/c$$



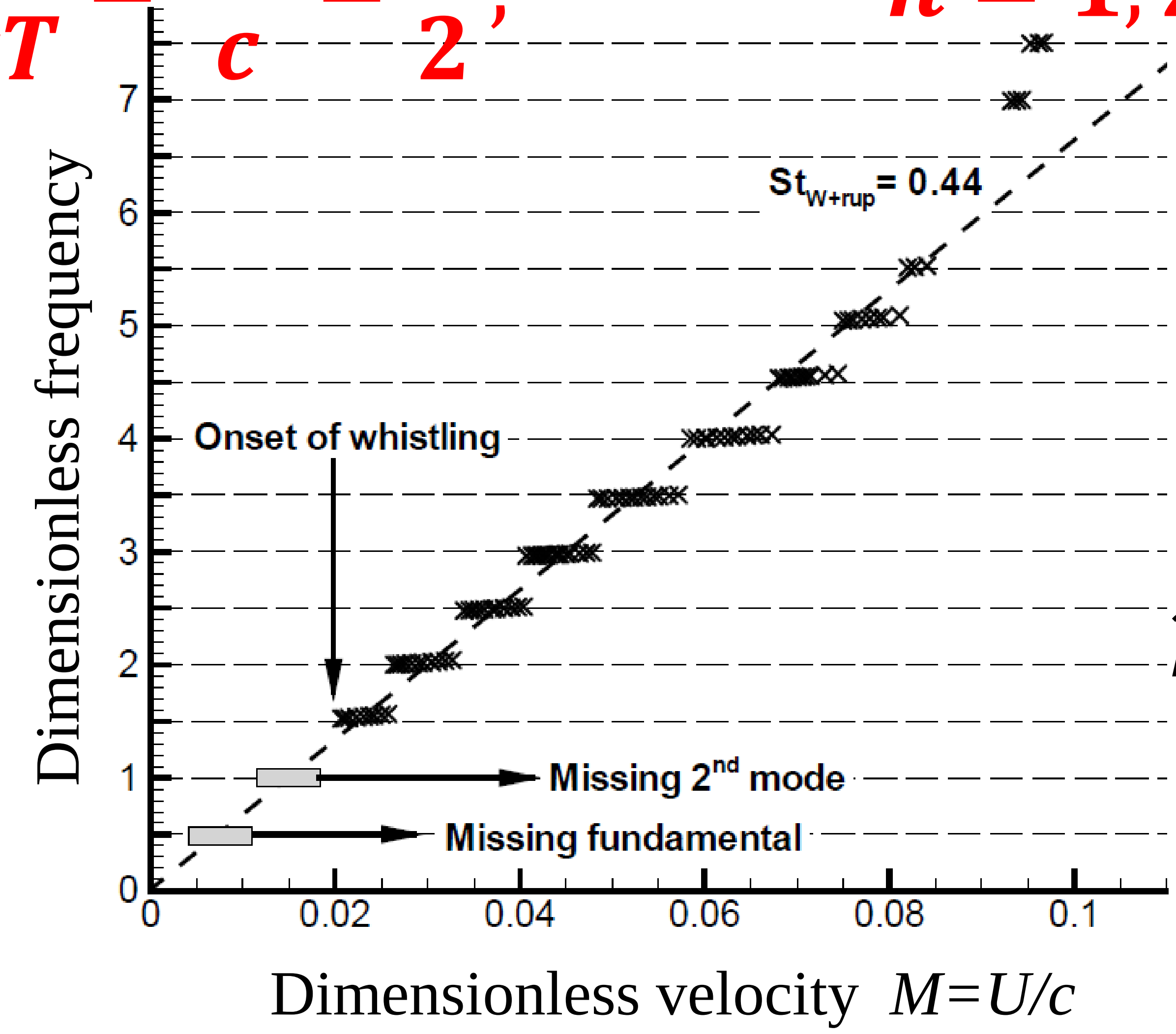


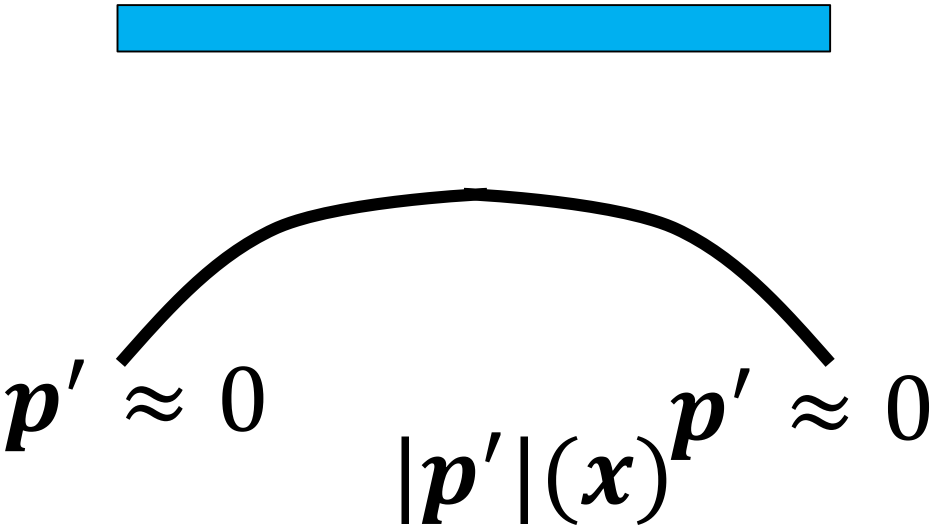
$$Sr = \frac{(W + r_{up})}{U\ T}$$

Stefan Belfroid
Jaap Bastiaansen
Rob Tummers

Acoustic Modes

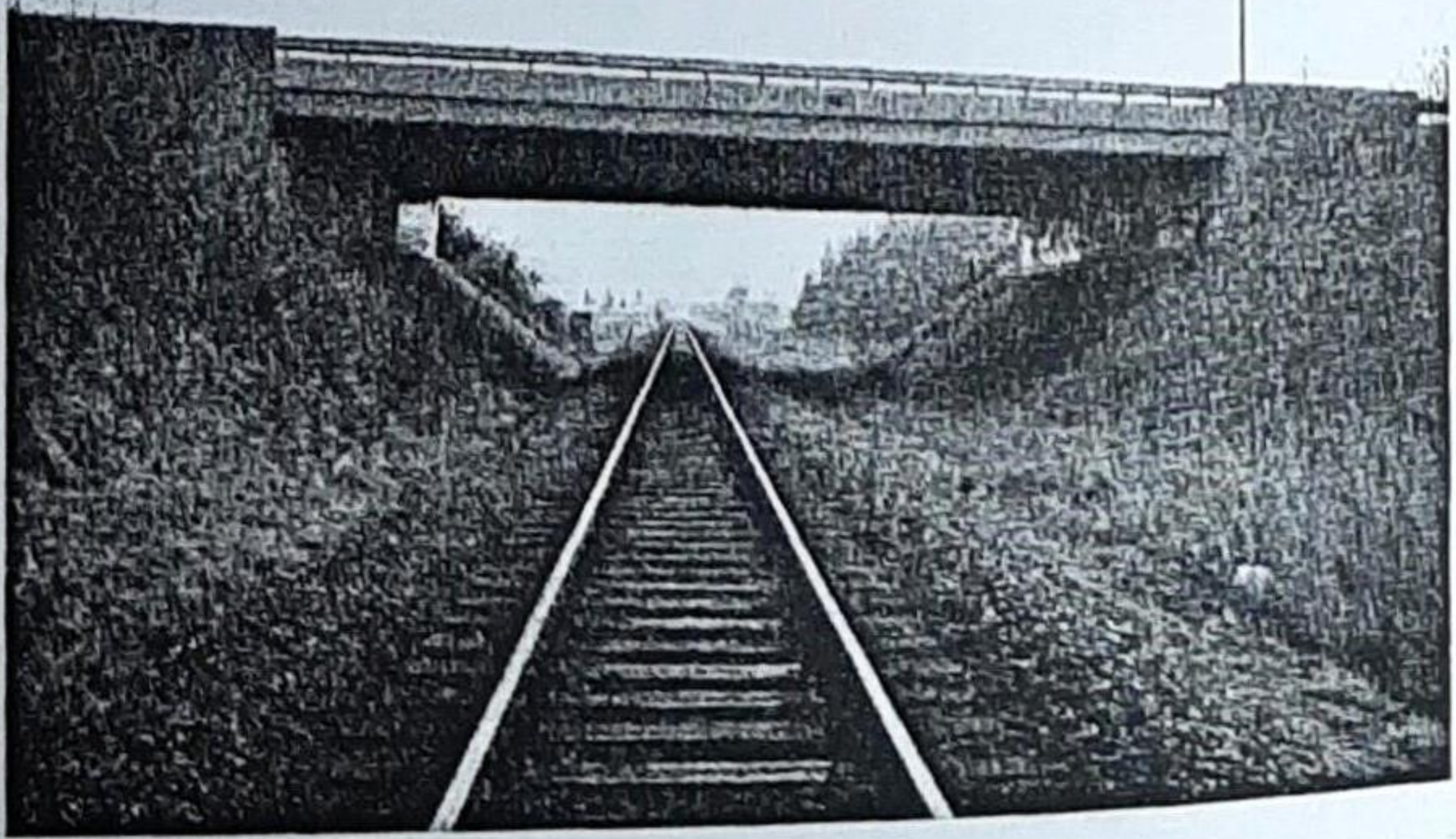
$$\frac{L}{cT} = \frac{fL}{c} = \frac{n}{2}, \qquad n = 1, 2, 3 \ldots$$



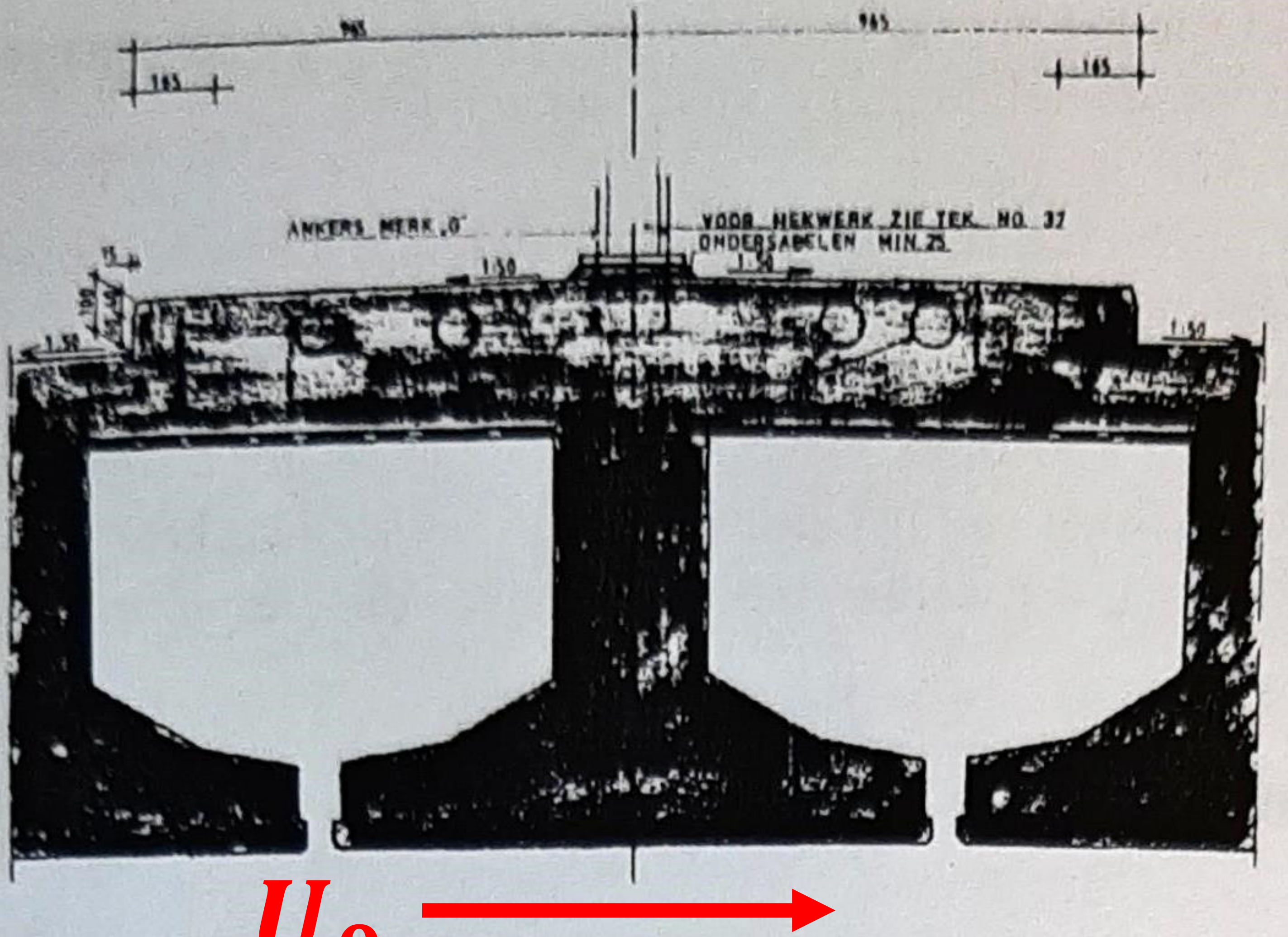


Vortex-Sound theory provides qualitative understanding (Powell 1964, Howe 1975/1980)

Hidden resonators

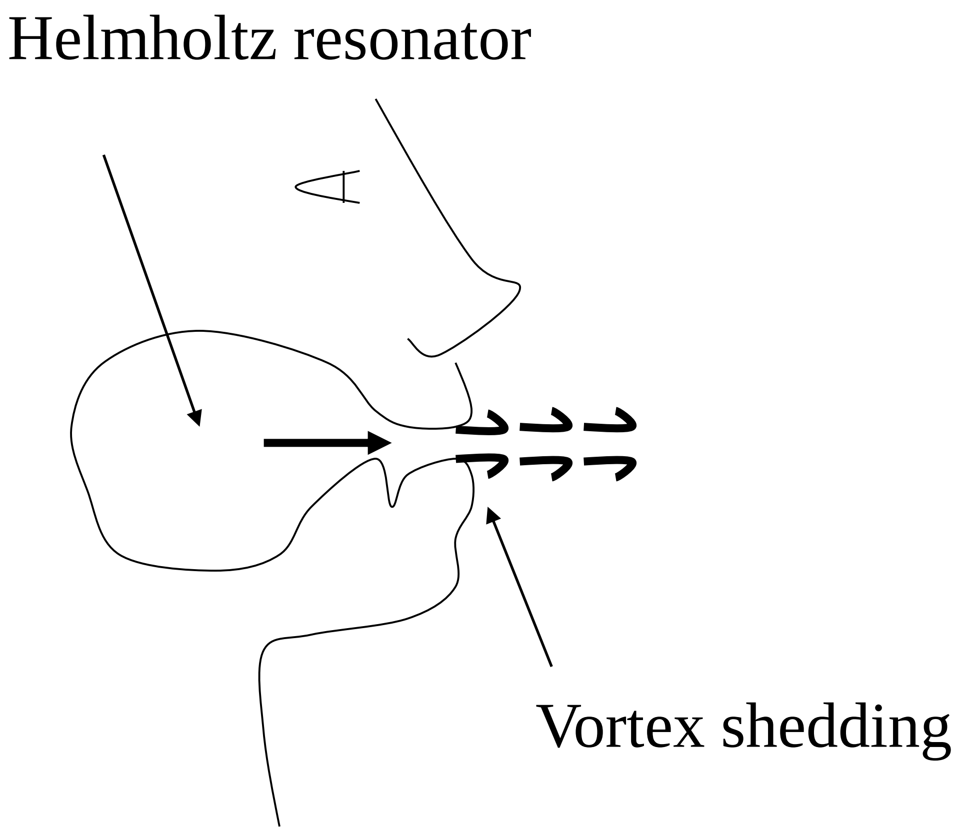


Figuur 1 Spoorwegviaduct in Leeuwarden.

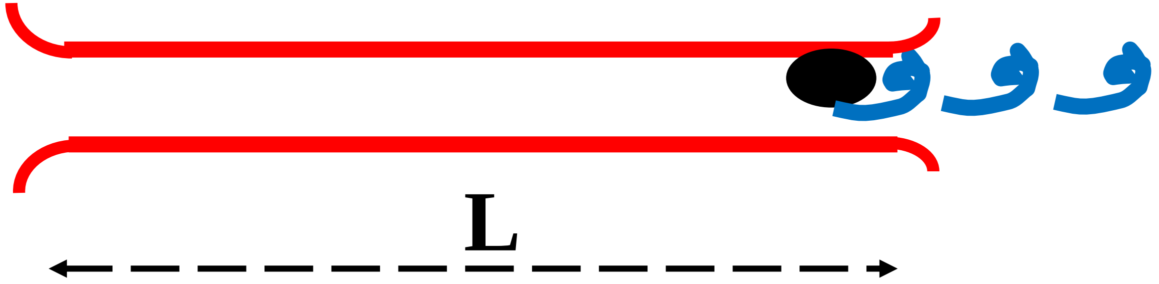


Figuur 2 Bouwtekening doorsnede viaduct.

Resonator: acoustical swing



Whistling slits (windows/doors)



L= 5 cm
Half wavelength resonance
c/f=L/2

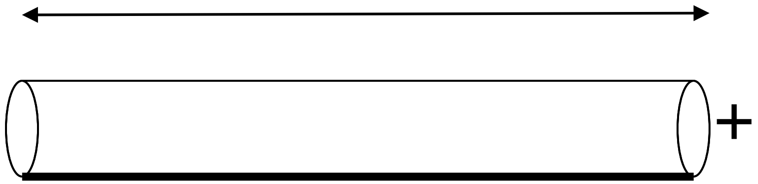
f=3.4 kHz

D=0.1 cm

Optimal whistling:
Sr=fD/U=0.4 => U=9 m/s
=> Fresh breeze (5 on Beaufort scale)!

Radiation from open-open pipes

L length



monopole

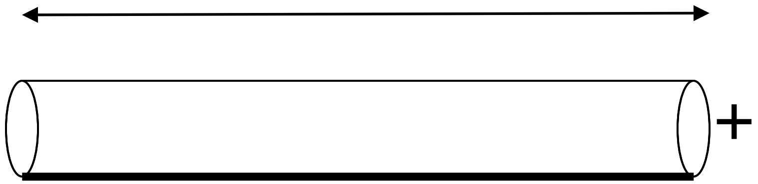
a_0 **pipe radius,**

$$k = \frac{2\pi}{\lambda}$$

$$\lambda = \frac{2L}{n} \qquad n = 1, 2, 3 \ldots$$

Radiation from open-open pipes

$$L = 300\ mm$$



monopole

$$a_0 = 10\ mm\ ,$$

$$k = \frac{2\pi}{\lambda} = \frac{\pi n}{L}$$

$$n = 1$$

$$I = < p'u' > \propto (ka_0)^4$$

$$(ka_0)^2 = (0.11)^2 = 10^{-2}$$

Radiation from open-open pipes

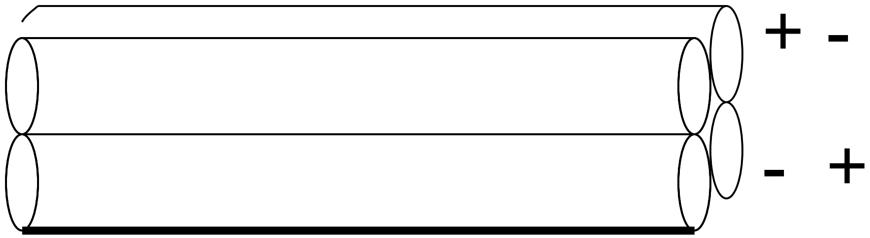
$$I =< u' \, p' >\propto (ka_0)^4$$

monopole

$$I =< u' \, p' >\propto (ka_0)^6$$

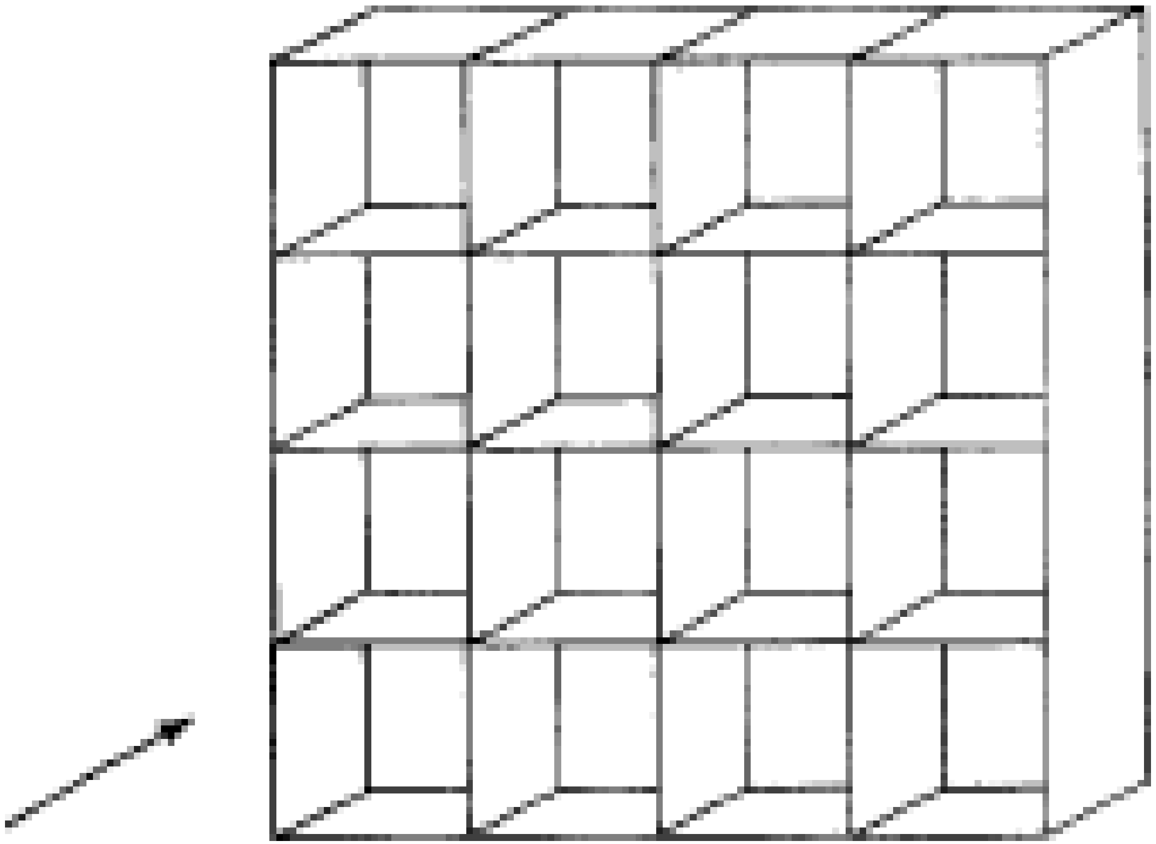
dipole

$$I =< u' \, p' >\propto (ka_0)^8$$



quadrupole

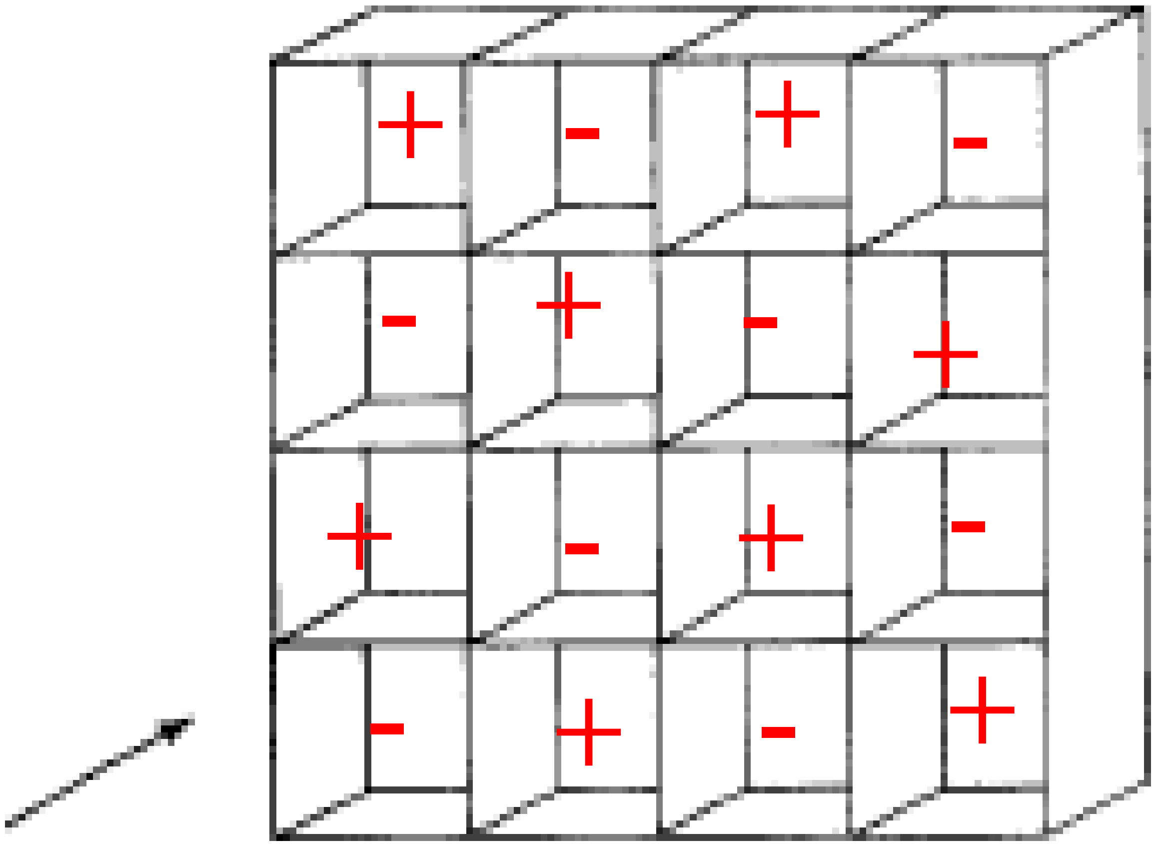
Spruyt (1972)



Bruggeman/Parchen 1990, Peutz 2008

Whistling protection grid of large ventilators

Spruyt (1972)

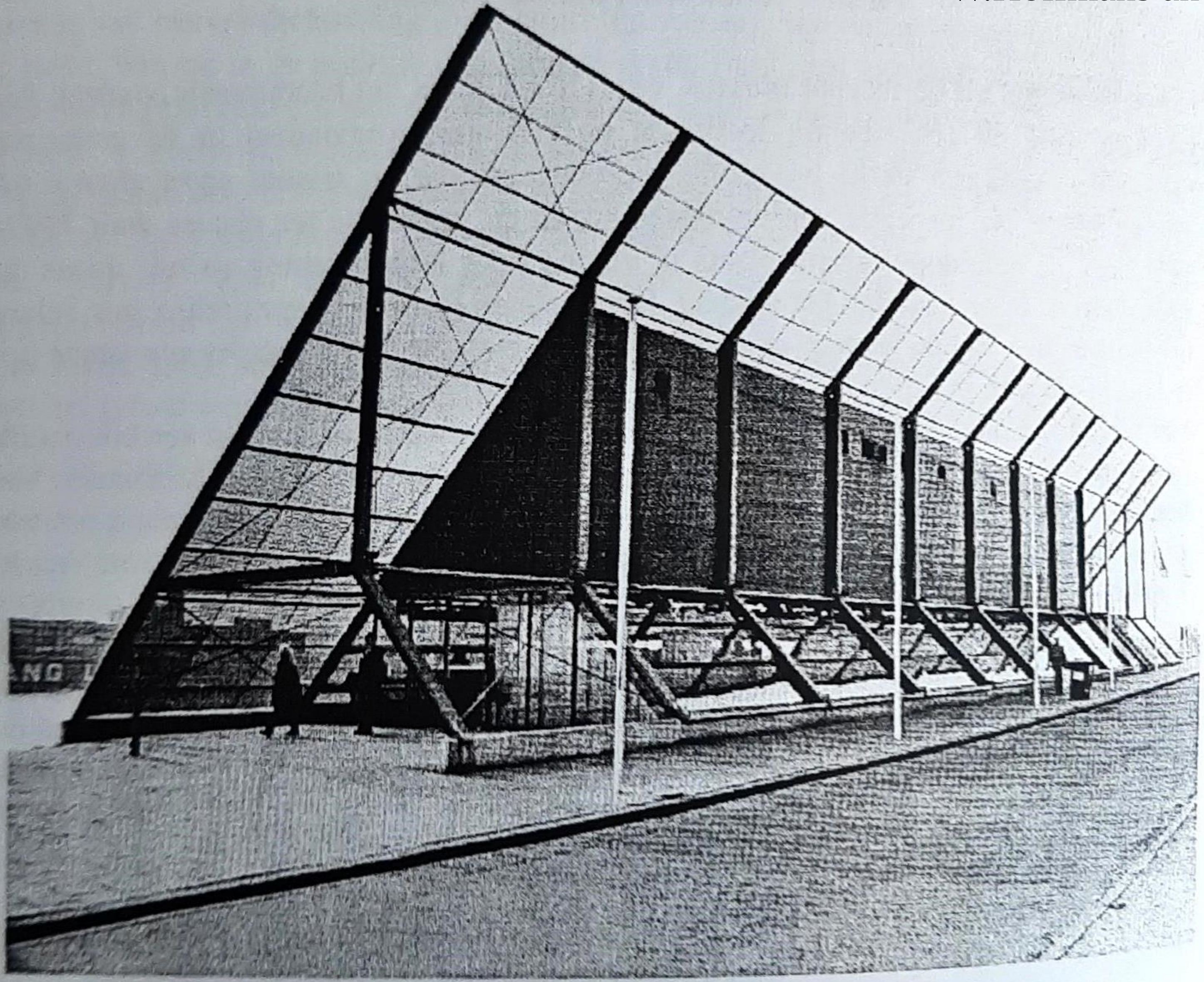


Hofmans and Looijmans 1999, Peutz 2008

Roof of EXPO Rotterdam: 95 dB in building

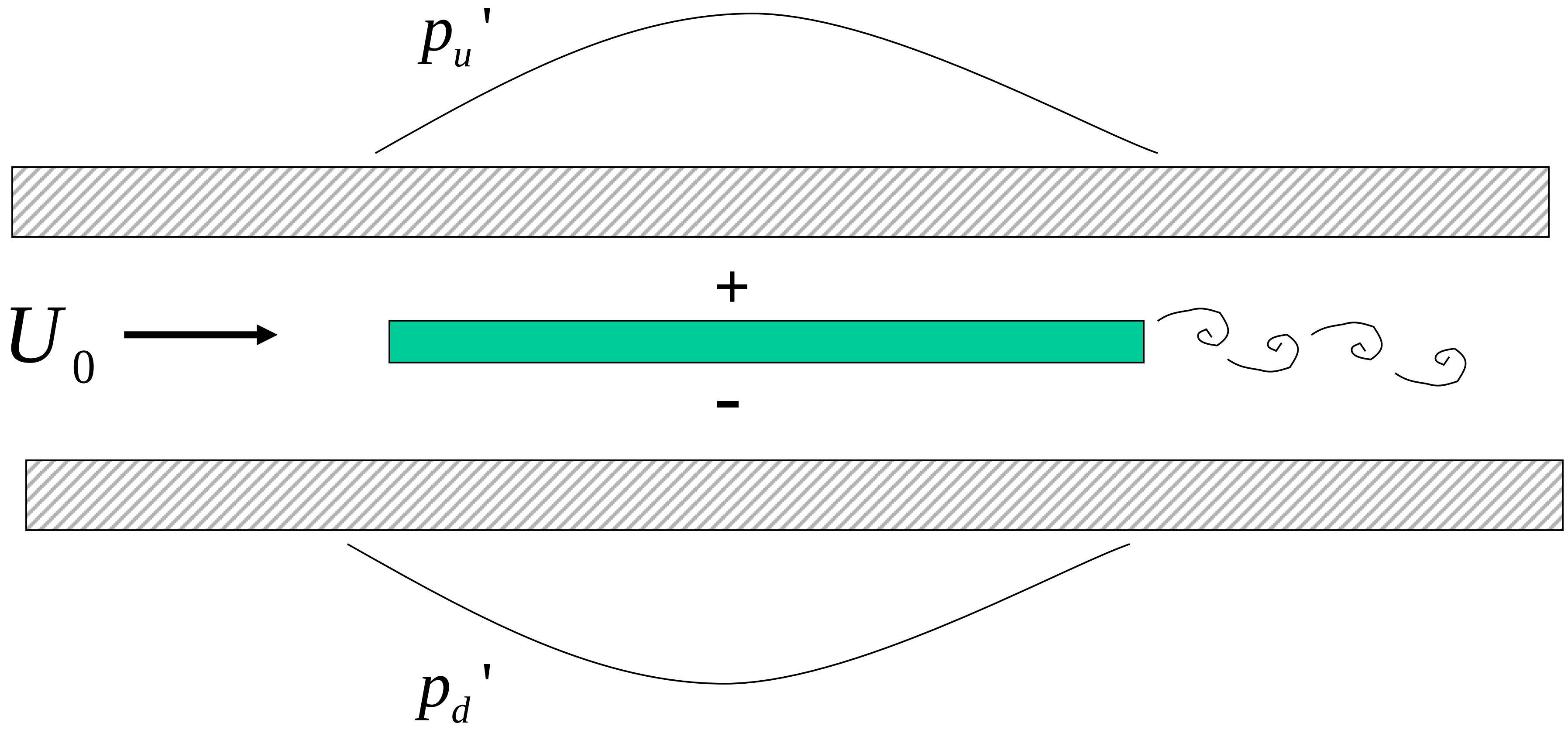
Het Expo Paviljoen

W.Hoffmans and K. Looijmans (1999)



Figuur 3 Het Expo-paviljoen.

Parker modes in ducts



No plane wave radiation, **Watch out for splitter plates in air-conditioning ducts**

Watch out for balcony balustrade design!

Peutz 2008

Beetham Tower Manchester

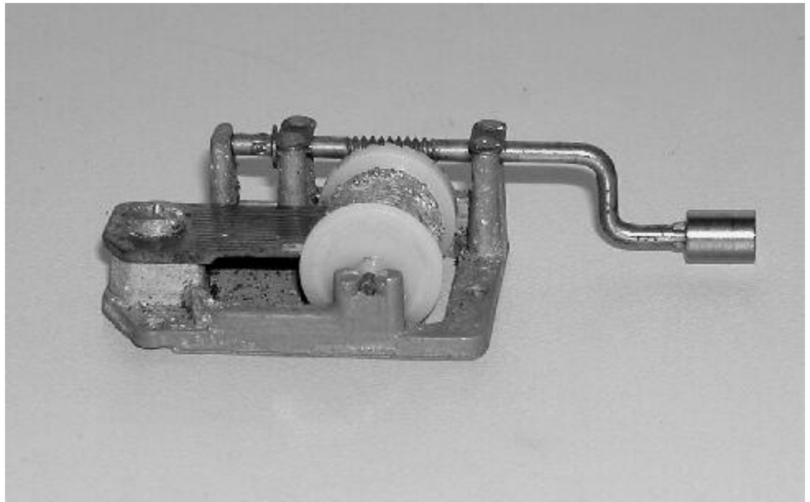
Whistling of Goldengate bridge (San Fransisco)

https://youtu.be/UEuvqNFJ9EY

Research at TU/e

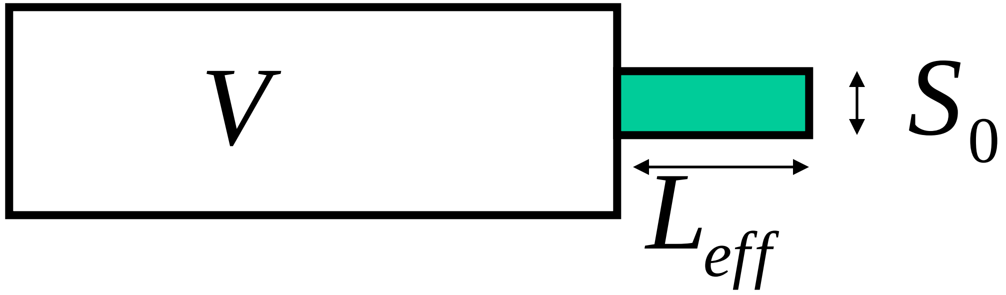
ASSA
AUTUMN SCHOOL SERIES
IN
ACOUSTICS

A.P.J.Wijnands



THANK YOU FOR YOUR ATTENTION

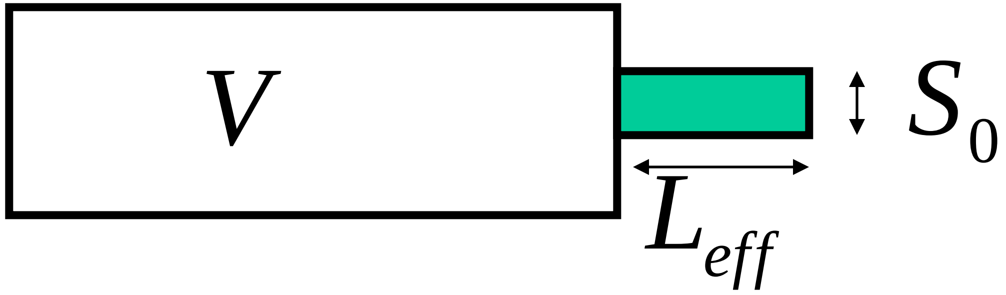
Mass-spring system



$$V' = S_0 x'$$

$$\frac{\rho'}{\rho_0} = -\frac{V'}{V}$$

Mass-spring system

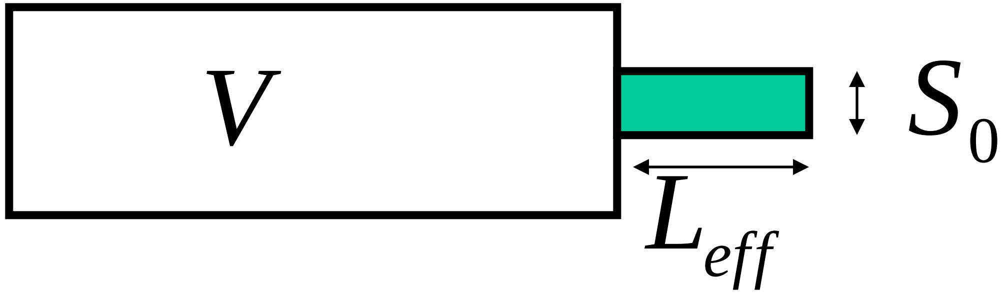


$$m = \rho_0 L_{eff} S_0$$

$$K = \rho_0 c_0^{\,2} \frac{S_0^{\,2}}{V}$$

$$\boldsymbol{m \frac{d^2 x'}{dt^2} = -Kx'}$$

Mass-spring system



$$\boldsymbol{K = \rho_0 {c_0}^2 \frac{{S_0}^2}{V}}$$

$$V' = S_0 x'$$

$$\frac{\rho'}{\rho_0} = -\frac{V'}{V}$$

$$F' = -Kx' = \left(\frac{\partial p}{\partial \rho}\right)_s \rho' S_0 = -c_0^2 \rho_0 \frac{V'}{V} S_0 = -{c_0}^2 \rho_0 \frac{x' S_0}{V} S_0$$