EFRC Workshop Pulsations
Introduction to pulsation source and propagation

Leonard van Lier

TNO Science & Industry

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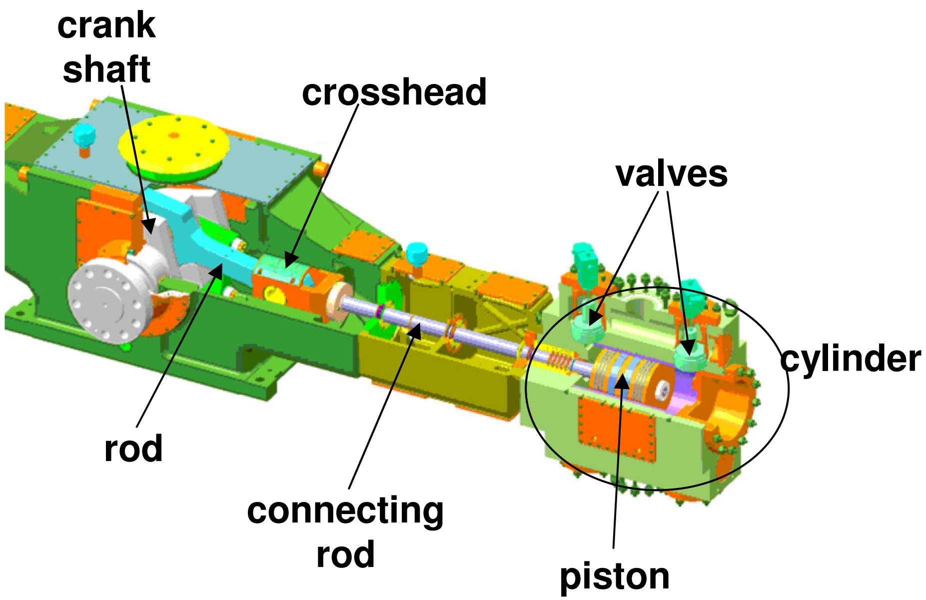
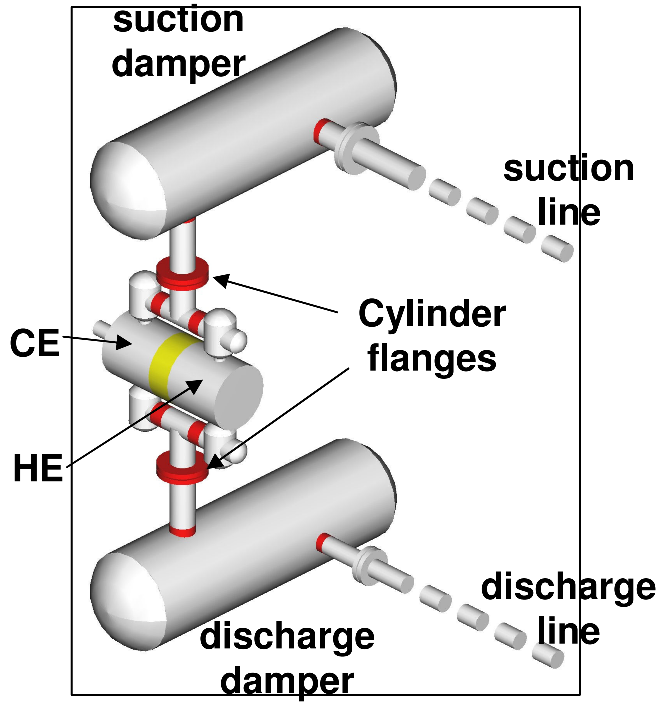
- Terminology
- Generation of pulsations
- Propagation of pulsations
- Impact effects of pulsations
- Mitigation of pulsations

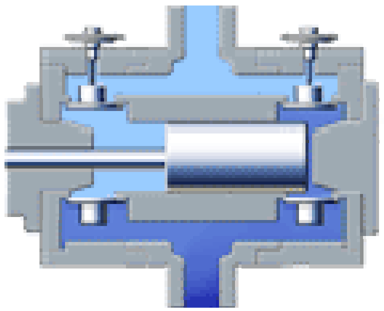
Terminology in relation to reciprocating compressors





Pulsation source

- Periodic piston movement
- Flow and pressure pulses are caused by gas compression/depression, and passage via compressor valves



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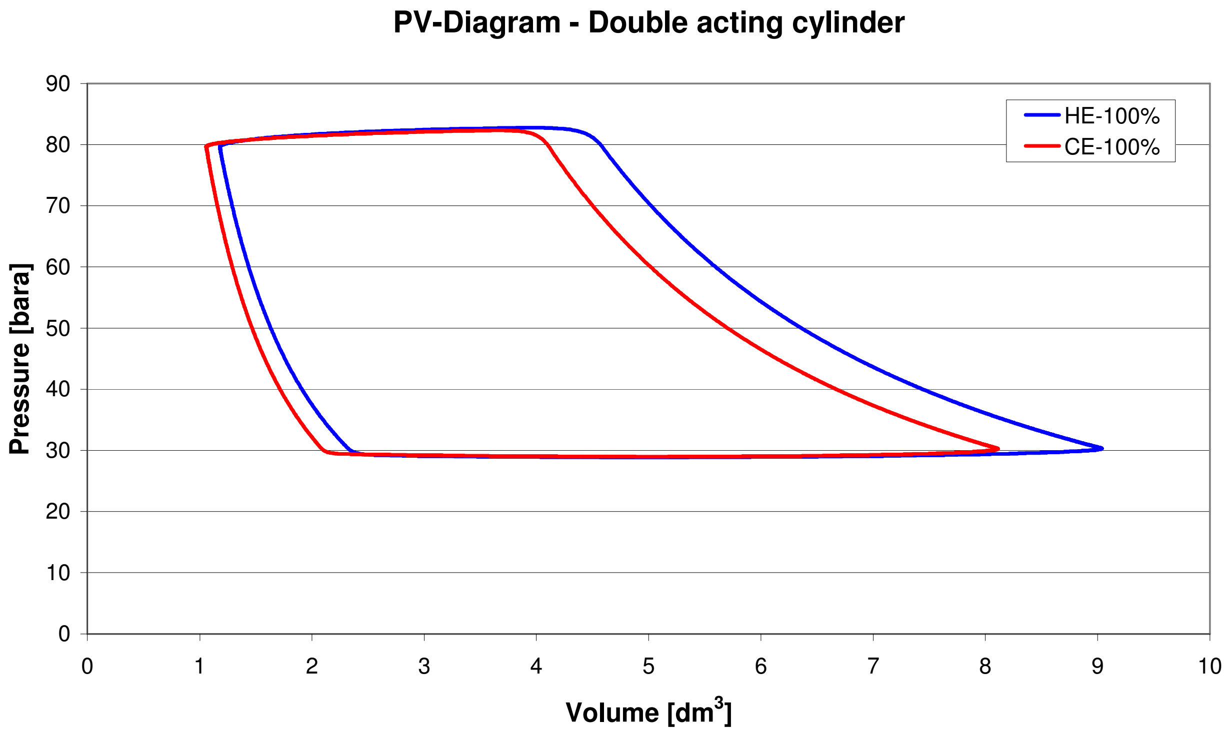
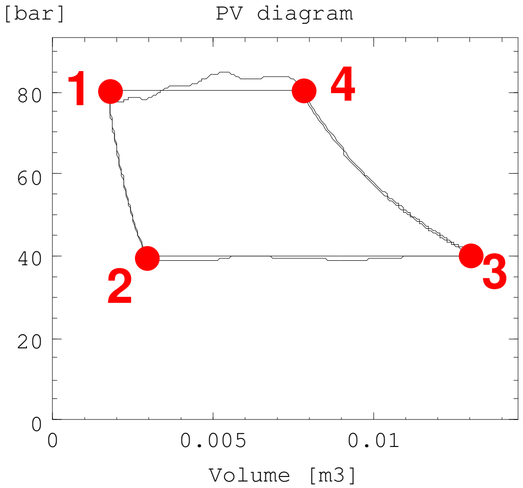
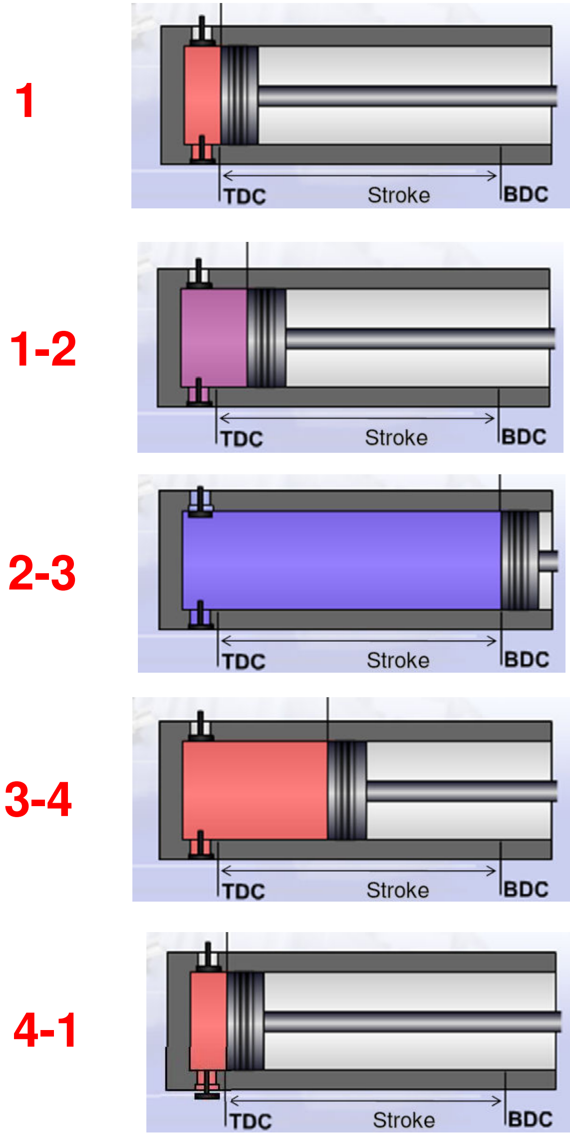


Typical compression cycle

Compressor cylinder performance
Headend, node 120
Bore 0.255, stroke 0.245, rod 0.075 [m]



Consumed power = 262.20 [kW]
Adiabatic power = 247.58 [kW]



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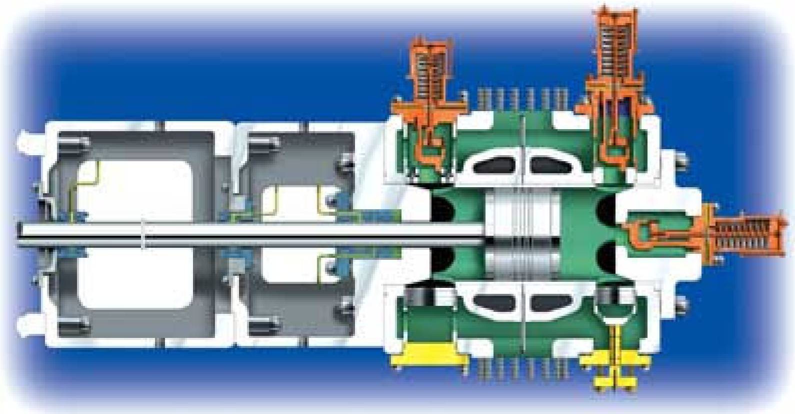
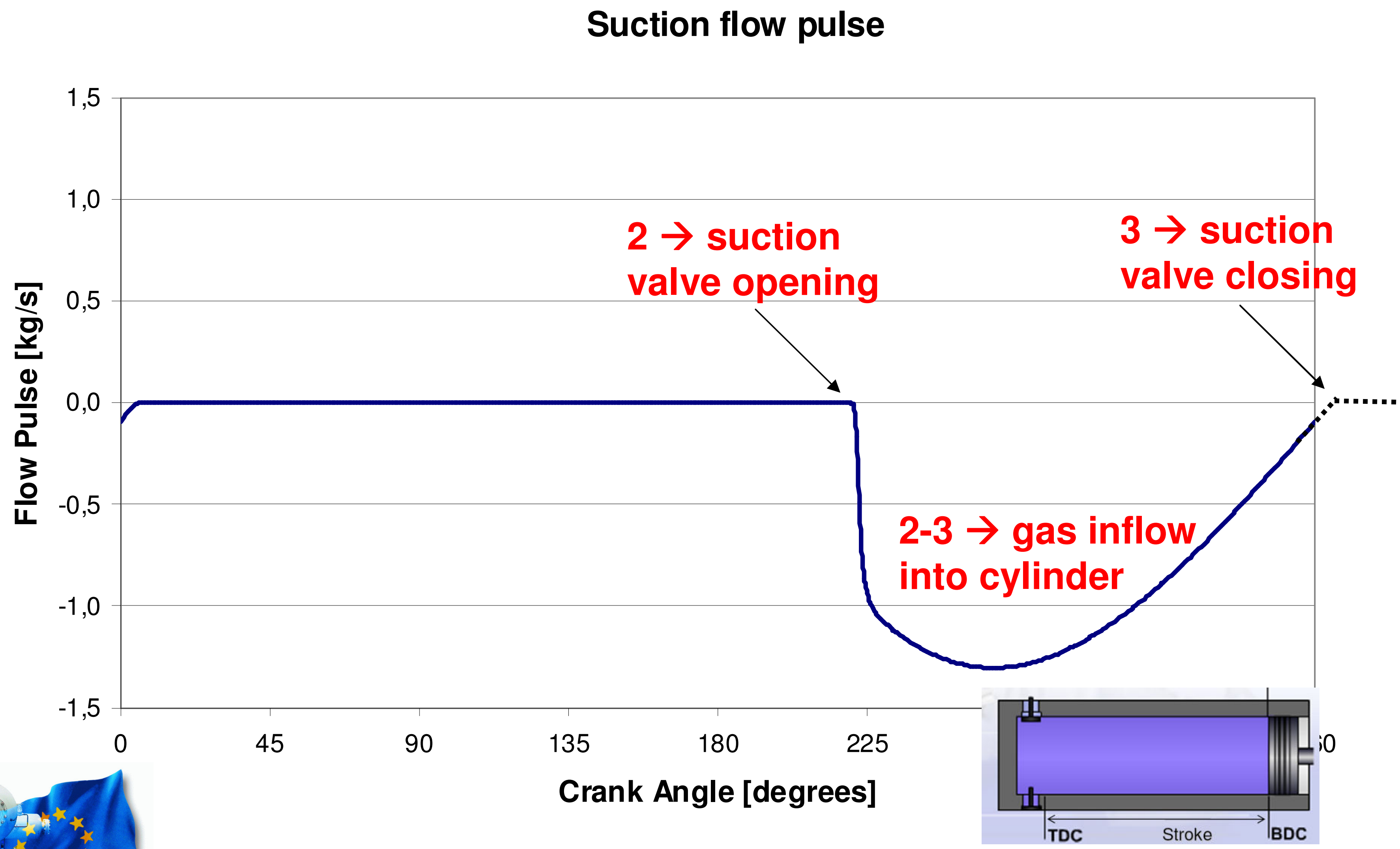
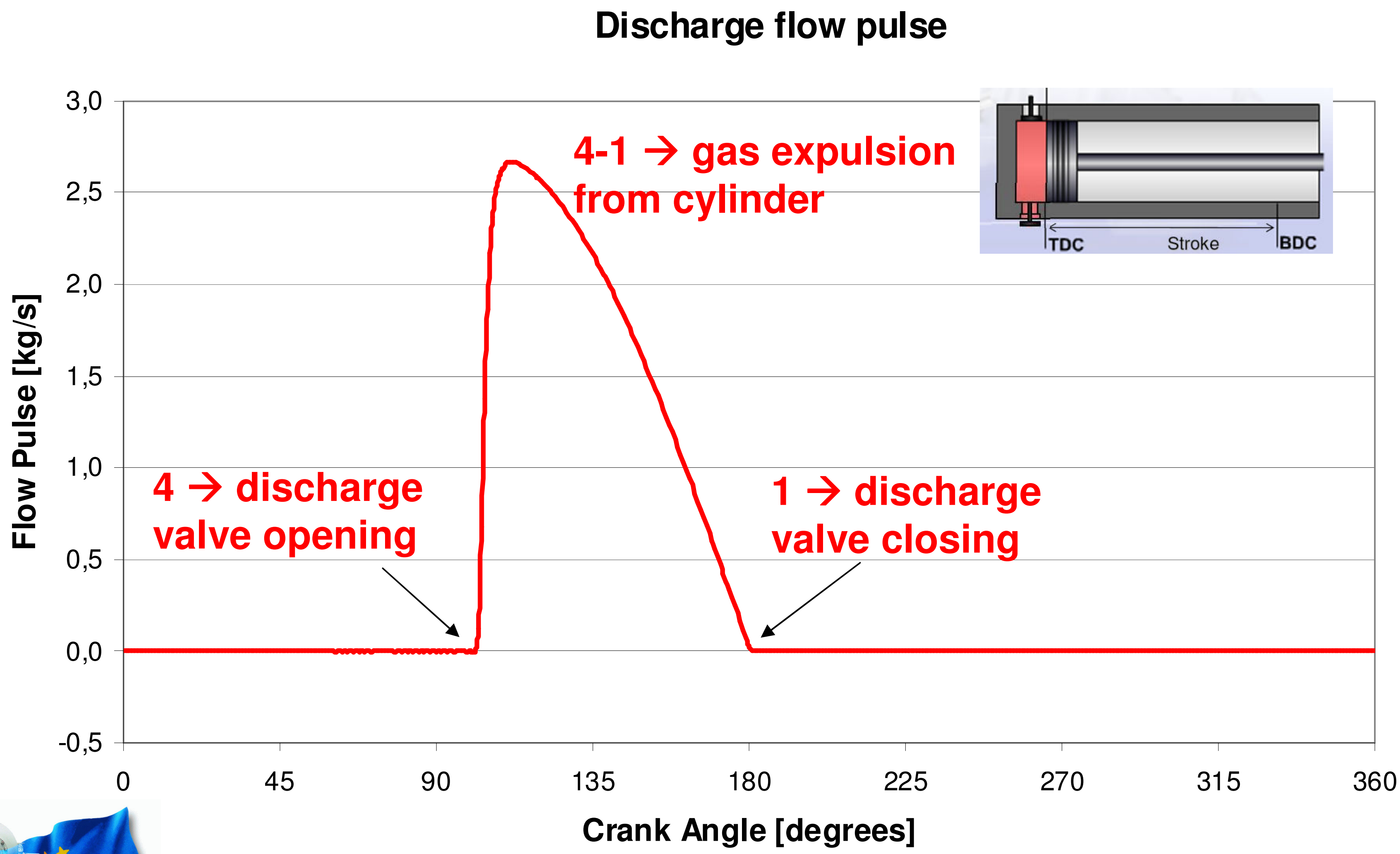
Parameters needed for quantitative modeling of pulsations

- Process conditions
  - Pressures
  - Temperatures
  - Gas composition
- Compressor parameters
  - RPM
  - Bore
  - Stroke
  - Crank/Rod Ratio
  - Clearances
- Operational parameters
  - Unloading/capacity control
- Valve properties

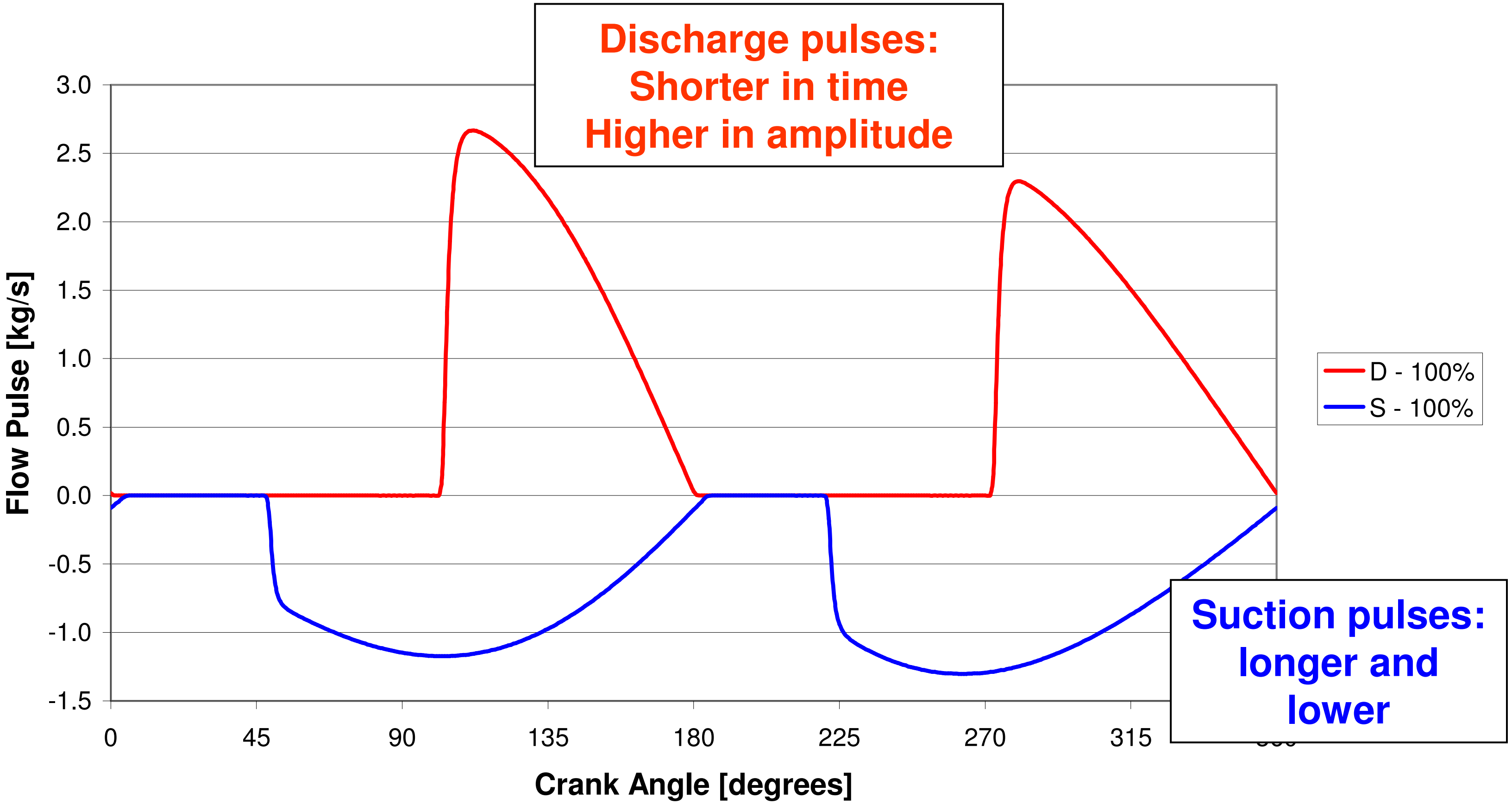




Suction flow pulse
1,5
1,0
0,5
0,0
-0,5
-1,0
-1,5
0
45
90
135
180
225
Flow Pulse [kg/s]
Crank Angle [degrees]
2 → suction valve opening
3 → suction valve closing
2-3 → gas inflow into cylinder
TDC
Stroke
BDC


Discharge flow pulse
Flow Pulse [kg/s]
3,0
2,5
2,0
1,5
1,0
0,5
0,0
-0,5
0
45
90
135
180
225
270
315
360
Crank Angle [degrees]
4-1 → gas expulsion from cylinder
4 → discharge valve opening
1 → discharge valve closing
TDC
Stroke
BDC

Pulses for double-acting cylinder

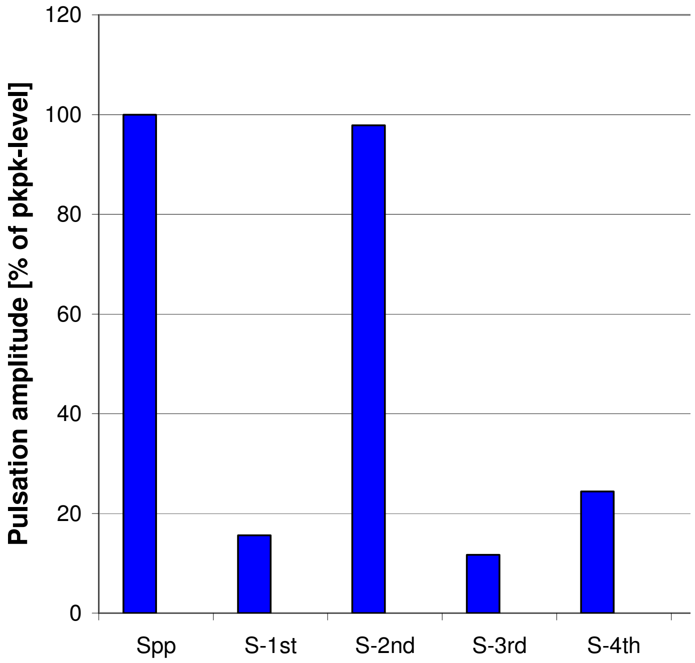


Frequency content of pulsations

- Fundamental frequency is related to RPM, however:
- Piston movement is not entirely sinusoidal;
- Valve opening introduces steep gradients in the pulse shape;
- Double-acting cylinder: shift to even harmonic; differences between HE and CE lead also to odd harmonics.
- Capacity control may add higher harmonics.

A **range of frequencies** must be considered!!

Example: typical frequency components for double-acting suction pulsations → 2nd and 4th harmonics are dominant



Propagation of pulsations

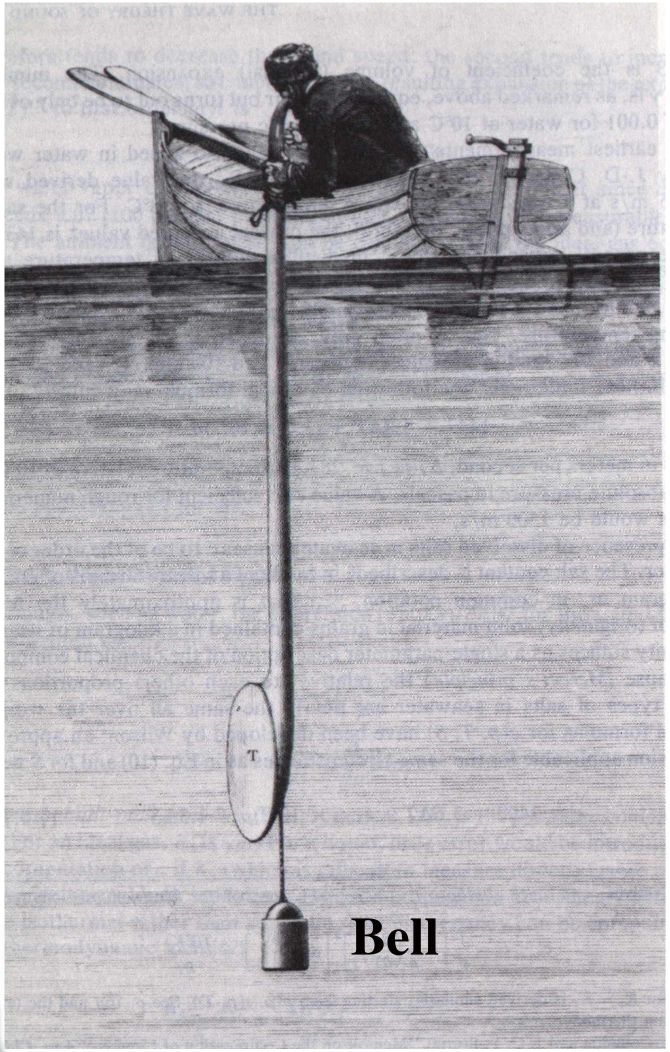
- Conservation equations
- Equation of state
- Gas law

Linearized (1D) wave equation

$$\frac{\partial^2 p}{\partial t^2} - \left(\frac{Dp}{D\rho}\right)_{s_o} \frac{\partial^2 p}{\partial x^2} = 0$$

Speed of sound c^2

Speed of sound



$$c = \sqrt{\frac{\gamma p}{\rho}} = \sqrt{\frac{\gamma R_o T}{Mw}}$$

Newton: isothermal process p/ρ = constant

$$c^2 = \left(\frac{Dp}{D\rho}\right)_{T_o} \approx \frac{p_o}{\rho_o} \xrightarrow{T=20^o C} c = 290\, m/s$$

1816 Laplace: isentropic process p/ρ^{γ} = constant

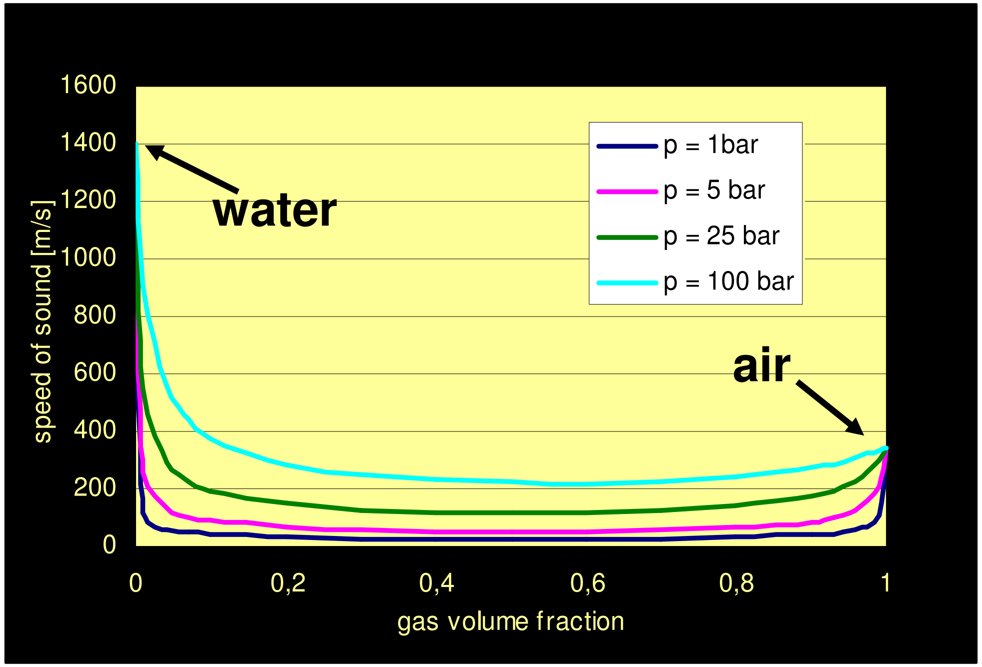
$$c^2 = \left(\frac{Dp}{D\rho}\right)_{S_o} \approx \frac{\gamma\, p_o}{\rho_o} \xrightarrow{T=20^o C} c = 343\, m/s$$

At standard conditions:

c_{air} = 340 m/s
c_{CO2} =266 m/s
c_{H2} = 1300 m/s

Speed of sound

- Inputs
  - Gas composition
  - Temperature
  - Droplets
  - Compressibility
  - *Elasticity of wall*

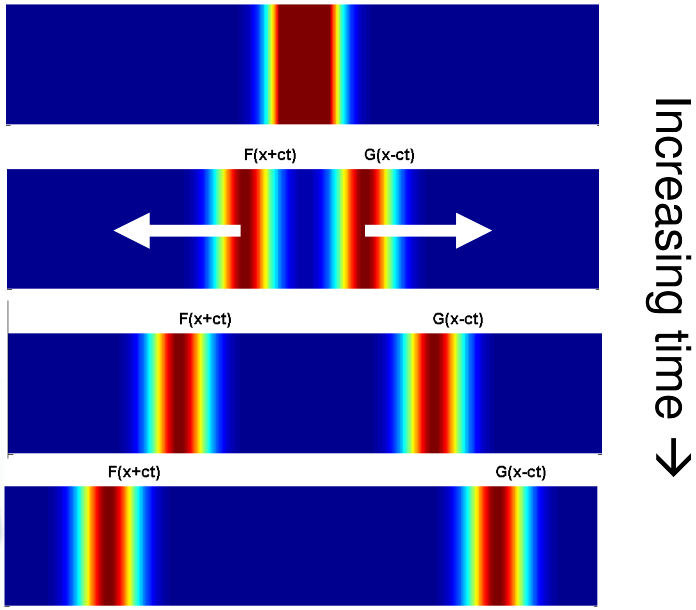


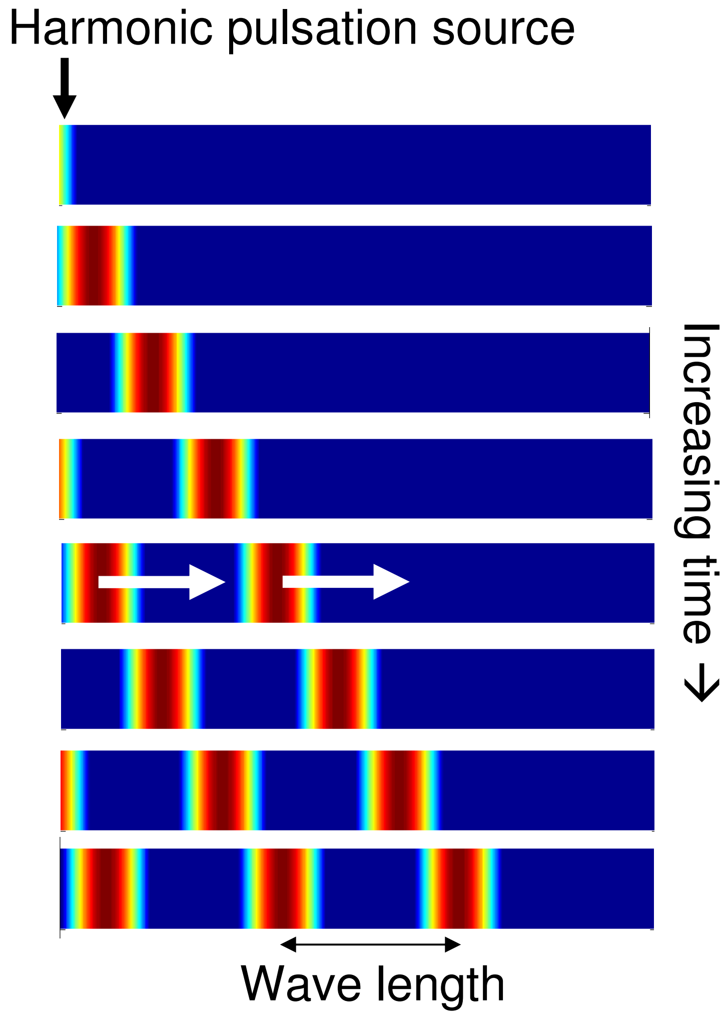
Propagation of pressure waves simple solution of wave eq.

$$\frac{\partial^2 p}{\partial t^2} - c^2 \frac{\partial^2 p}{\partial x^2} = 0$$

$p(x,t) = f\,(x + ct)$ backward propagating wave

$p(x,t) = g\,(x - ct)$ forward propagating wave





Wave length

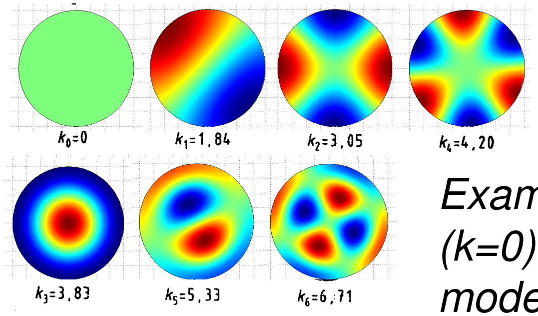
$$\lambda = c / f$$

In general: $\lambda >> D_{pipe}$!

- For a typical reciprocating compressor (600 RPM, f_0=10Hz):
  - c = 400 m/s, λ = 40 m (natural gas)
  - c = 266 m/s, λ = 26.6 m (CO_2)
  - c = 1300 m/s, λ = 130 m (H_2)
- 1-dimensional approximation of wave propagation is valid
- Effect of damping is limited

Plane wave propagation in pipes

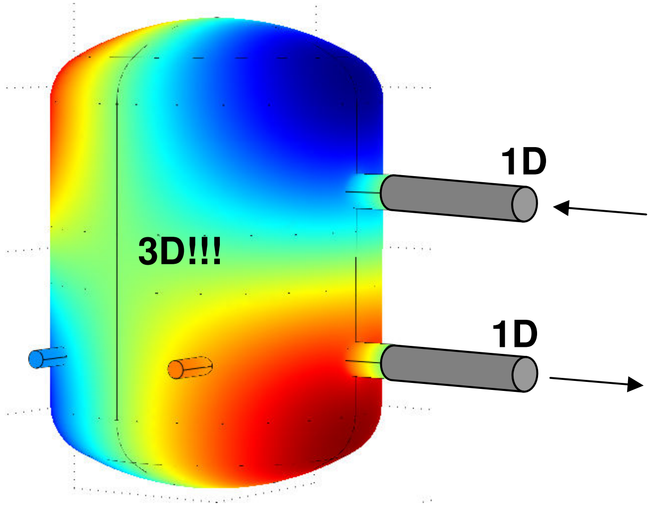
$$f < f_c = 0.586 \frac{c}{d_i}$$



Example of plane wave (k=0) and higher order modes

diameter	f_c
0.05 (2")	4 kHz
0.1 (4")	2 kHz
0.2 (8")	1 kHz
0.4 (16")	500 Hz
0.8 (30")	250 Hz

- For frequencies (below the cut-off frequency f_c) → plane wave propagation (1D)
- For higher frequencies → more complex (3D) propagation
- Plane wave approximation generally valid for piping in reciprocating compressor systems
- Most energy is contained in lower harmonics.



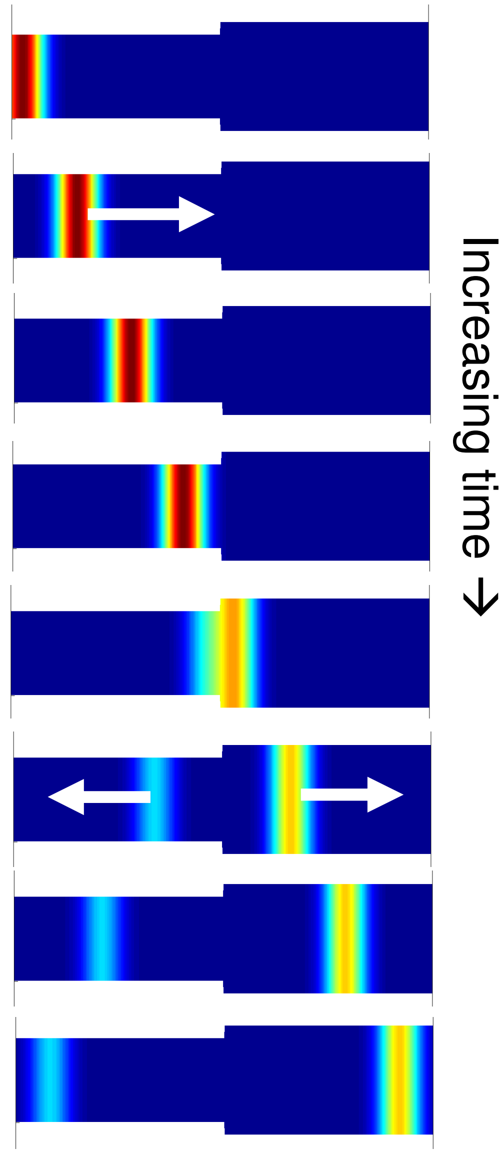
Acoustic damping

- Damping of pulsating flow in pipelines is small
  - wall friction/heat conductivity
  - flow/turbulence (reducers/vessels/orifices)
- Pulsations can propagate over a large distance in the piping
- Effective damping after approximately >>10 times the wavelength

- For typical reciprocating compressor system piping:
  - λ = 40 m, i.e. after 400 m (natural gas)
  - λ = 26 m, i.e. after 260 m (carbon dioxide)
  - λ = 130 m, i.e. after 1300 m (hydrogen)

Reflection of acoustic waves

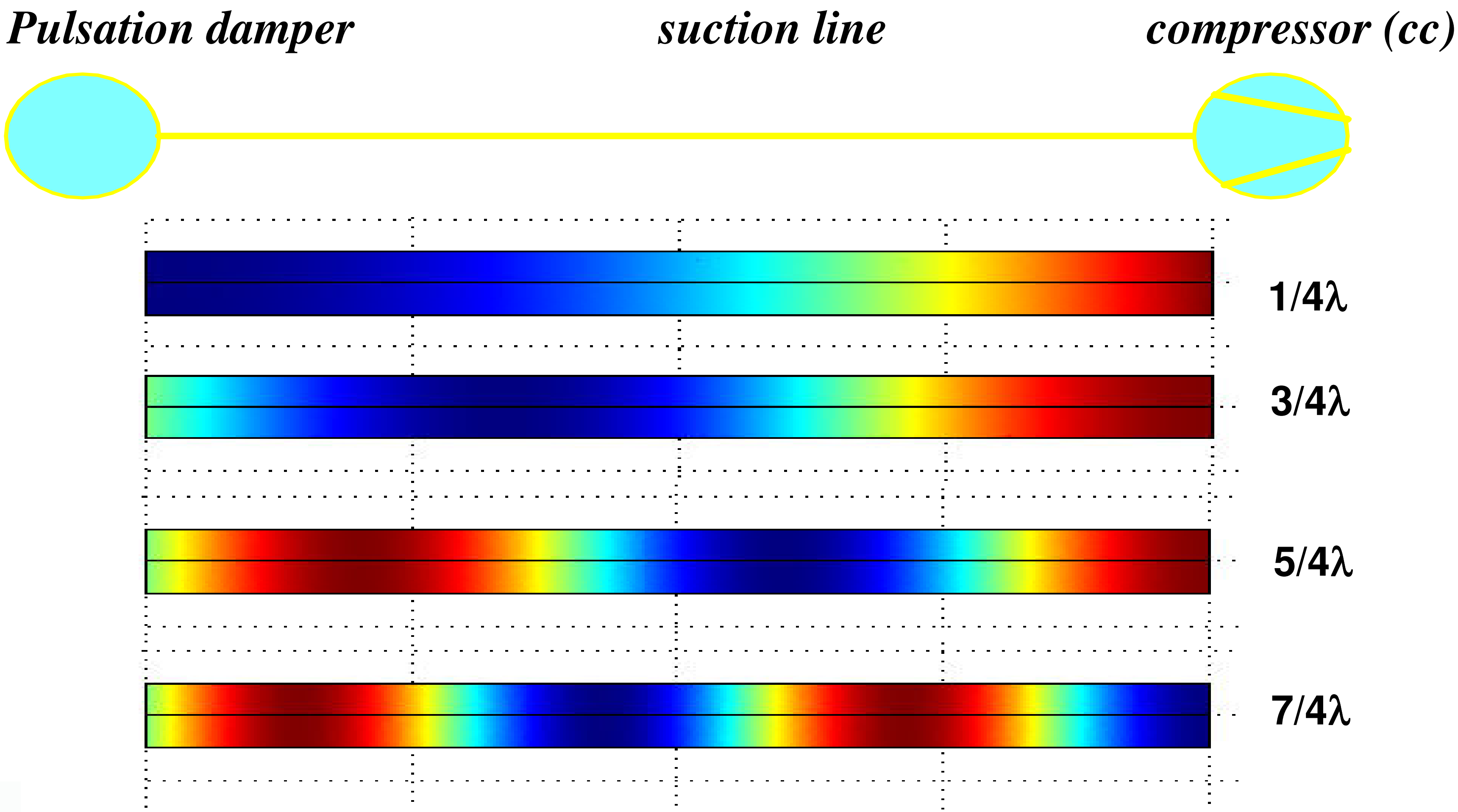
- Pressure waves are (partly) reflected when there is:
    - a change in pipe cross section
    - a branch connection
    - a change in impedance $Z = \rho c$ (different density/sound speed)
- Part of the incident wave is reflected, part is transmitted



Resonances

- Occur due to reflection → buildup of acoustic energy
- Limited by damping mechanisms→ Quality factor (amplification) up to 100!
- Standing waves in main piping
- Helmholtz resonances
- Standing waves in side branches
- Thus, to manage the pulsations in a system, we cannot consider only the compressor itself. The piping periphery needs to be considered as well.

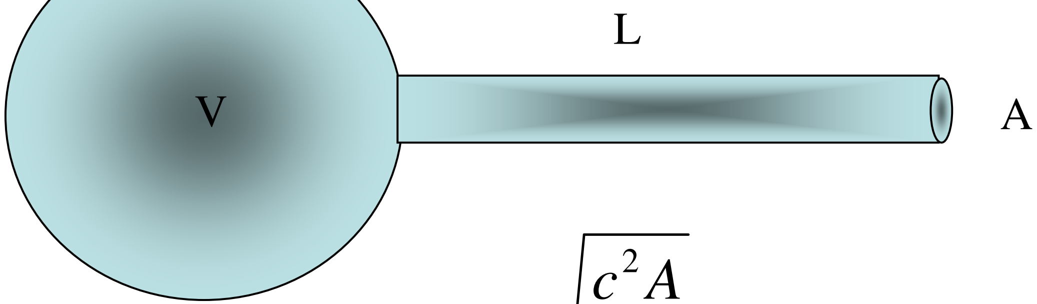
Standing wave resonance

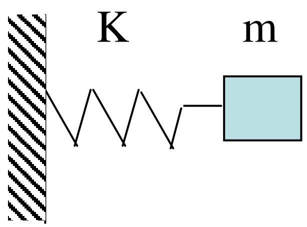


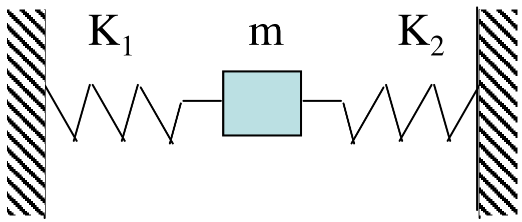
Standing wave resonances in a suction line of a compressor

Helmholtz resonances

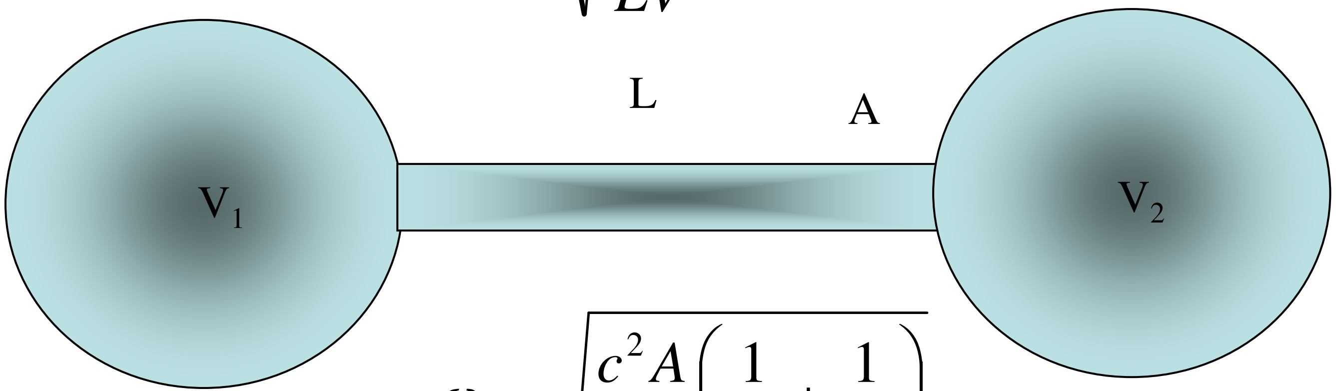
Resonance frequency







$$\omega_o = \sqrt{\frac{c^2 A}{LV}}$$

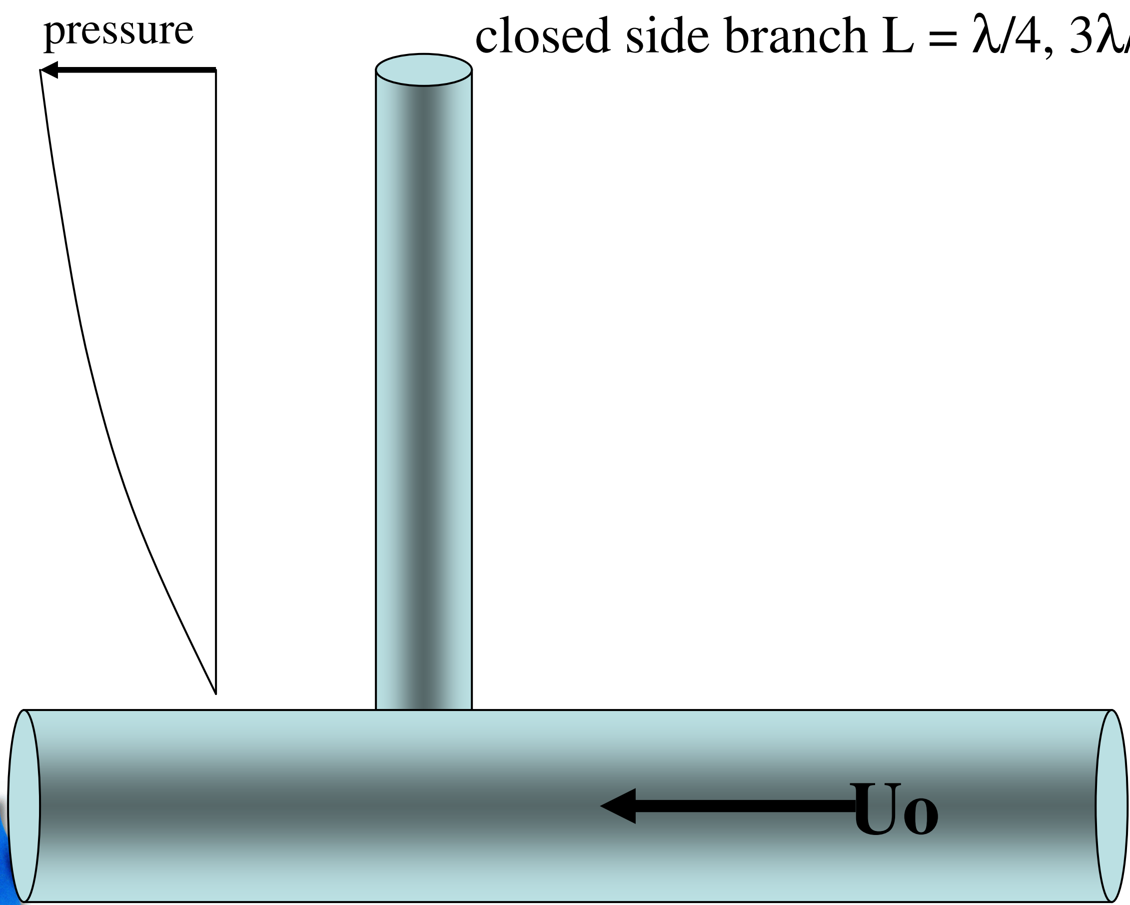


$$\omega_o = \sqrt{\frac{c^2 A}{L}\left(\frac{1}{V_1} + \frac{1}{V_2}\right)}$$

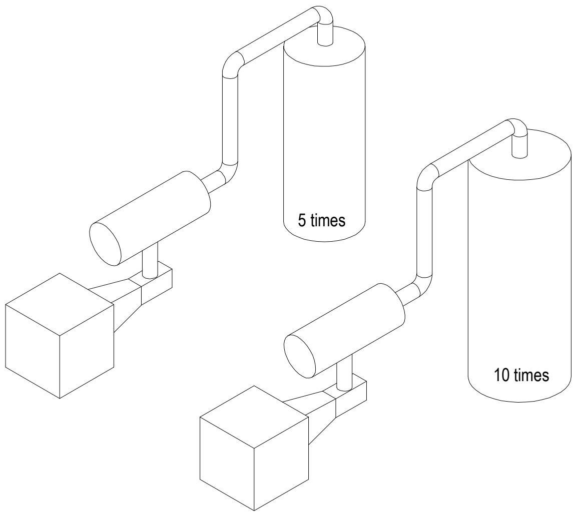
Side branch resonance

(Strong reflection if d/D < 0.2)

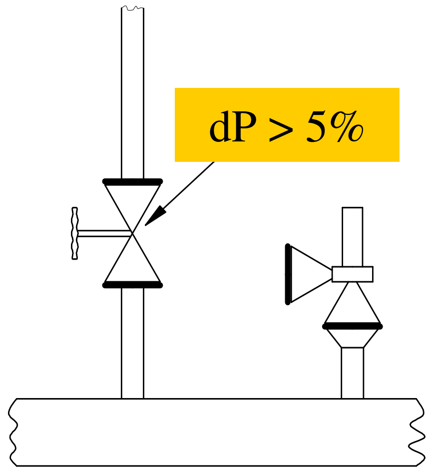
Resonator:
closed side branch L = $\lambda/4$, $3\lambda/4$, $5\lambda/4$ …



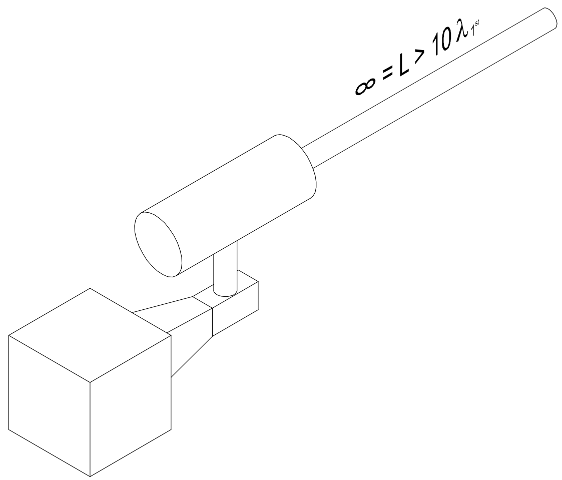
Appropriate acoustic boundary conditions



Large volumes



Valves



Long pipe lines

Impact of pulsations

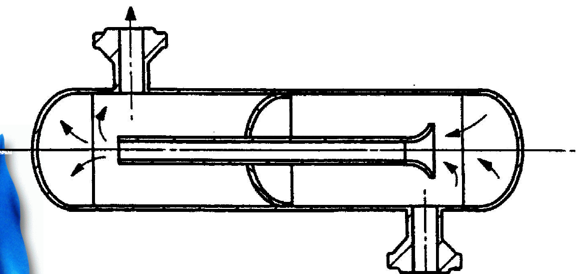
- Compressor performance → lecture 2
- Compressor valves → lecture 3
- Mechanical reliability → lecture 4
- *Flow metering equipment*
- *Fluttering check valves*
- *Radiated noise*

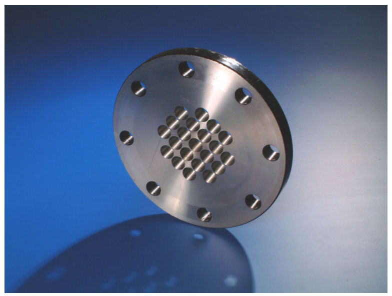
Mitigation of pulsations

- Well-designed pulsation dampers
- Well designed restriction orifices

→ lecture 5

- *Optimize system piping layout*
- *Additional supporting*





Summary

- ***Pressure pulsations are generated by the compressor and propagate through the upstream and downstream piping.***
- ***Piping systems have little intrinsic damping.***
- ***Due to resonances, amplification may occur, even at large distances from the source.***
- ***Thus, the complete system of compressor & piping must be considered***
- ***Efficient mitigation measures are available to control the pulsations (dampers, orifices).***
- ***This requires understanding and robust modeling tools of the source (compressor), and the propagation in the pipe system.***

- ***To manage possible negative side-effects of pulsations, we recommend to perform a design review in accordance with API-618 for each new installed compressor installation or major revamping projects...***

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Thank you!