EFRC Training Workshop
Design and operation of reciprocating compressors

Pulsations & Vibrations

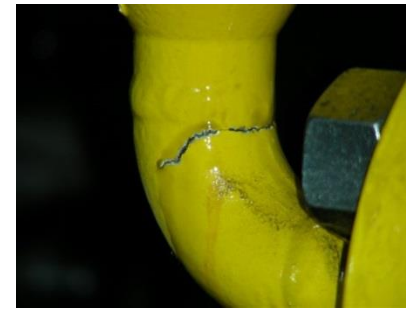
Leonard van Lier & André Eijk - TNO

Outline

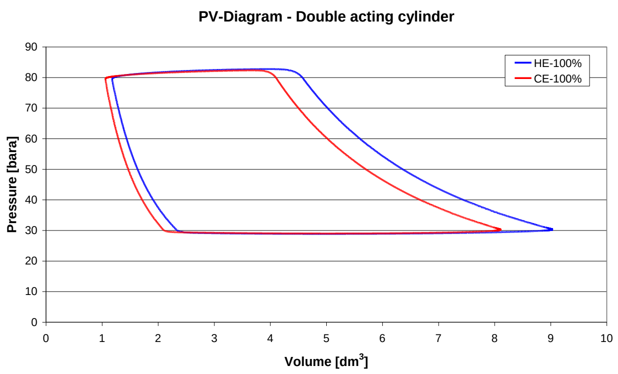
- Pulsations
- Vibrations
- Pulsation and vibration analysis according to API 618 standard, 5th edition

Why Pulsation & Vibration Analysis?

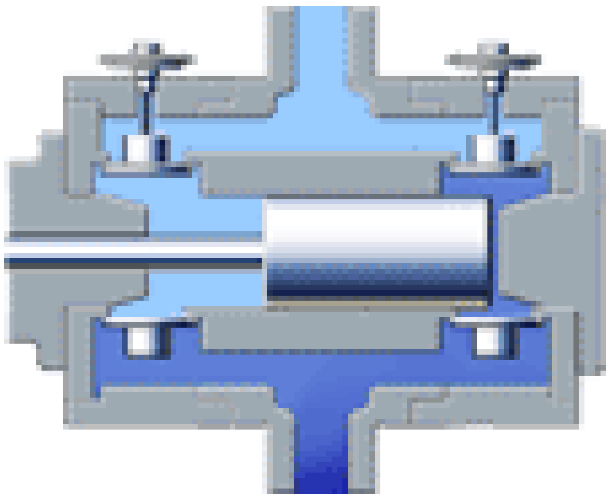
- Pulsations and vibrations should be minimized to avoid:
  - – Integrity issues in piping (fatigue)
  - – Increased wear of compressor parts
  - – Increased power consumption
  - – Flow metering errors
  - – Hammering of check valves



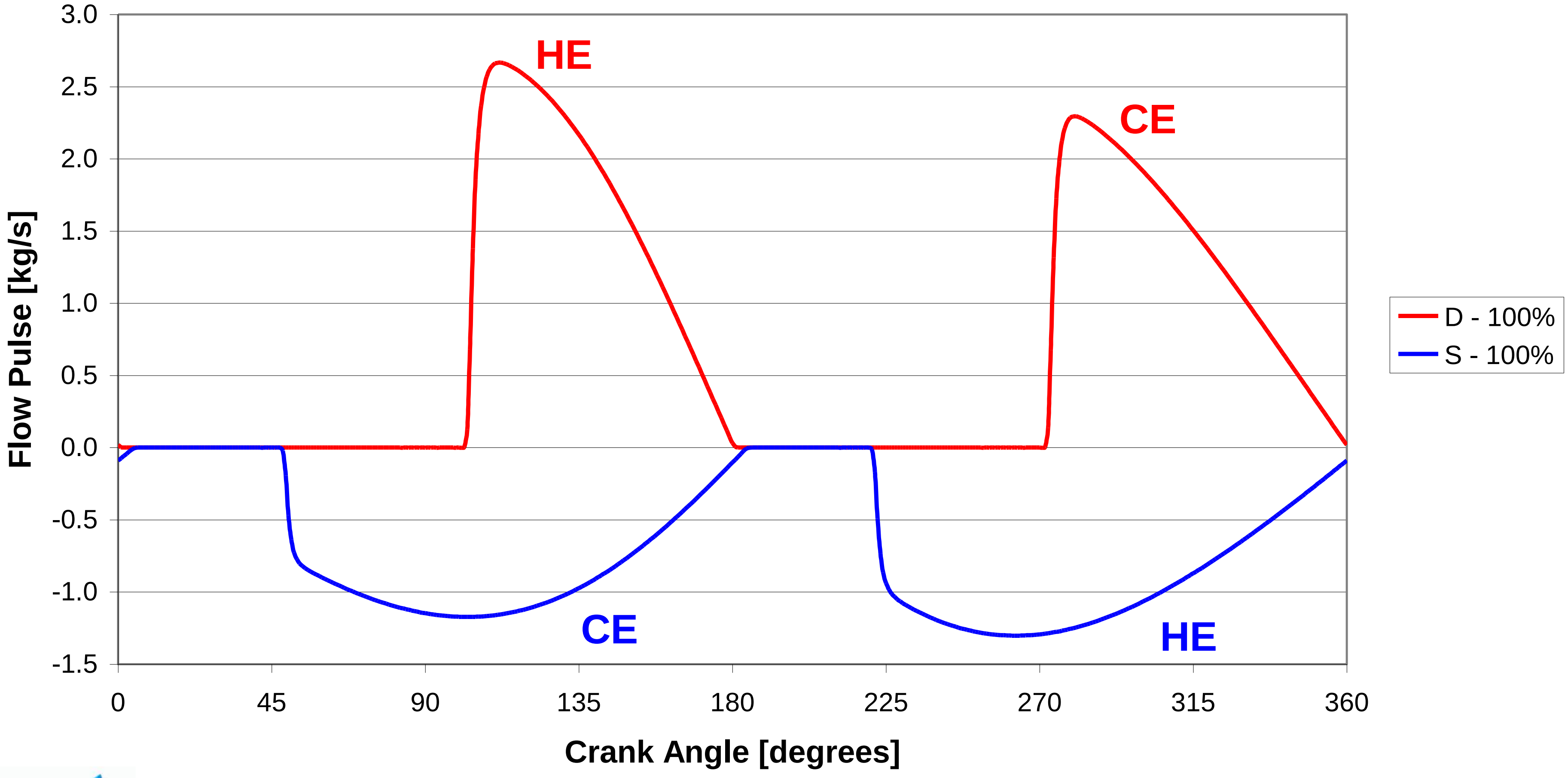
Pulsations



- Intrinsic feature of the reciprocating compressor
- Fluctuations of pressure and flow in the gas
- Occurs at suction and discharge side
- Strong interaction with the pipe system



Reciprocating, double-acting



Pulsation frequencies

- The frequency of pressure fluctuations is related to the *compressor speed*
- The pulsation spectrum contains the fundamental plus higher orders
- The frequency content of pulsations is essential for the propagation in pipe systems and interaction with the mechanical structure

Harmonic distribution

- Pulsation signal can be decomposed into the fundamental order plus higher orders:

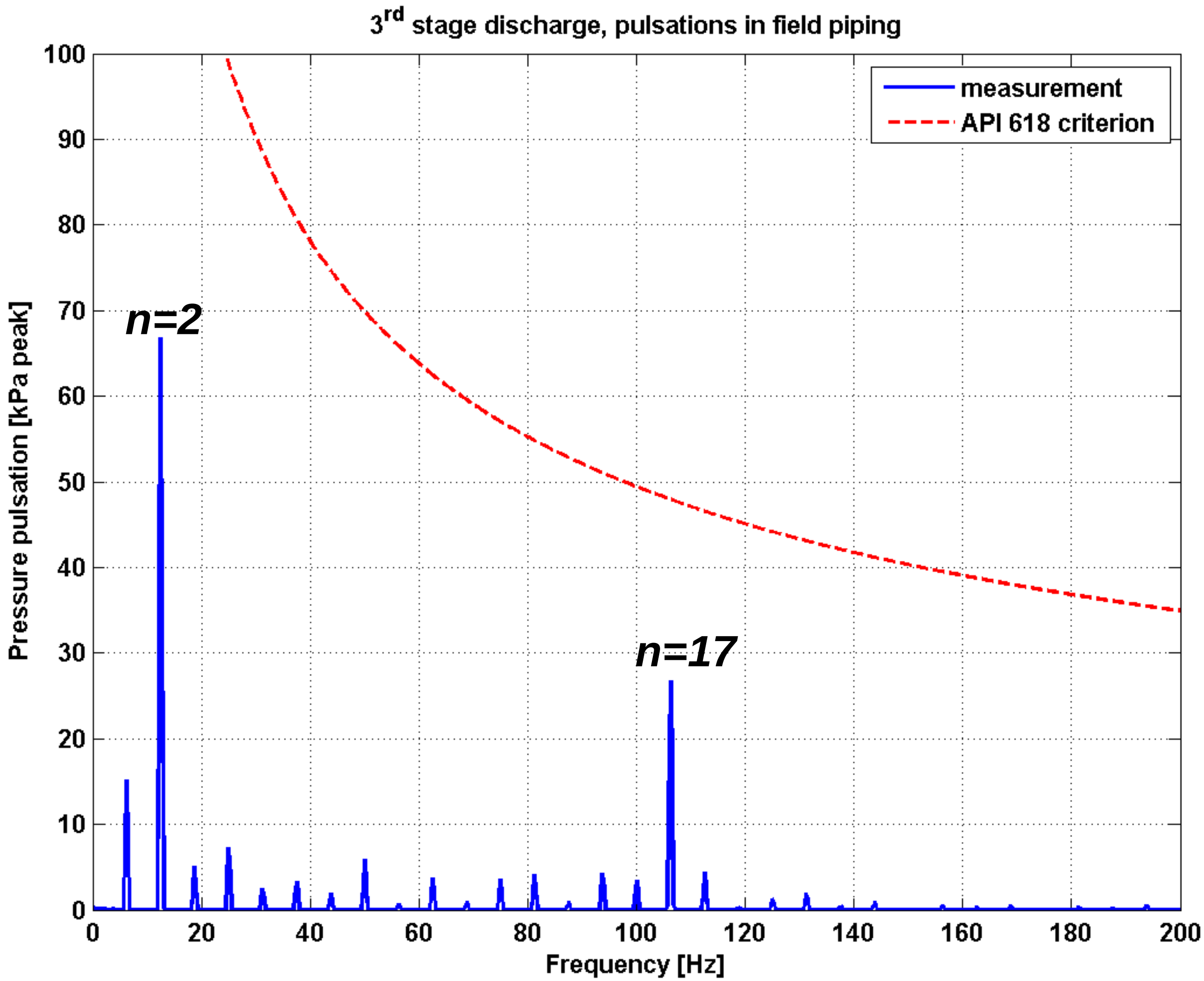
$$p(t) = \sum_i A_i \sin\left(2\pi f_i t + \phi_i\right) \qquad f_i = i * \frac{RPM}{60}$$

- Example: compressor running at 480 rpm
- Fundamental frequency = 8 Hz
- Higher orders: 16, 24, 32Hz …

Dominant spectral signatures

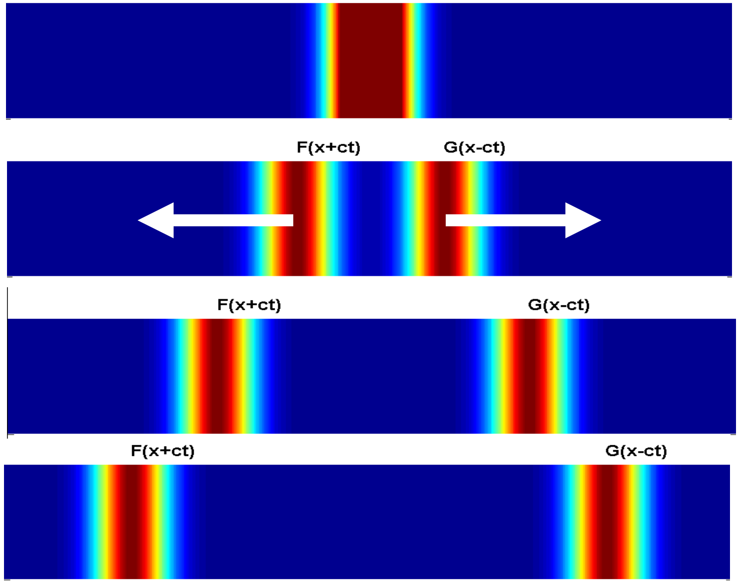
- Single-acting cylinder: 1^{st} order + …
- Double-acting cylinder: 2^{nd} order + …
- Unloaded cylinder: 1^{st} order + …
- Step-less capacity control: increased contribution at higher orders

Illustration



Propagation

- Wave equation $$\frac{\partial^2 p}{\partial t^2} - c^2 \frac{\partial^2 p}{\partial x^2} = 0$$
- Pulsations are *acoustic waves*, propagating at the speed-of-sound *c*
- Pulsations travel up- and downstream



Increasing time ↓

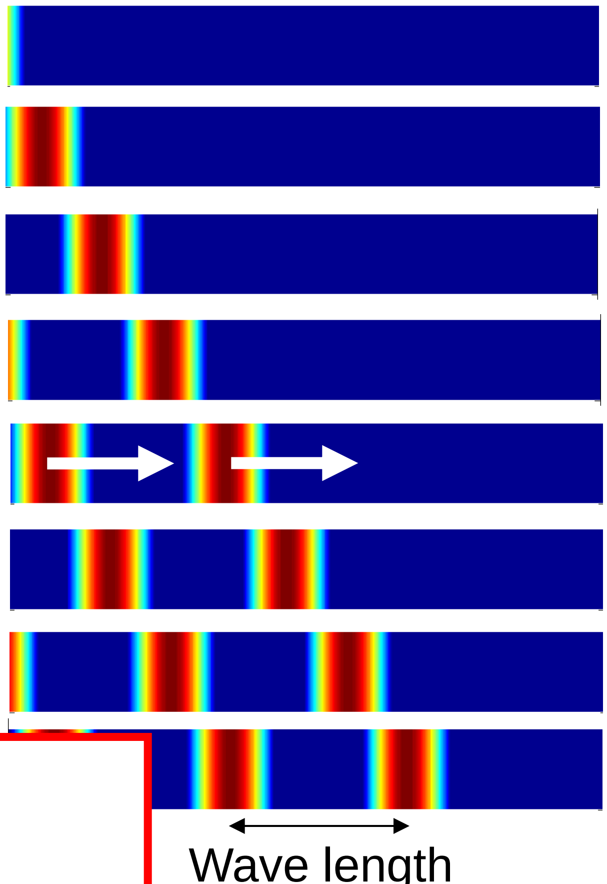
Speed of sound

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

- Increases with increasing T $\quad c \sim \sqrt{T}$
  - Generally higher at discharge side than at suction side
- Decreases with increasing Molecular Weight $\quad c \sim \dfrac{1}{\sqrt{MW}}$
  - CH_4 ~ 400 m/s
  - CO_2 ~ 260 m/s
  - H_2 ~ 1300 m/s

Wavelength

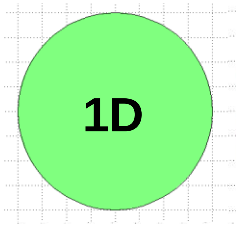
- Assume a harmonic source of frequency *f*
- Speed-of-sound *c*
- Acoustic wavelength $\lambda \sim \frac{c}{f}$
- Example:

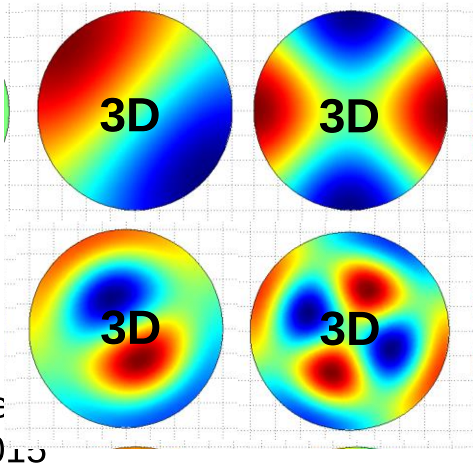


In general: $\lambda \gg D_{pipe}$

Plane waves

- If $\lambda >> D_{pipe}$: plane waves
- 1-dimensional acoustic theory
  - Engineering tools for pulsation analysis are generally based on this assumption
  - 1D theory fails for frequencies $f > 0.59 * c/D_i$
  - Reciprocating compressors generally obey 1D theory
  - Screw compressors may **not necessarily** obey 1D theory
  - Pulsations of turbo compressor do **not** obey 1D theory!



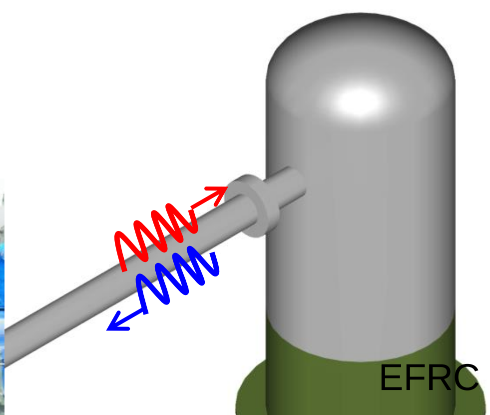


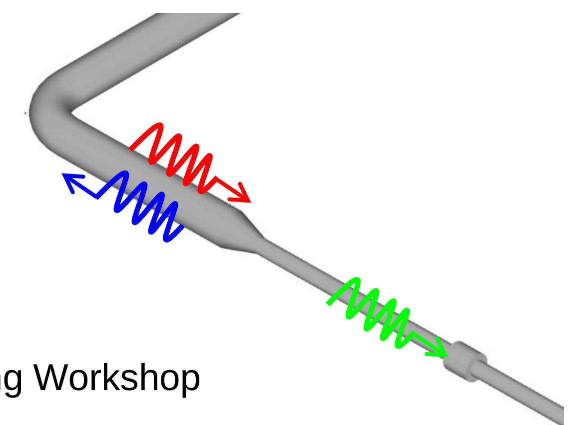
Damping

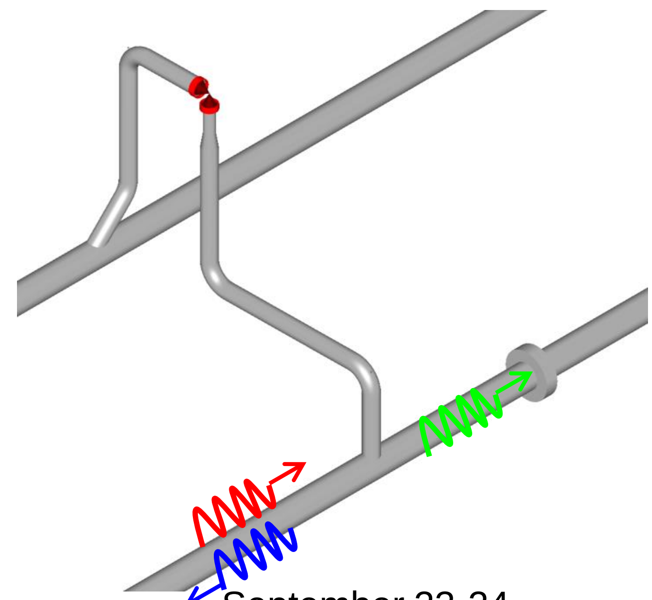
- Damping mechanisms
  - Turbulence, wall friction, heat exchange with the wall, viscosity …
- In general, damping is small
- Effective damping for L >> 10*λ
- Example: L >> 500 m
- Pulsations propagate over large distances!!

Reflection and transmission

- Acoustic waves reflect at ‘discontinuities’ in the piping
  - Diameter change
  - Temperature change
  - Side branches

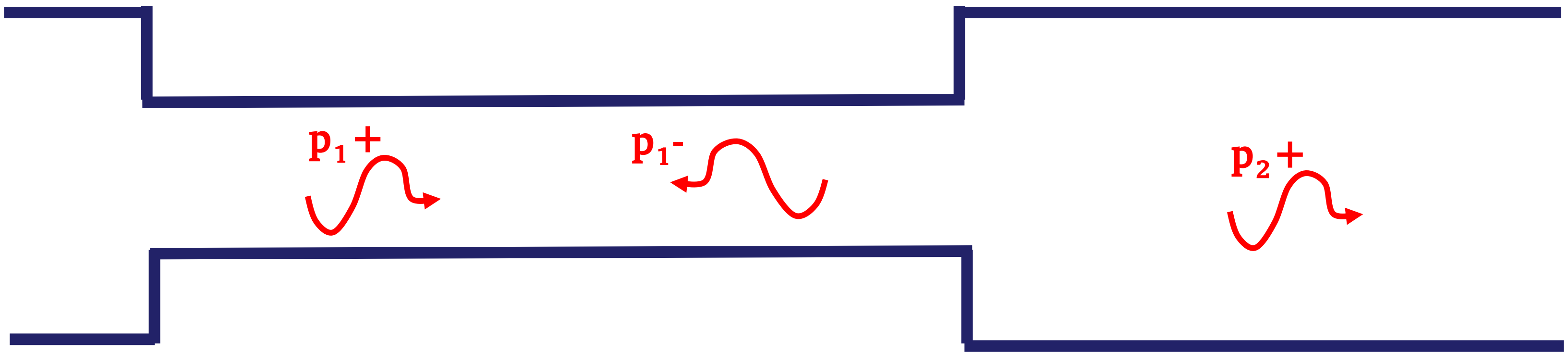






Interference of waves

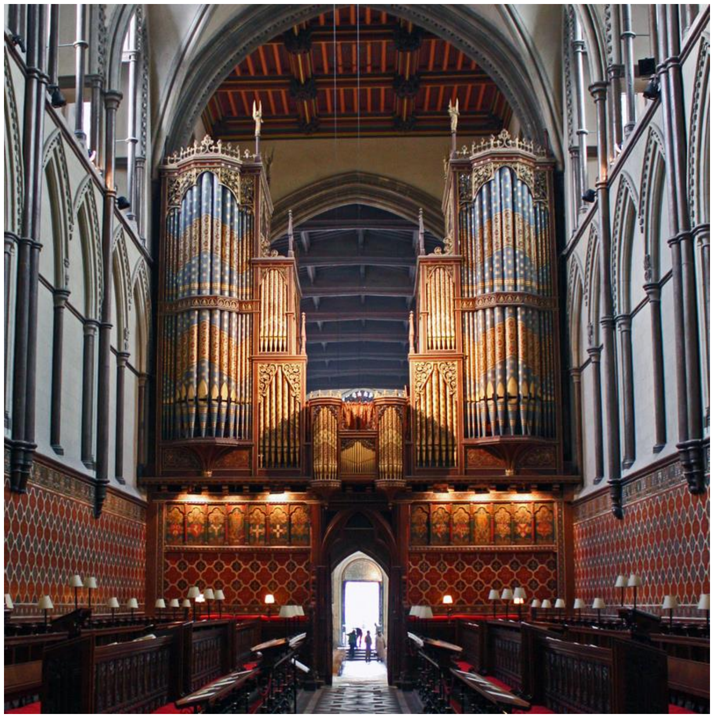
- Constructive / destructive interference

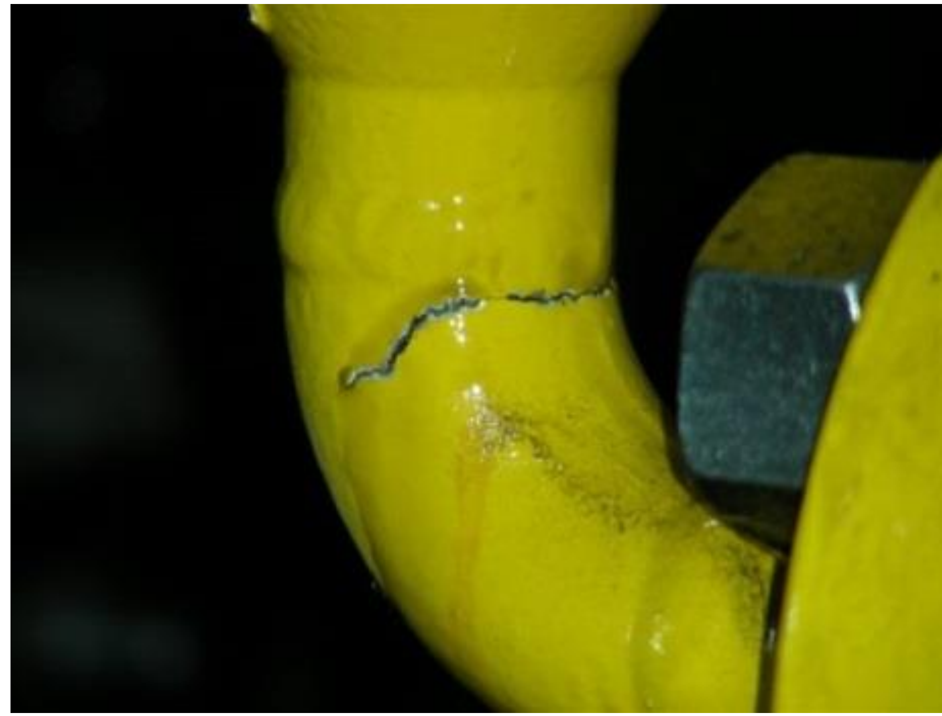


- Depending on the phase of the ...) and maxima (anti nodes) in pulsation amplitude

Acoustic resonance!

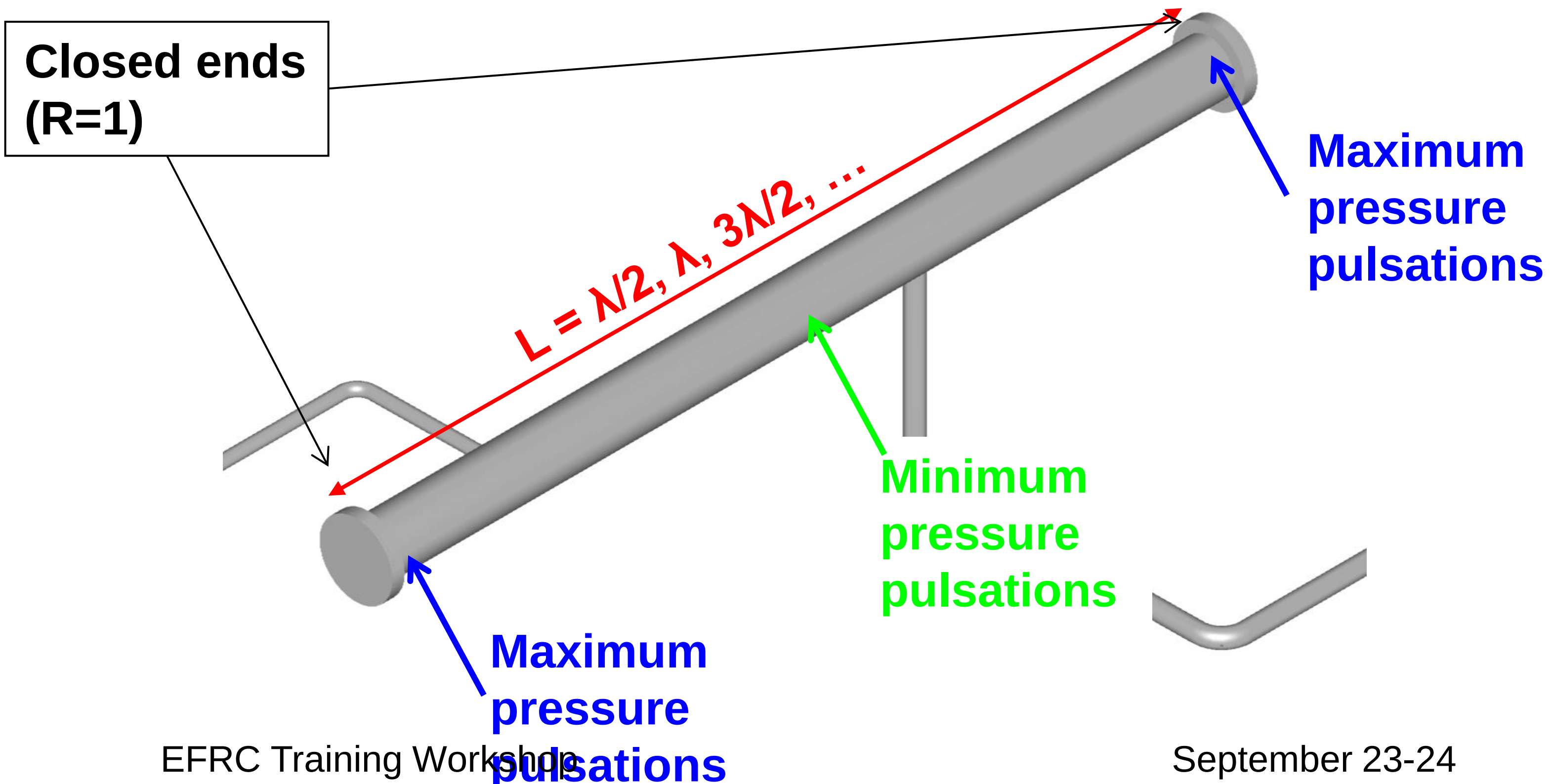
Acoustic resonance



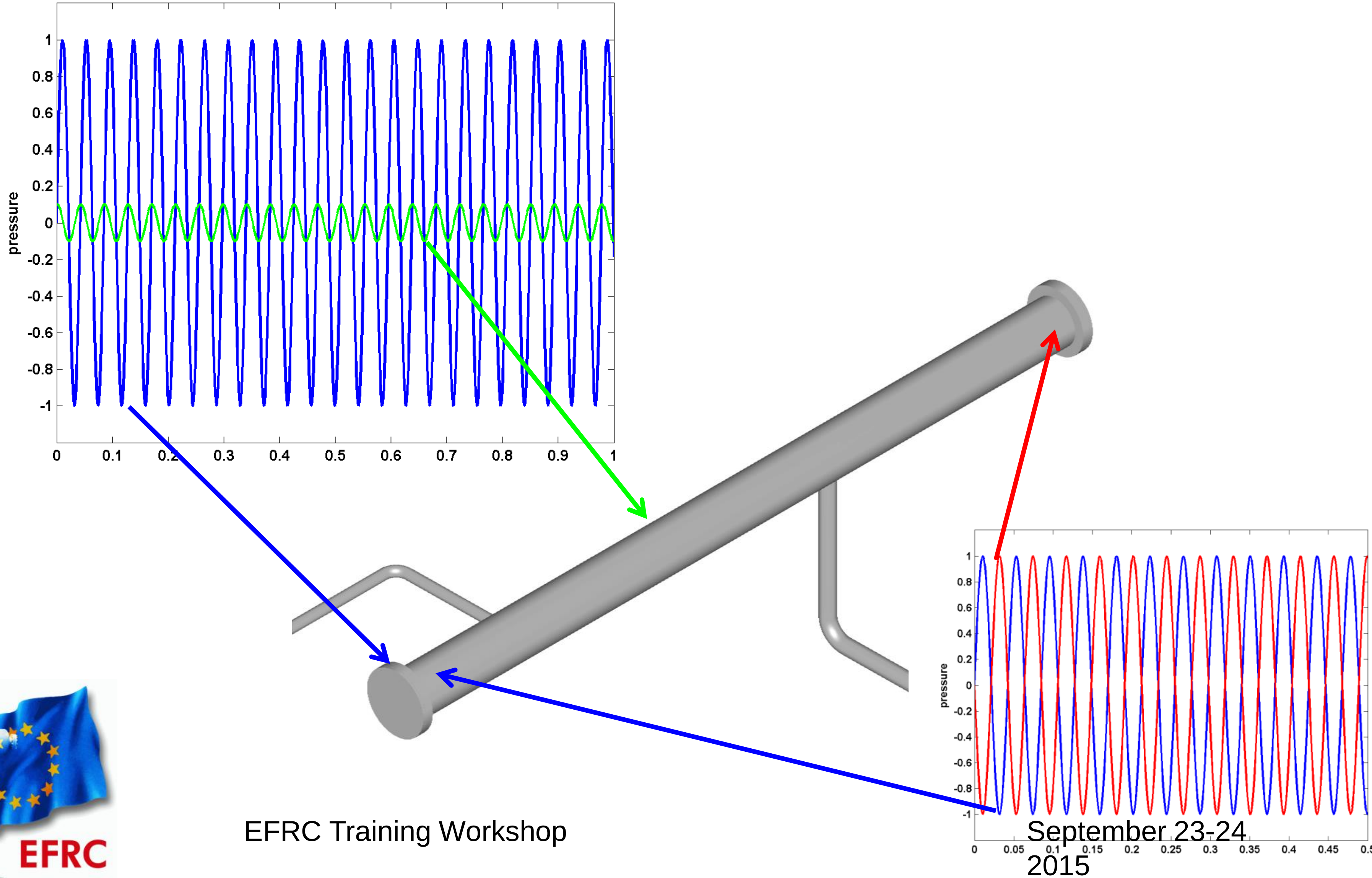


Standing waves

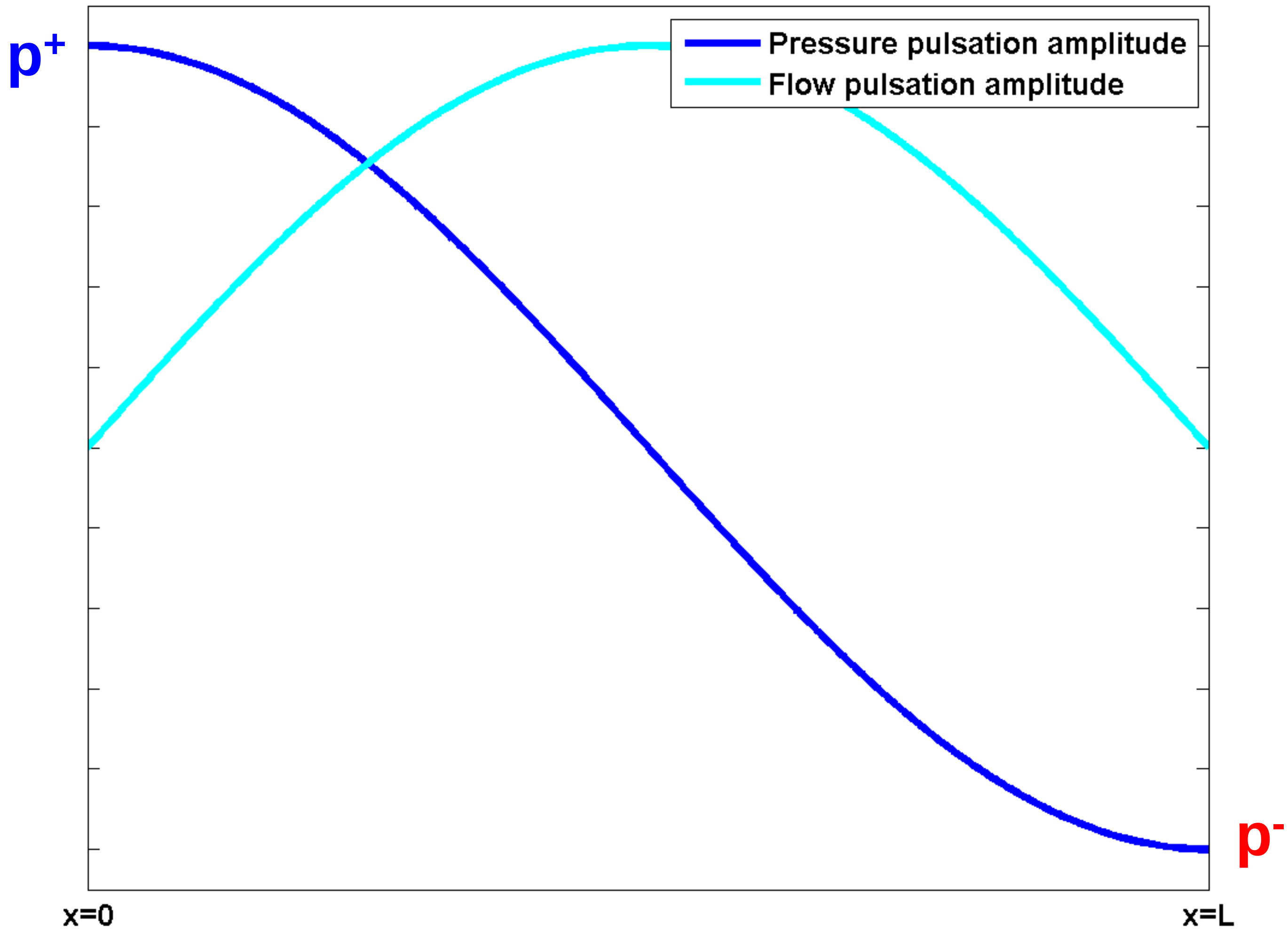
- Maximum amplification occurs when the wavelength matches the pipe length



Standing waves

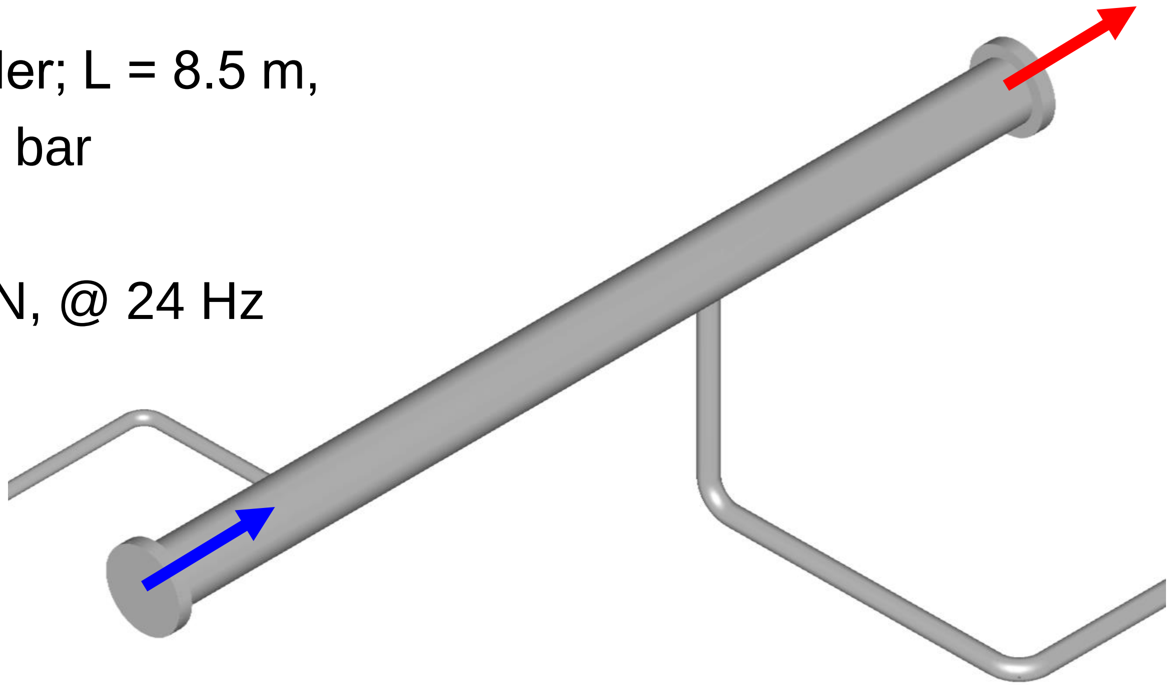


Standing wave (λ/2)



Shaking force on piping

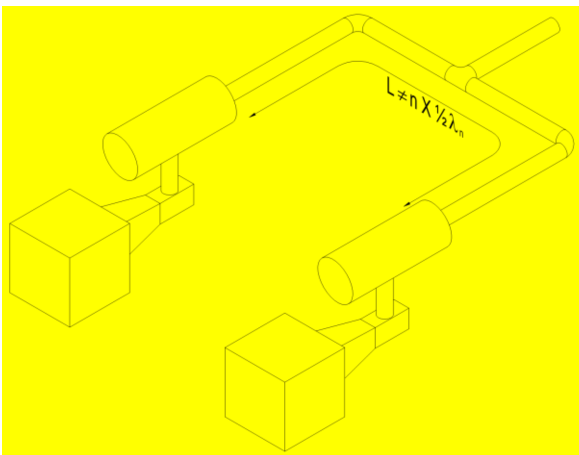
- 20” header; L = 8.5 m,
- P_0 = 200 bar
- p’ = 1%
- F = 40 kN, @ 24 Hz

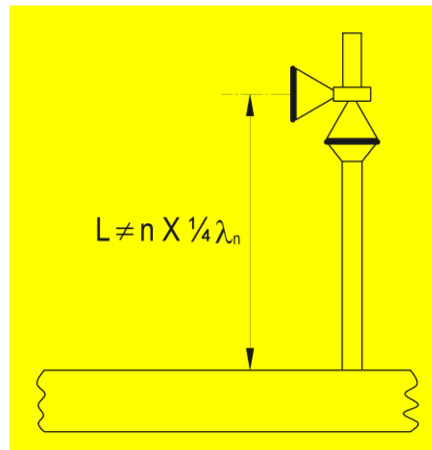


- Also acting on elbows, reducers, tees …

Control of pulsation issues

- Avoid coincidence of pulsation and resonance frequencies

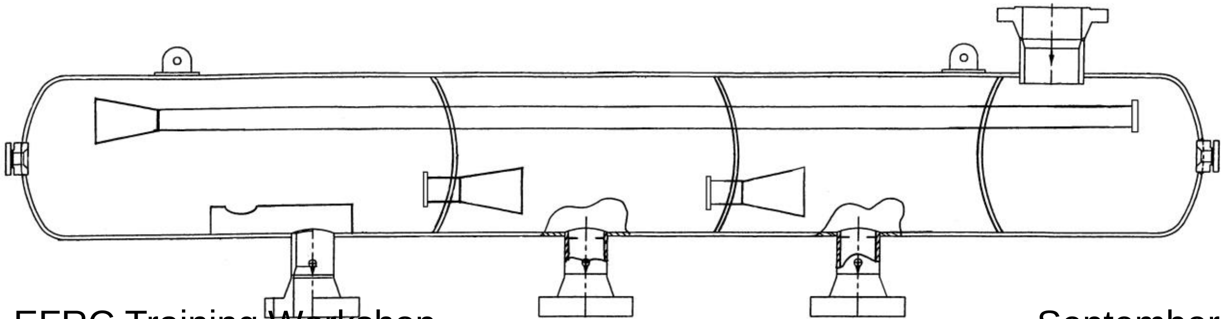




- Pulsation dampers
- Restriction orifice plates

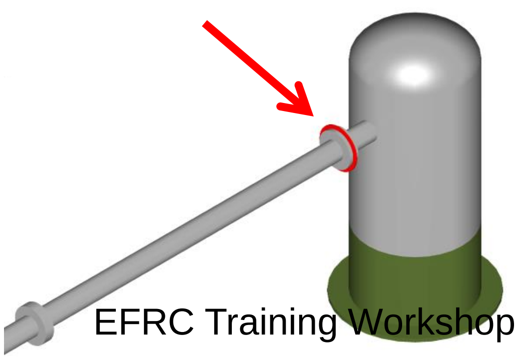
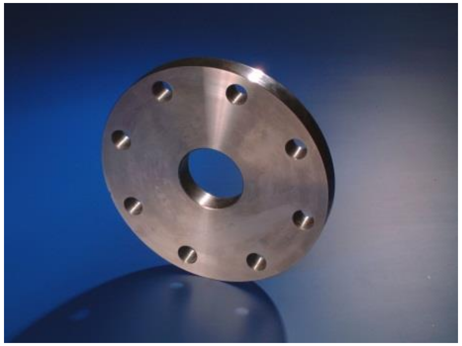
Pulsation dampers

- Mitigate the transfer of pulsations from the compressor to the piping,
- while reducing:
  – pulsations near compressor valves
  – Shaking forces on the damper
  – Pressure drop over damper



Restriction Orifice plates

- Mitigate the acoustic resonances in the piping
- Essential for performance:
  - Location in the pipe system
  - Pressure drop
  - Layout of the orifice (for higher frequencies)


Mechanical Vibrations

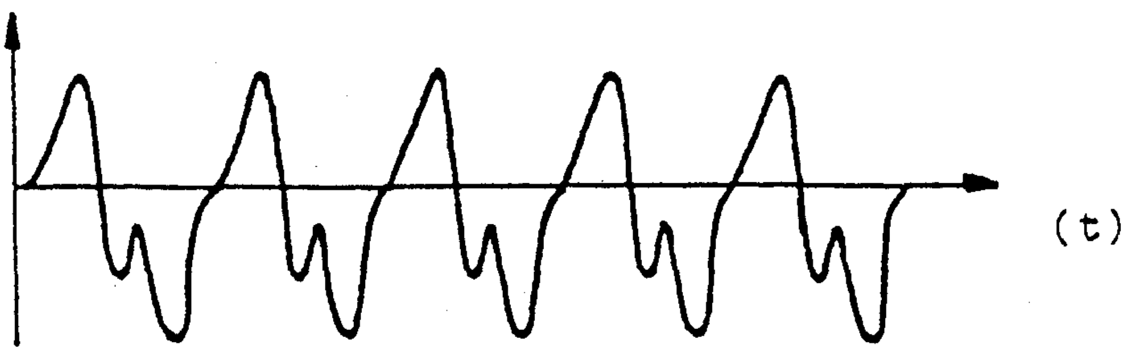
Mechanical Vibrations

- Why a mechanical vibration analysis?
  - Too high vibration and cyclic stress (fatigue) can occur, even in case pulsation levels are within the allowable levels: mechanical resonances
- What is a vibration?
  - A vibration is a more or less regular movement of a body as a function of *time*
- Examples:
  - Oscillating motor due to internal combustion
  - Oscillating flag stag due to the wind
  - Pipe vibrations caused by a reciprocating compressor (pulsation-induced shaking forces and mechanical loads)

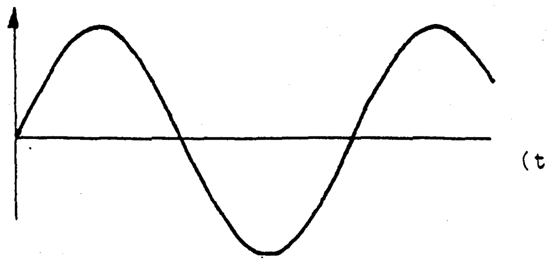
Vibration Forms

- Non periodic:
  - A vibration which amplitude is not repeated
- Examples:
  - Opening of a relief valve
  - Vibrations of a bridge due to traffic
  -

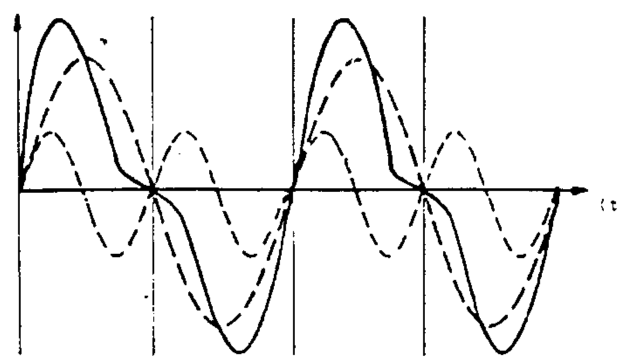
- Periodic vibration:
  - Vibration whereby the amplitude is repeated after a discrete time period
- Examples:
  - Combustion forces in a cylinder
  - Unbalanced loads of reciprocating compressors
  - Pulsation-induced shaking forces



- Harmonic vibration
  - Vibration of which the amplitude is a sine
  - Can only occur when the excitation force exists of only one frequency component
- Example:
  - Unbalance of a rotor

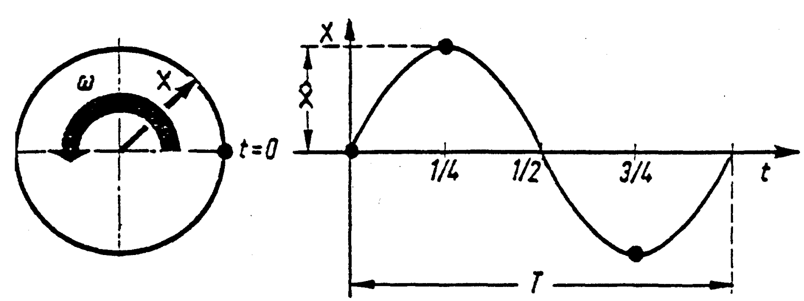


- Two or more summed harmonic vibrations with different frequencies:
  - periodic vibration but not harmonic



Definitions of Vibrations

- Period (T):
  - The time after which the vibration repeats
- Frequency:
  - the reciprocal value of T ($f=1/T$) [Hz]
- Amplitude (X):
  - The maximum value of the sine over one period
- Phase angle:
  - the argument of the sine function as follows: $X=x\sin(\omega t+\theta)$
- Circle frequency (ω):
  - $\omega = 2\pi f$

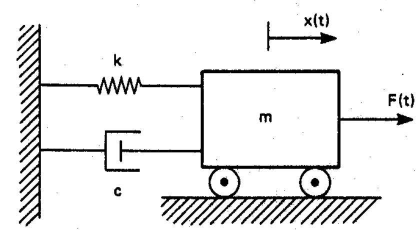


Theory of Mechanical Vibrations

- General equation of motion:

$$m\ddot{x}+c\dot{x}+kx=Fe^{j\omega t}$$

Pulsation forces and mechanical loads



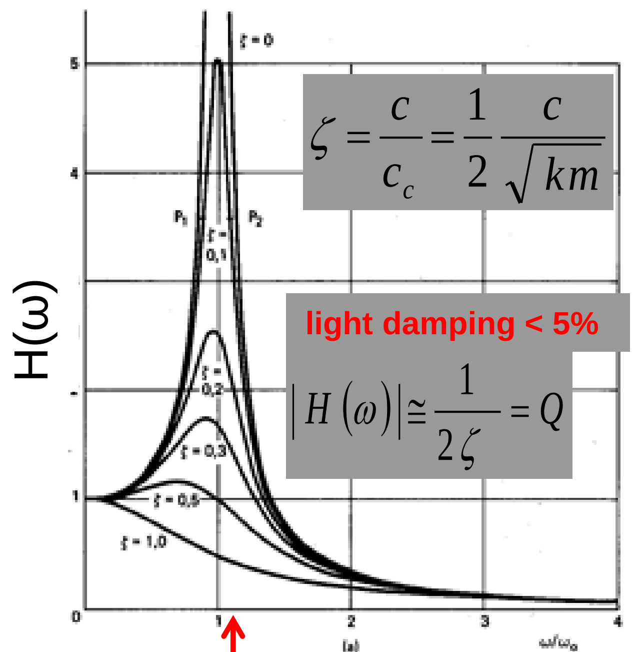
m= mass
c= damping
k= stiffness

$\ddot{x}$ = acceleration
$\dot{x}$ = velocity
x = displacement

- Resonance condition:

$$\omega_0 = \sqrt{k/m}$$

ω_0 = mechanical natural frequency
ω = excitation frequency ($\omega = 2\pi f$)
$\omega = \omega_0$ at resonance



$$\zeta = \frac{c}{c_c} = \frac{1}{2}\frac{c}{\sqrt{km}}$$

light damping < 5%

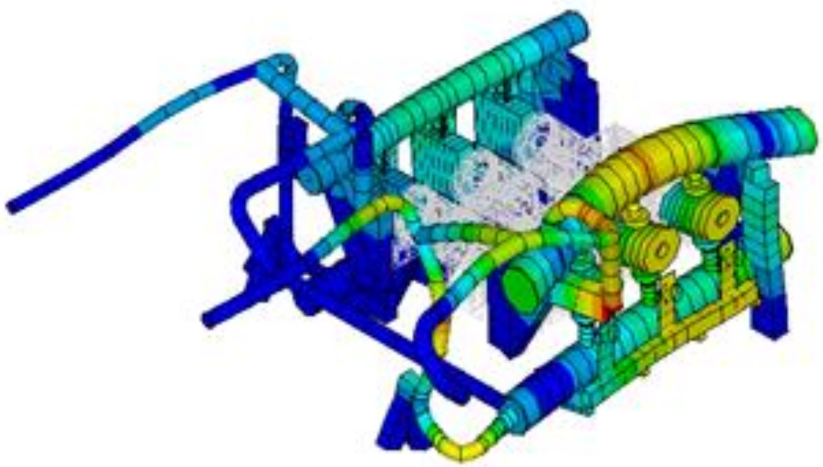
$$\left|H(\omega)\right| \cong \frac{1}{2\zeta} = Q$$

$|H(\omega)|$ as a function of ω/ω_0

Resonance

Theory of Mechanical Vibrations

Mode shape at resonance



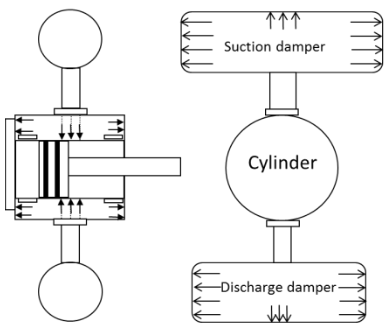
Fatigue failure

Remark:

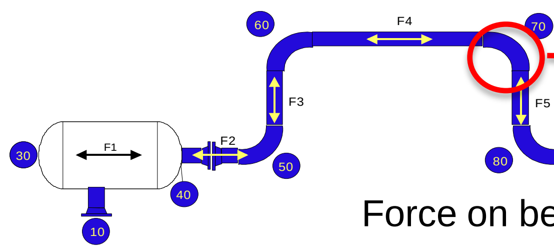
- In many cases the highest vibration levels occur at resonance conditions.
- However, high vibration levels may also be generated by high pulsation-induced shaking forces not occurring at resonance conditions.
- The distinction between both is difficult to determine. In many cases additional supports may only decrease the vibrations but will introduce high local stresses.

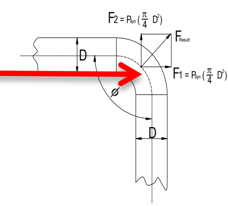
Dynamic Forces generated by Reciprocating Compressors

- Pulsation-induced shaking forces (pulsation dampers, cylinders, pipe system, separators, coolers etc.)

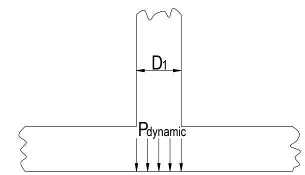


Forces on dampers and cylinder





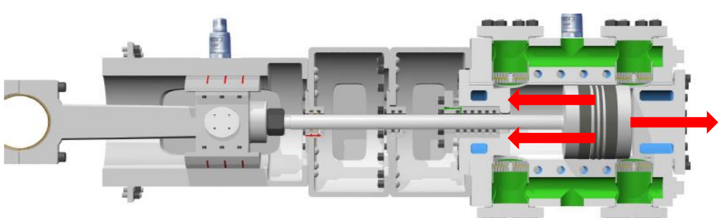
Force on bends

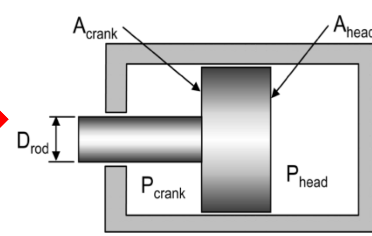


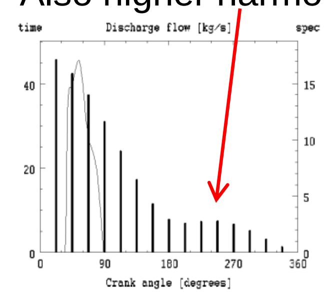
Force on Tee

- Cylinder gas stretching forces
  - MNF of suction dampers and suction piping can be excited
  - Not only forces of 1X but also higher harmonics are important

Also higher harmonics







Spectrum of flow pulse

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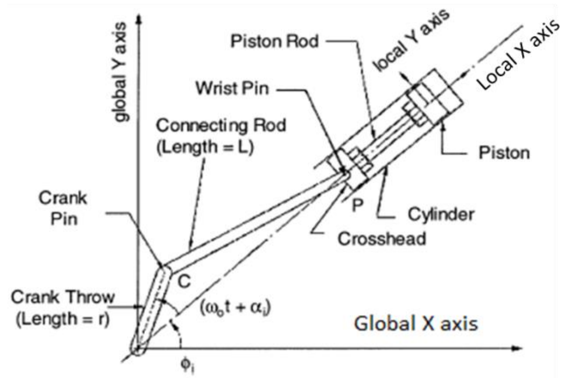
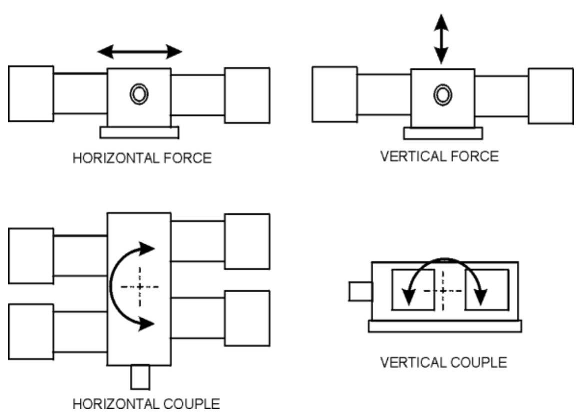
Dynamic Forces generated by Reciprocating Compressors

- Free forces & moments caused by rotating and translating parts:



Working principle of a crank mechanism



Summary of free forces & moments for multiple cylinders

Inertia force in piston direction:

$$F_x = (m_{rec} + m_{rot}) r \omega_0^2 \underbrace{\cos \omega_0 t}_{1X} + m_{rec} \frac{r^2}{L} \omega^2 \underbrace{\cos 2\omega_0 t}_{2X}$$

Inertia force perpendicular to piston

$$Fy = m_{rot} r \omega_0^2 \underbrace{\sin \omega_0 t}_{1X}$$

In which:

- F_x : load in piston direction
- $F_{y:}$ load perpendicular to piston
- m_{rec}: reciprocating mass
- m_{rot}: rotating mass
- r: stroke
- L: connection rod length
- $\omega_{0:}$ circular velocity
- t: time

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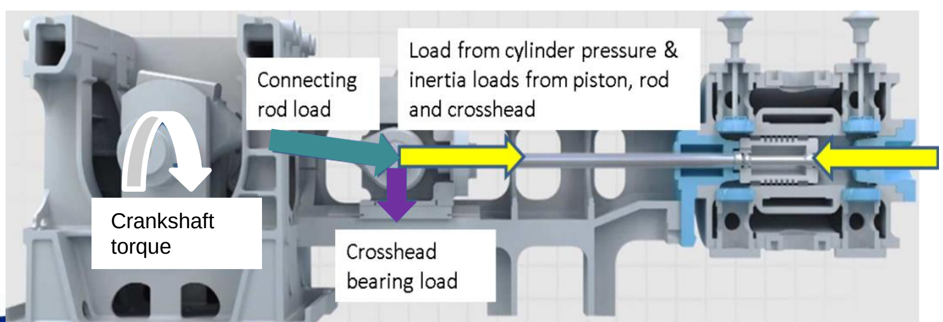
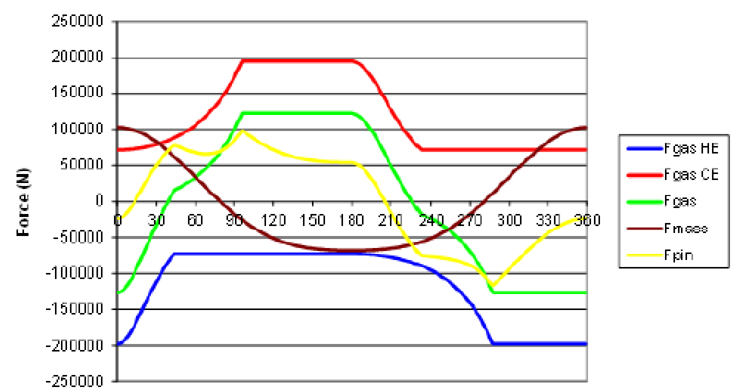
Dynamic Forces generated by Reciprocating Compressors

Vertical crosshead forces

- important when supporting structures in vertical direction are flexible
- created when rotation motion is converted into reciprocating motion
- can be retrieved from crosshead pin load (horizontal direction)



Forces on crosshead

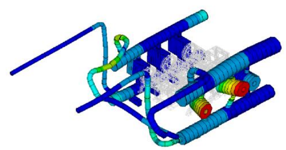


Example of gas & inertia loads on crosshead pin (yellow line indicates total pin load)

Mechanical response analysis according to API 618

FEM model of pipe system

General FE programs, e.g. ANSYS



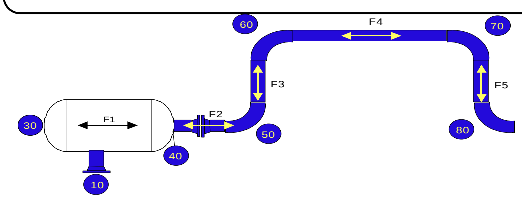
Natural frequencies, mode shapes

Non-resonance system?

YES

NO

maximum forces and phases from pulsation analysis (worst-case situations)



Response calculation

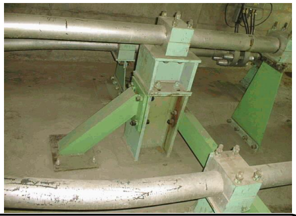
Pulsation analysis

Vibrations, cyclic stresses allowable

NO

YES

Modifications



E.g. additional pipe supports, stiffening steel structures, braces, etc.

Optimum Design

Avoid unacceptable vibrations and fatigue failures

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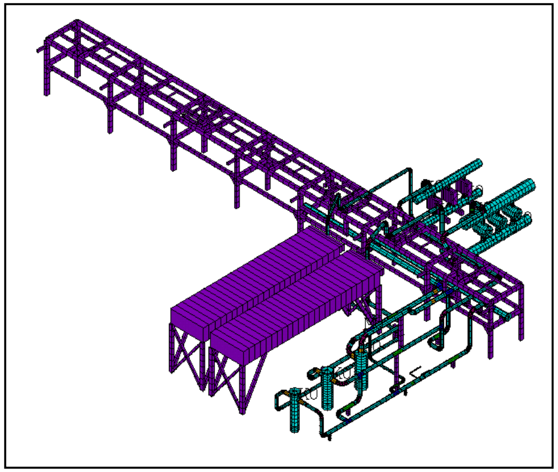
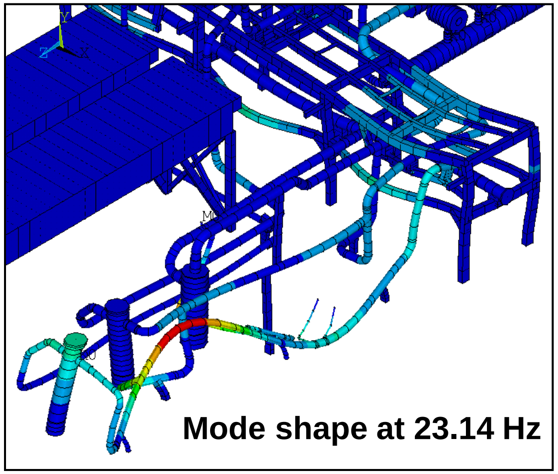
Example of an Underground Gas Storage (UGS) system

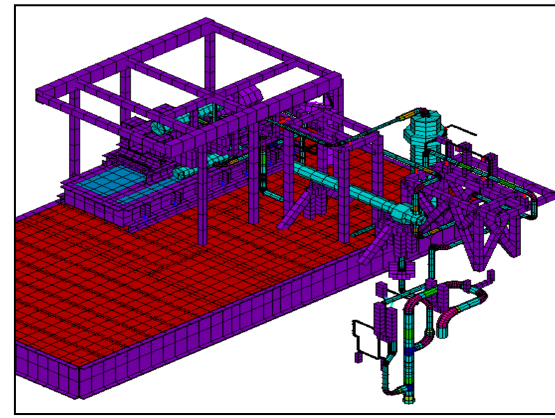




<u>Challenges UGS systems</u>:

1. Large variation in pressure ratio's and flows
2. Many unloading conditions:
   - HE unloaders, stepless flow reverse control
   - Variable speed

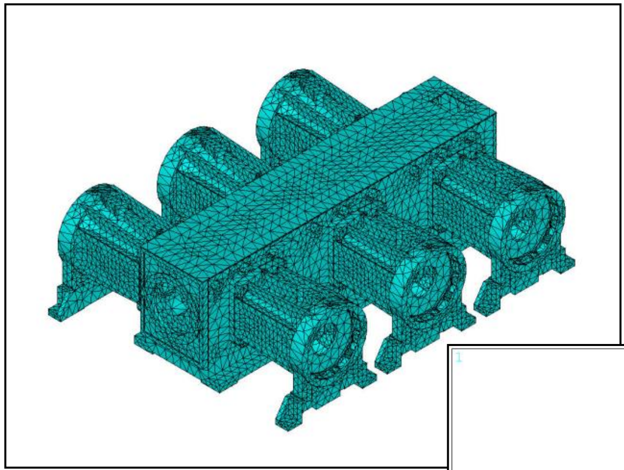
Some examples of off-shore models



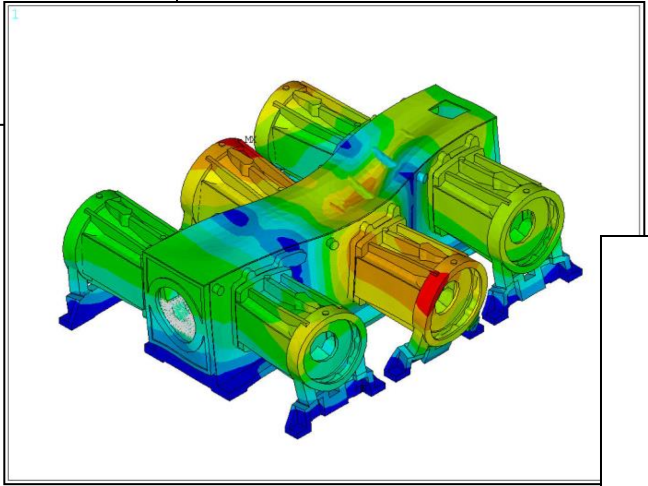
Challenges in offshore systems:

- Noise limitations in living quarters
- Space limitations
- Dead weight limitations
- Flexible deck structure

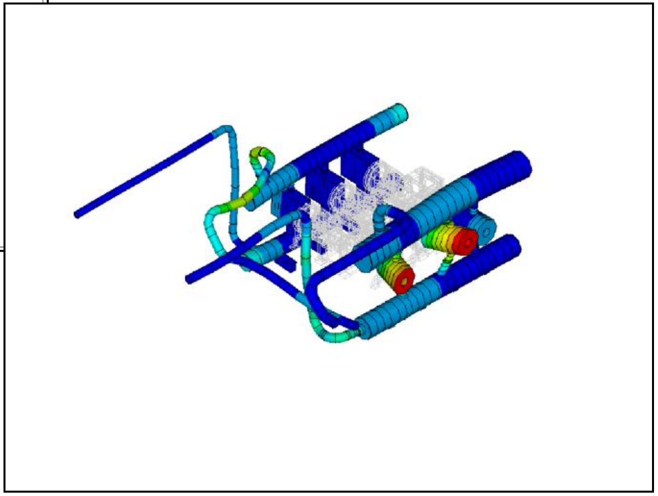
Examples of Compressor Finite Element models



Mode shape at 156.7 Hz



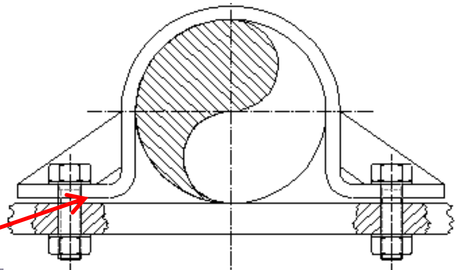
Mode shape at 94.7 Hz

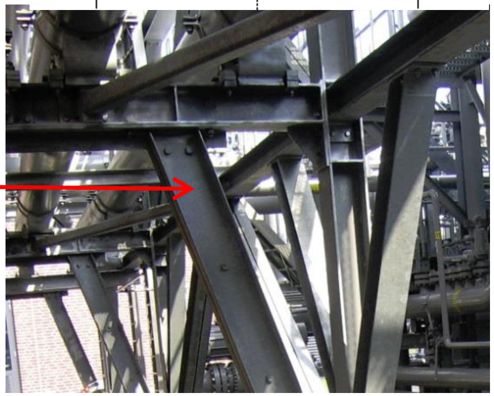


Mitigation Vibrations & Cyclic Stress Levels

- <u>Shifting resonances</u>:
  - frequencies of excitation forces should not coincide with mechanical natural frequencies

$$\omega_0 = \sqrt{k/m}$$

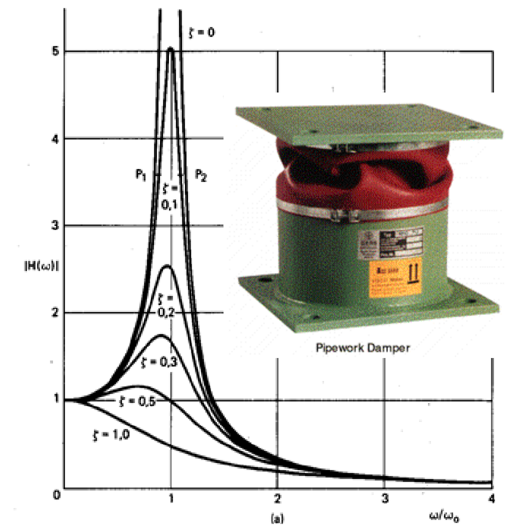




  - Shifting to higher values by:
    - Additional pipe supports
    - Stiffer pipe support structures
    - Difficult to achieve for variable speed compressor
  - Shifting to lower values by:
    - Increasing mass

Mitigation Vibrations & Cyclic Stress Levels

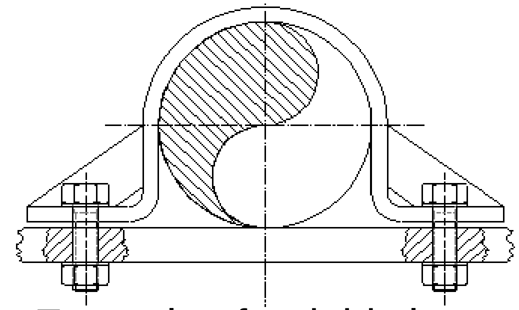
- Damping:
  - Most effective at resonance conditions
  - Viscous dampers (allow thermal motions)
  - Most effective for frequencies < 50 Hz



- Lower cyclic stress:
  - Increase wall thickness
  - Add braces

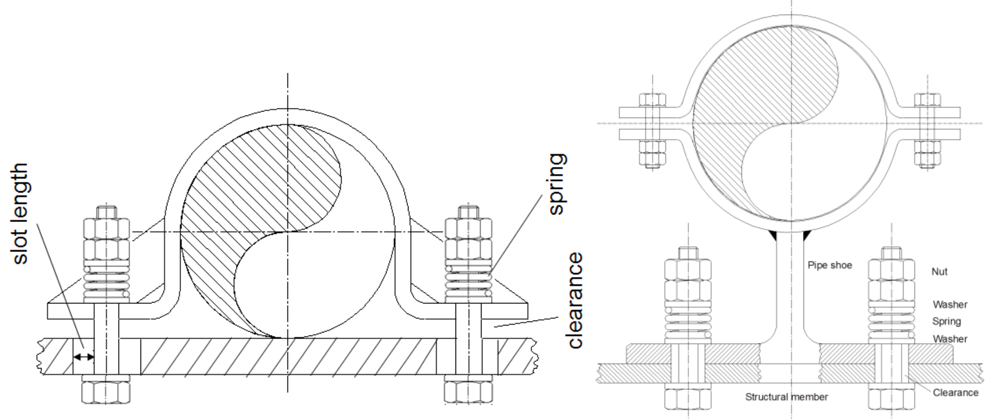
Pipe Supports

- Rigid clamps are required for systems which are subjected to vibrations
- Disadvantage of additional pipe clamps:
  - Introduction of too high expansion stresses



Example of a rigid clamp

- Solution:
  - spring hold down supports



Examples of spring hold down supports

- Required spring preload:

$$Fn \geq \frac{Fw}{f} \quad [N]$$

F_w= pulsation-induced reaction force

f = friction coefficient (0.3 steel-steel; 0.1 steel-teflon)

API 618 Standard

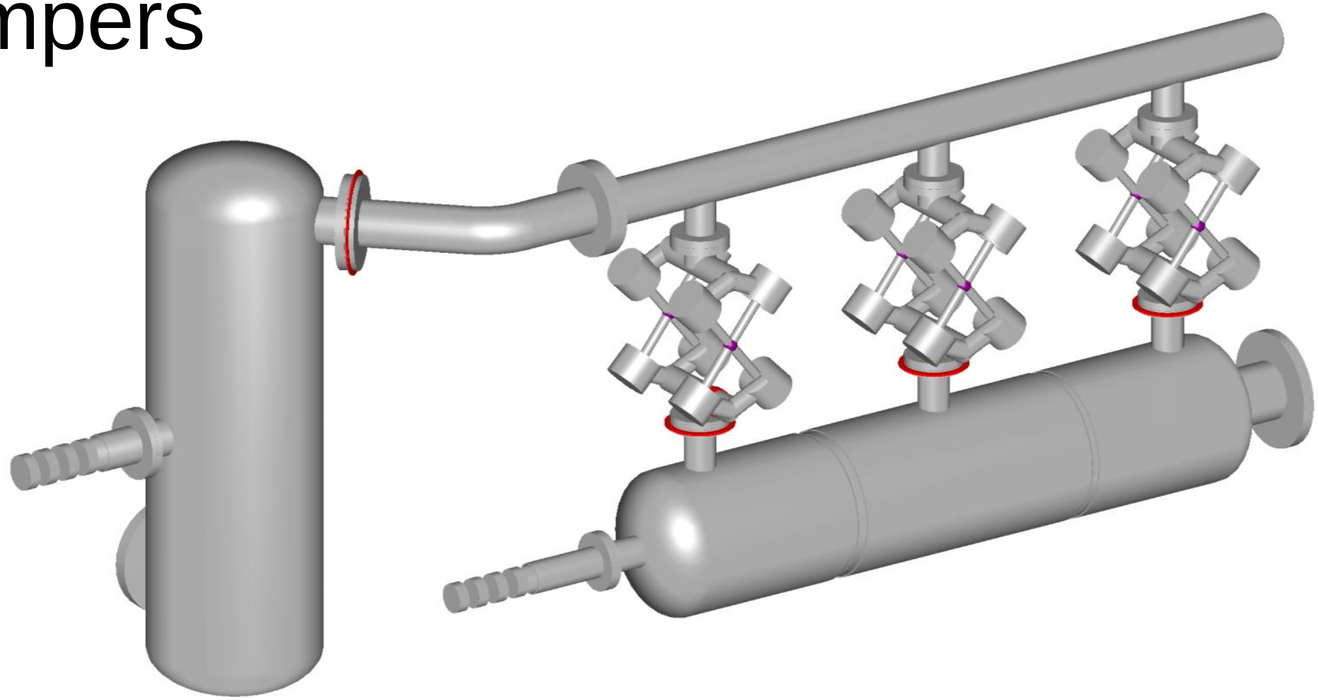
- Specifies allowable pulsation, vibration & cyclic stress levels
- Stipulates a design approach

Absolute Discharge Pressure	Rated Power per Cylinder		
	Kw/cyl < 55 (hp/cyl < 75)	55 < Kw/cyl < 220 (75 < hp/cyl < 300)	220 < Kw/cyl (300 < hp/cyl)
P < 35 bar (P < 500 psi)	1	2	2
35 bar < P < 70 bar (500 psi < P < 1000 psi)			3
70 bar < P < 200 bar (1000 psi < P < 3000 psi)	2	3	3
200 bar < P < 350 bar (3000 psi < P < 5000 psi)	3	3	3

High power, high pressure

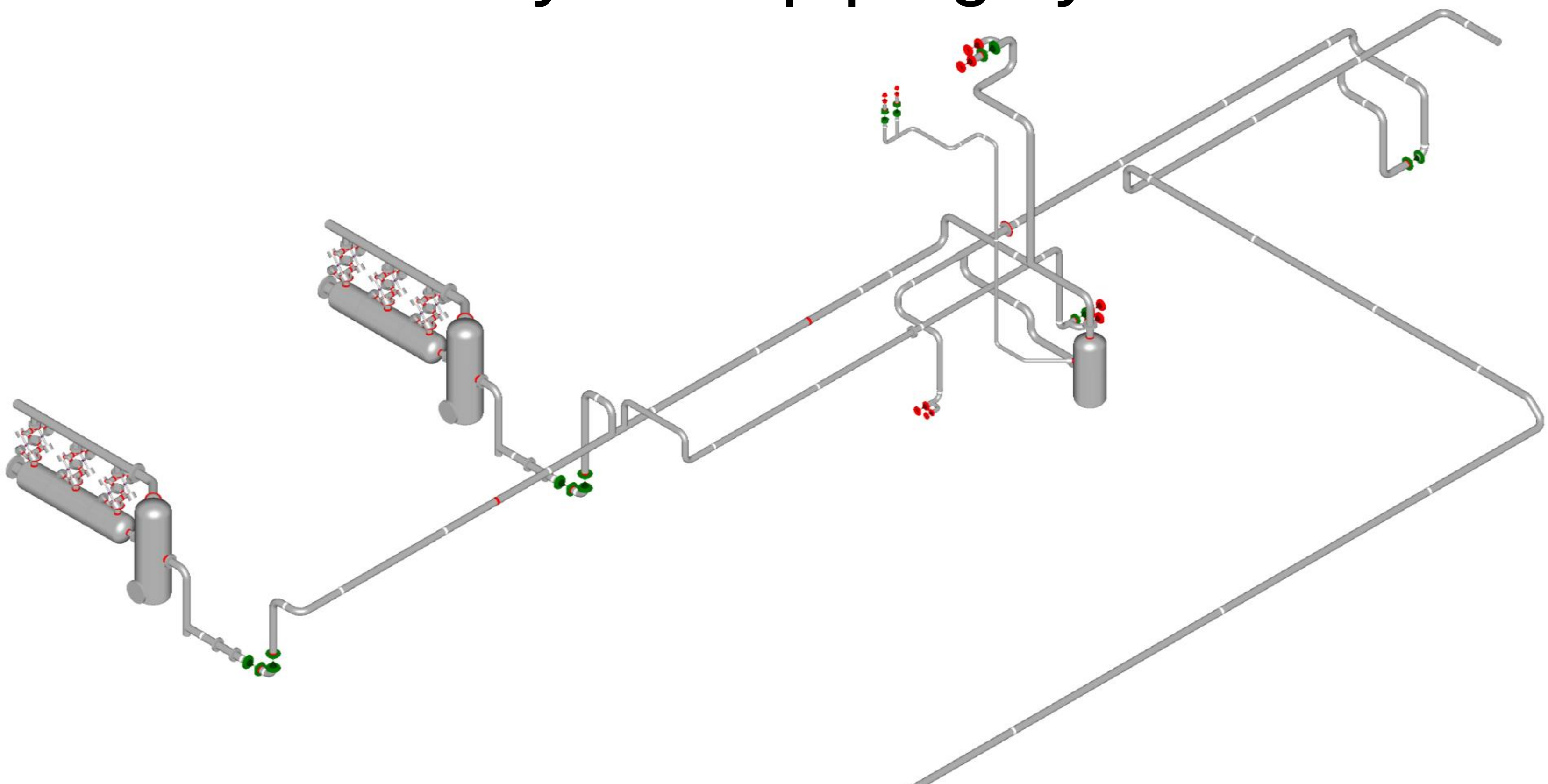
Design approach 3

1) Acoustic evaluation & design of pulsation dampers



Design approach 3

2) Pulsation analysis of piping system

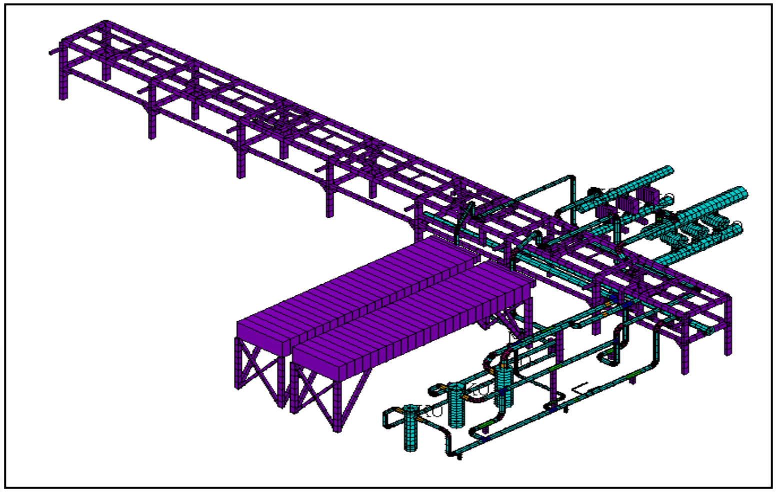


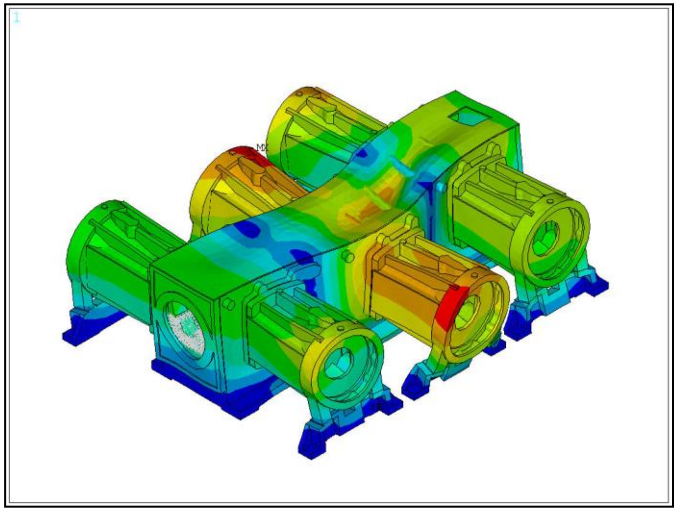
Design approach 3

3) Forced mechanical response analysis

Vibrations and cyclic stresses of:

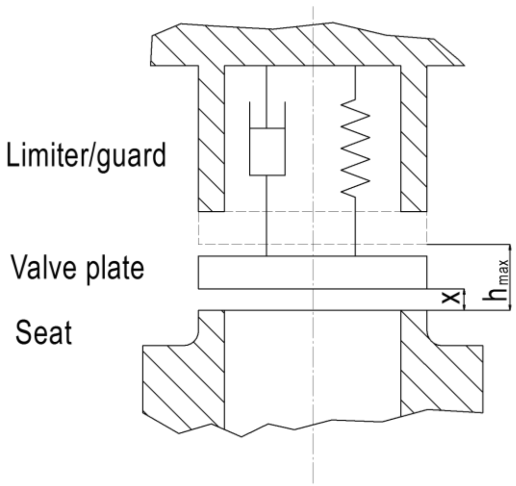
- Piping
- Compressor manifold

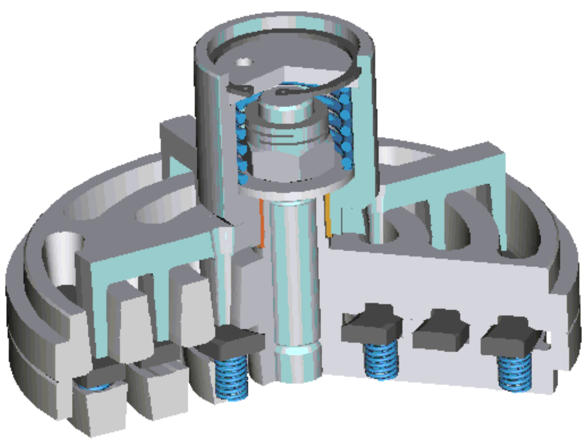


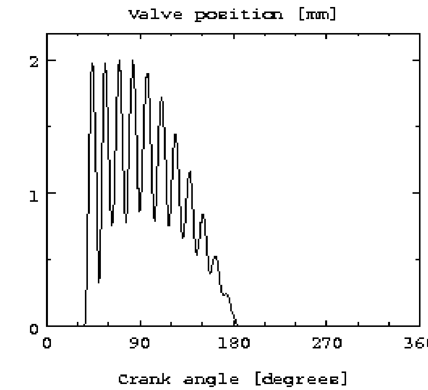


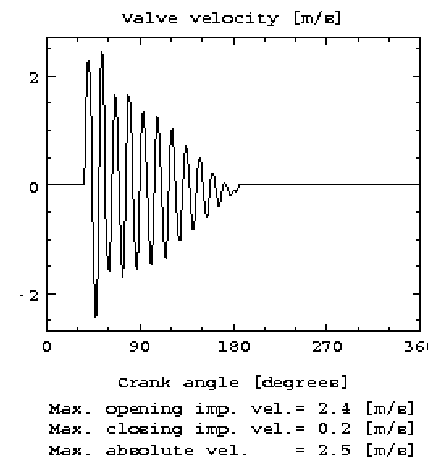
Design approach 3

4) Analysis of compressor valve dynamic behaviour









Thank you for your attention!

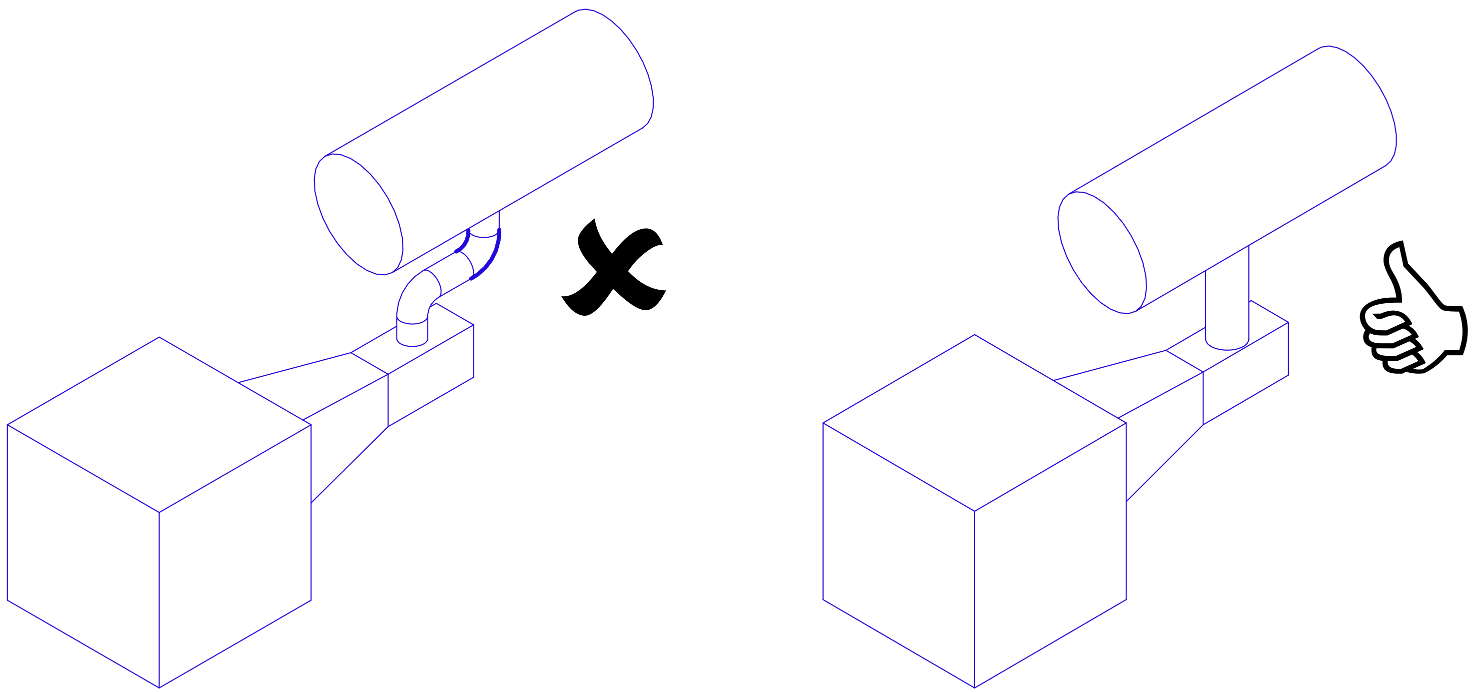
Questions ?

Leonard van Lier
+31 888 666 317
Leonard.vanlier@tno.nl

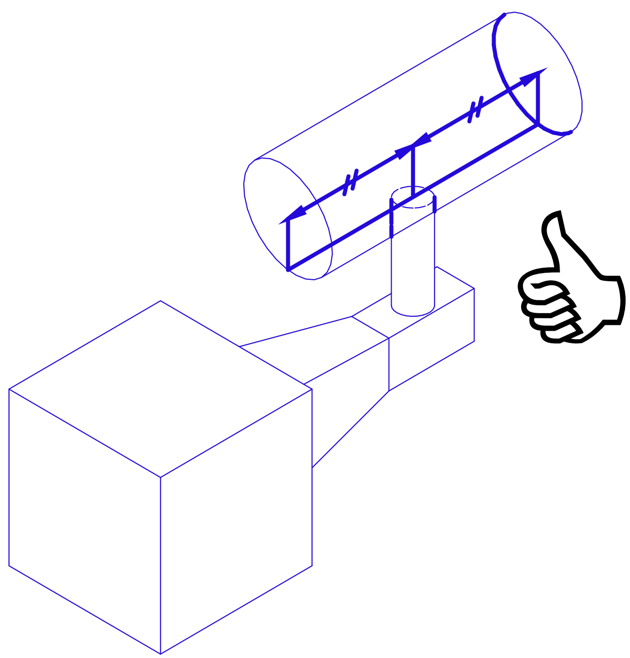
André Eijk
+31 888 666 354
Andre.eijk@tno.nl

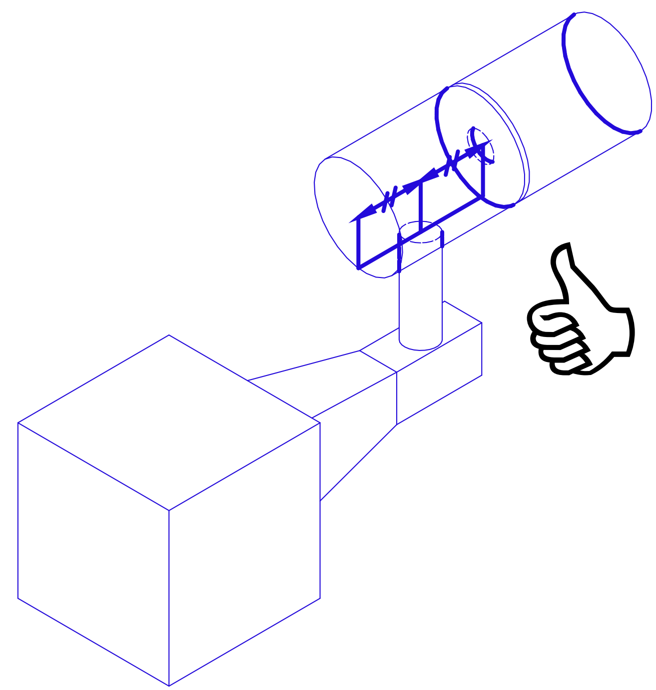
Encore: basic design rules (do’s and dont’s)

Keep cylinder connection of pulsation damper as short as possible

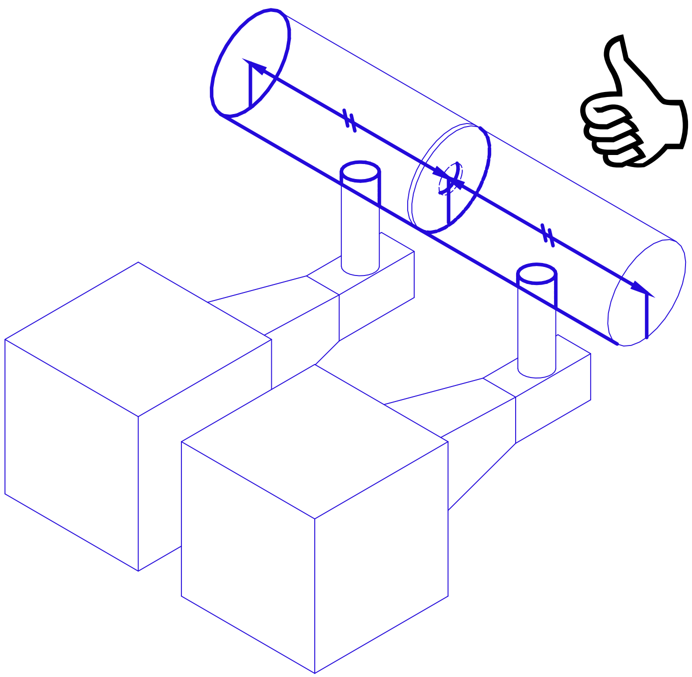


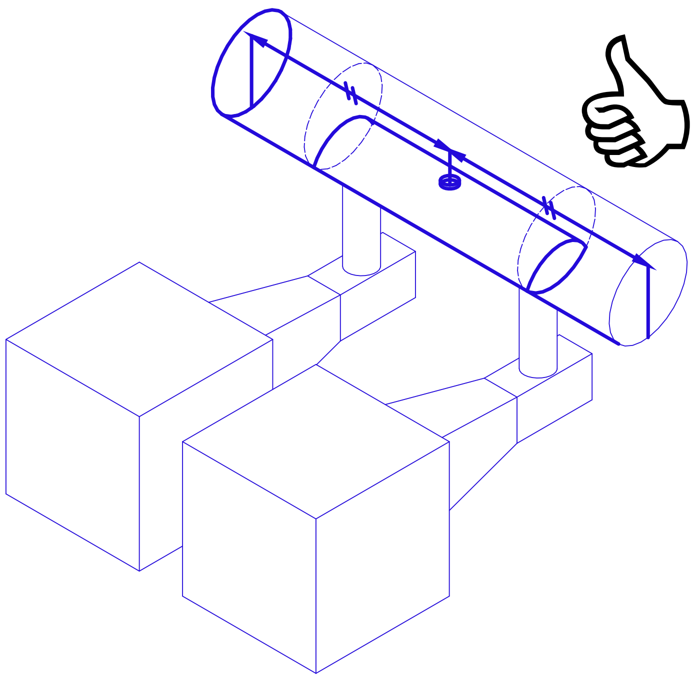
Symmetric layout of cylinder connection in the damper compartment



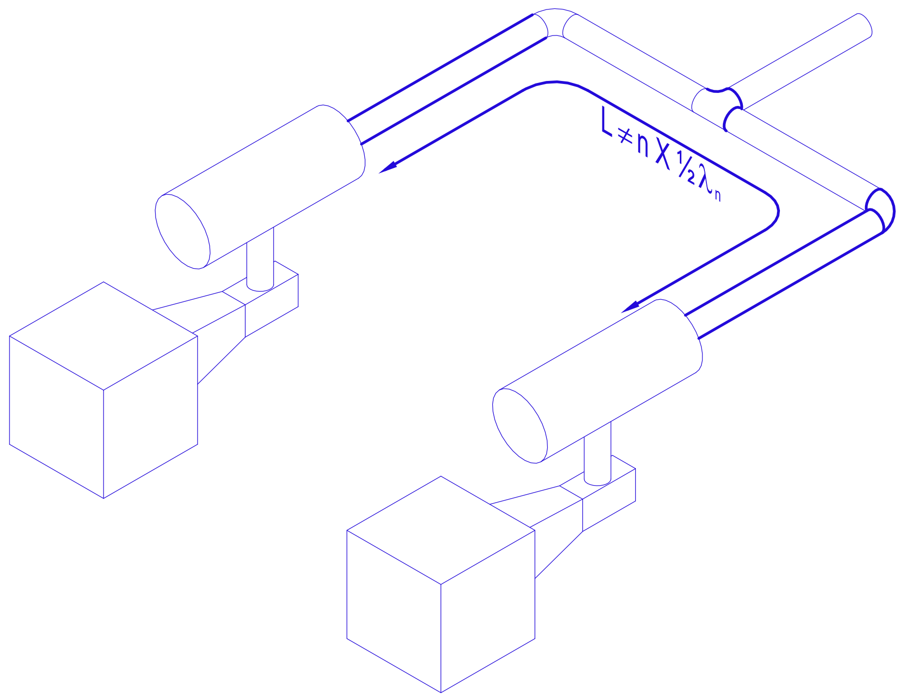


Manifold damper:
Baffle plate or extended cylinder connection

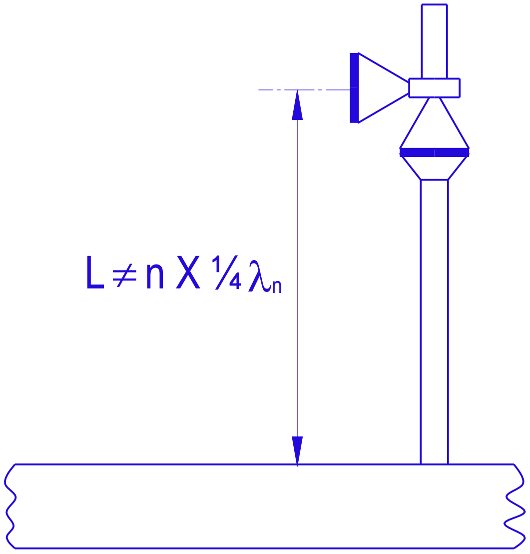




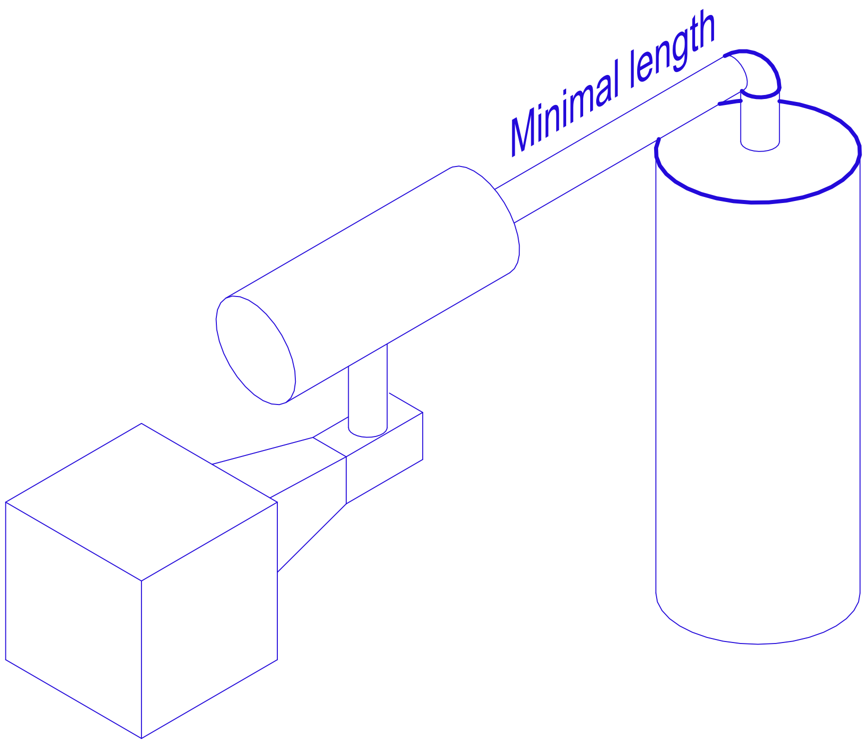
Avoid standing waves and Helmholtz resonance between vessels



Avoid standing waves in closed side branches

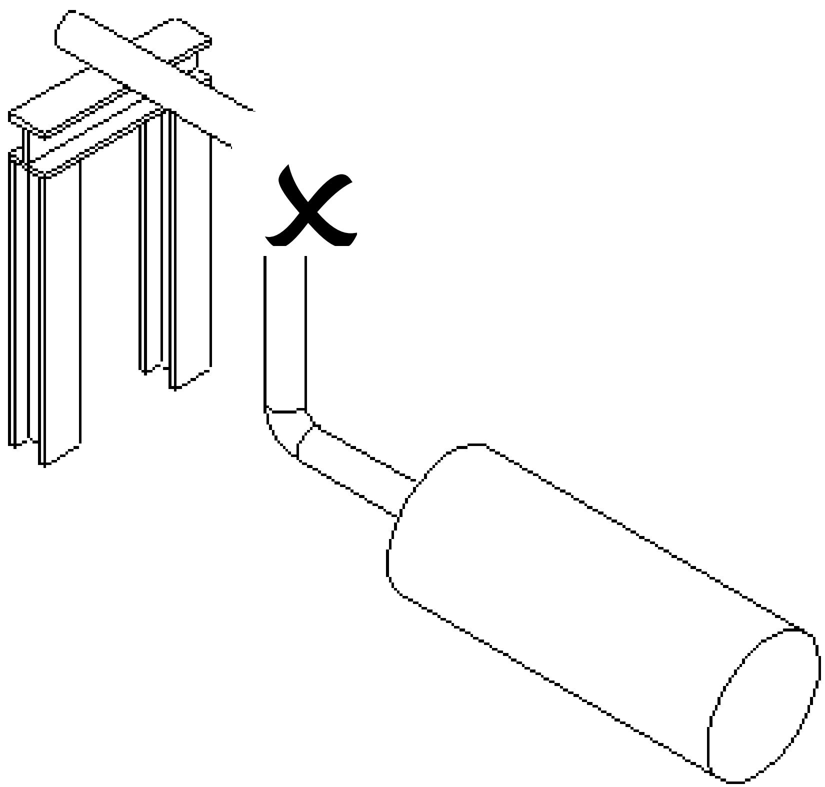


Minimize length between large vessel and damper

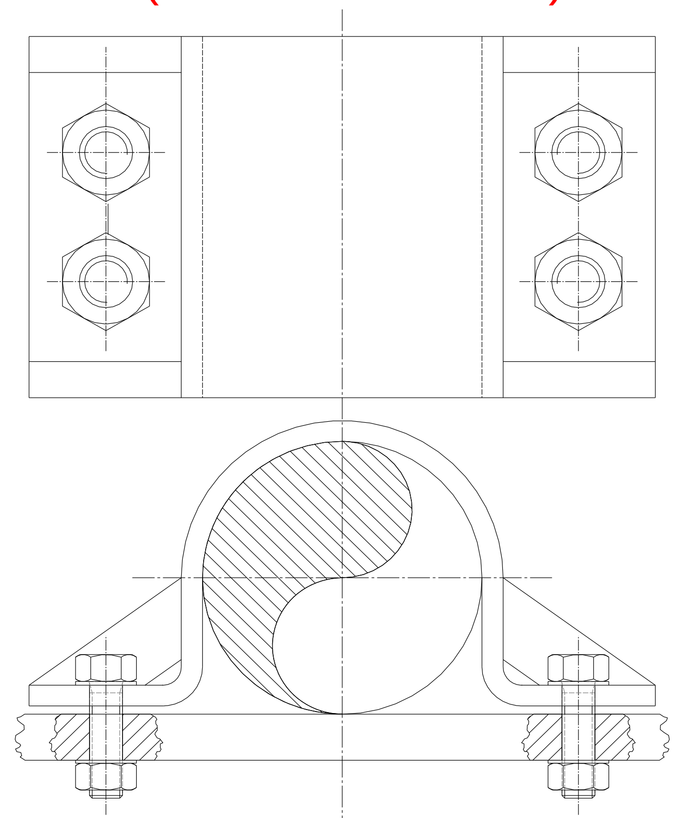


Piping layout, clamps

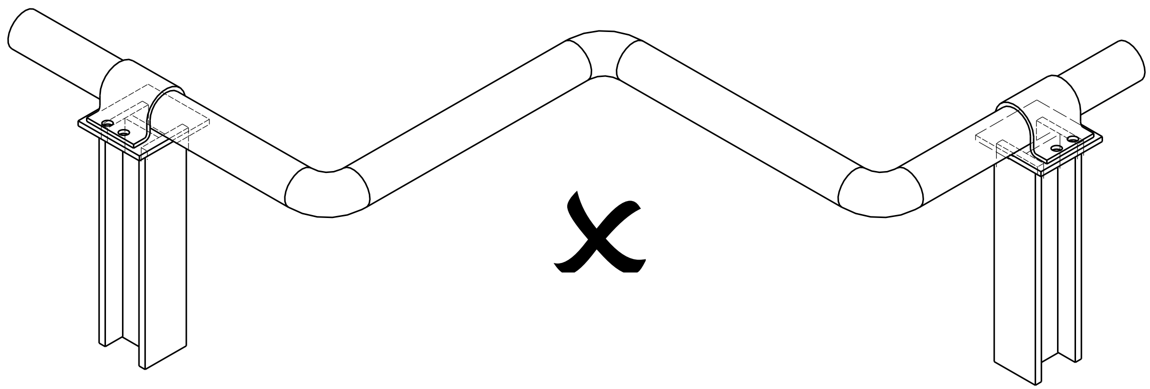
Keep all piping low



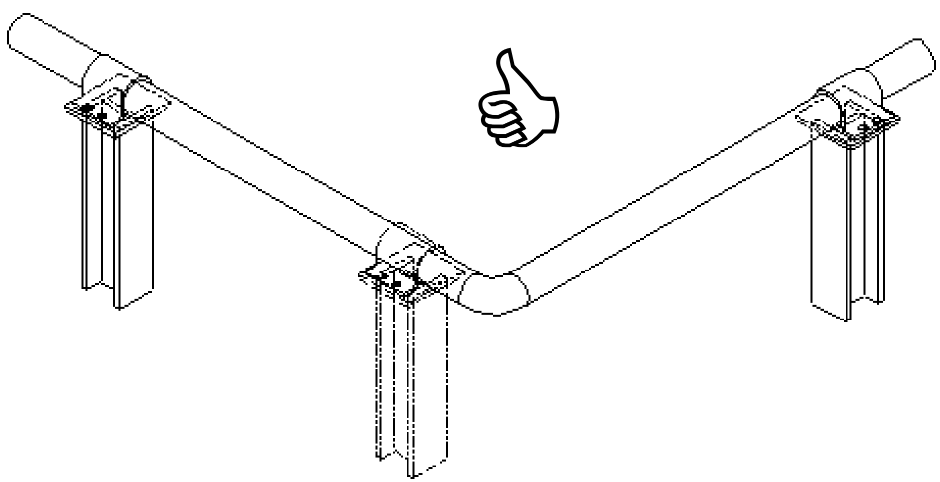
Good Clamps have width
(do not use U-bolts)



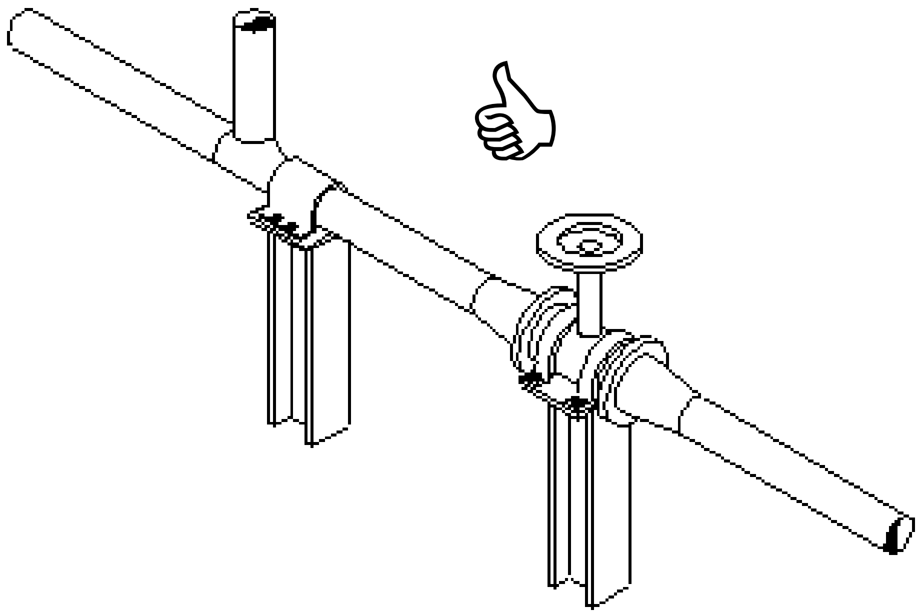
Do’s, Don’ts Design Rules

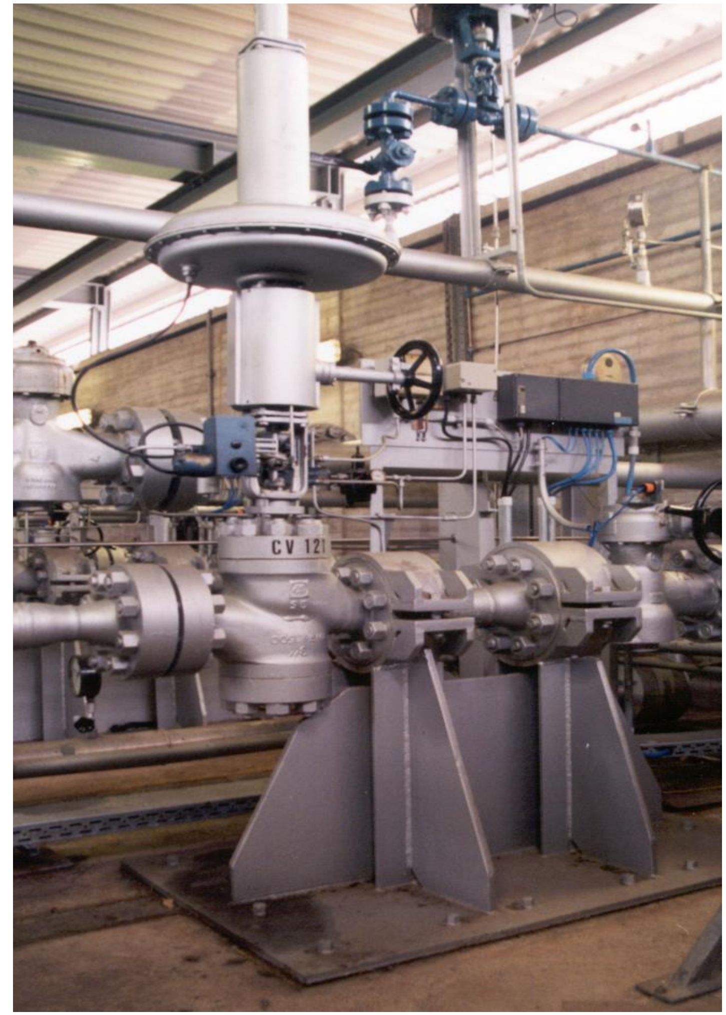


Minimise number of elbows and Tees
and avoid freestanding elbows



Do's, Don'ts Design Rules





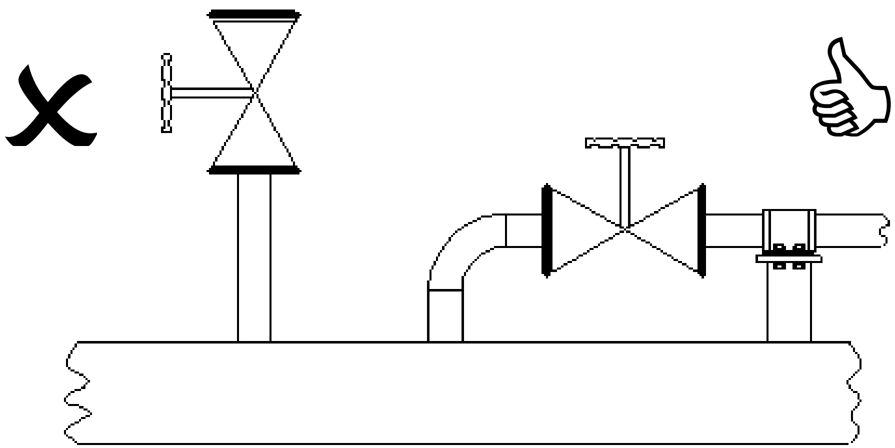
Locate supporting directly under heavy components (valves, flanges etc.) and Tee joints

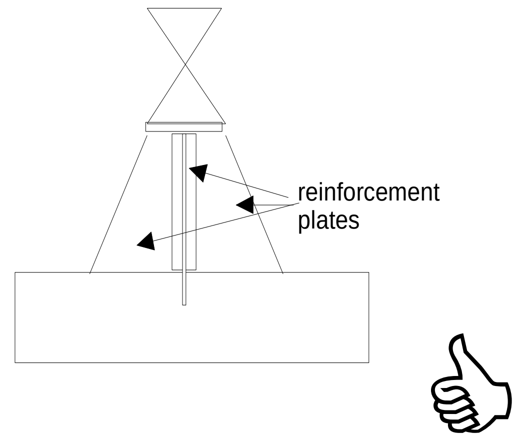
Do’s, Don’ts Design Rules

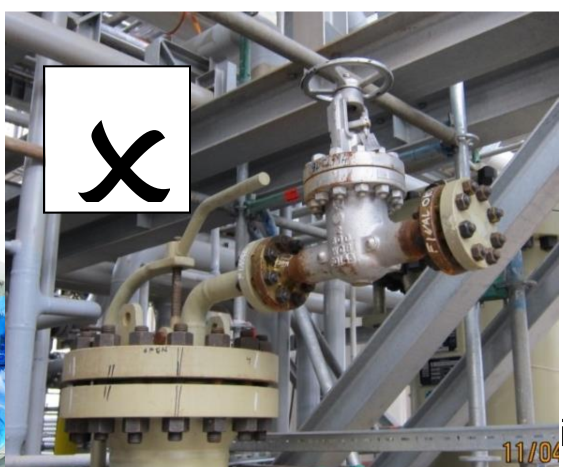
Brace small lines (drains, purge lines)

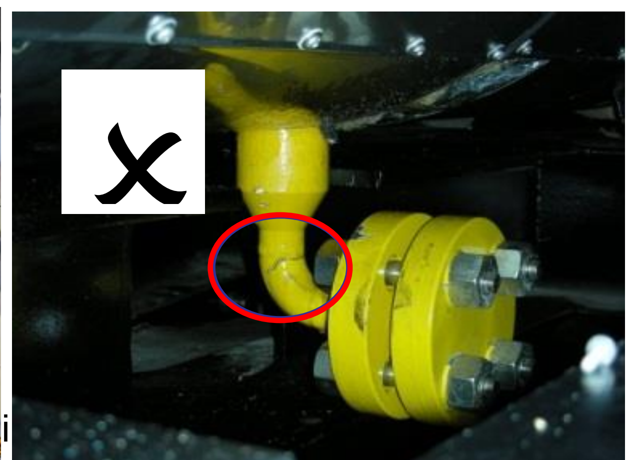
Do not use unreinforced branch connections

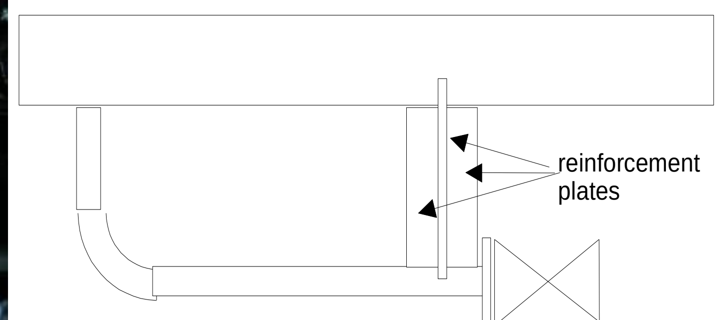
Apply two-plane bracing of small bore side branches back to main pipe





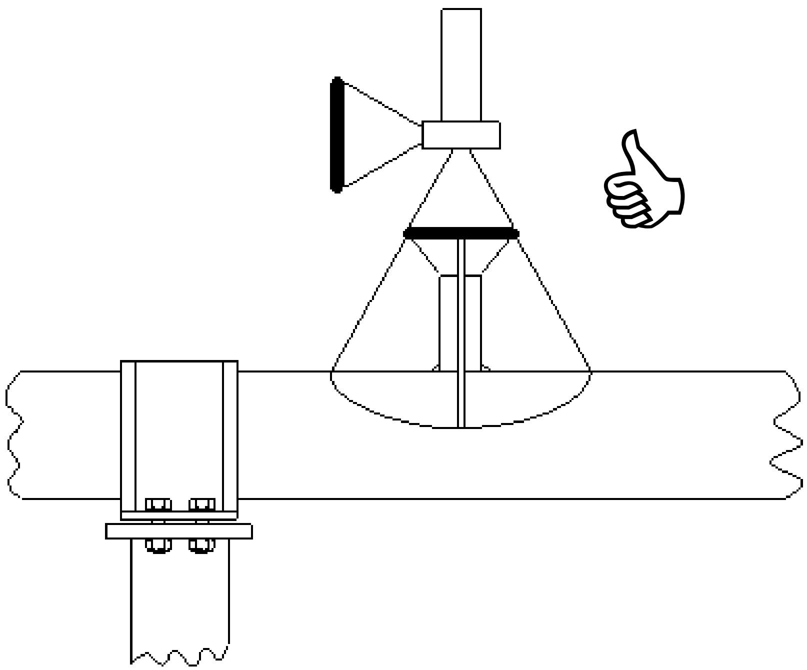


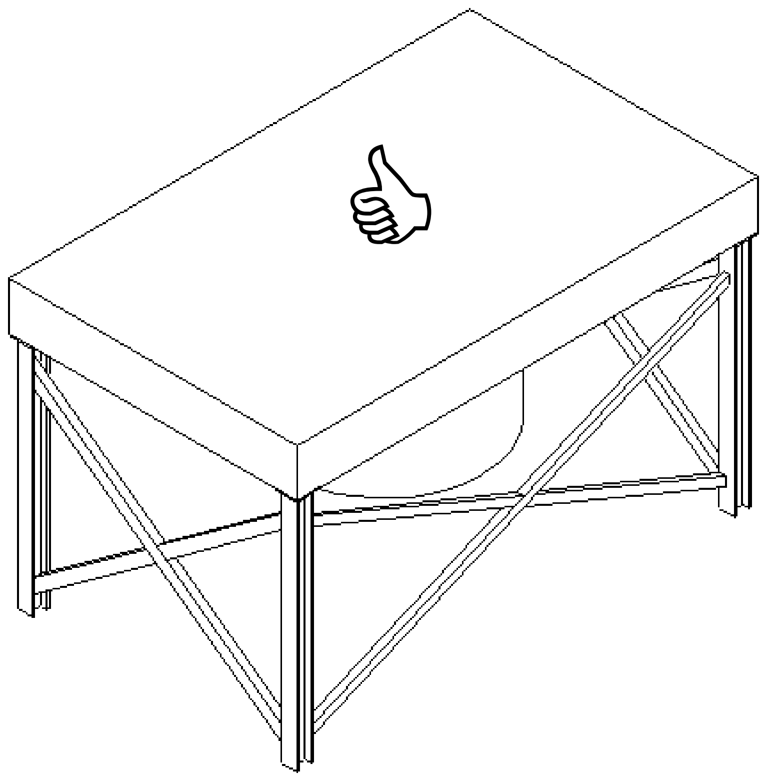




Do’s, Don’ts Design Rules

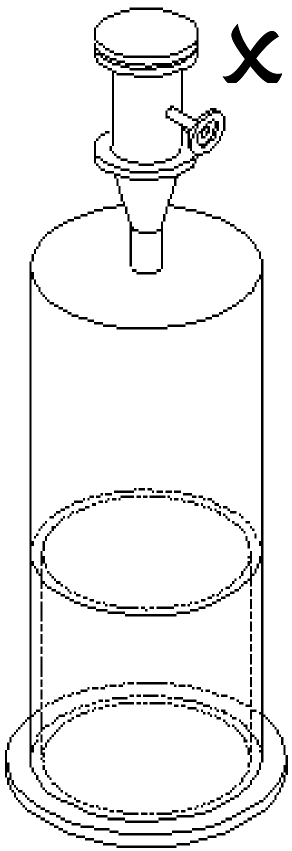
Keep relief valves close to main line – Apply X-bracing in air cooler frames

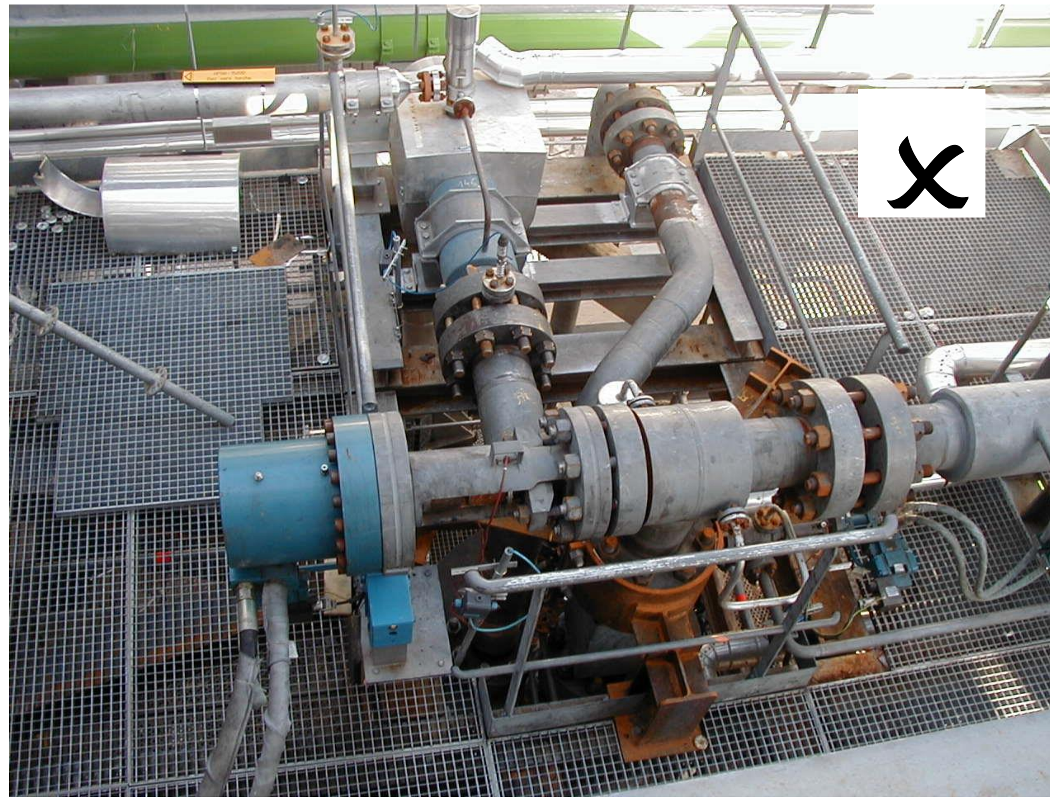




Do's, Don'ts Design Rules

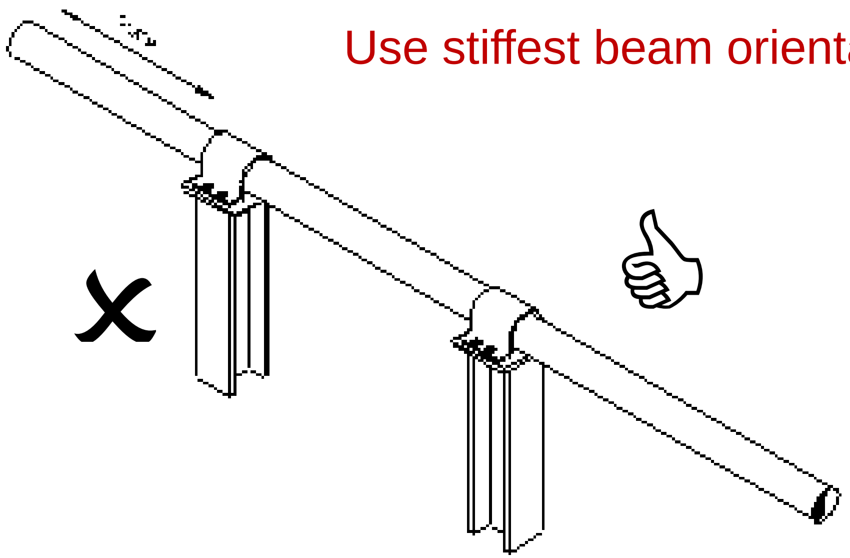
Avoid heavy valves at high elevation (also on top of separators)

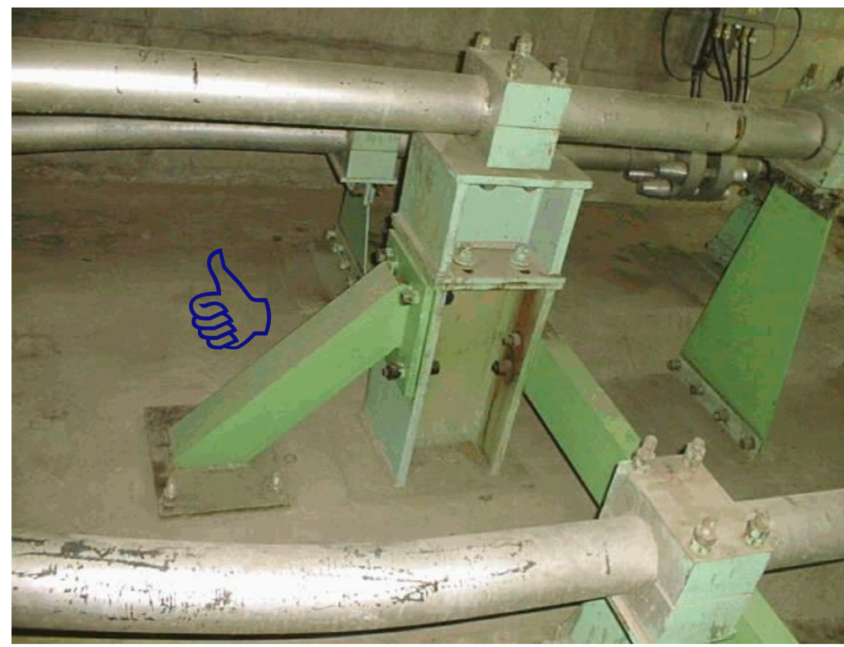




Do’s, Don’ts Design Rules

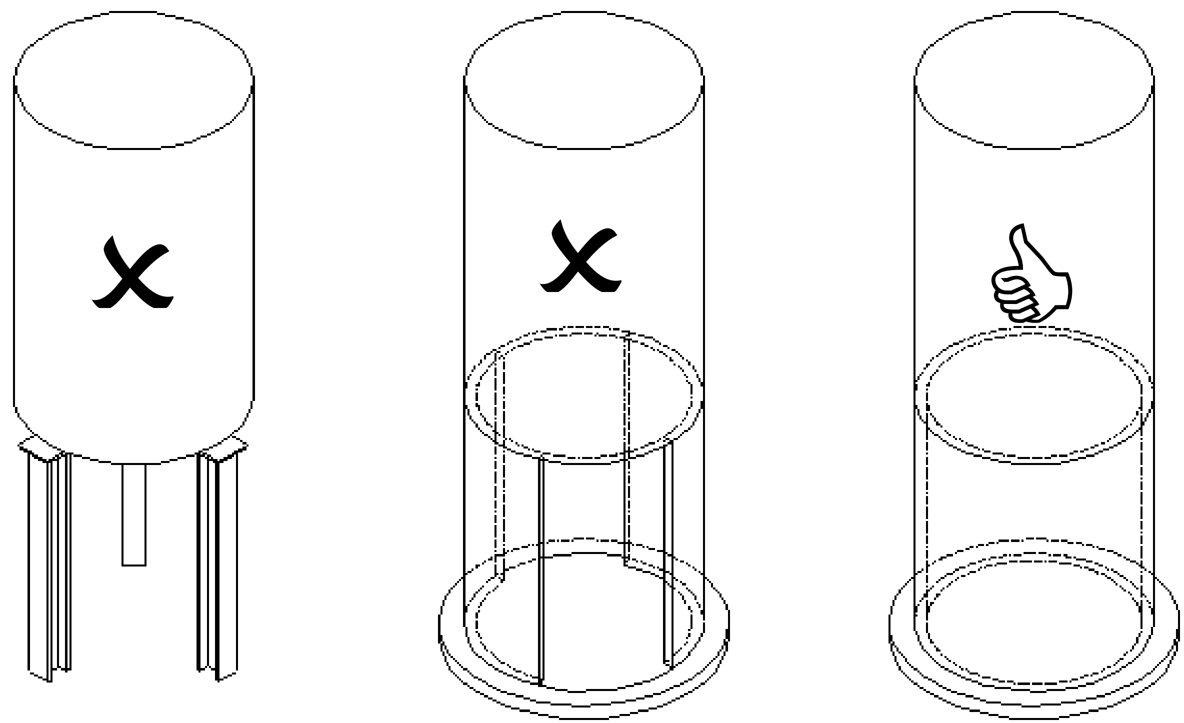
Use stiffest beam orientation in the force direction





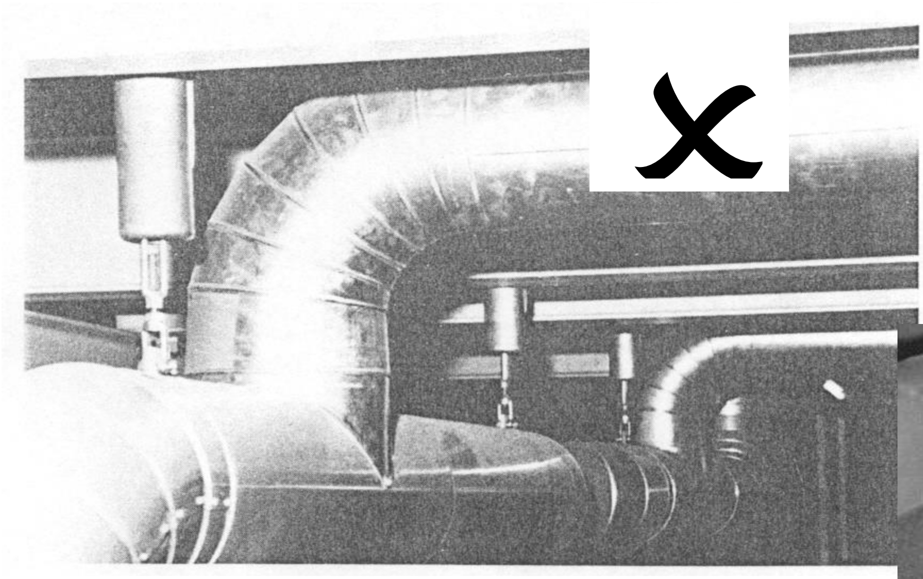
Do's, Don'ts Design Rules

Use full skirts in vessel supporting

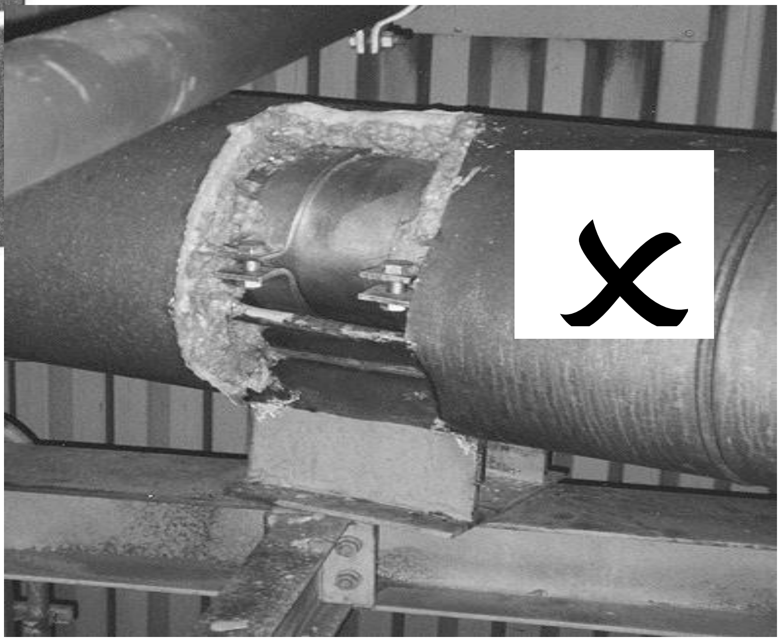


Do's, Don'ts Design Rules

Avoid rod and constant load hangers

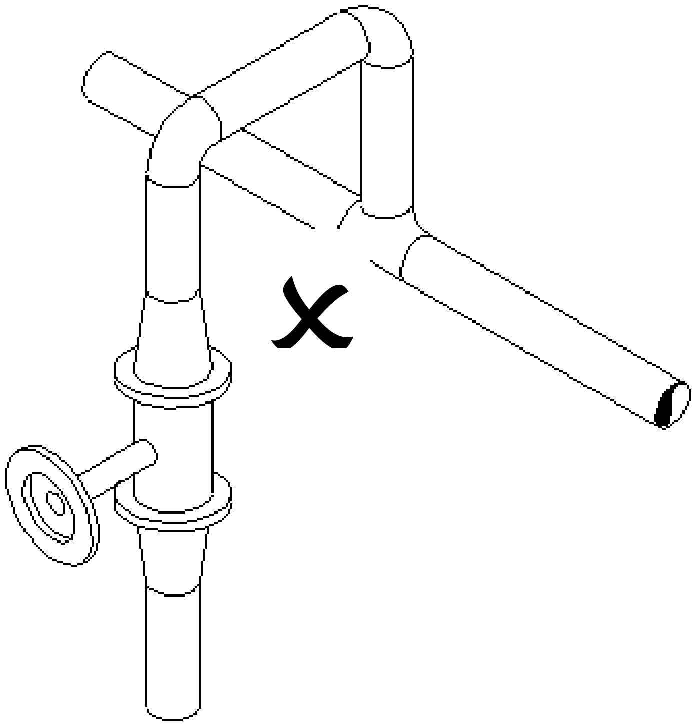


Avoid weight only supports

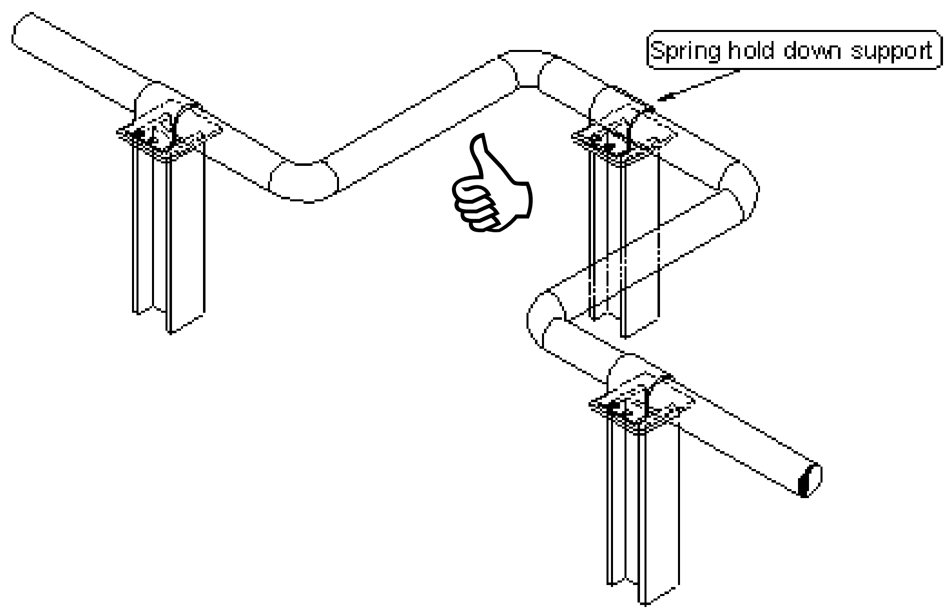


Do's, Don'ts Design Rules

Avoid unsupported overhanging weight



Avoid unsupported expansion loops



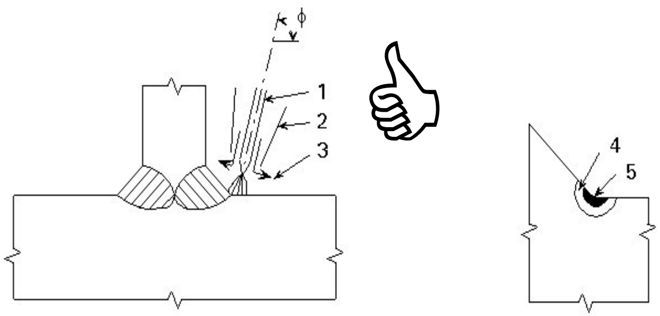
Do’s, Don’ts Engineering Rules

Welds:

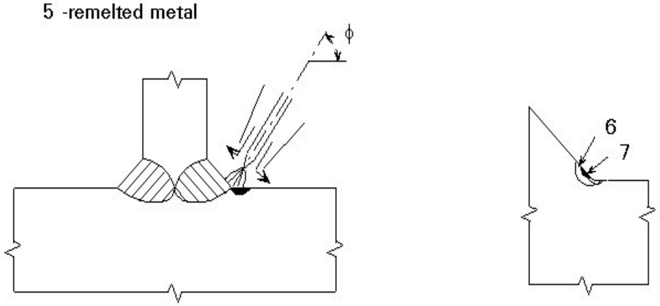
a) avoid weld imperfections

b) apply full penetration welds

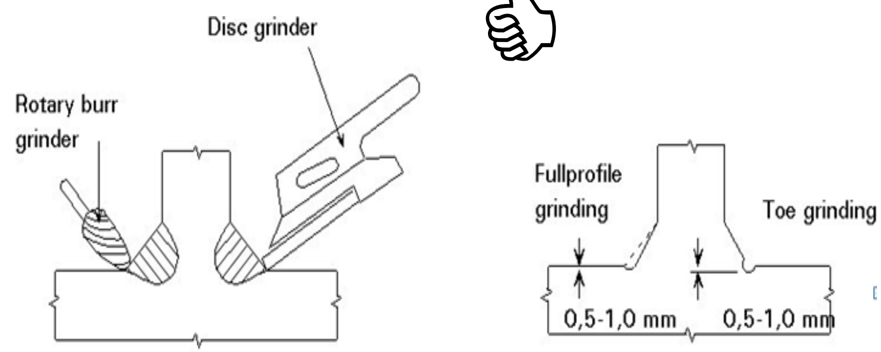
c) avoid sharp corners (grind welds)



(a) Single run
1 -tungsten electrode, 2 - nozzel, 3 -shielding, 4 -HAZ
5 -remelted metal



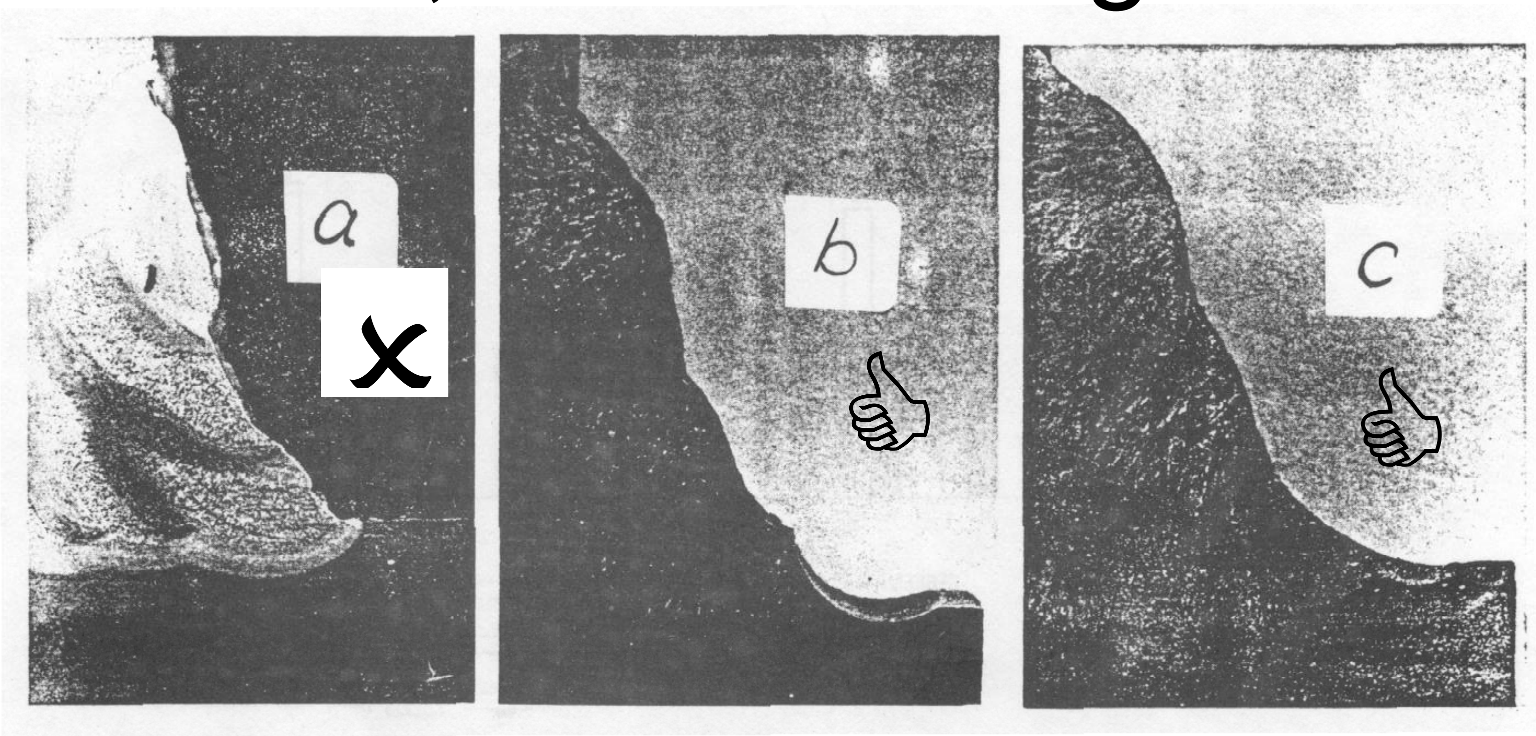
(b) Double run
6 -remelted metal from second TIG run, 7 -HAZ from run ref (8)



(a) 1 -Rotary burr grinding, 2 -Disc grinding

(b) 3 -Full profile grinder, 4 -Toe grinding

Do’s, Don’ts Design Rules



a) as welded
b) after burr grinding
c) after TIG dressing

Do’s, Don’ts Design Rules

Use adequate grouting (epoxy resins)