Training session
Pulsation & Vibration Control

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Delft, The Netherlands

Leonard van Lier,
Lennert Buijs

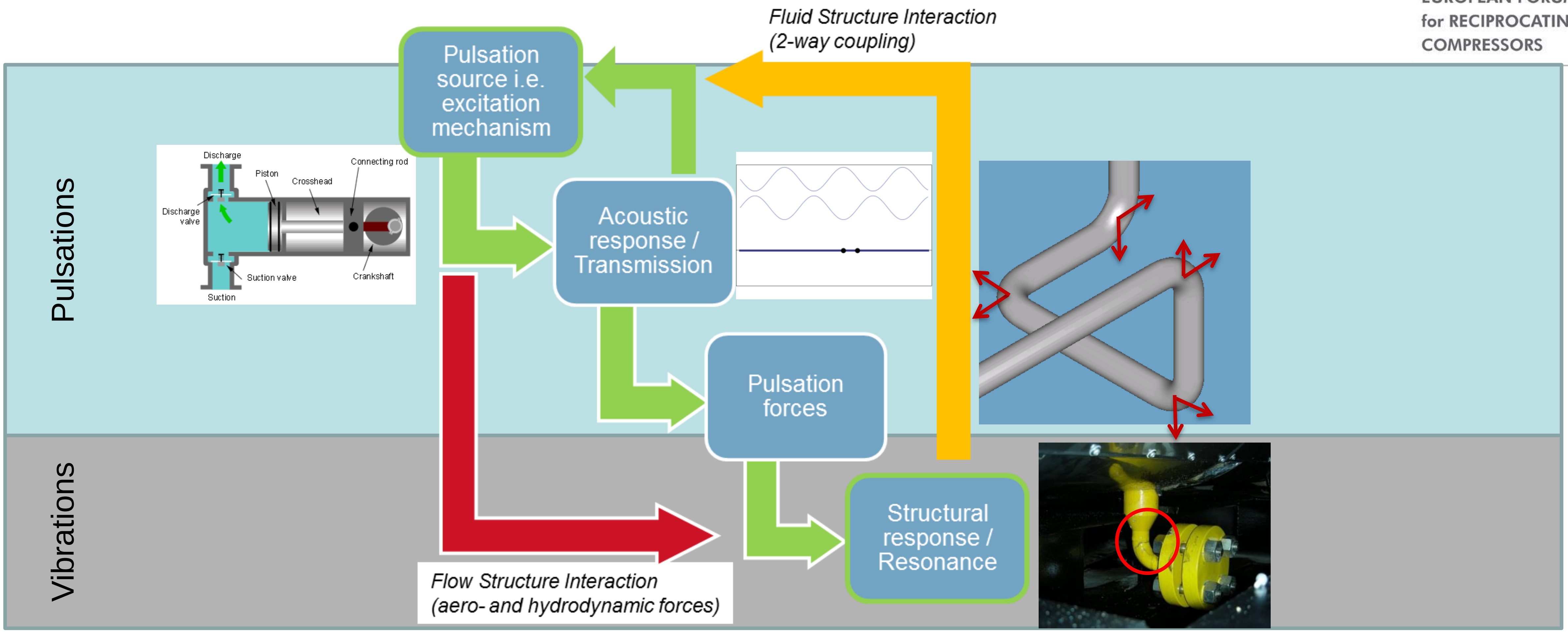
Wijnand Schoemakers

Vibrations

- Vibration is a mechanical phenomenon whereby oscillations occur about an equilibrium point.

- Vibrations may lead to fatigue failure and consequentially:
  - unsafe situations
  - lost of capacity
  - increase in maintenance
  - repair costs

Vibrations


Fluid Structure Interaction (2-way coupling)
Pulsations
Vibrations
Pulsation source i.e. excitation mechanism
Acoustic response / Transmission
Pulsation forces
Structural response / Resonance
Flow Structure Interaction (aero- and hydrodynamic forces)
Discharge
Piston
Crosshead
Connecting rod
Discharge valve
Suction valve
Crankshaft
Suction

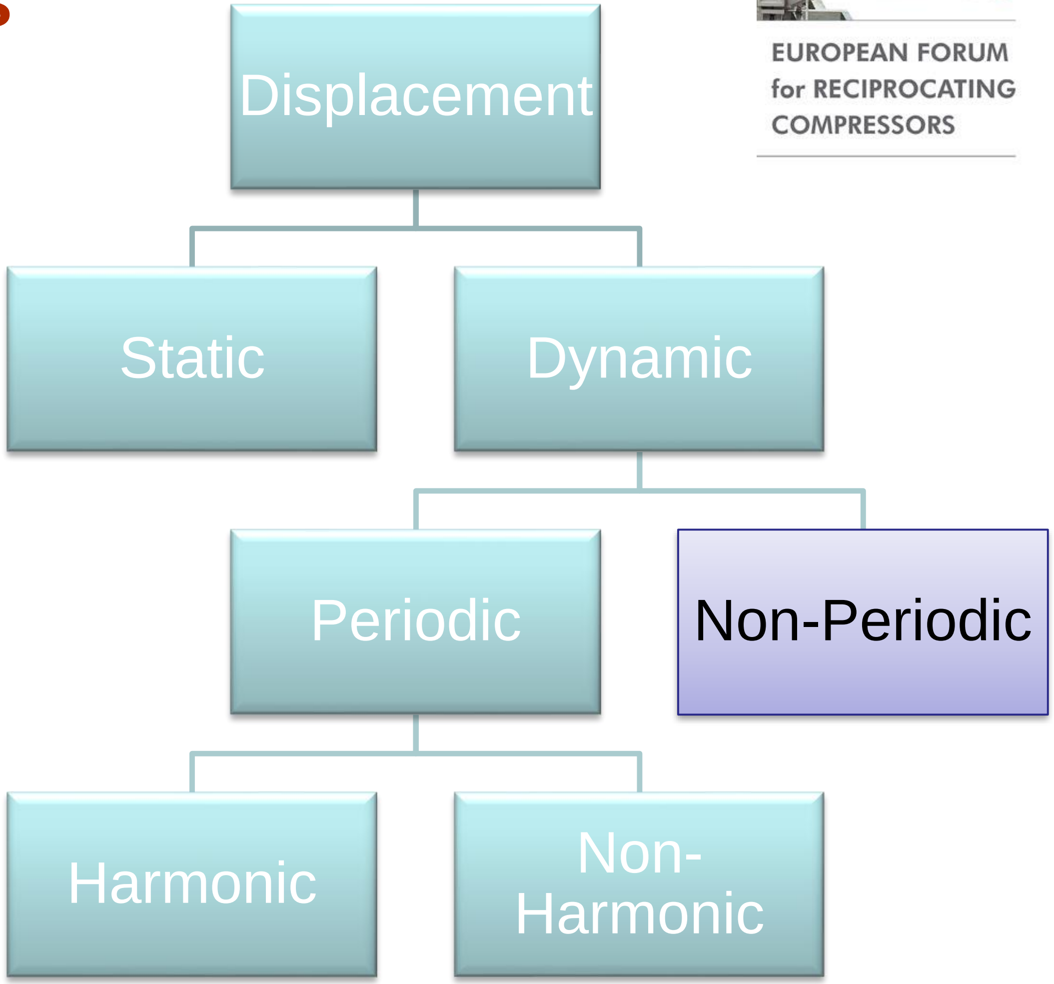
Vibrations

- **Vibration types**
- Description of vibrations
- Vibration sources
- Evaluation of vibrations
- Vibration Mitigation
  - Analyses
  - In practice
- Basic guidelines

Vibration types

- Non-Periodic Vibrations
  - Results from transient or random forces

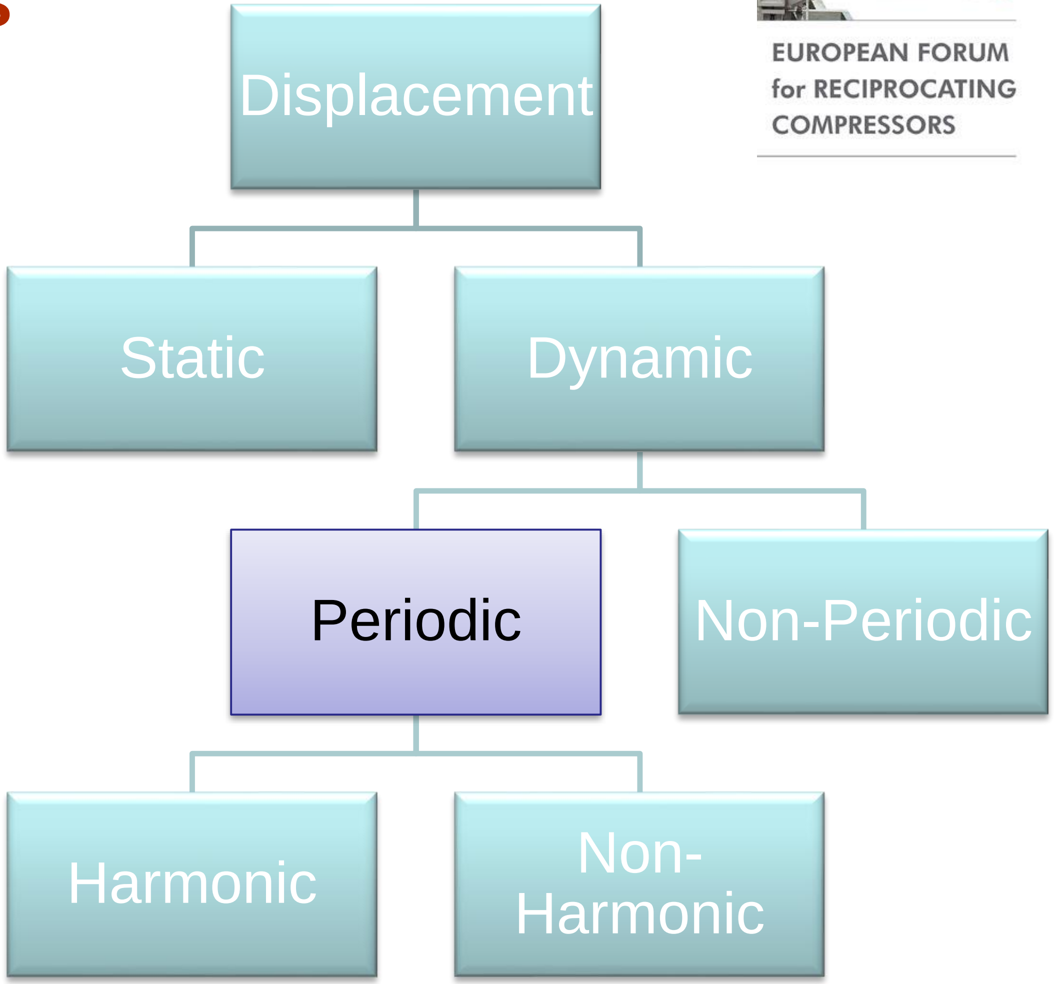
- Examples:
  - Vibrations of a bridge due to traffic
  - Vibration of a building due to wind



Vibration types

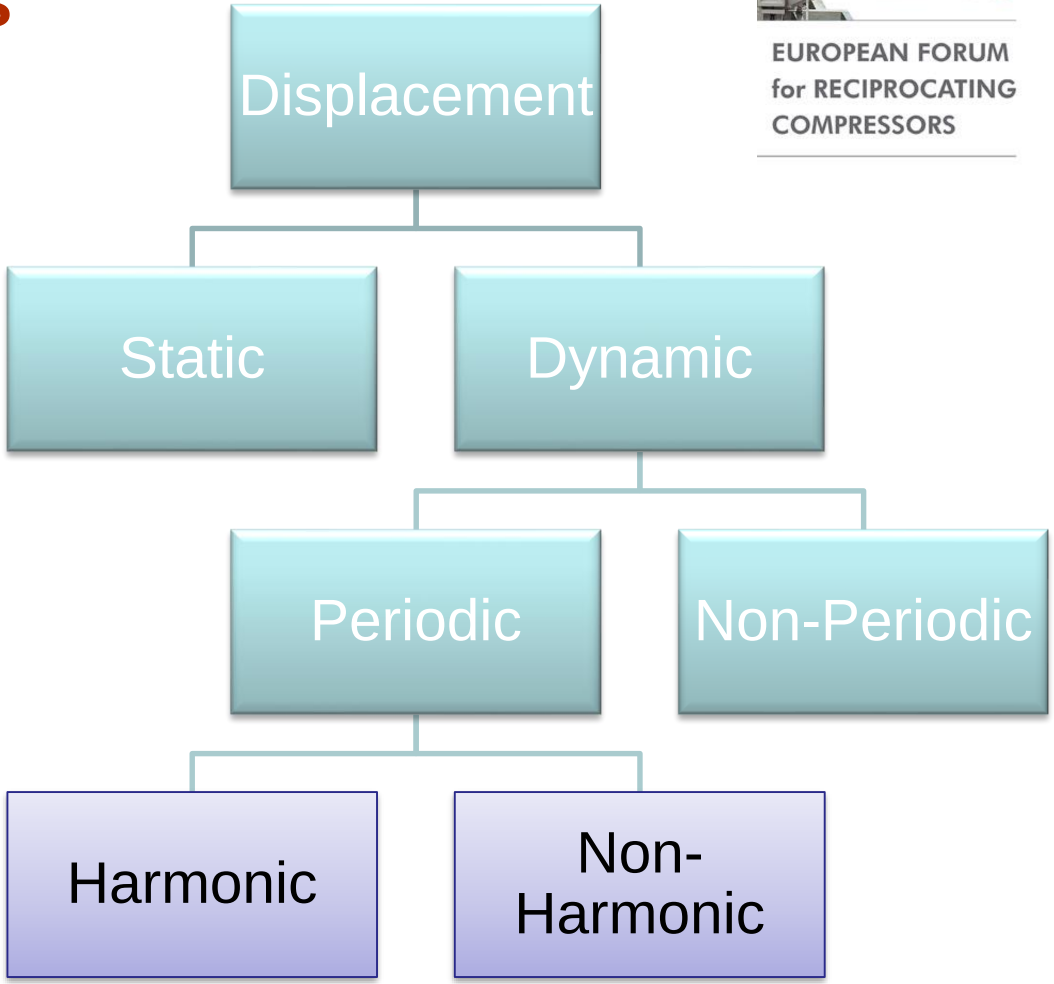
- Periodic Vibrations
  - Results from periodic forces, where the amplitude is repeated after a discrete time period.

- Examples:
  - Combustion forces in a cylinder
  - Reciprocating forces
  - Pulsation-induced forces



Vibration types

- Harmonic Vibrations
  - Vibration of which the amplitude is a sine
  - Can only occur when the excitation force exists of only one frequency component
- Non-harmonic vibrations:
  - The result of two or more added harmonic vibrations with different frequencies



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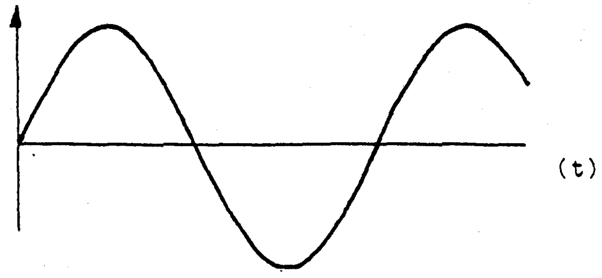

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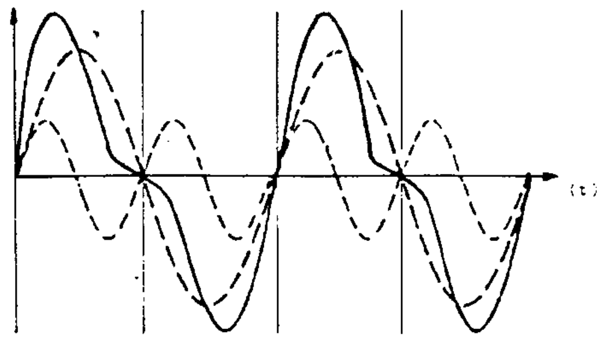
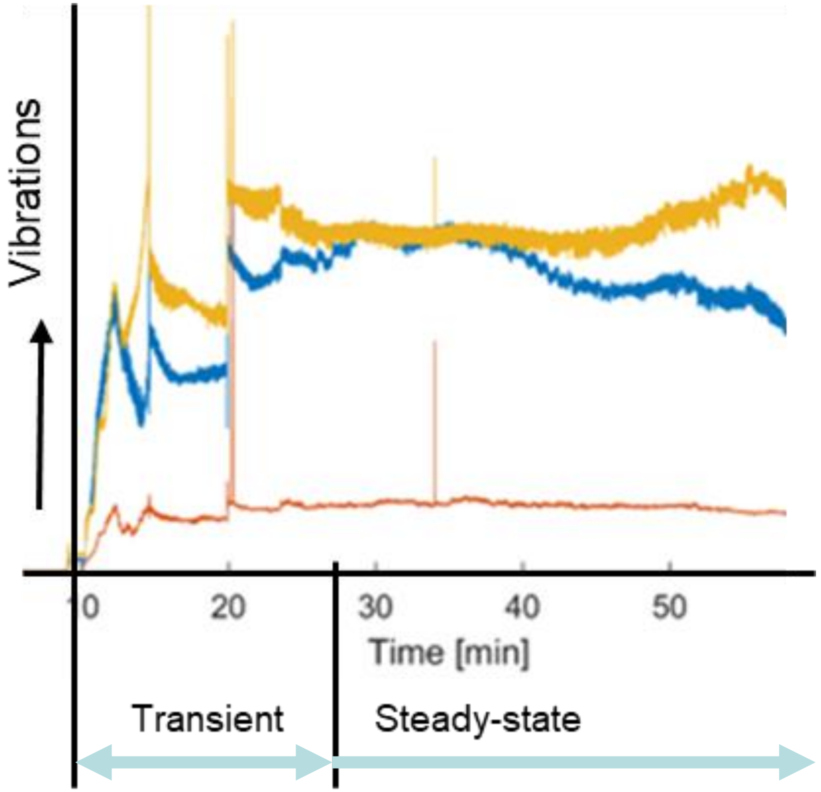


Vibration types

- Transient vibration:
  - the response of a system to a sudden change from an equilibrium or a steady state (start/stop of a machine, severe slugging, opening of a relief valve, etc.)
- Steady-state vibration
  - the behavior of a mechanical system after a time when steady conditions have been reached after a transient excitation



Vibrations

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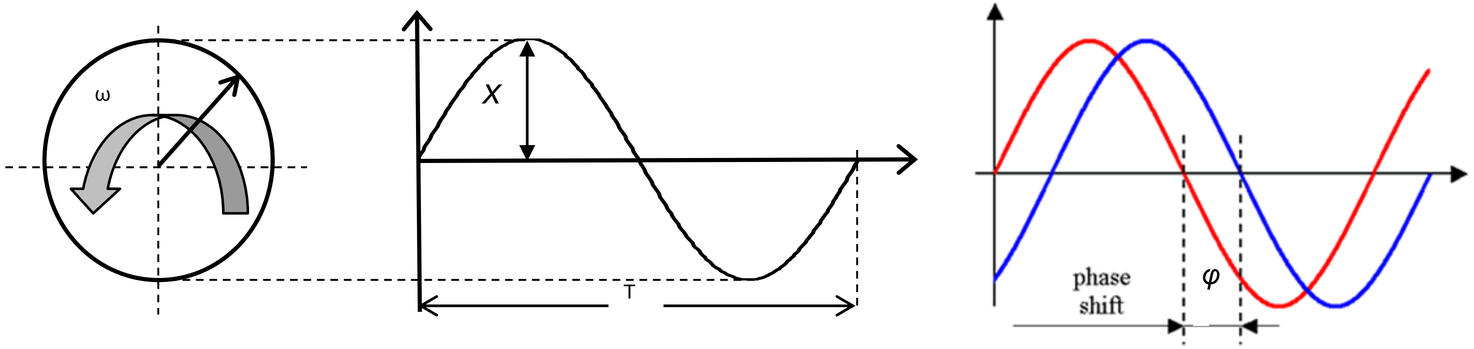
Harmonic Vibrations



- $x = \hat{x}\sin(\omega t + \varphi)$

- Amplitude ($\hat{x}$): The maximum value of the sine over one period
- Angular velocity (ω): 2p times the frequency f
- Phase angle(φ): the argument of the sine function as follows:

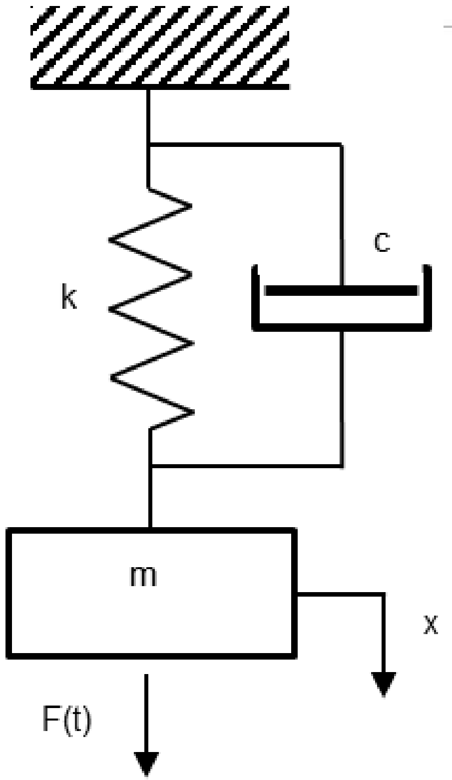
- Period (T): the time T is the time after which the vibration repeats
- Frequency (f): number of periods in 1 seconds ($f = 1/T$) [Hz]

Vibrations - Single degree of freedom system

- General equation of motion of a SDOF

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

- With:
- x displacement, $\dot{x}$ velocity, $\ddot{x}$ acceleration
- m mass, c viscous damping, k spring stiffness
- F excitation force, $j = \sqrt{-1}$, ω excitation frequency



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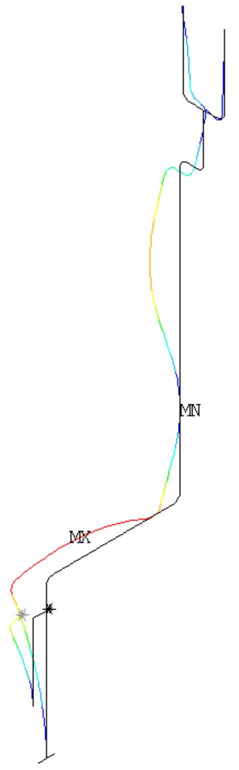
Vibrations – Free undampened vibrations

- Solving the equation from previous slide, with
  - $c = 0$, $F = 0$
  - $\omega_0 = \sqrt{k/m}$ → Mechanical Natural Frequency (MNF)

- Mode shape (eigen vector):
  - is the ratio of the amplitudes at various points;
  - represents a deformation pattern of the structure for the corresponding natural frequency.

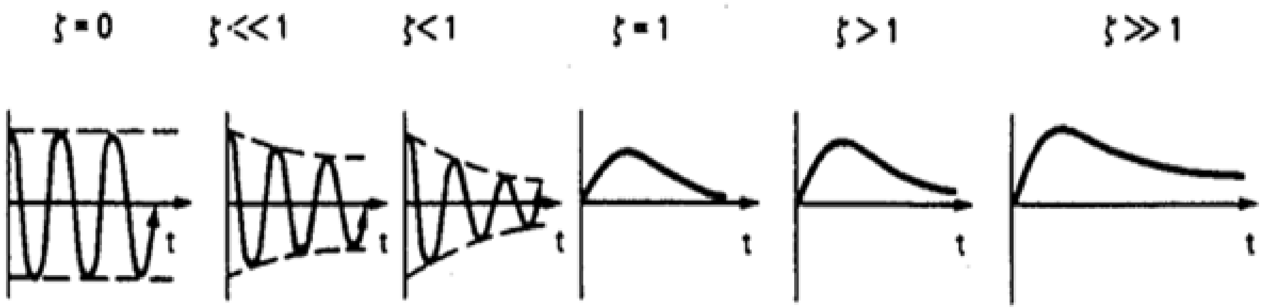


Vibrations – Free damped vibrations

- Solving the equation from previous slide, with
  - $c \neq 0$, $F = 0$
  - $\omega_d = \omega_0\sqrt{1-\zeta^2}$ → Damped natural frequency
- Damping ratio, related to the critical damping:
  - $\zeta = \frac{c}{c_c} = \frac{c}{2\sqrt{km}}$

Vibrations – Possible solutions

- Solutions for ζ = 0:
  - undamped vibrations at the natural frequency of the system
- Solutions for 0 < ζ < 1:
  - underdamped case
- Solutions for ζ =1:
  - critically damped case
- Solutions for ζ > 1:
  - overdamped case



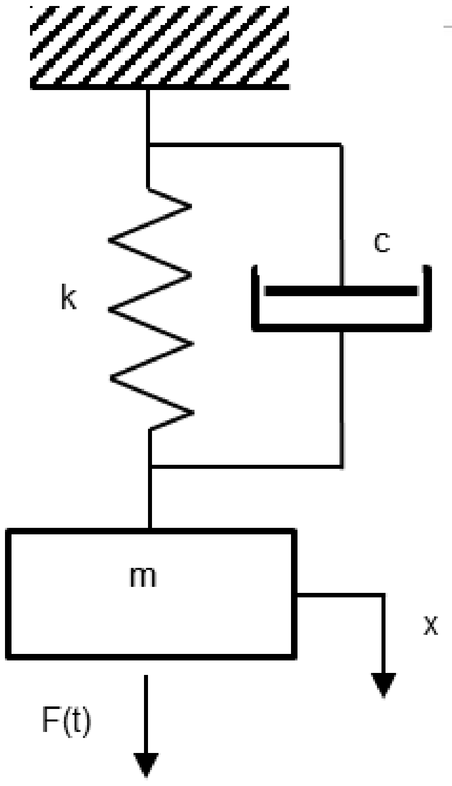
Vibrations as a function of time and damping ratio ζ

Vibrations – Forced vibrations

- General equation of motion of a SDOF
  - $m\ddot{x} + c\dot{x} + kx = Fe^{j\omega t}$

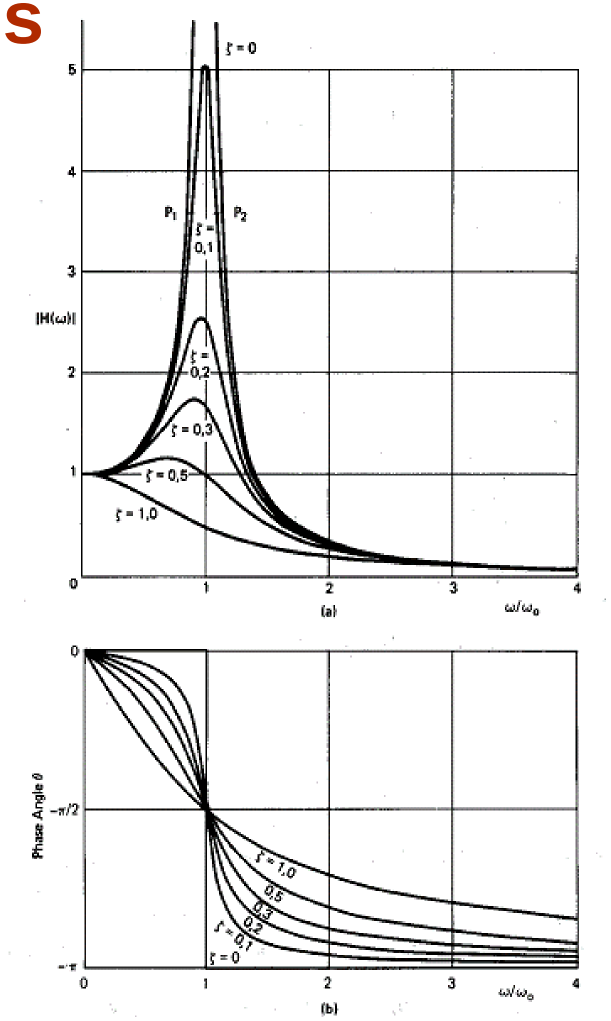
- Steady state solution:
  - $x = \left[\frac{1}{\sqrt{(1-(\omega/\omega_0)^2)^2+\left(2\zeta(\omega/\omega_0)\right)^2}}\right]\frac{F}{k}e^{j(\omega t-\theta)}$

- Proportionality factor:
  - $H(\omega) = \left[\frac{1}{\sqrt{(1-(\omega/\omega_0)^2)^2+\left(2\zeta(\omega/\omega_0)\right)^2}}\right]$



Vibrations - Resonances

- If excitation frequency $\omega = \omega_0$ → resonance
  - $\omega_d = \omega_0\sqrt{1-\zeta^2}$
  - $H(\omega) = \frac{1}{2\zeta\sqrt{1-\zeta^2}}$
- For light damping (ζ < 5%), the magnification is:
- $H(\omega) = \frac{1}{2\zeta}$ → for ζ = 2%, $H(\omega)$ = 25!



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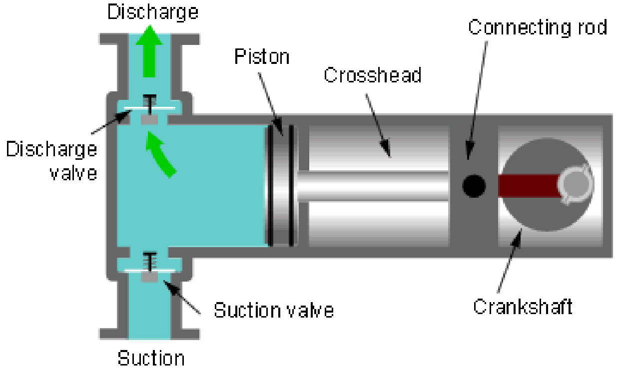
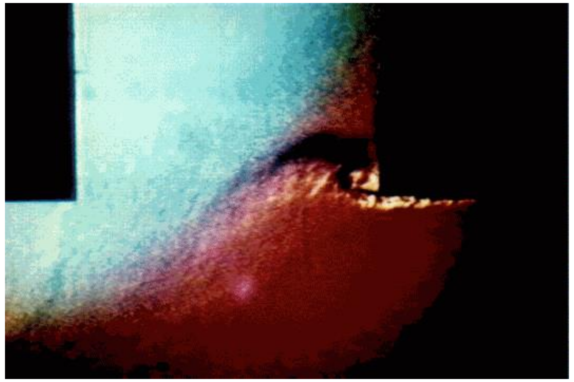
Vibration sources

- Pressure pulsation induced forces
  - Compressor pulses
  - FIP sources
  - Flow transients / pressure surge



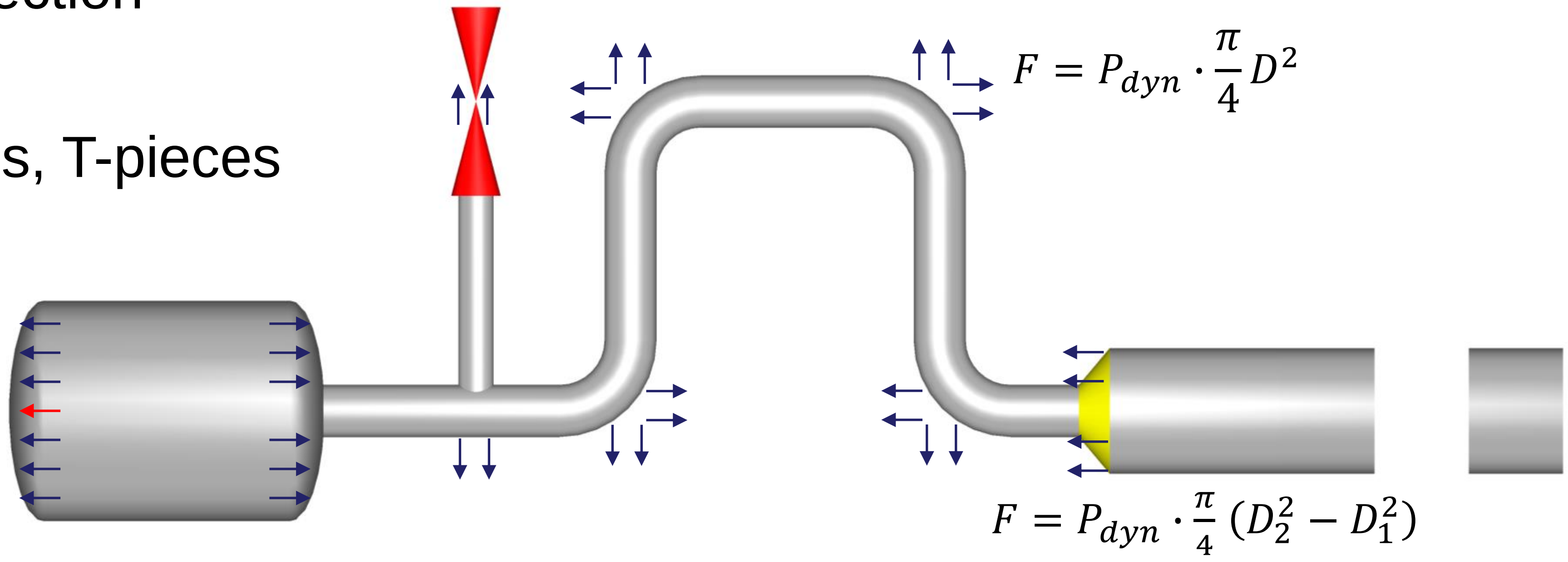


- Multiphase flow induced forces

- Mechanically induced/transferred
  - Compressor free forces and moments

Vibrations – Forcing in pipe systems

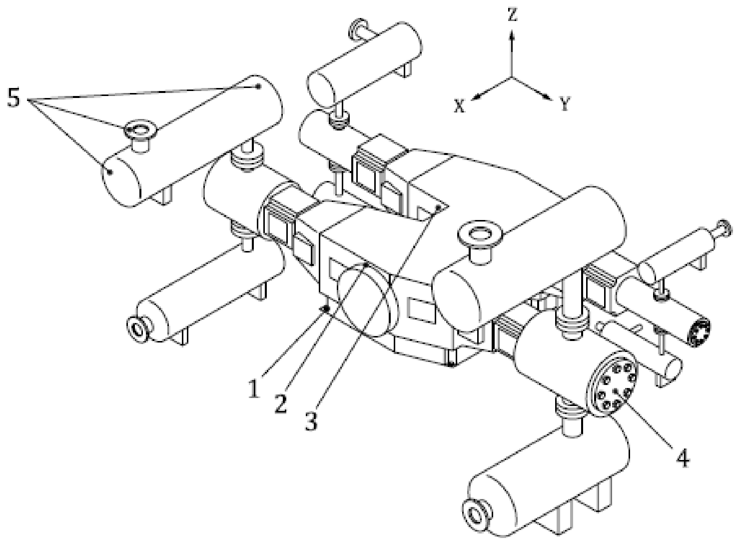
- Pressure pulsation induced forces act on locations with:
  - Diameter changes
  - Change in pipe direction
- Elbows, reducers, caps, T-pieces



Vibrations - Evaluation

- Design:
  - API 618 – 5th edition
  - API 688 in future

- In field:
  - ISO 20816-8 (Measurement and evaluation of machine vibration - Part 8: Reciprocating compressor systems)



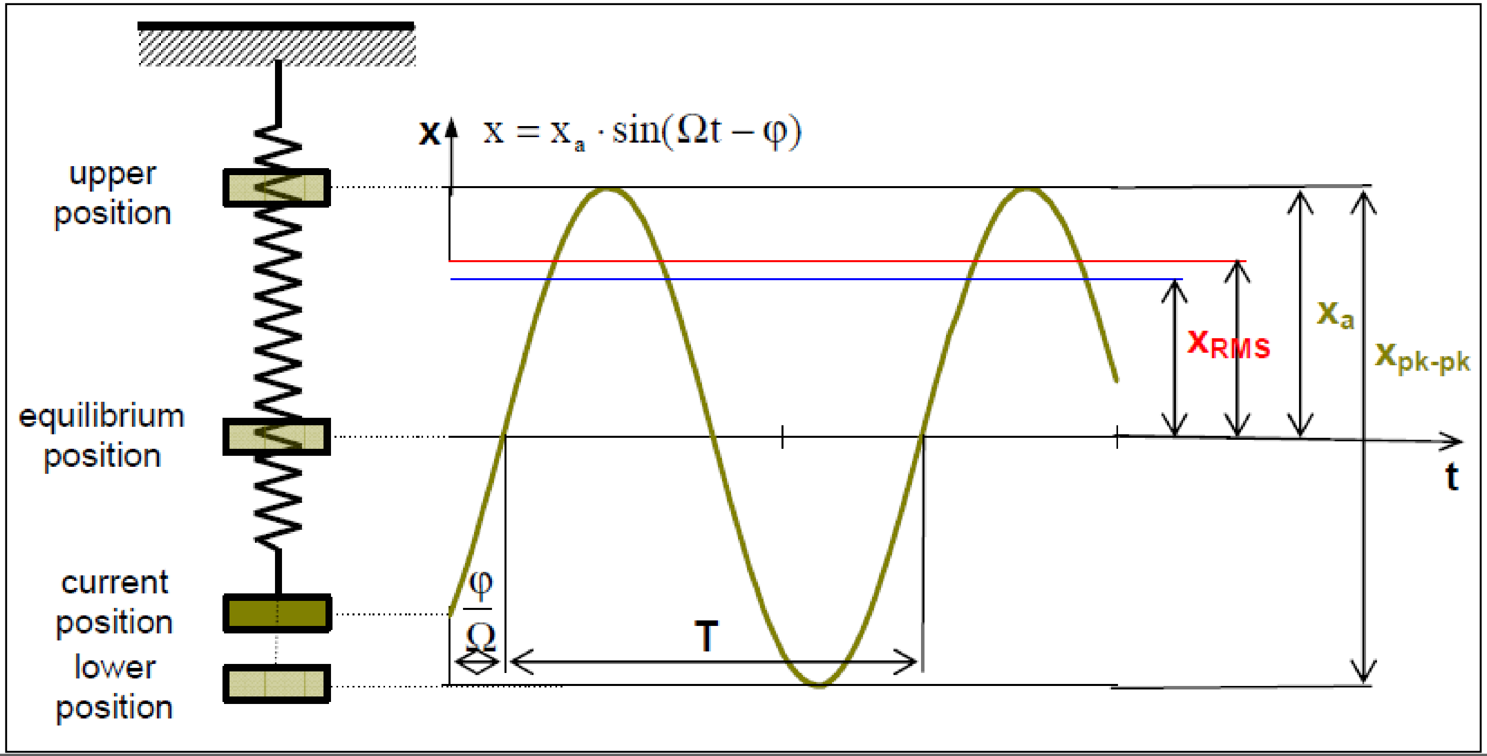
Many more standards, like AVIFF, VDI, etc.

Vibrations - Evaluation

- Different norms/standards have different allowable levels:
  - RMS
  - Amplitude
  - PkPk

  - Crest Factor

    $CF = X_a / X_{RMS}$



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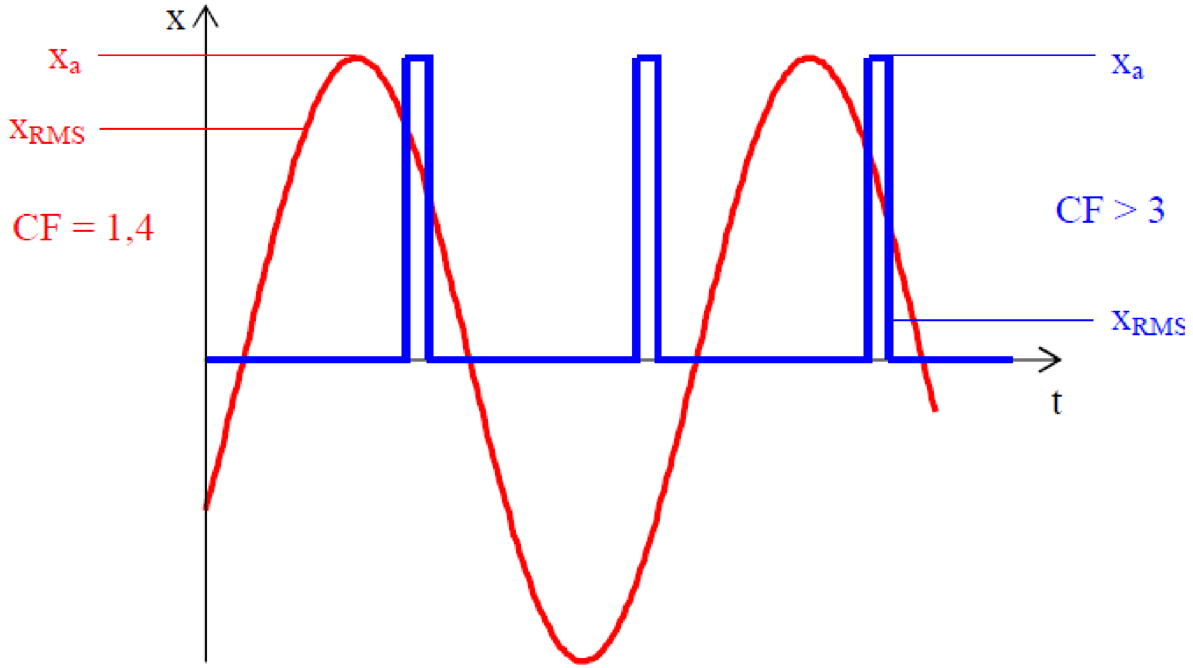

Vibrations - Evaluation

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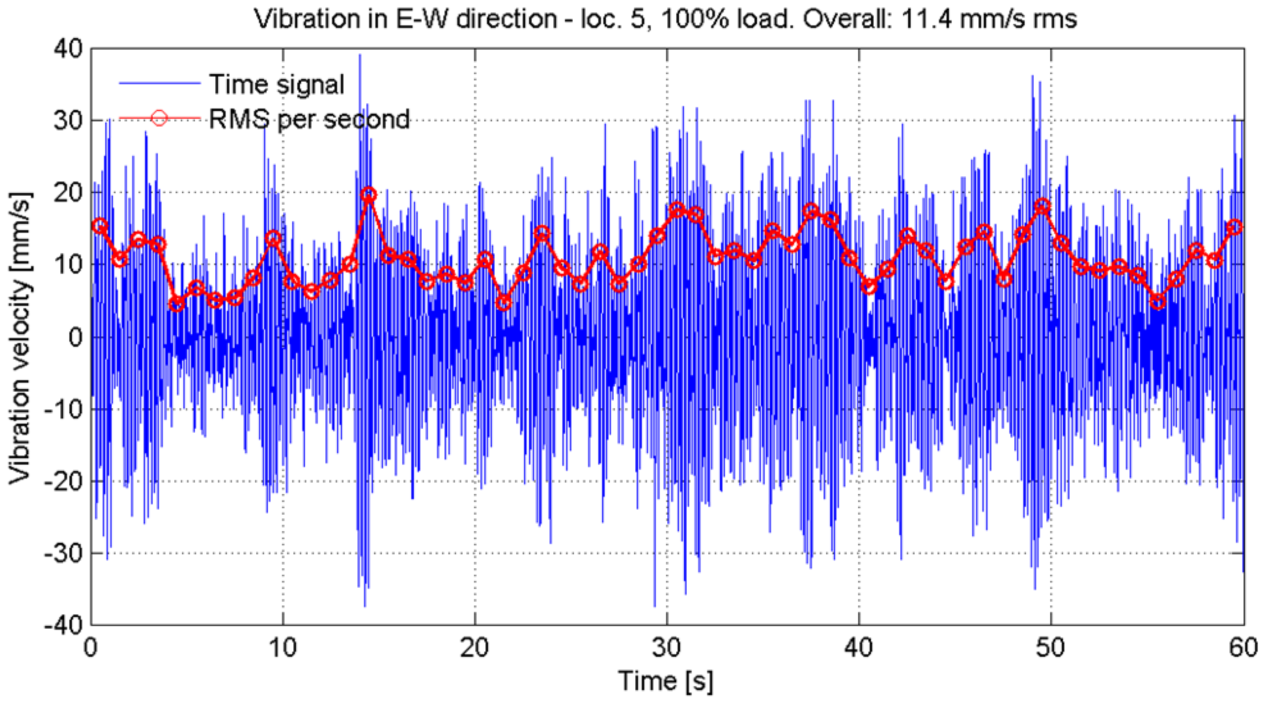

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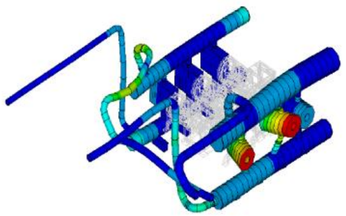
Vibrations

- Typical steps in a mechanical analysis of pipe systems



FEM model of pipe system

General FE programs, e.g. ANSYS

Natural frequencies, mode shapes

Non-resonance system?

YES

NO

Modifications

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

maximum forces and phases from e.g. pulsation analysis (worst-case situations), mechanical loads and cylinder stretch loads

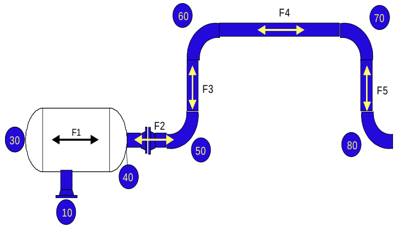
Response calculation

Pulsation analysis

Vibrations, cyclic stresses allowable

NO

YES



OPTIMAL DESIGN

Vibrations – non-resonance system

- Non-resonance systems will have acceptable vibration and cyclic stress levels → no fatigue failure

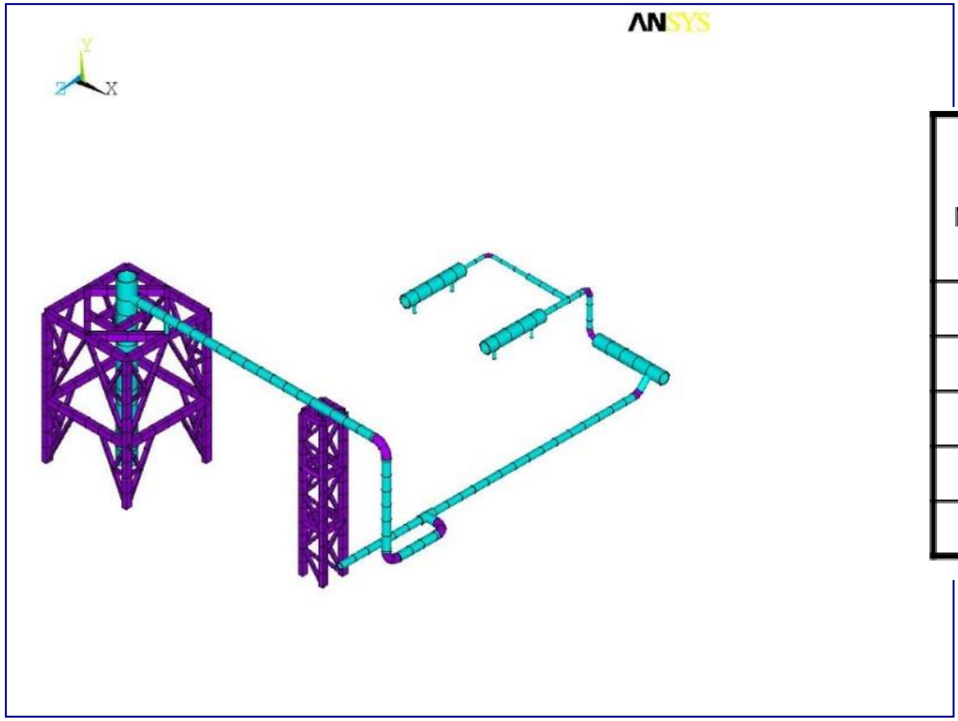
- To achieve non-resonant systems:
    - Maximum pipe supports span shall be such that frequency of dominant forces shall not coincide within a range of $\pm 20\%$ with MNF's ($\omega \neq \omega_0$)
    - Number of pipe supports can be considerable, especially for small pipes and high speed machines

Vibrations – non-resonance system

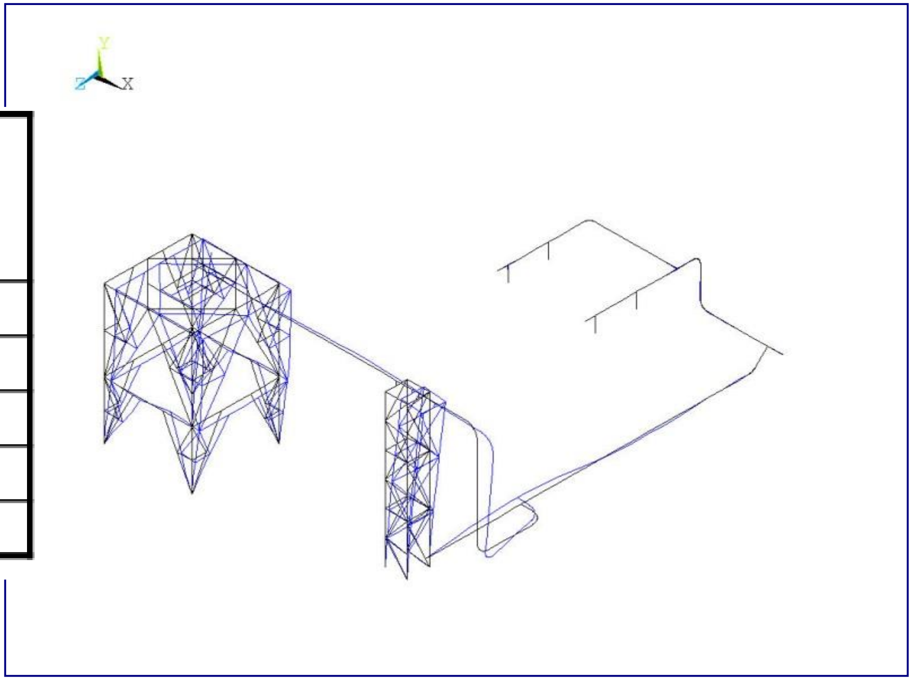
- Most effective way: achieving a system which will not be excited in its resonance conditions: called non-resonant system (acceptable vibration and cyclic stress levels)

- Non-resonant systems are in general very difficult to achieve in reality due to:
  - Too flexible supporting structures
  - No stiff structures in the vicinity to mount pipe supports
  - Variable speed compressors and pumps (several MNF’s in speed range)

Vibrations



Mode shape Number	Frequency [Hz] Without Rack	Frequency [Hz] Racks included
1	19.9	12.8
2	25.1	18.6
3	26.3	19.1
4	28.2	20.5
5	28.7	24.2



Vibrations – how to optimize the design

- Possibilities:
  - Add pipe supports
  - Increase steel structure stiffness (braces)
  - Change masses

change MNF of system

  - Viscous dampers
  - Tuned Mass Damper (TMD)
  - Constrained layer damping
  - Change source strength / frequency

Vibrations – pipe supports

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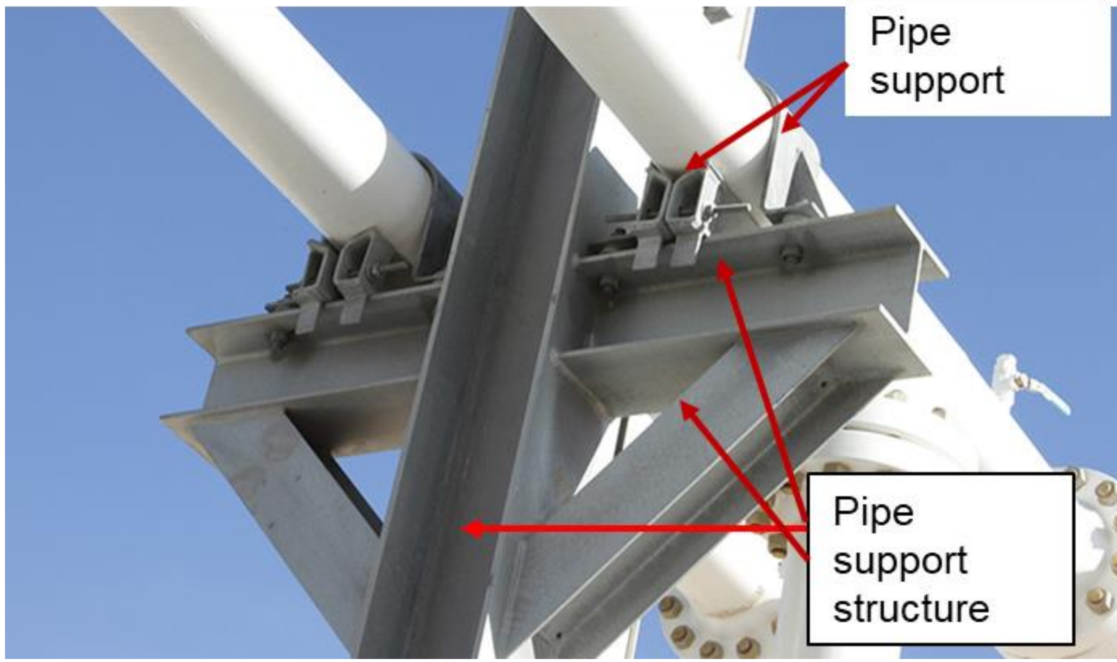
- Connection of pipe with (steel) structure shall be suitable to restrain the dynamic loads
- Support layout is in general optimised to allow thermal expansion → flexible system required:
- This is in conflict with a “dynamic” design to keep vibrations acceptable

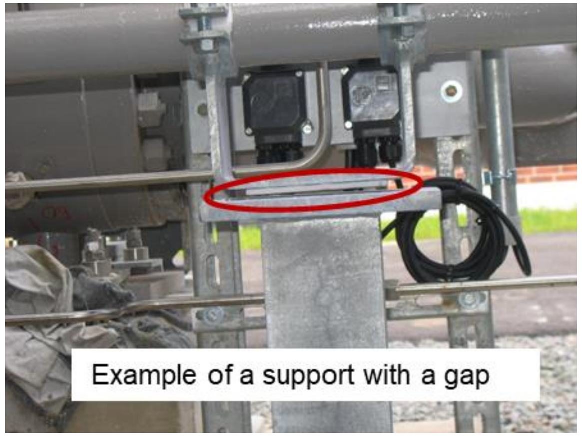


Vibrations – how to optimize the design

- Typical applied supports in thermal design:
- Spring hangers
  - Are very flexible elements which lead in general to very low MNF’s and unacceptable pipe vibrations

Typical spring hanger support

- Rest type supports
  - not always able to restrain the dynamic loads if:
    - friction force between support and support structure is too small
    - extreme case: pipe is lifted-off (happens often during start-up due to thermal expansion)



Example of a support with a gap

Vibrations – how to optimize the design

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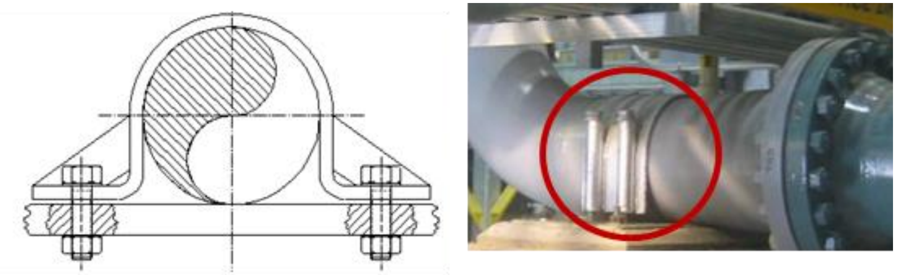
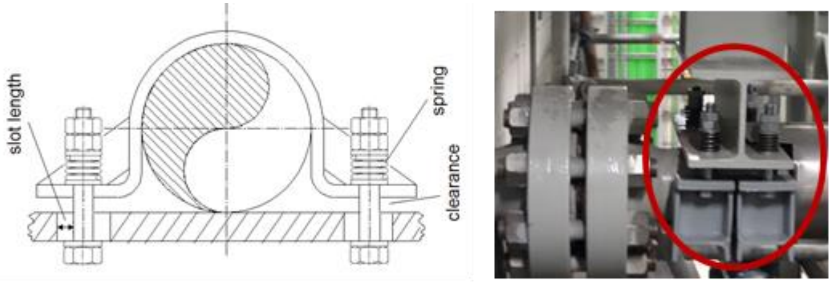
Vibrations – how to optimize the design

- Preferred supports:
  - Rigid Clamp (U-bolt is not rigid enough)
    - can introduce too high expansion stress
  - Spring hold down support
    - allows thermal expansion and restrain dynamic loads (enough friction)



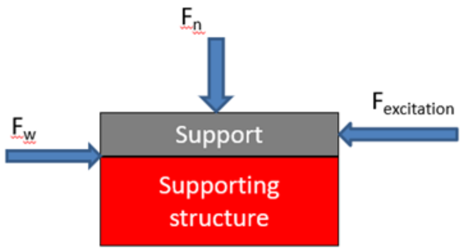
Examples of rigid clamp supports



Examples of spring hold down supports

Vibrations – how to optimize the design

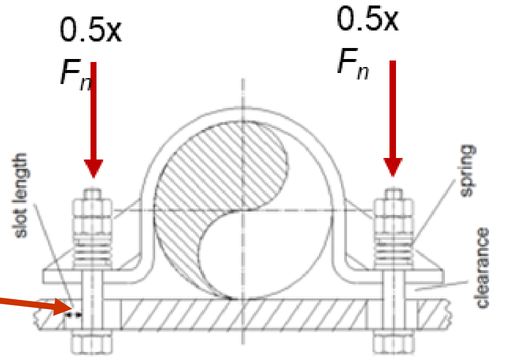
- Design parameters for spring hold down supports:



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

$F_{n=}$ **Total** bolt preload
$F_{excitation}$ = excitation force
F_w= friction force > $F_{excitation}$
f = friction coefficient

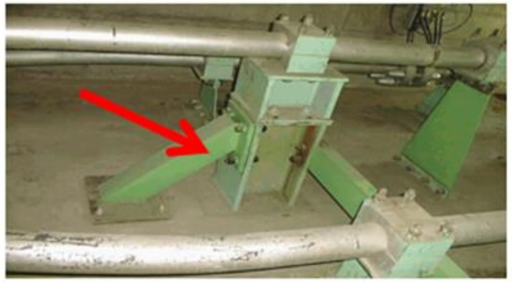
- Preload per bolt: F_n / number of bolts
- Slot length: > thermal expansion
- f (friction coefficient):
  - steel-steel ≈ 0.3
  - steel-teflon ≈ 0.1 (F_n teflon = 3 x F_n steel !)



Spring hold down with 2 bolts

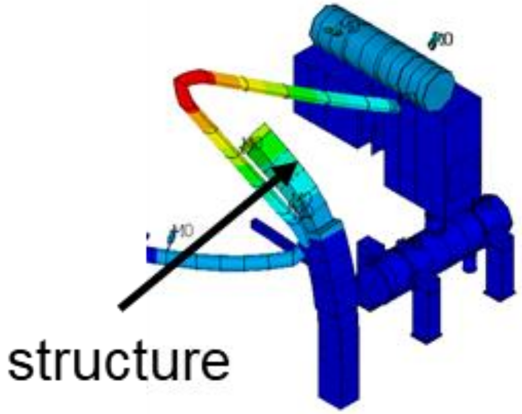
Vibrations – how to optimize the design

- Increase steel structure stiffness



- Braces
- Correct orientation of beams

- This methodology is not always effective for vibrations at high frequencies:
  - Structure can become in resonance and does not add to the stiffness.



Vibrations – how to optimize the design

- Viscous dampers:

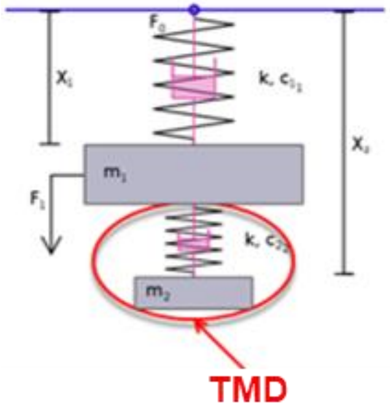
- Require very stiff steel structure to restrain damping force.
- Advantages:
  - high damping ratio
  - works in 3 directions
  - allow thermal motion (up to 120 mm)
- Disadvantages:
  - costs are higher than for a pipe clamp
  - lower damping ratio for high frequencies:

Vibrations – how to optimize the design

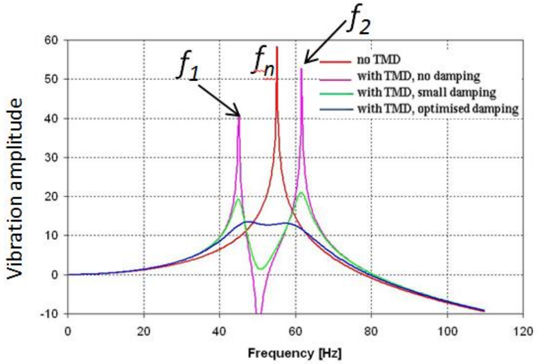
- Tuned Mass Damper (TMD)
  - consists of a mass, spring and damper
  - frequently seen in buildings, not (yet) in compressor systems

Taipei tower, Taiwan

Millennium bridge London



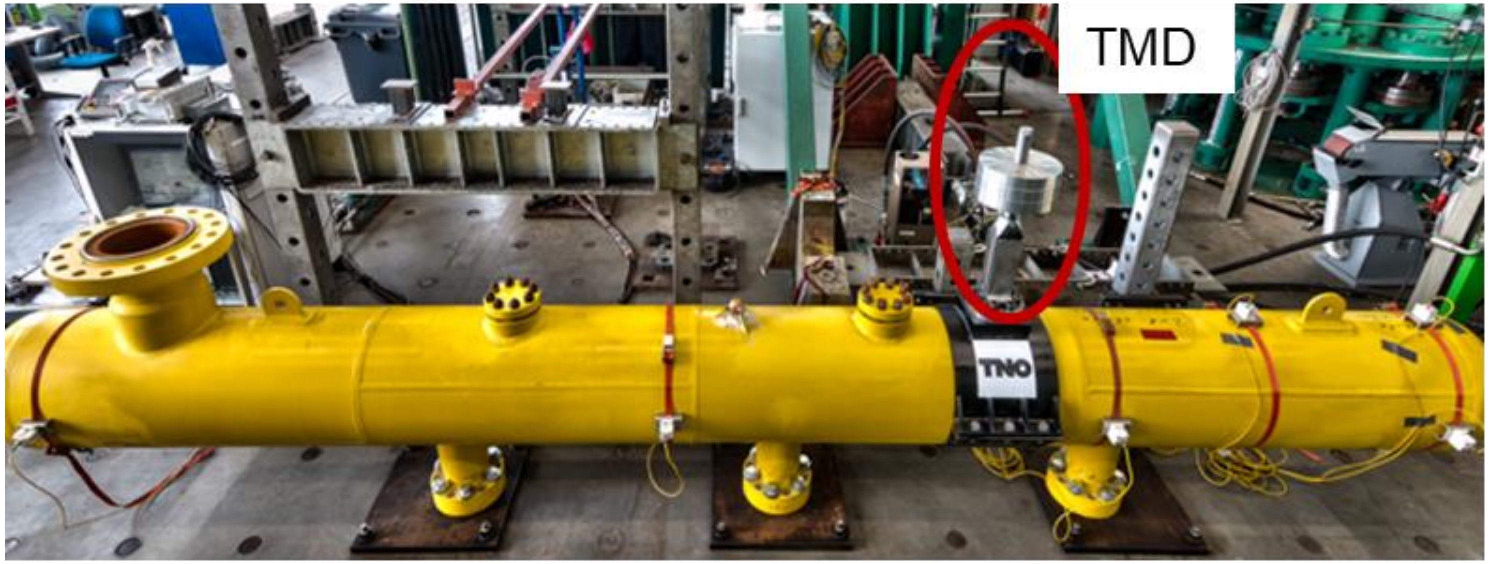
- Based on detuning MNF’s from excitation frequencies
- The TMD is connected to the structure to be mitigated
- A TMD shall always be tuned in the field



Frequency response function

Vibrations – how to optimize the design

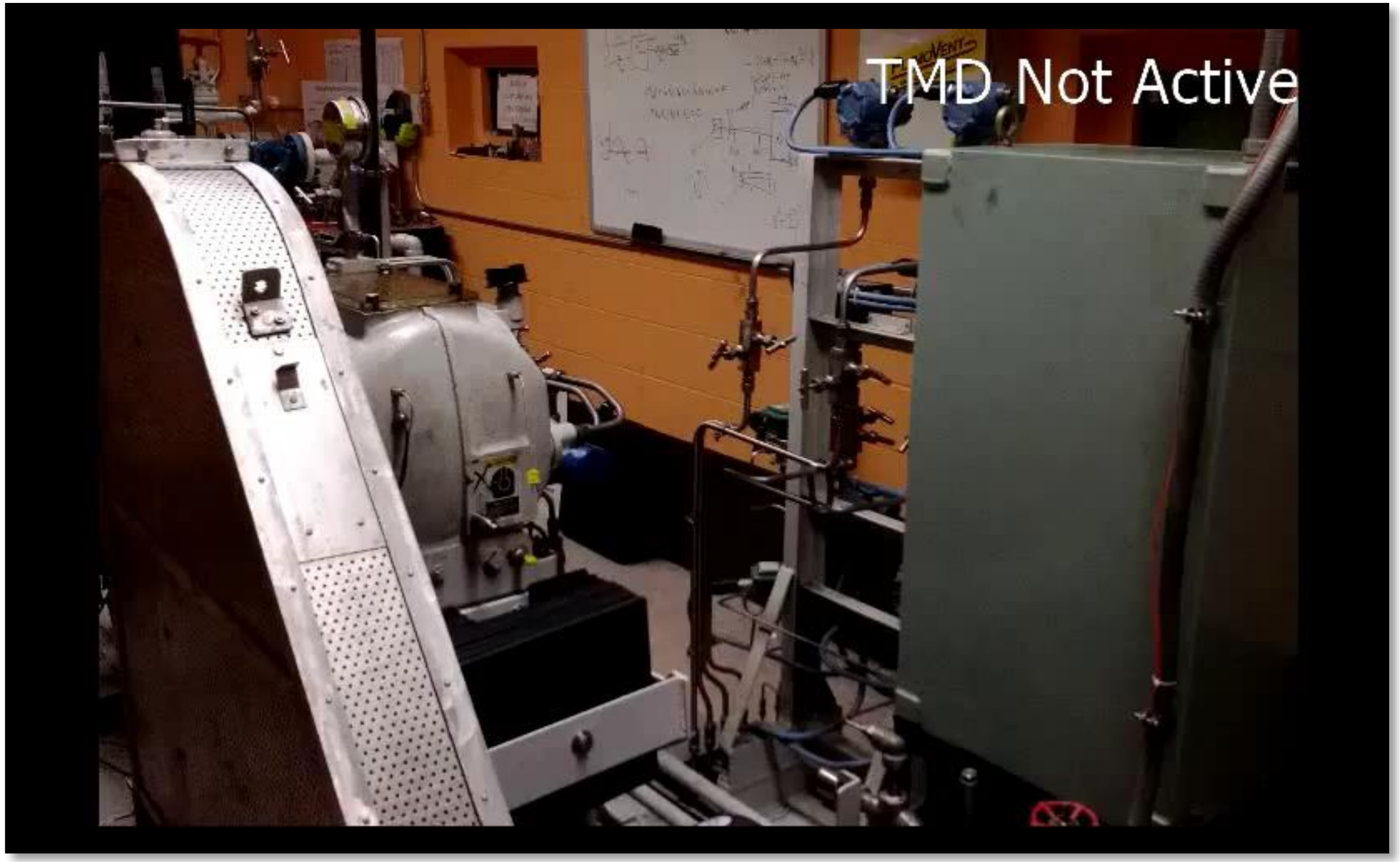
- TMD can be applied for systems with:
  - Limited space to install braces;
  - Absence of stiff structures in the vicinity.
  - High elevated structures.



Example of a TMD for a pulsation damper

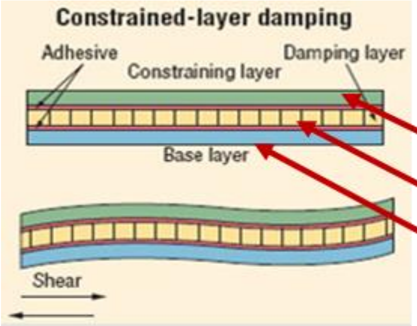
Vibrations – how to optimize the design

- Tuned Mass Damper



Vibrations – how to optimize the design

- Constraint Layer Damping (CLD):



CLD: based on shear between two deforming layers which are mounted on the pipe

- Constraining layer: stiff (metal) material
- Damping layer: visco-elastic material
- Base layer: pipe

- CLD is very beneficial for:
  - mitigation of high (≈> 50Hz) frequency vibrations;
  - Mitigations of pipe systems with low damping ratios (<2%)
- Traditional supporting requires in general very stiff and heavy structures; CLD can be a good alternative.

Vibrations – how to optimize the design

- Other advantages of Constraint Layer Damping (CLD):
  - material and installation costs are low
  - is very effective for a large frequency range
  - Not necessary to tune in field

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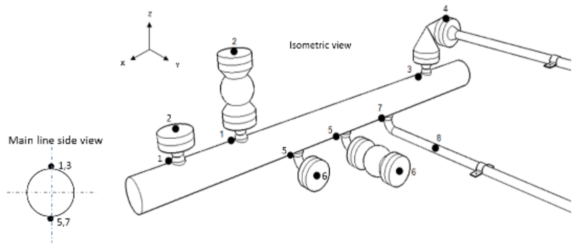
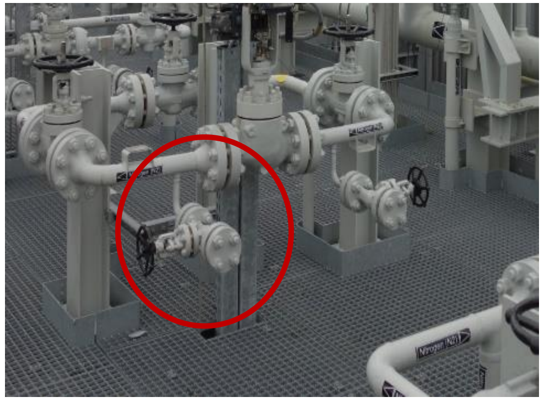
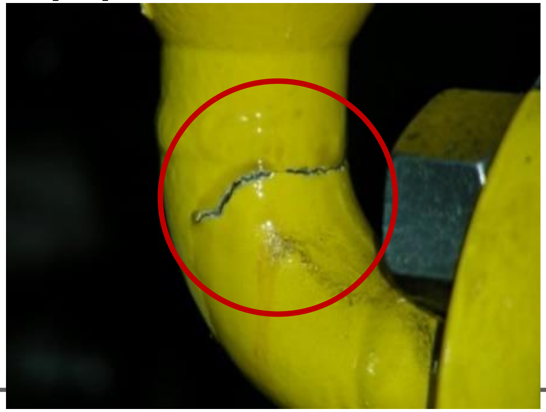
Vibrations – how to optimize the design



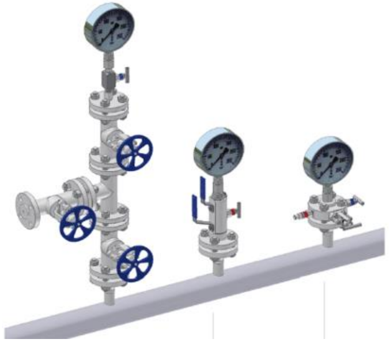
- SBC's are small diameter side branches:
  - See SBC definition and allowable levels in:
  - 2017 edition of the EFRC Vibration Guidelines
  - New ISO 20816-8
- Typically low stiffness and a heavy mass→ low MNF's
- Fatigue failure can occur even when the main pipe vibrations are acceptable:
  - At resonance vibration (and cyclic stress): Q> 30
  - High frequency excitation can be fatal
  - Damping ratio is in general small <1%
- Level gauges of separators often fail

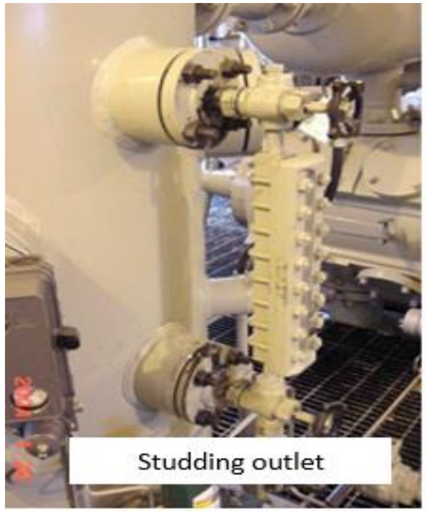




Vibrations – how to optimize the design

- Small bore connections
- Possible mitigation measures:
  - If not necessary or not used: remove SBC's
  - Remove heavy mass→ mono flange
  - Stiffen with braces:

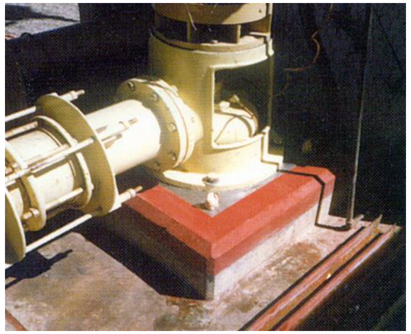


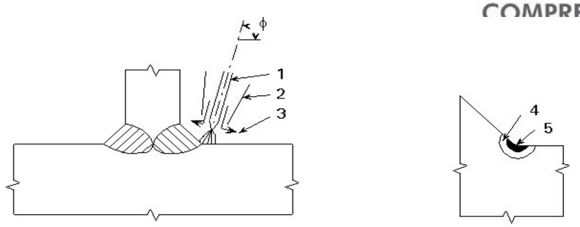


- Increase damping ratio using Constrained Layer Damping

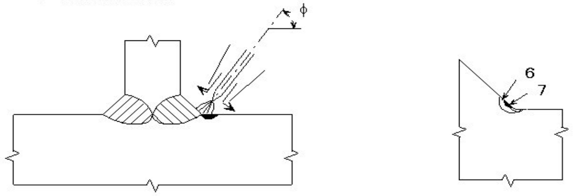
Vibrations – how to optimize the design

- Other considerations:
  - Fatigue failure is the result of stresses, not vibrations
  - Mitigate stresses by:
    - avoiding weld imperfections
    - applying full penetration welds
    - avoiding sharp corners (grind welds) (SCFs)
  - Use adequate grouting of foundations
    - Epoxy resins

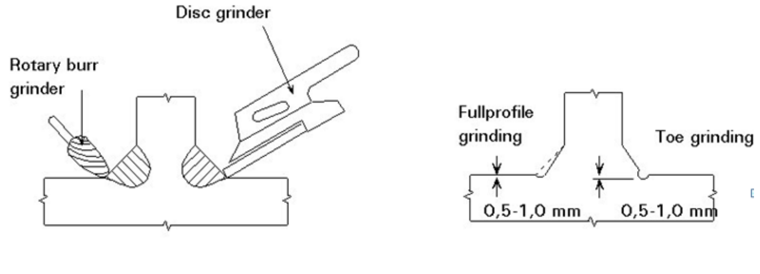




(a) Single run
1 -tungsten electrode, 2 - nozzel, 3 -shielding, 4 -HAZ
5 -remelted metal



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



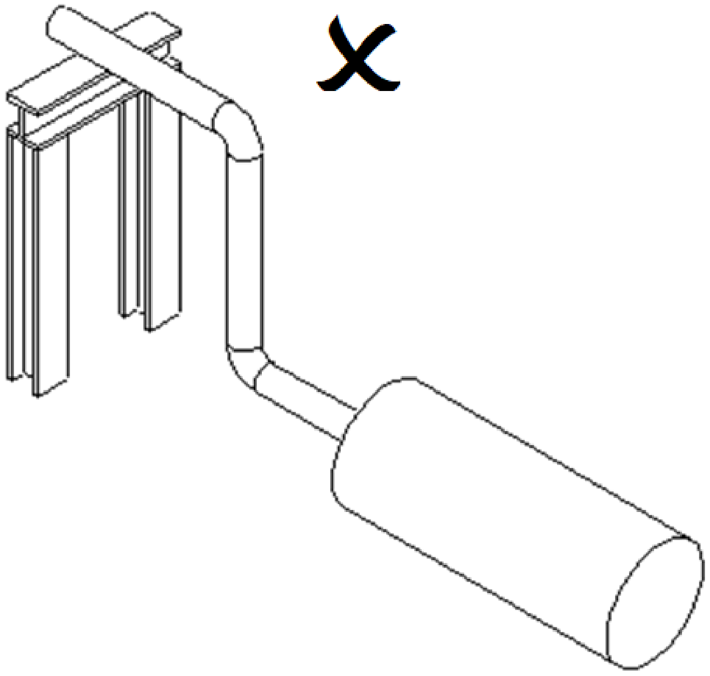
(a) 1 -Rotary burr grinding, 2 -Disc grinding
(b) 3 -Full profile grinder, 4 -Toe grinding

Vibrations

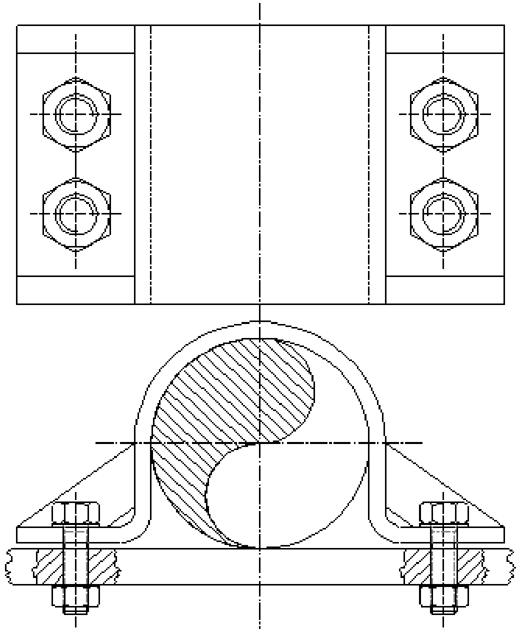
- Vibration types
- Description of vibrations
- Vibration sources
- Evaluation of vibrations
- Vibration Mitigation
  - Analyses
  - In practice
- **Basic guidelines**

Vibrations – Basic guidelines

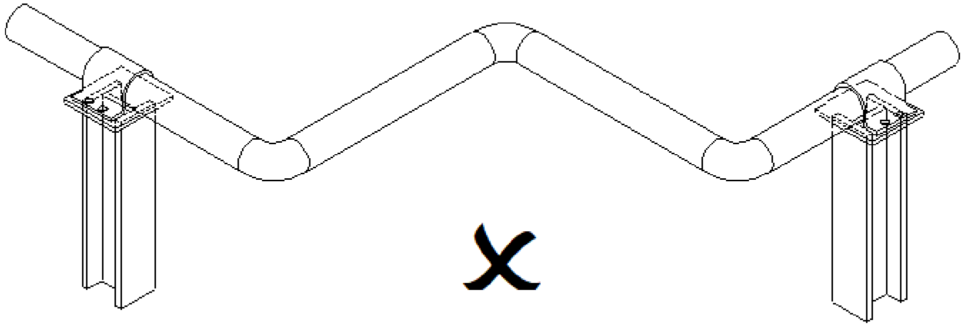
- Keep all piping low



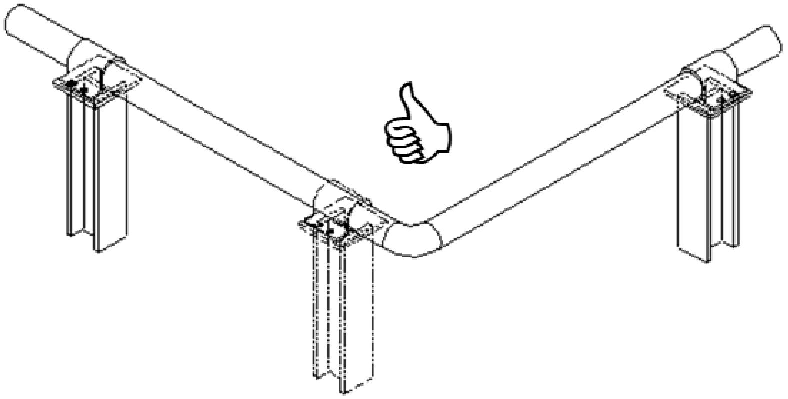
- Good Clamps have width (do not use U-bolts)



Vibrations – Basic guidelines

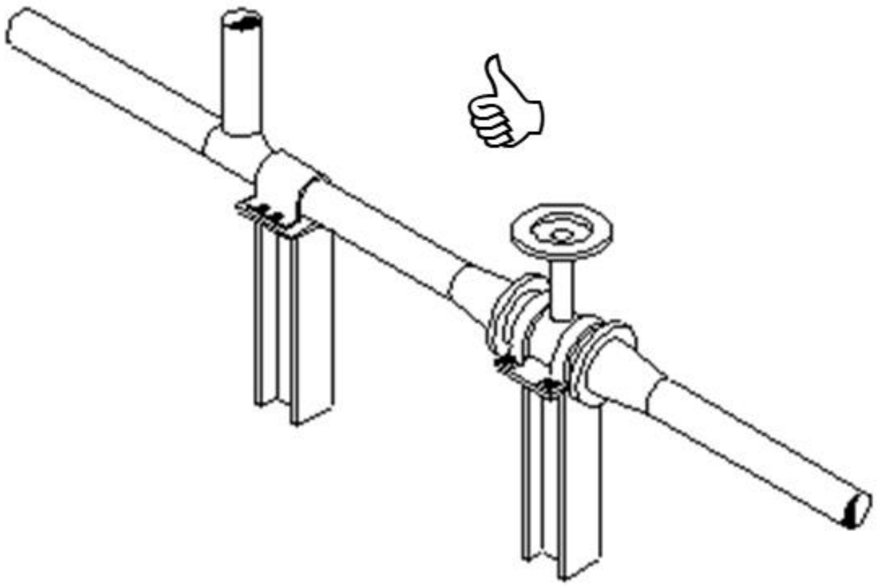


- Minimise number of elbows and Tees and avoid freestanding elbows



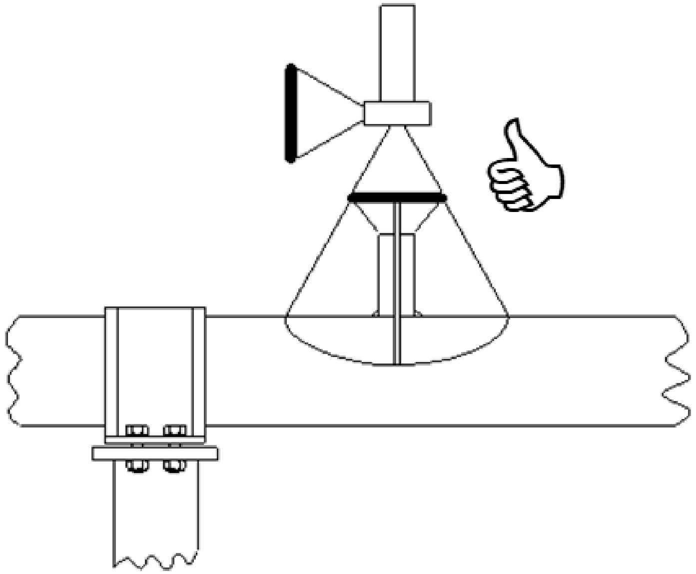
Vibrations – Basic guidelines

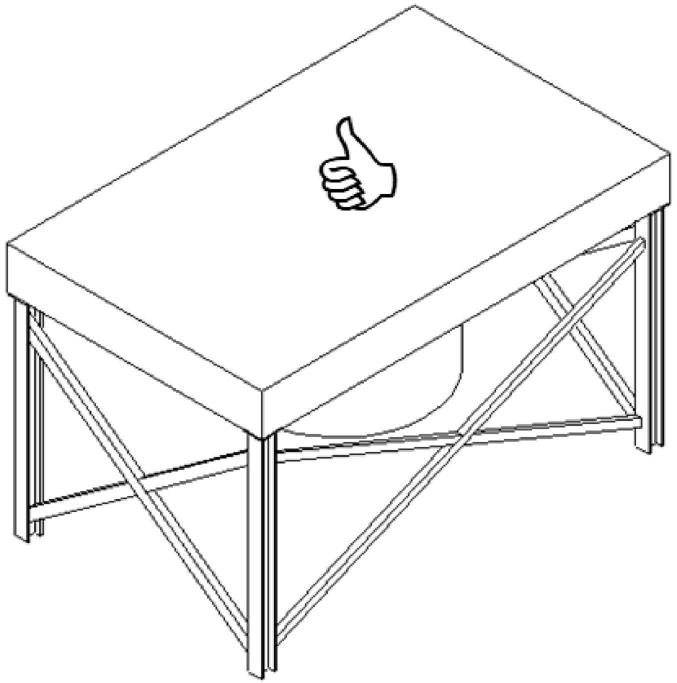
- Locate supporting directly under heavy components (valves, flanges etc.) and Tee joints



Vibrations – Basic guidelines

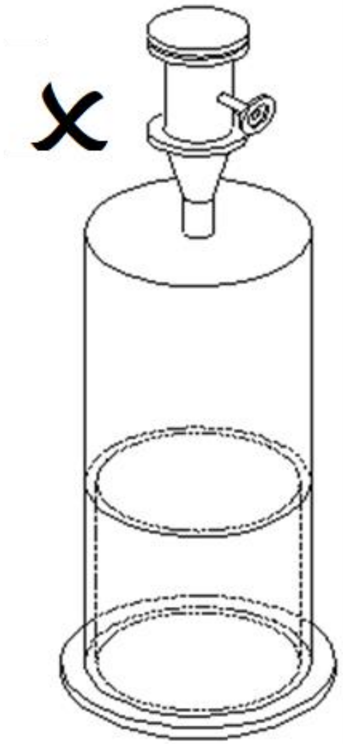
- Keep relief valves close to main line – apply X-bracing in air cooler frames

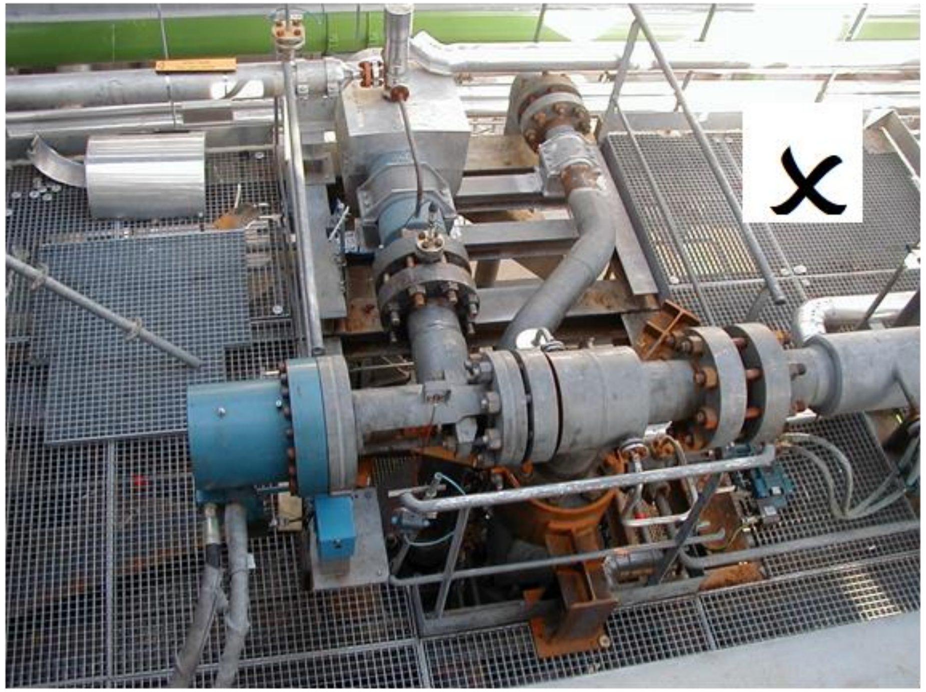




Vibrations – Basic guidelines

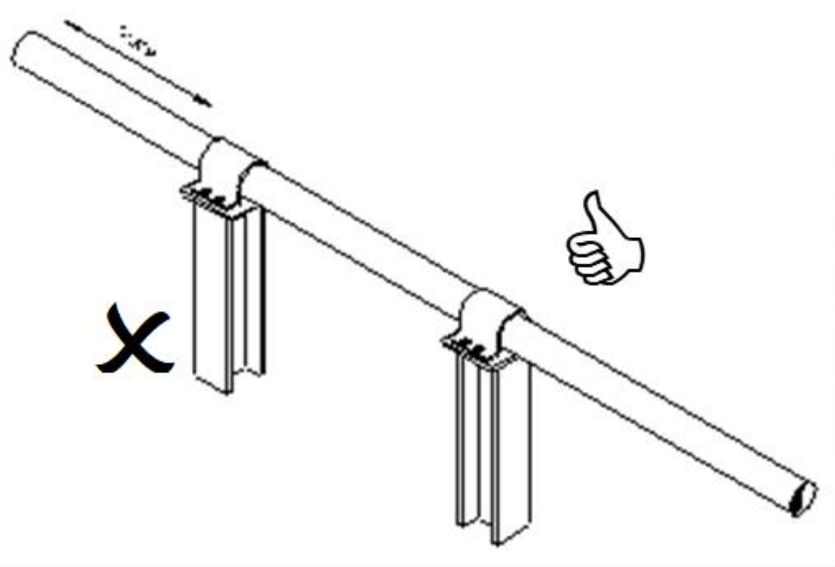
- Avoid heavy valves at high elevation (also on top of separators)

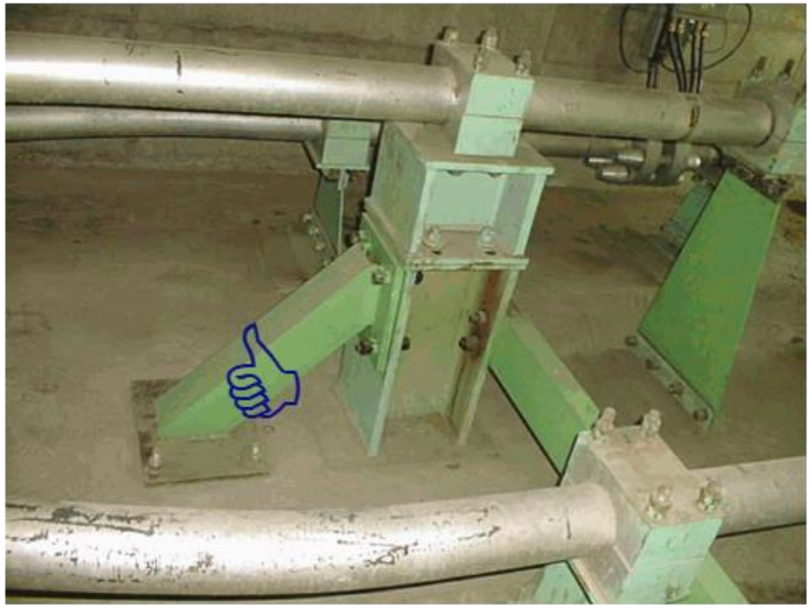




Vibrations – Basic guidelines

- Use stiffest beam orientation in the force direction





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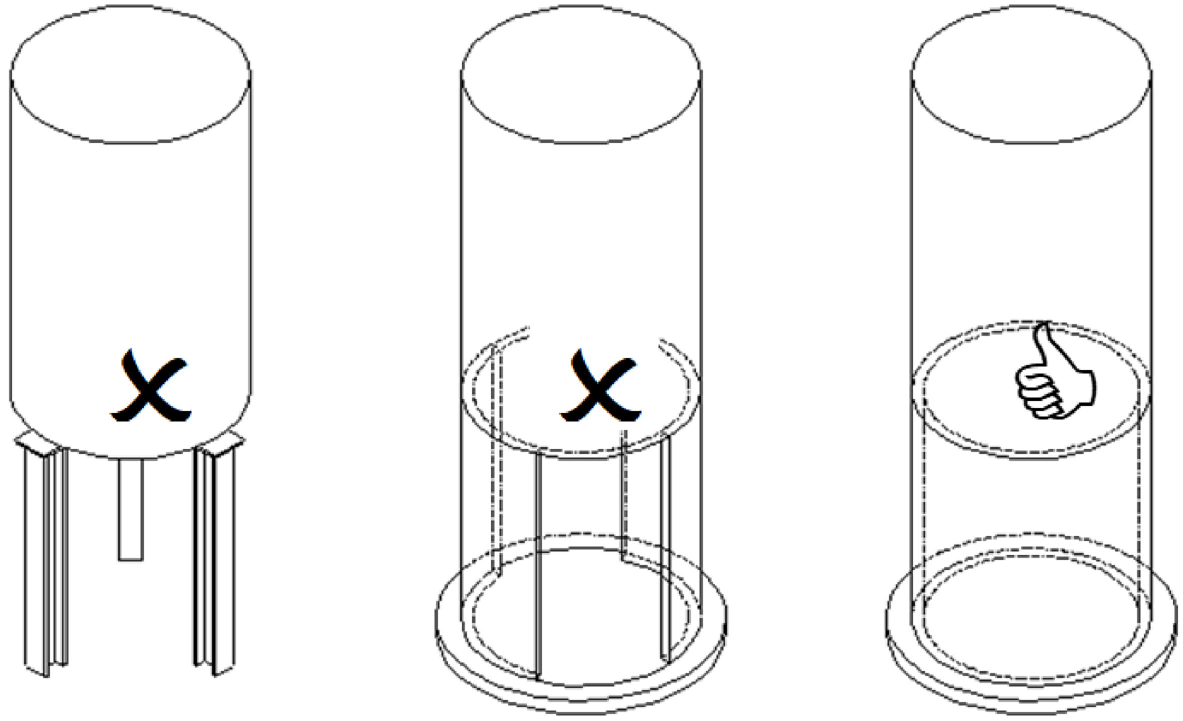
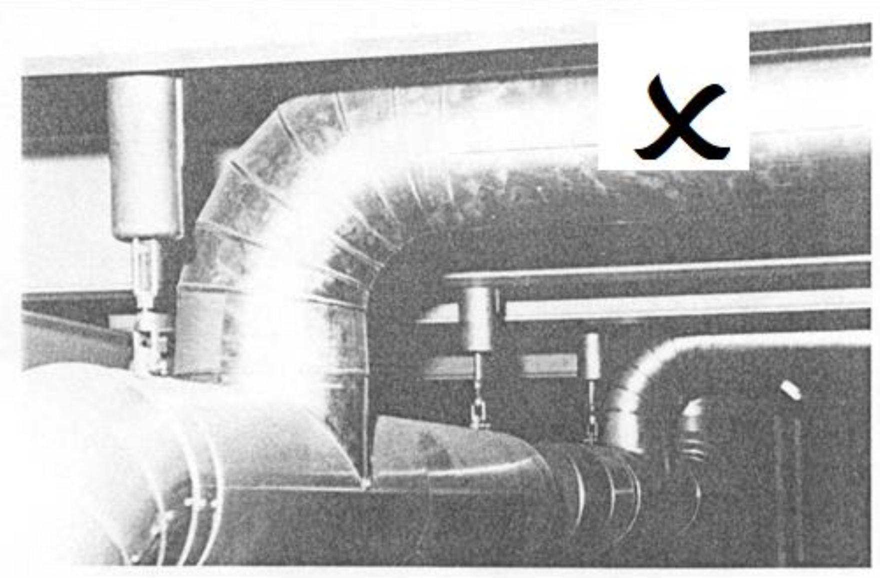
Vibrations – Basic guidelines

- Use full skirts in vessel supporting

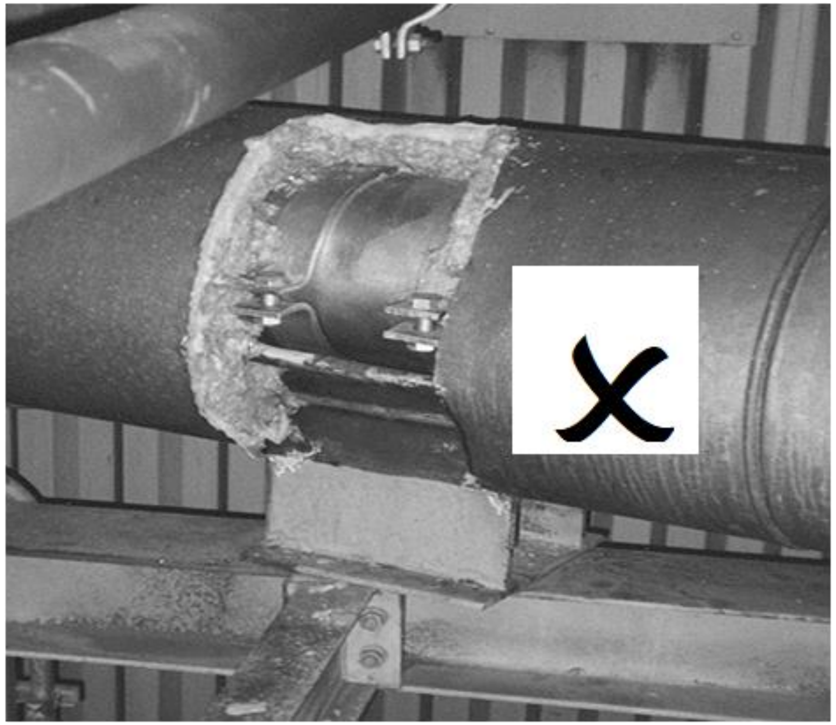


Vibrations – Basic guidelines

- Avoid rod and constant load hangers

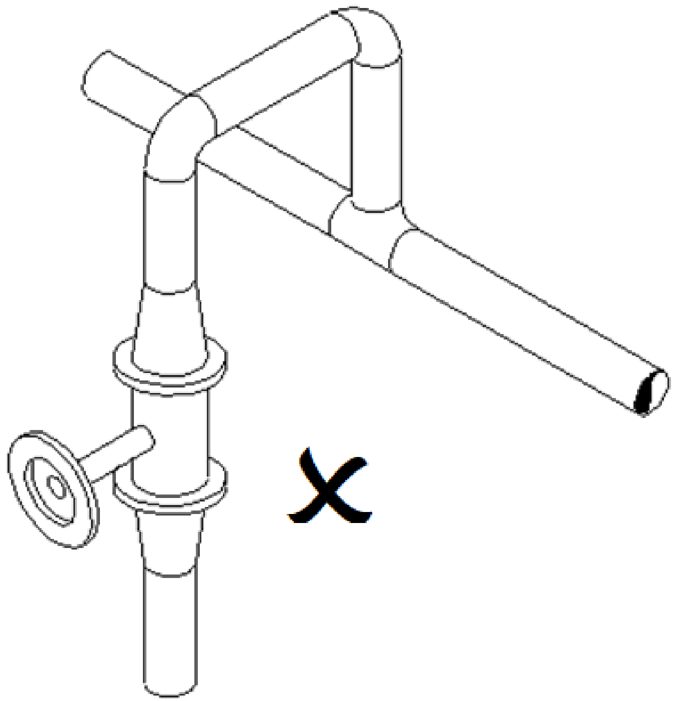


- Avoid rest type supports

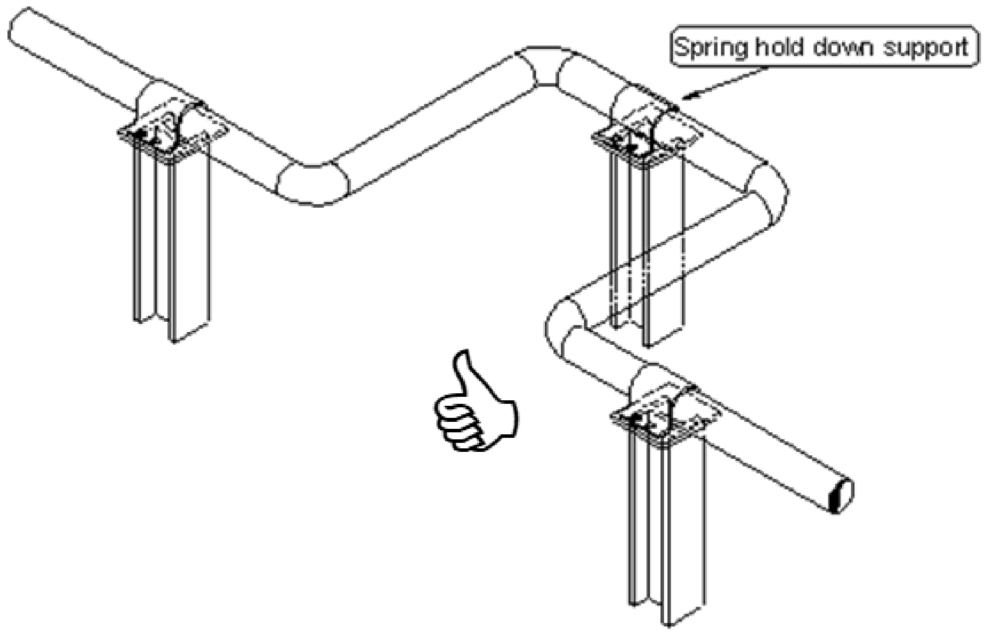


Vibrations – Basic guidelines

- Avoid unsupported overhanging weight



- Avoid unsupported expansion loops



Vibrations – Basic guidelines

- 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