EFRC Training Workshop

State-of-the-art Design of Reciprocating Compressor Systems

Options for vibration control

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TNO innovation for life

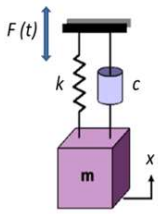
Contents

- Mechanical Vibrations
- Vibration reduction measures:
  - Pipe supports
  - Increasing system stiffness
  - Viscous dampers
  - Constrained Layer Daming
  - Small Bore Connections
  - Tuned Mass Damper system
- Conclusions

Mechanical Vibrations

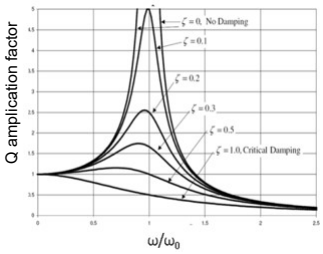
- General equation of motion:

Pulsation forces and mechanical loads



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

m= mass
c= viscous damping
k= spring stiffness
F= force
x= displacement
$\dot{x}$= velocity
$\ddot{x}$= acceleration
ω= excitation frequency



- Mechanical Natural Frequency (MNF):

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

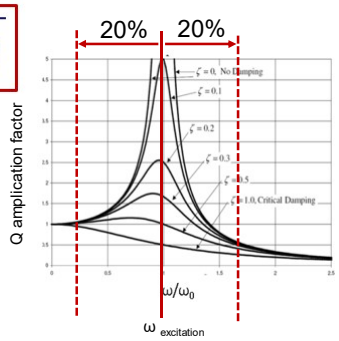
- If excitation frequency (ω) equals MNF (ω_o) → resonance
- For systems with low damping (ζ< 5%) at resonance→→ $Q \approx \frac{1}{2\zeta}$
- Too high vibrations can lead to fatigue failure

Vibration Reduction Methods

- Separate (detune) MNF's from excitation frequencies
- In general: separation margin of ± 20% is sufficient

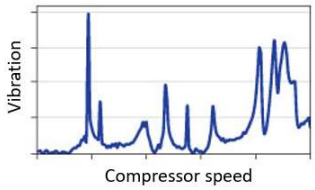
$$\omega_0 = \sqrt{k/m}$$

- Possibilities:
  - Add pipe supports
  - Increase system stiffness (braces)
  - Change mass
  - Add Tuned Mass Damper (TMD)
  - Combination of above measures

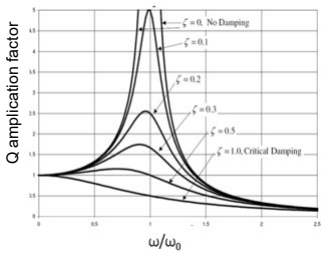


Vibration Reduction Methods

- Detuning is more difficult to achieve for variable speed compressors:
  - each system has more than one MNF
  - high chance on excitation of more MNF's over the complete speed range

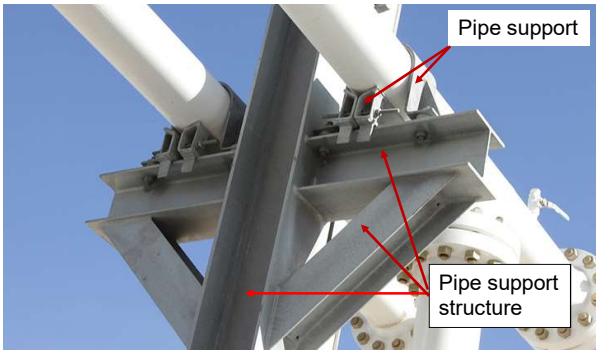


- Increase damping ratio ζ
  - For light damped systems: $Q \approx \frac{1}{2\zeta}$
- Possible with:
  - Viscous dampers
  - Constrained Layer Damping (CLD)



Pipe Supports

Connection of pipe with (steel) structure shall be suitable to restrain the dynamic loads → adequate pipe support



Structure shall be stiff enough to avoid resonances → $\omega_0 = \sqrt{k/m}$

Pipe Supports

- Support layout is in general optimised to allow thermal expansion → flexible system required
- Typical applied supports in thermal design
  - Spring hangers
  - Rest type supports (with or without guides, gaps, limiters, etc)

Typical spring hanger support

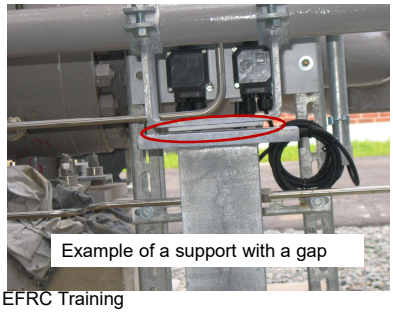
Typical rest type support

- Spring hangers:
  - Are very flexible elements which lead in general to very low MNF's and unacceptable pipe vibrations

Pipe Supports

- Rest type supports are not always able to restrain the dynamic loads (called dynamically loose) 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)
  - consequence: MNF's and vibration levels will change

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

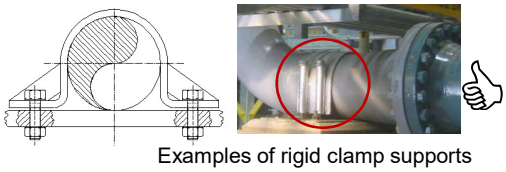


Example of a support with a gap

Pipe Supports

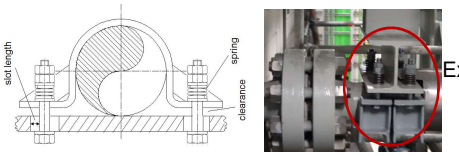
- Solution: Rigid clamp (U-bolt is not rigid enough)

U-bolt



Examples of rigid clamp supports

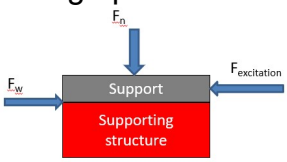
- Rigid clamp can introduce too high expansion stress, solution: spring hold down type support:
  - allows thermal expansion and restrain dynamic loads (enough friction)



Examples of spring hold down supports

Pipe Supports

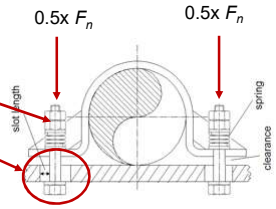
- Design parameters for spring hold down supports:



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

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

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

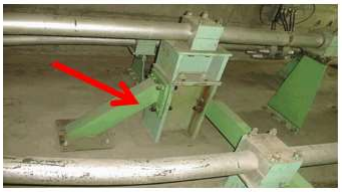


Spring hold down with 2 bolts

Steel Structure Stiffening

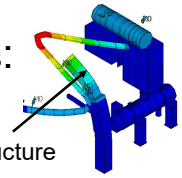
- Target: increase MNF's
- Braces are most effective

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



stiffened steel structures

- Is not always effective for high frequencies:
  - Structure can become in resonance and does not work anymore

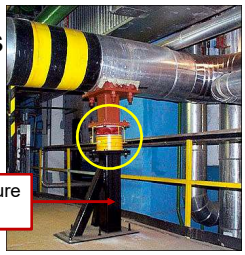


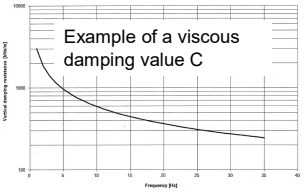
Viscous Dampers

Damping force

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

- 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

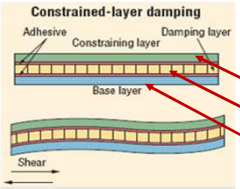




Requirement: stiff steel structure to restrain damping force

Constrained Layer Damping

- Mitigation high (≈> 50Hz) frequencies require in general very stiff and heavy structures
- Experience showed that this is very challenging
- If the damping ratio is low (<2%), an increase in damping can be very efficient
- This can be done with Constrained layer Damping

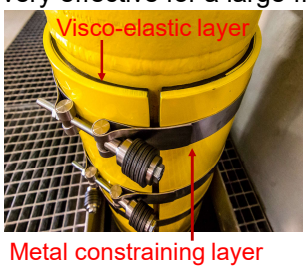


CLD: based on shear between two deforming layers which are mounted on the pipe

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

Constrained Layer Damping

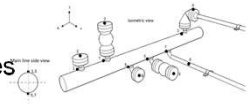
- Advantages of CLD:
  - material and installation costs are low
  - is very effective for a large frequency range



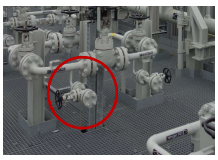
- If you are interested in more details:
  - Visit EFRC presentation: Thursday 14.00 hr

Small Bore Connections (SBC's)

- SBC's are small diameter side branches:
  - See SBC definition in EFRC Vibration Guidelines



- SBC's have in general a low stiffness and a heavy mass→ low MNF's $\omega_0 = \sqrt{k/m}$



- 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%

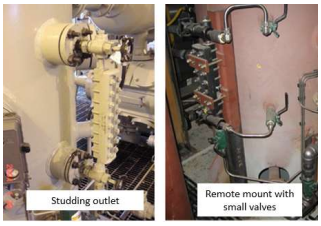
$$Q \approx \frac{1}{2\zeta}$$

- Level gauges of separators often fail

Small Bore Connections (SBC's)

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

Improved design



Level gauge improvement

- Increase damping ratio:
  - Constrained Layer Damping:

Flexible Mounted Compressors

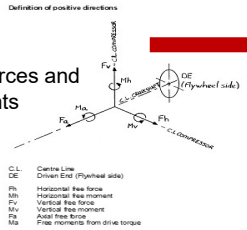
- Reciprocating compressors are sometimes installed on Anti-Vibration Mounts (AVM's) to avoid:
  - structure borne noise (off-shore applications)
  - too high dynamic settlement if a compressor is mounted on weak soil (free forces and moments act like a ram)
  - transfer of static deformations of an FPSO to the compressor frame
- Consequence of AVM mounting:
  - compressor vibrations will increase
- Solutions:
  - lower excitation forces
  - Add mass
  - Combination of both

Pulsation forces and mechanical loads

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

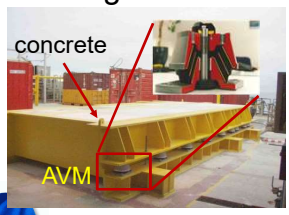
Flexible Mounted Compressors

Free forces and moments



- Change (vertical) excitation loads by:
- 90 versus 180 degrees (flat) crank shaft

Change Mass

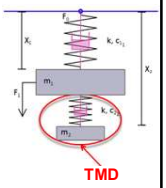


Example of a skid with 40 tons additional concrete

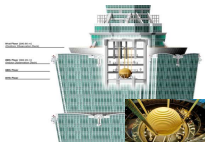
- Change counterweight balancing, keeping in mind that:
  - one load will be decreased but the other will be increased
- Reduction factor:
  - ≈2-4 (or more) depending on configuration and type of compressor

Tuned Mass Damper (TMD)

- A TMD is consists of a mass, spring and damper
  - Based on detuning MNF's from excitation frequencies
- A TMD is often used in building structures, not (yet) often in compressor system

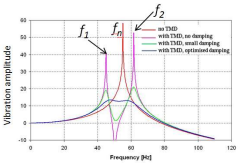


Millennium bridge London



Taipei tower, Taiwan

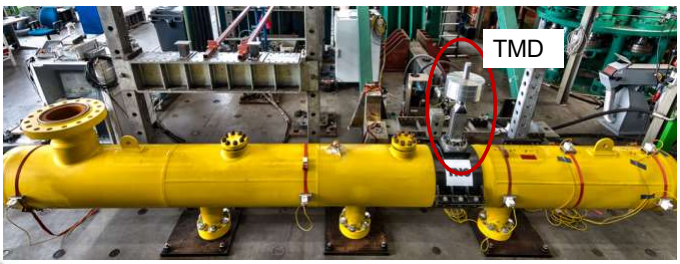
- The TMD is connected to the structure to be mitigated, not to a rigid point
- A TMD shall always be tuned in the field



Frequency response function

Tuned Mass Damper (TMD)

- TMD's 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

Conclusions

- Too high vibrations can lead to fatigue failure
- Vibrations shall be reduced to acceptable levels:
  - During the design: API Standard 618
  - During field surveys: EFRC Vibration Guidelines, ISO 10816-8
- Most applied vibration reduction methods:
  - Detune MNF's
  - Increase of (mechanical) damping ratio
- Shall be analysed carefully:
  - A change in mass or stiffness can even increase vibrations, which is especially the case for VSD driven compressors

Thank you for your attention

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