Compressor Control Workshop - Prague 2007

Pulsation effects of capacity control options

TNO Science & Industry - PULSIM
Harry Korst
harry.korst@tno.nl

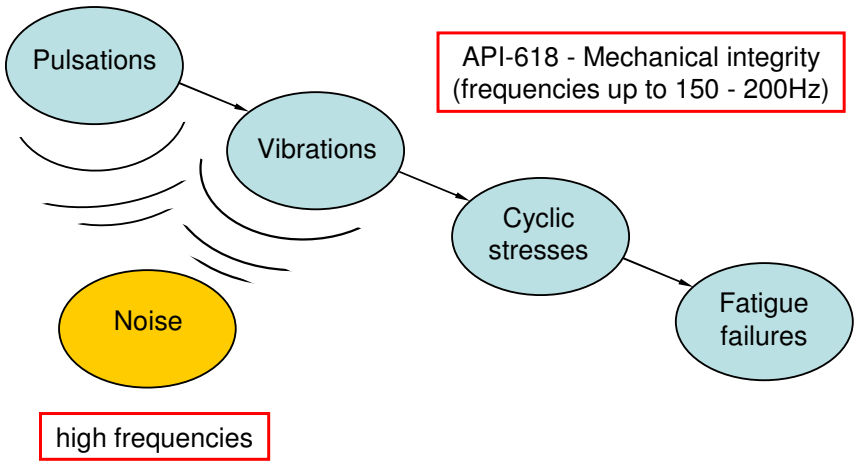
Contents

- Introduction
- Effect of capacity control systems
  - Flow pulses (amplitudes and frequencies)
  - Damper sizing
- Pulsation Dampers
- Restriction Orifices (single and multiple)
- Prevention of Noise
- Conclusions & Recommendations

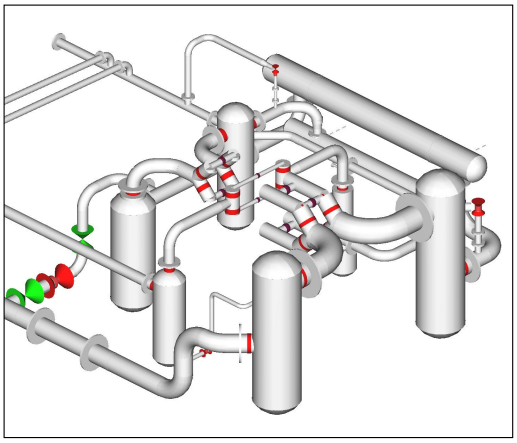
Contents

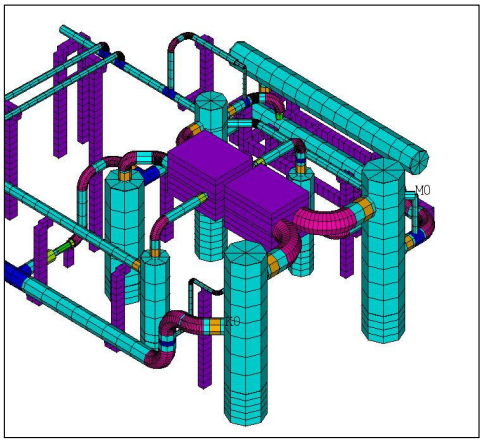
- **Introduction**
- Effect of capacity control systems
  - Flow pulses (amplitudes and frequencies)
  - Damper sizing
- Pulsation Dampers
- Restriction Orifices (single and multiple)
- Prevention of Noise
- Conclusions & Recommendations

Introduction



Introduction





Example of a three-stage compressor
Pulsation levels – Vibrations and cyclic stresses

Introduction

PV-diagram (HE & CE)

↓

Flow pulse (Suc. & Dis.)

↓

Source Amplitudes & frequencies

↓

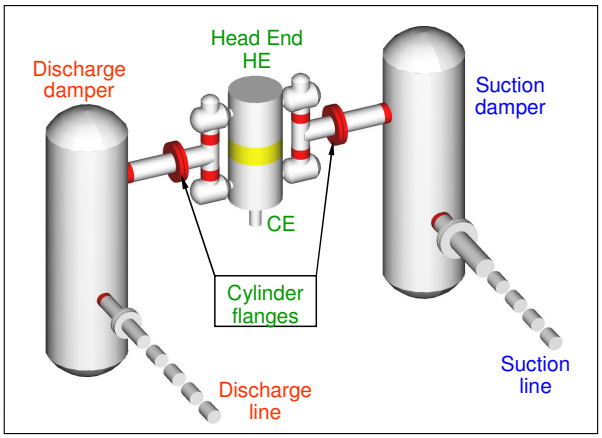
Allowable levels

↓

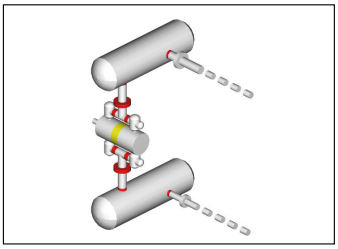
Damper size

Introduction

- Some terms often used in relation to piston compressors:



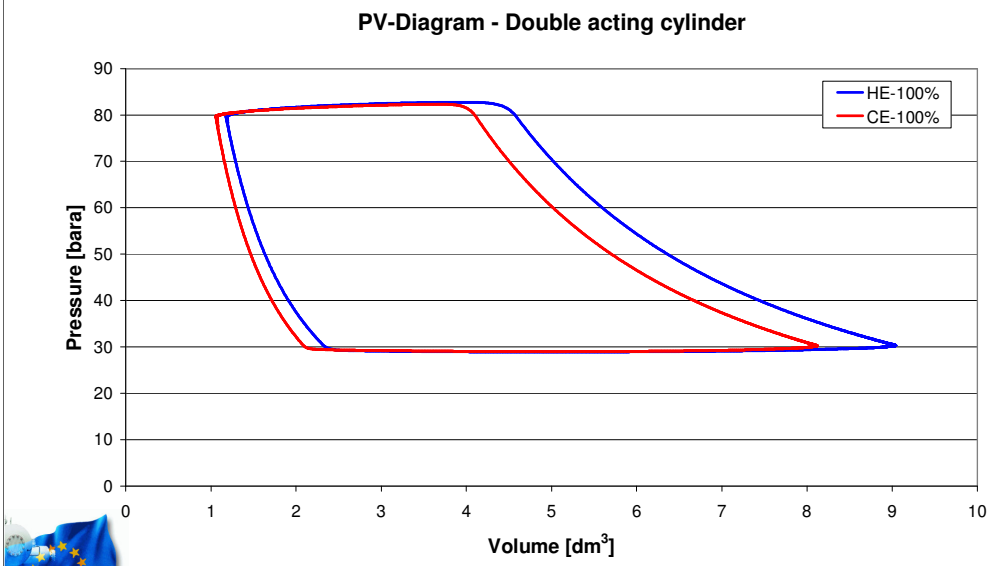
Typical layout vertical compressor



and a horizontal one

EFRC

Introduction



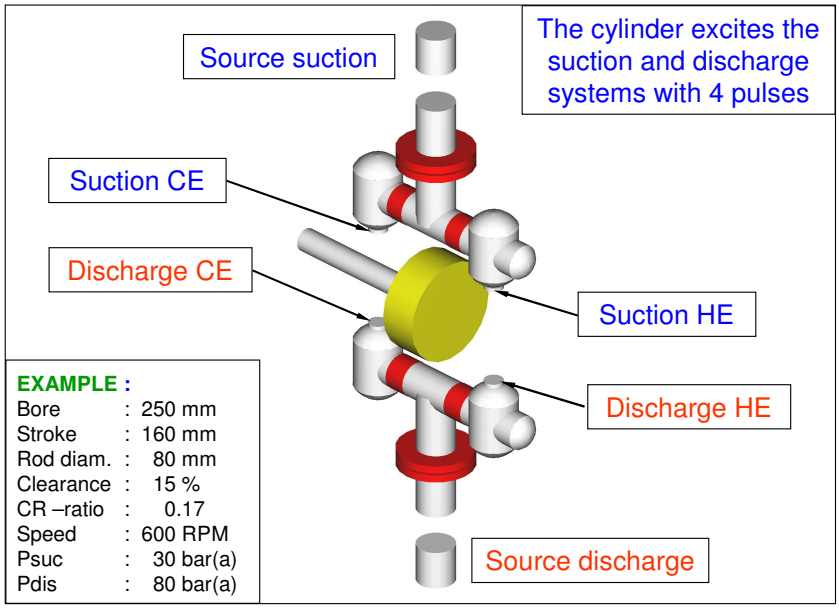
EFRC

Compressor Control Workshop 21 March 2007

PV-diagram on the cylinder's Head End is usually a little larger than on the Crank End side

Valve losses can be seen during the suction and discharge phase

Introduction

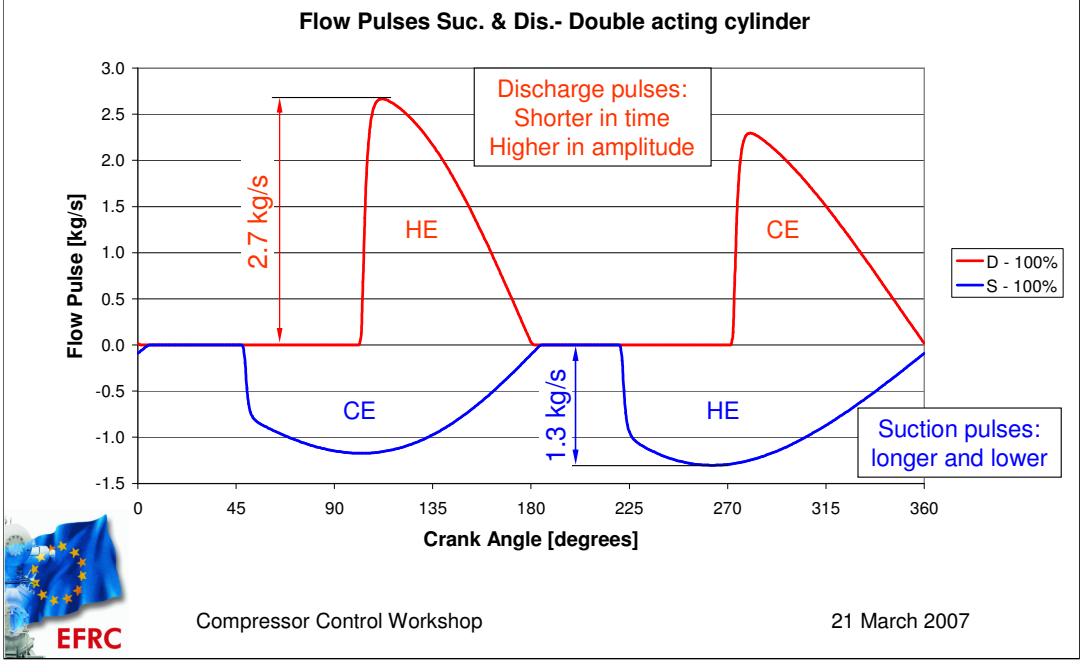


EXAMPLE :

Bore	:	250 mm
Stroke	:	160 mm
Rod diam.	:	80 mm
Clearance	:	15 %
CR –ratio	:	0.17
Speed	:	600 RPM
Psuc	:	30 bar(a)
Pdis	:	80 bar(a)

EFRC

Introduction



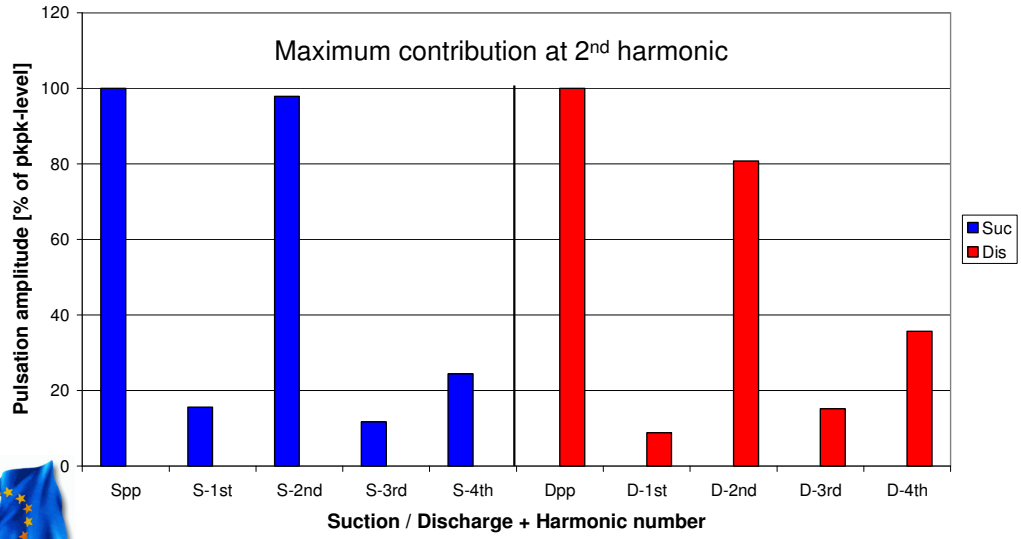
EFRC

Compressor Control Workshop 21 March 2007

These flow pulses have a direct effect on damper size

Introduction

Typical frequency content DA-cylinder



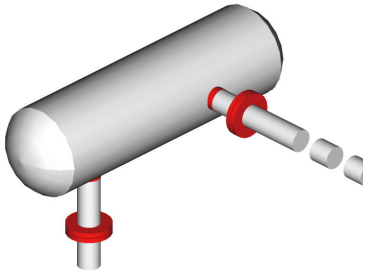
EFRC

Compressor Control Workshop 21 March 2007

Introduction

Based on the amplitude of the most important frequency an initial damper volume can be calculated according to the following equation:

$$V = \frac{a}{\omega} \cdot \sqrt{a^2 \cdot \left(\frac{Q_{pp}}{P_{pp}} \right)^2 - F^2}$$



Where:

V = Volume [m³]

a = speed of sound [m/s]

ω = 2π · f [rad/s]

Qpp = Max. peak-to-peak flow pulsation level [kg/s pp] (source)

Ppp = Required pulsation level at the line connection [Pa pp] (criterion #1)

F = The area of the line connection [m²]

EFRC

Compressor Control Workshop 21 March 2007

This equation can be used as an **initial** indication of the required volume.

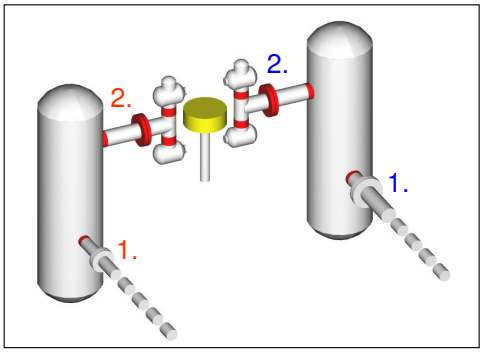
The required volume is frequency dependent: lower frequencies lead to larger volumes

A final volume should be determined in a full pulsation analysis in which the effects of resonances are taken into consideration.

Introduction

Allowable pulsation levels (API-Standard 618)

1. Pulsations at the line connections (Equation 8 of sect. 3.9.2.7)
2. Pulsations at the cylinder flanges (Equation 4 of sect. 3.9.2.2.3)
3. Minimisation of dyn. forces on the damper (No absolute criterion)
4. Pressure drop (Equation 5,6 of sect. 3.9.2.2.4)



Introduction

1. Allowable pulsation levels at the line connection:
   (API-Standard 618 pressures between 3.5 and 200 Bar)

$$P_{all}(\%) = \frac{397.1}{\sqrt{P_l \cdot ID \cdot f}}$$

Where:

$P_{all}(\%)$ = Allowable peak to peak pulsation level as a percentage of the static line pressure

P_l = Line pressure in Bar

ID = Inside diameter in mm

f = Pulsation frequency in Hertz

2. Allowable pulsation levels at the cylinder flanges:

$$P_{cf} = 3*R \text{ or } 7\%pp \quad \text{(whichever is lower)}$$

Where:

P_{cf} = Allowable peak-to-peak pulsation level at the cylinder flange

R = Stage pressure ratio

Compressor Control Workshop 21 March 2007

Note on Criterion 1:

During a damper check (endless line check, so without interaction with a pipe system) we recommend 70% of this level !

Note on Criterion 2:

Most important frequency components (with high amplitudes) should be far away from mechanical natural frequencies of the compressor valves !

Note on Criterion 4:

Maximum pressure drop depends on stage pressure ratio

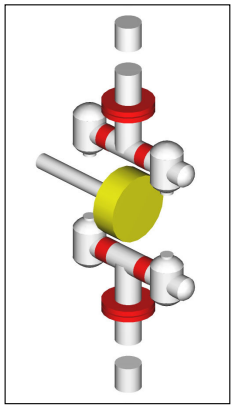
dP[%] = 1.67(R-1)/R

dP[%] = 2.17(R-1)/R (in case of a combined damper-separator)

Introduction

Summary of capacity control options:

- Cylinder unloading – Valve lifting
- Clearance Pockets (fixed and variable)
- Speed control
- By-pass control
- Suction throttling
- Reverse flow



Contents

- Introduction
- **Effect of capacity control systems**
  - Flow pulses (amplitudes and frequencies)
  - **Damper sizing**
- Pulsation Dampers
- Restriction Orifices (single and multiple)
- Prevention of Noise
- Conclusions & Recommendations

Damper sizing

PV-diagram (HE & CE)

↓

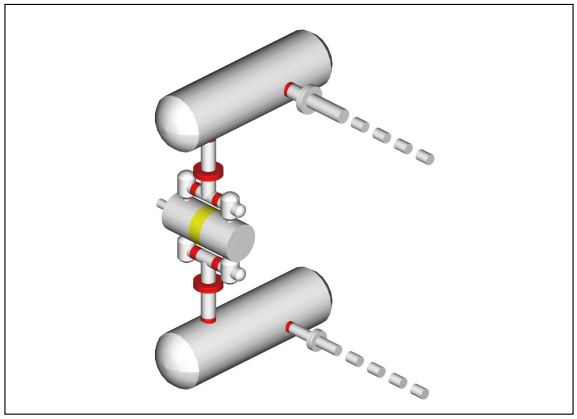
Flow pulse (Suc. & Dis.)

↓

Source Amplitudes
Most important frequency

↓

Damper size



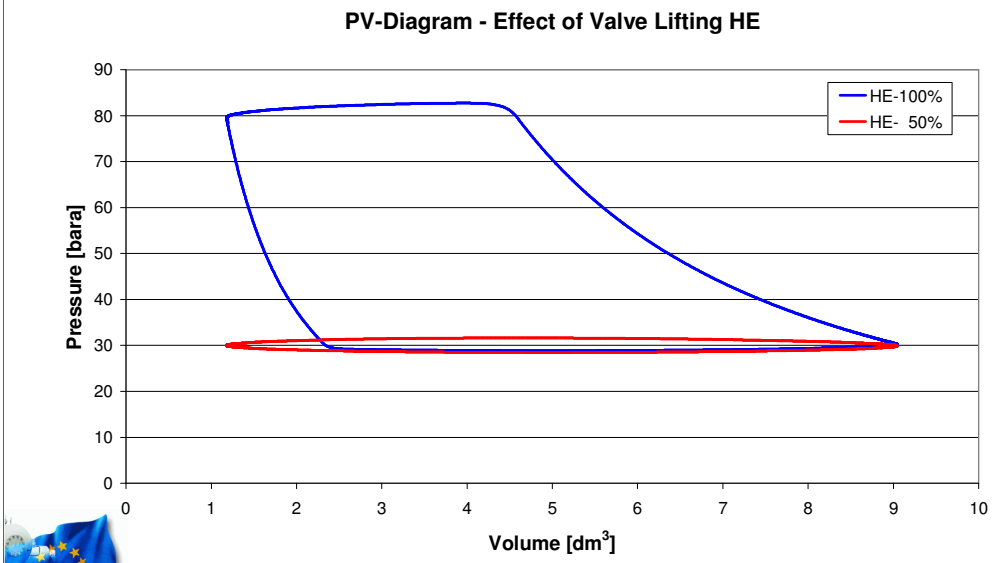
EFRC

Compressor Control Workshop 21 March 2007

The normal Head End PV-diagram disappears at HE valve lifting

The small remainder is related suction valve losses

Damper sizing

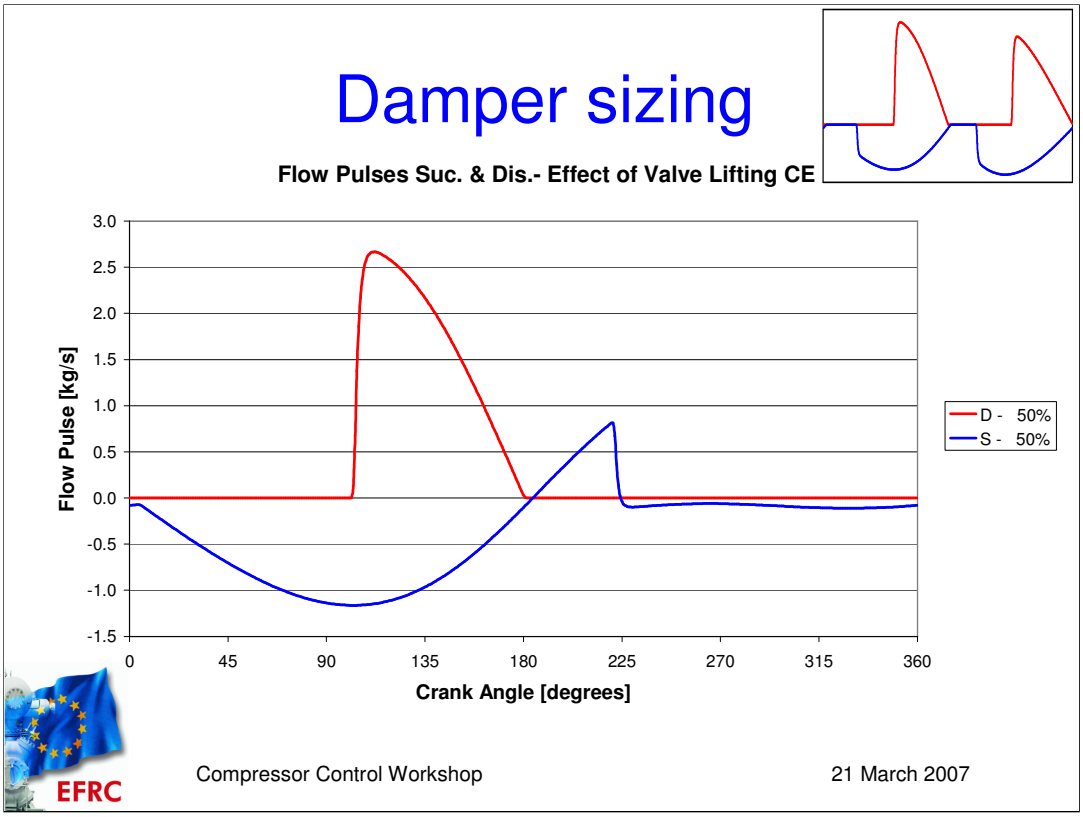


EFRC

Compressor Control Workshop 21 March 2007

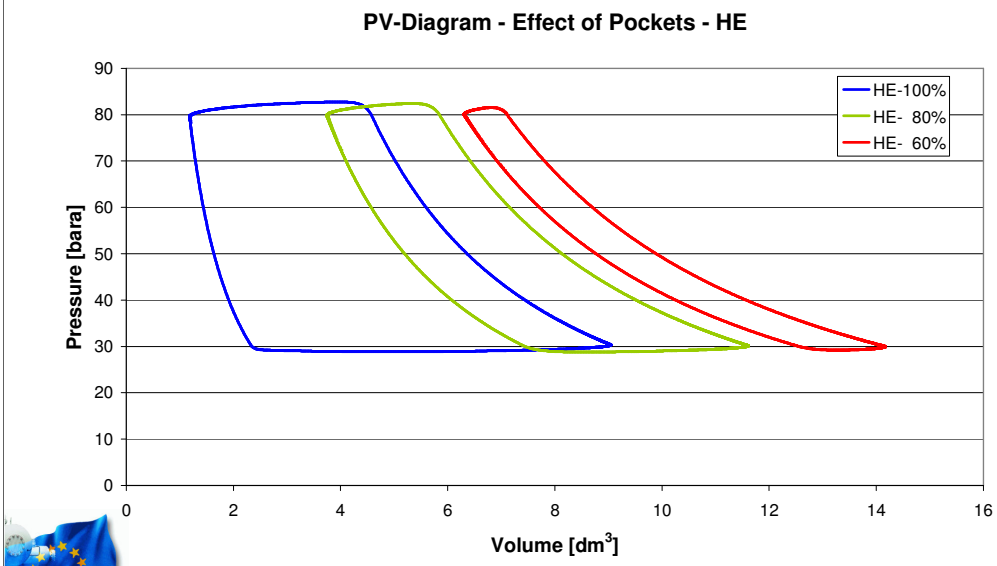
The normal Head End PV-diagram disappears at HE valve lifting

The small remainder is related suction valve losses



Higher peak-to-peak flow pulse at the suction

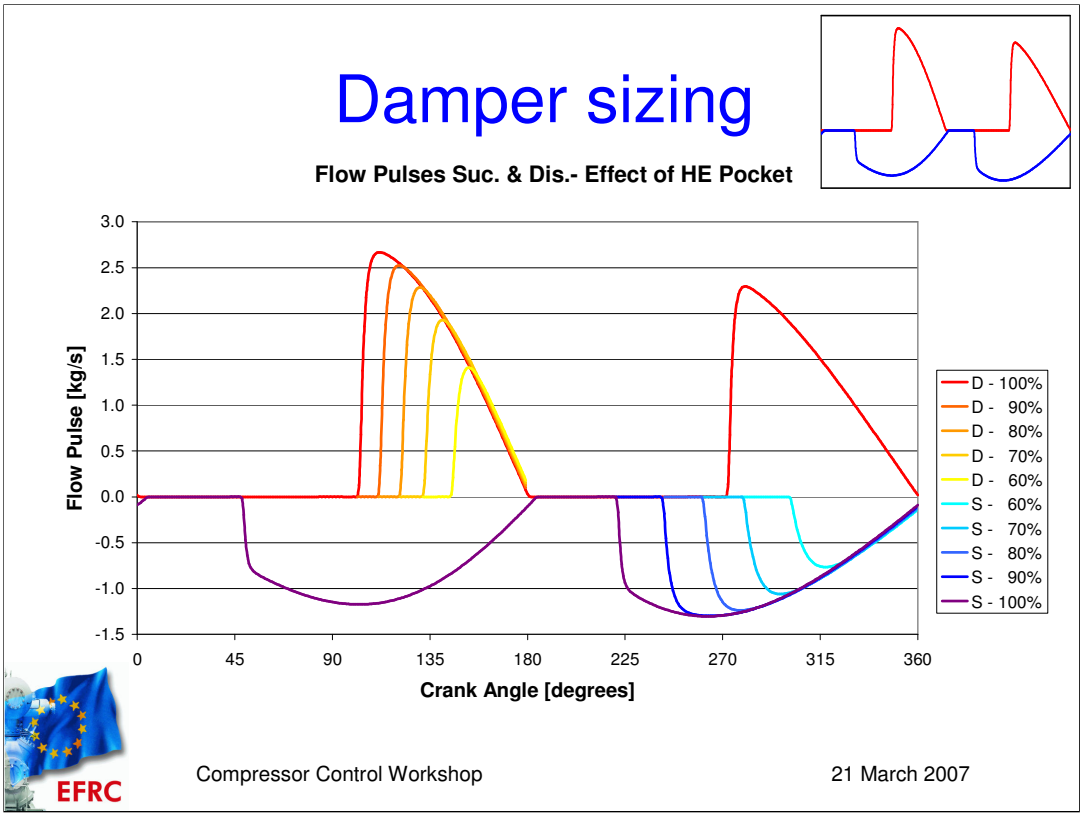
Damper sizing



EFRC

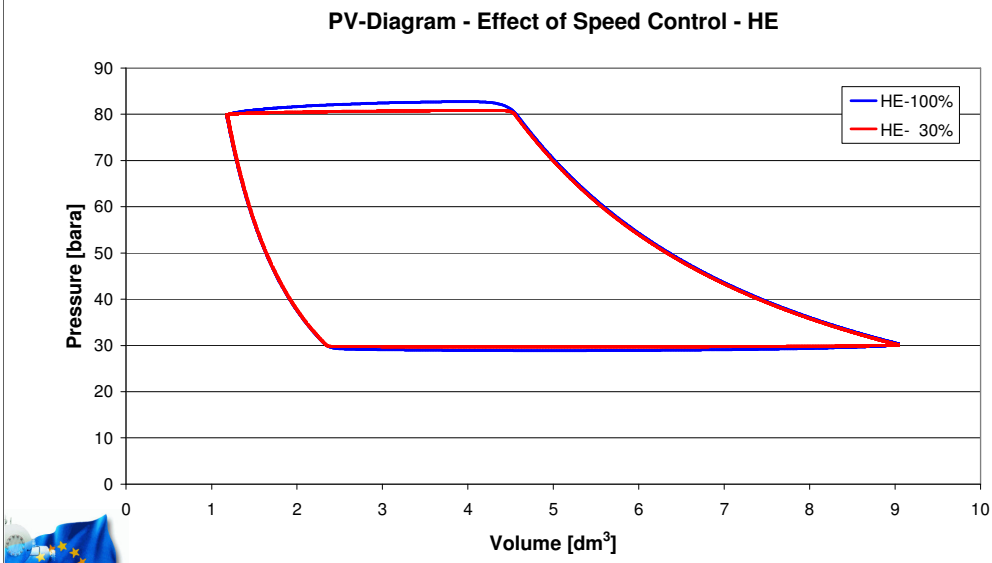
Compressor Control Workshop 21 March 2007

The PV-diagrams with clearance pockets narrows up to a point where it disappears (when the discharge pressure can no longer be reached)



Suction and Discharge flow pulse amplitude: equal or lower

Damper sizing

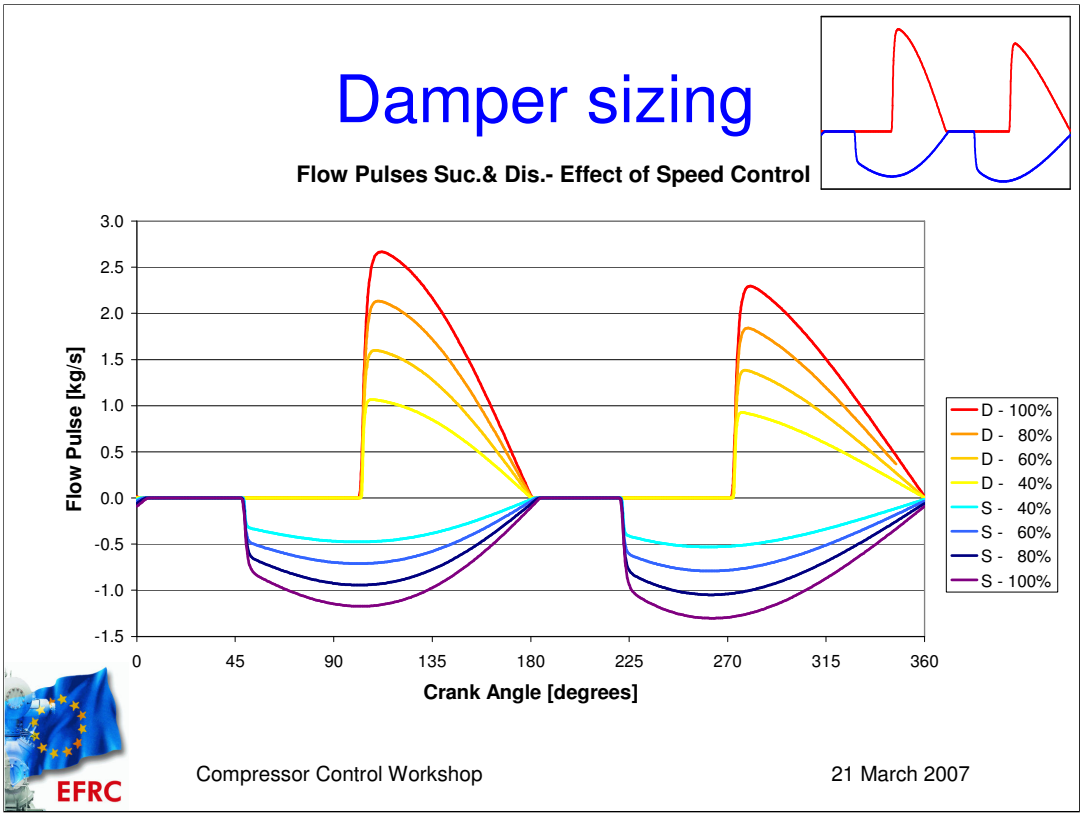


EFRC

Compressor Control Workshop 21 March 2007

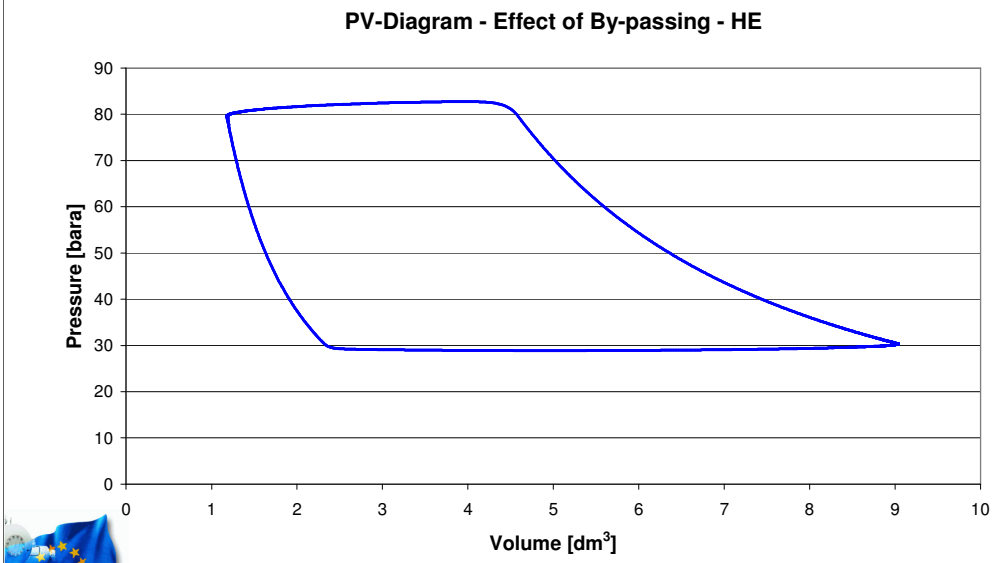
Spot the difference 1:

Lower valve losses



Speed control: Lower amplitudes both on suction and discharge

Damper sizing



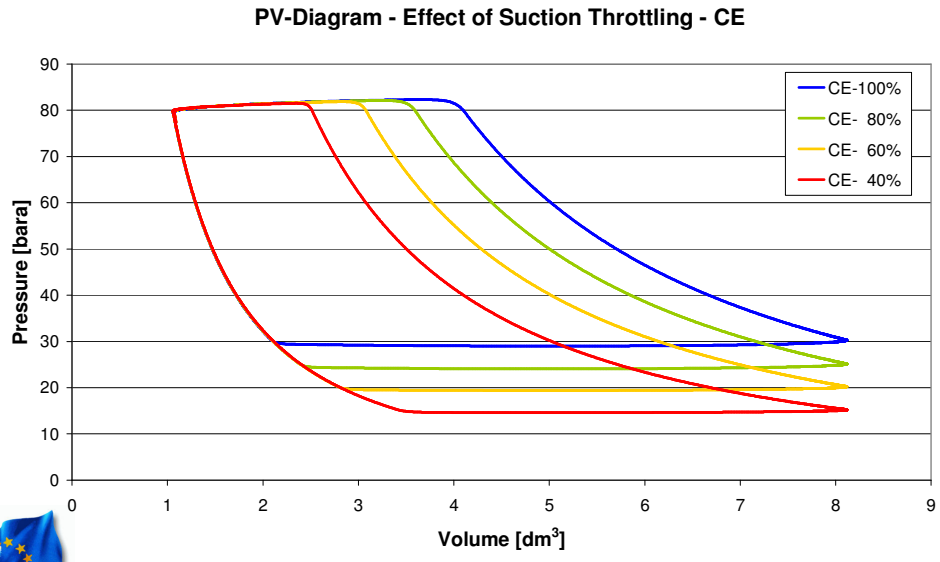
EFRC

Compressor Control Workshop 21 March 2007

Spot the difference 2

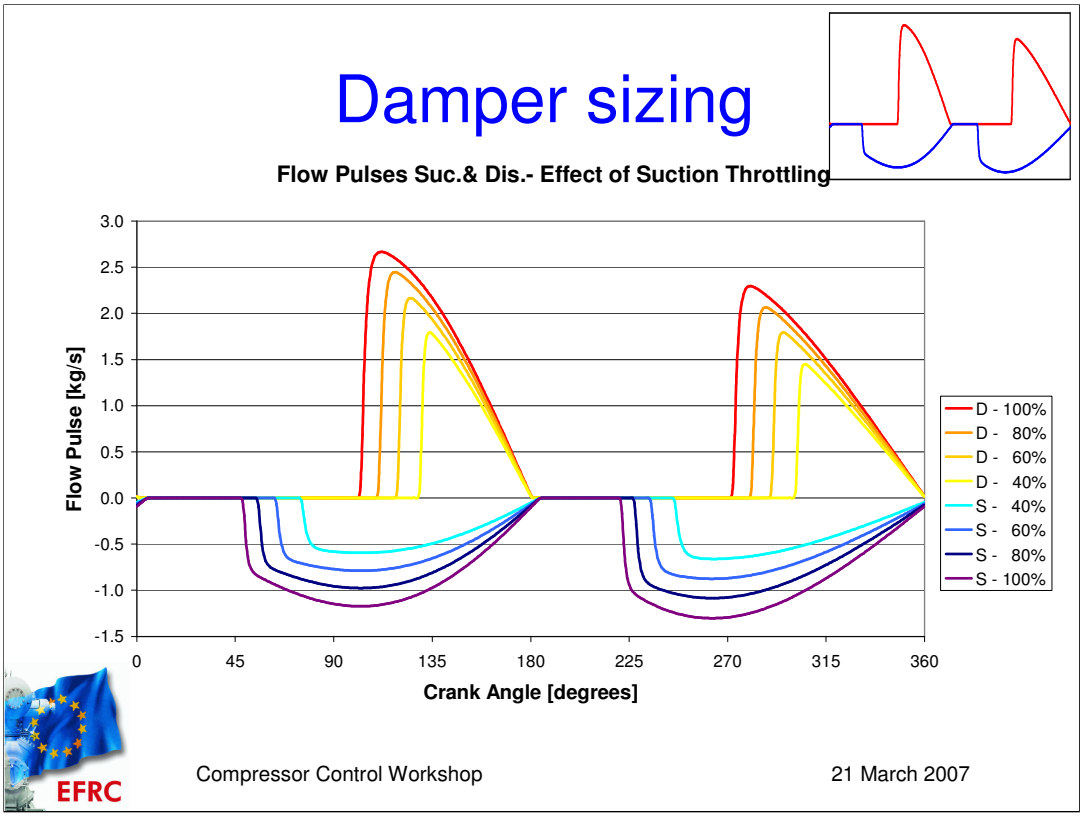
(there is no difference)

Damper sizing



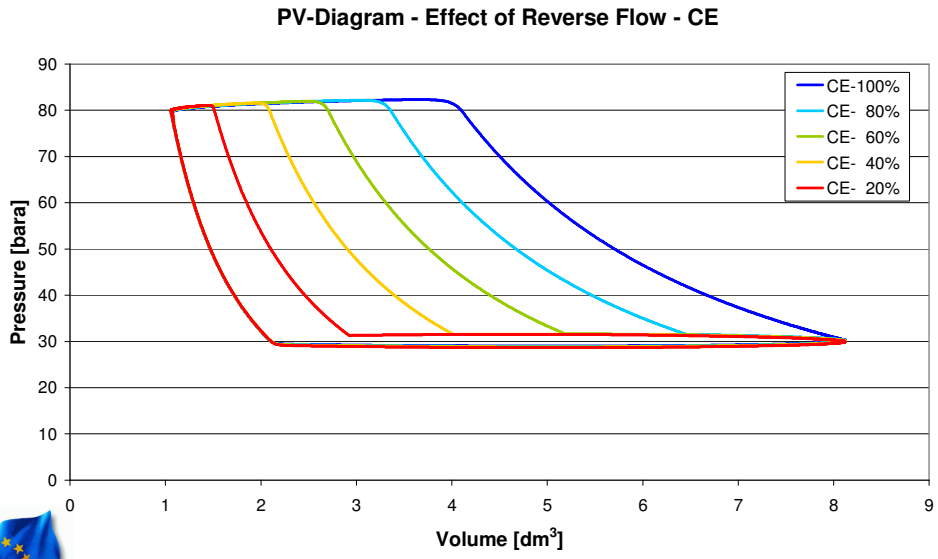
EFRC

Compressor Control Workshop 21 March 2007

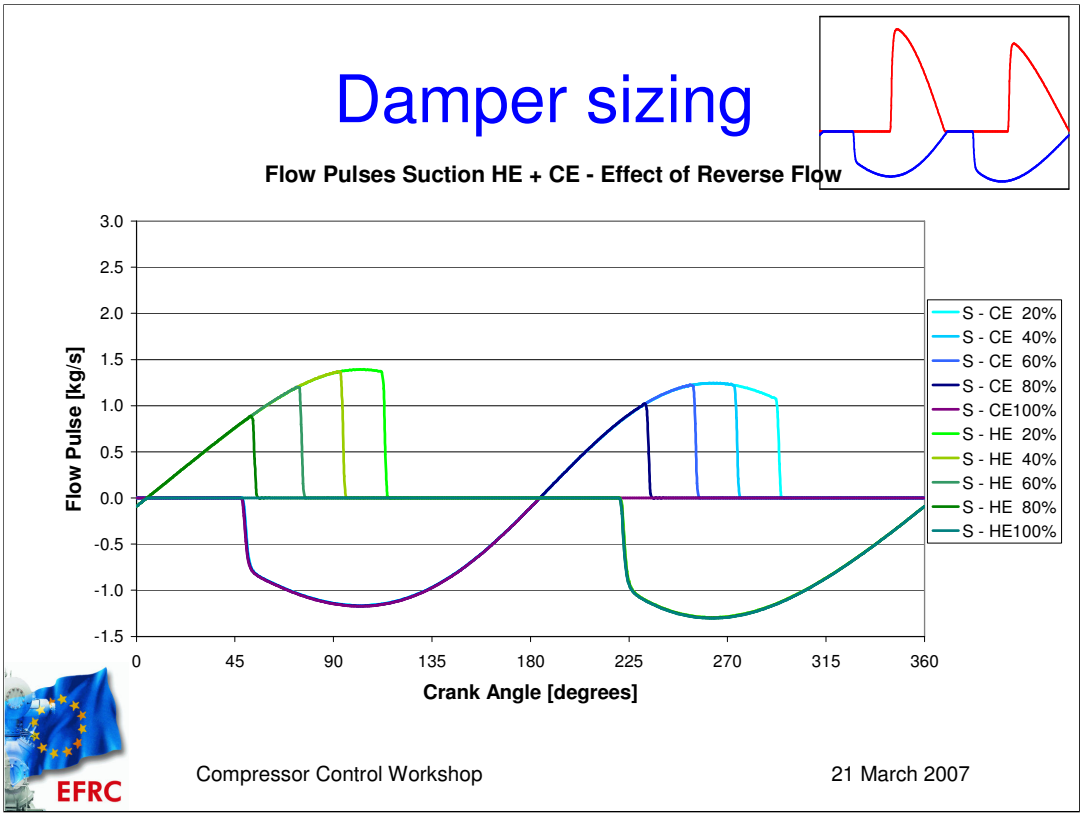


Flow pulses are shorter and lower in amplitude

Damper sizing

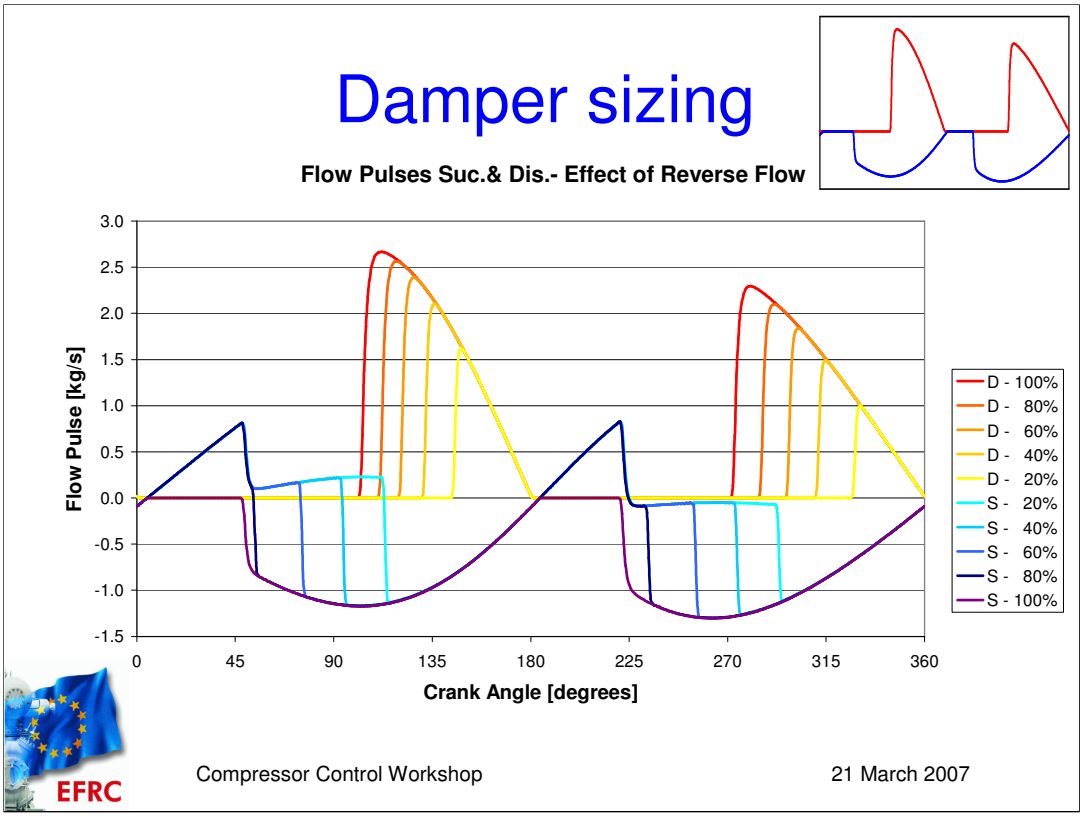


EFRC



Amplitudes increase on the suction side

Amplitudes decrease on the dischagre



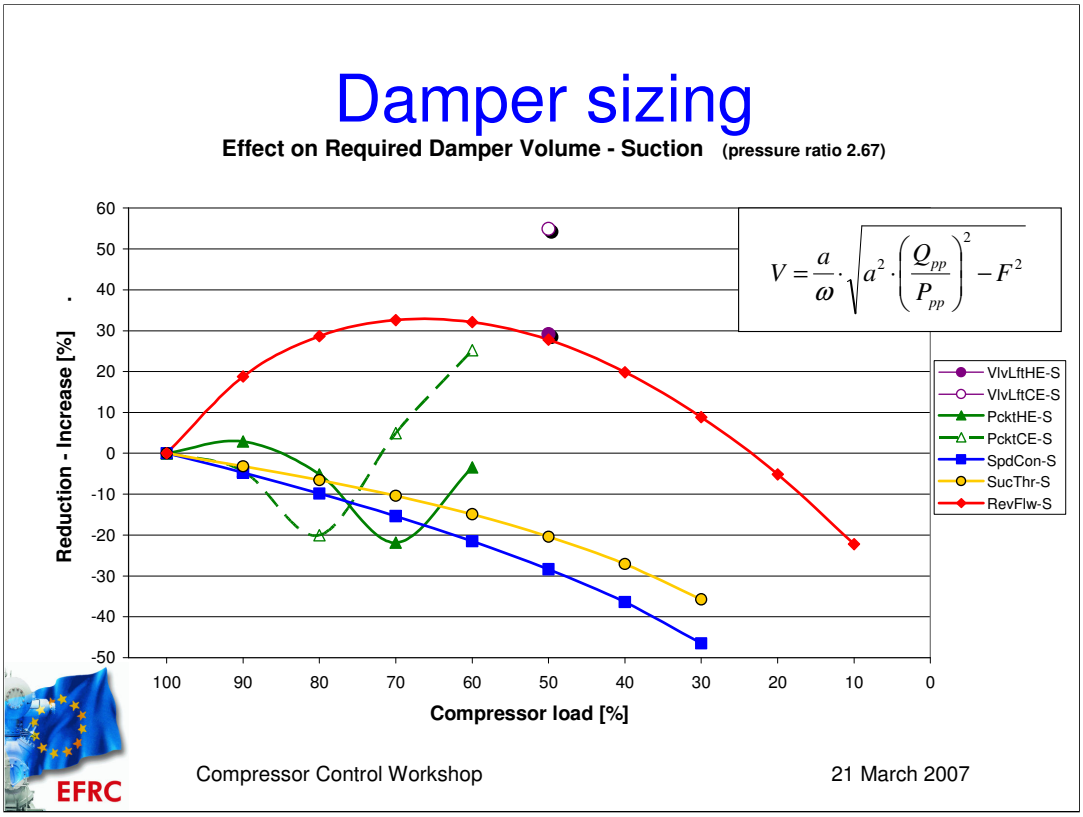
Amplitudes increase on the suction side

Amplitudes decrease on the dischagre

Damper sizing

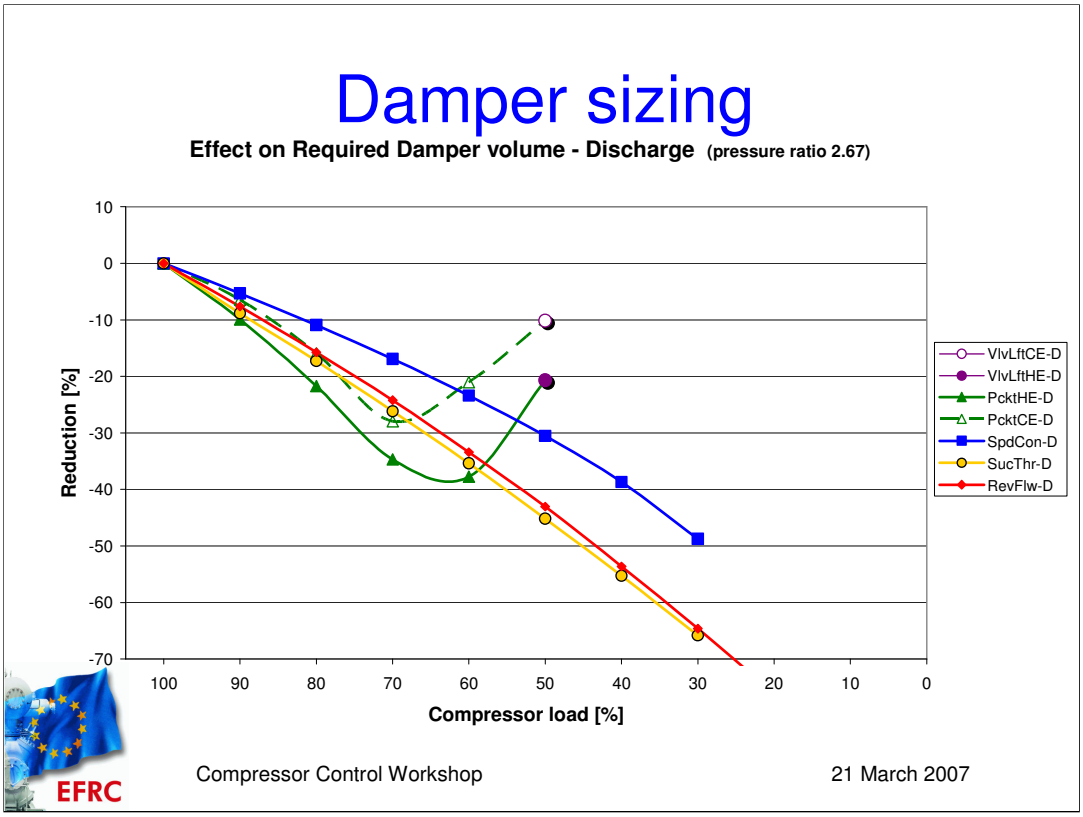
Control system	PV-diagram	Source Freq.	Suction Source Amplitude
Double acting	HE & CE	2nd	-
Valve lifting	only 1 left	1st	higher on suct.
Pockets	one narrows	2nd -> 1st	higher on suct.
Speed control	nearly identical	2nd	lower
By-passing	identical	2nd	identical
Suction throttl.	higher, narrow	2nd	lower
Reverse flow	narrow	2nd	higher on suct.

Discharge source amplitudes at part load are lower for all control systems.



The indicated trends are directly related to the differences in the flow pulse shapes.

Note that the mutual relation between the different control systems depend on the actual pressure ratio (in this case 2.67)



The indicated trends are directly related to the differences in the flow pulse shapes.

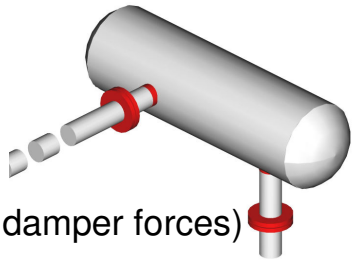
Note that the mutual relation between the different control systems depend on the actual pressure ratio (in this case 2.67)

Contents

- Introduction
- Effect of capacity control systems
  - Flow pulses (amplitudes and frequencies)
  - Damper sizing
- **Pulsation Dampers**
- Restriction Orifices (single and multiple)
- Prevention of Noise
- Conclusions & Recommendations

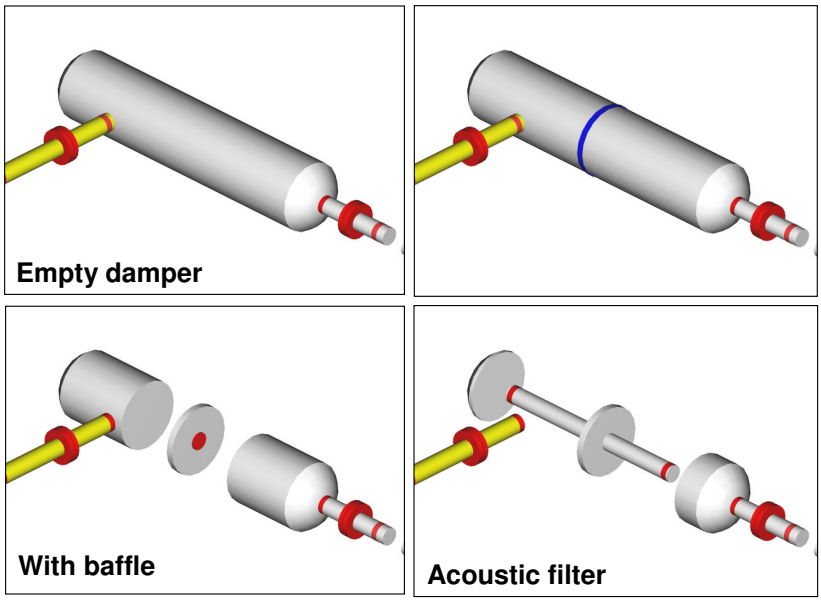
Pulsation dampers

A pulsation damper is the most important part in shielding the pipe systems from the source. It should be designed to cope with the complete operating envelope of the compressor.



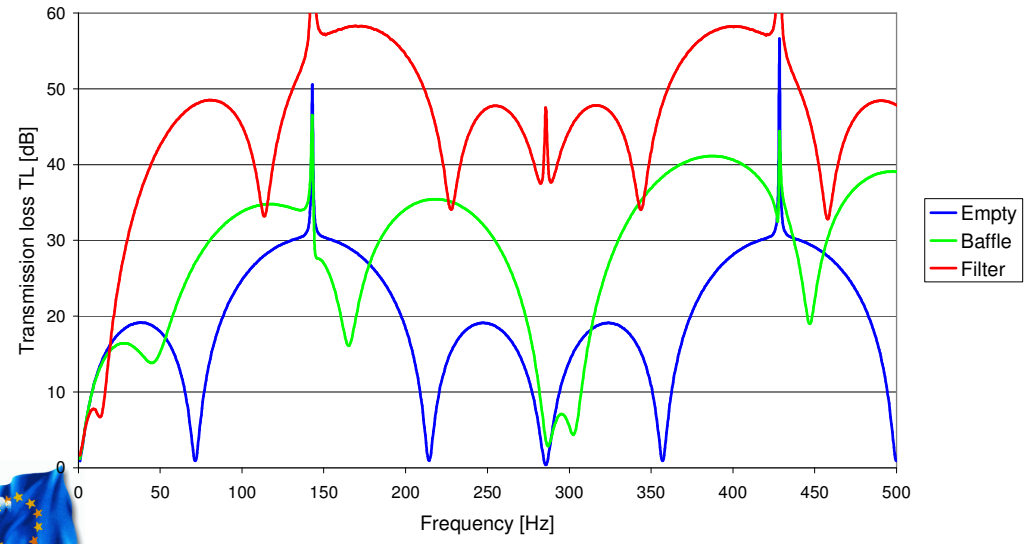
- Empty vessel
- Vessel Incl. baffle (to minimise damper forces)
- Acoustic filter (multi-chamber or 2nd-ary bottles)

Pulsation dampers



Pulsation dampers

Transmission loss for different damper types

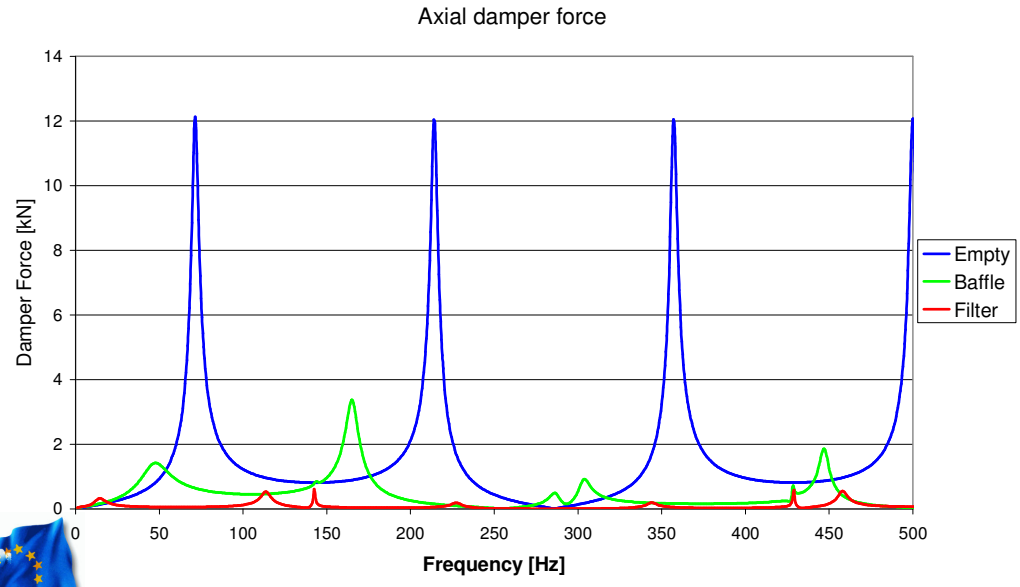


EFRC

Compressor Control Workshop

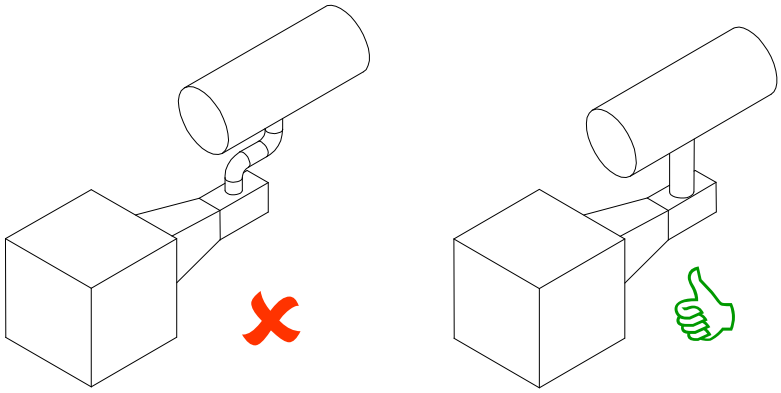
21 March 2007

Pulsation dampers



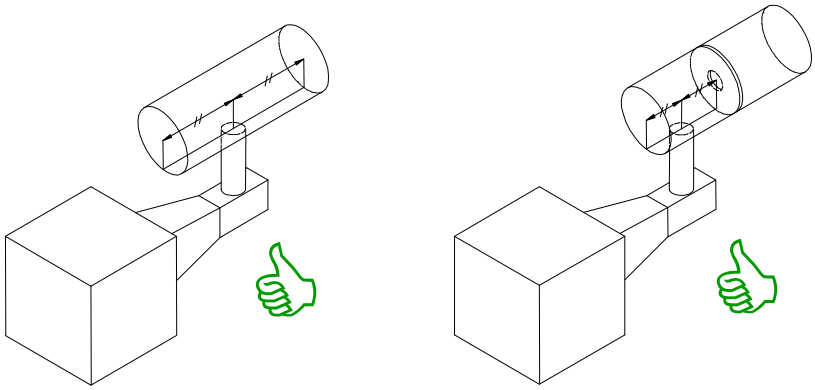
Pulsation dampers

Does and Don’ts in damper design



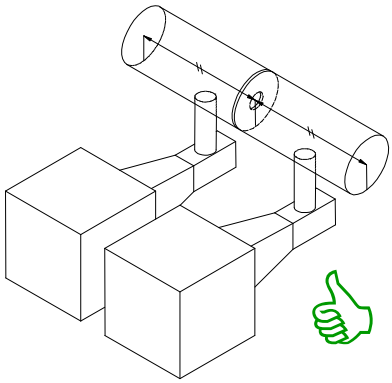
Pulsation dampers

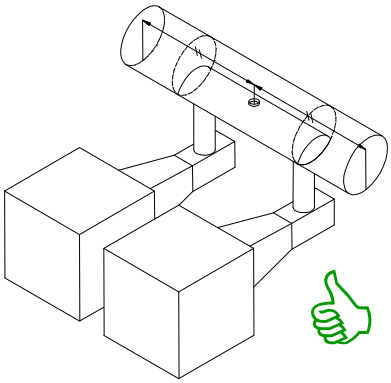
Does and Don’ts in damper design



Pulsation dampers

Does and Don’ts in damper design





Contents

- Introduction
- Effect of capacity control systems
  - Flow pulses (amplitudes and frequencies)
  - Damper sizing
- Pulsation Dampers
- **Restriction Orifices** (single and multiple)
- Prevention of Noise
- Conclusions & Recommendations

Restriction Orifices (RO's)

Purpose is to dampen resonances

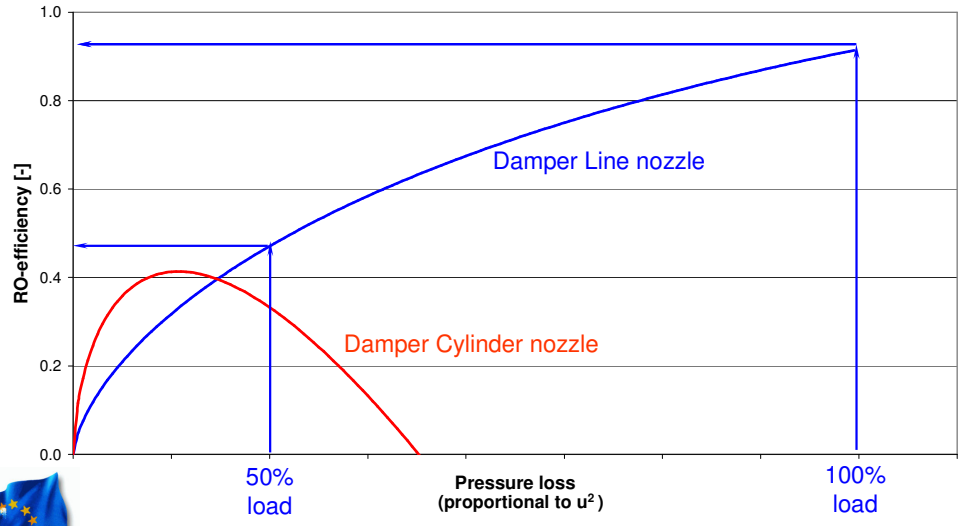
(they can not replace a damper that is too small)

- Efficiency mainly depends on pressure drop
- Location is all important as they are only effective in a flow node (pressure anti node)

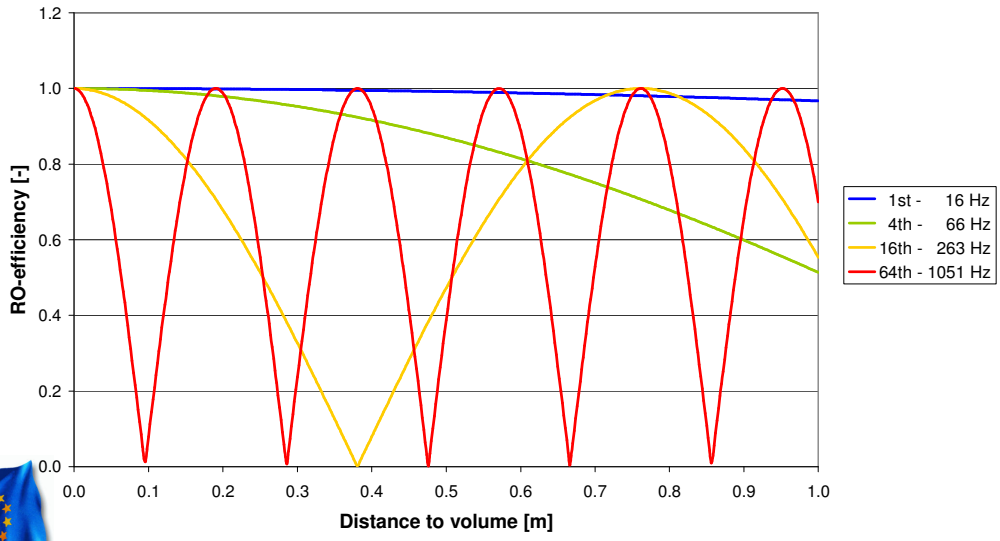
- Single bore orifices are only effective up to a certain frequency

Restriction Orifices (RO's)

RO-efficiency as function of Pressure loss



Restriction Orifices (RO's)



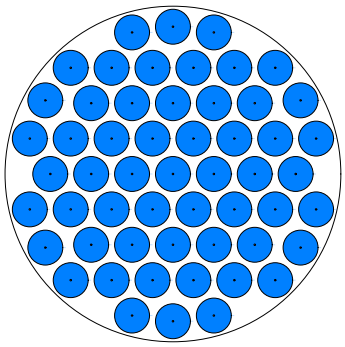
EFRC

Compressor Control Workshop 21 March 2007

Restriction Orifices (RO's)

- RO's (single and multiple hole) are only effective in a flow node (close to volumes)
- Efficiency is frequency dependent

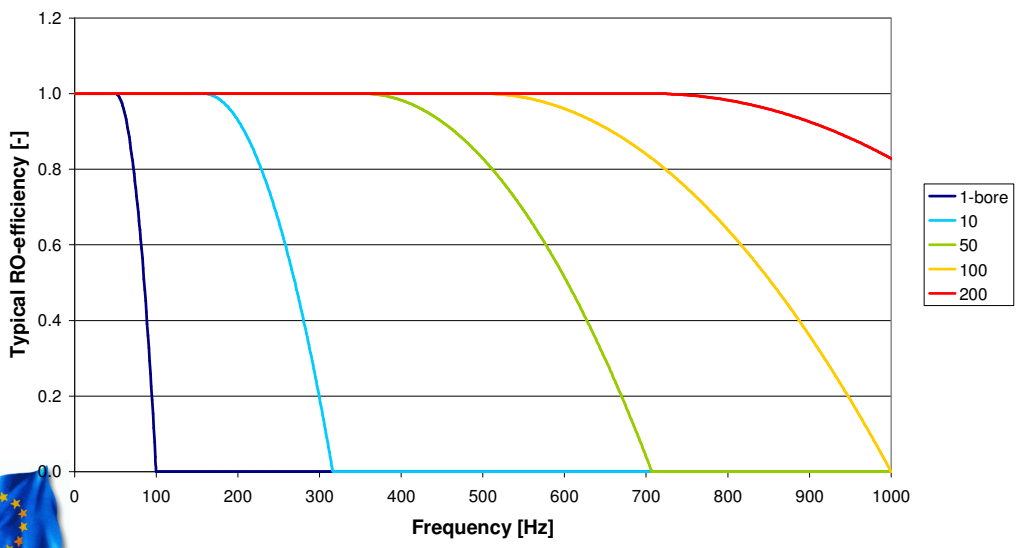
$$F_{max} = \frac{0.1 * U_{hole}}{D_{hole}}$$



Pressure drop depends on:
hole diameter, number of holes, RO-location, plate thickness, up- and downstream bevelling

Maximum frequency up to which a MRO is effective is proportional to the square root of the number of holes

Restriction Orifices (RO's)



EFRC

Compressor Control Workshop 21 March 2007

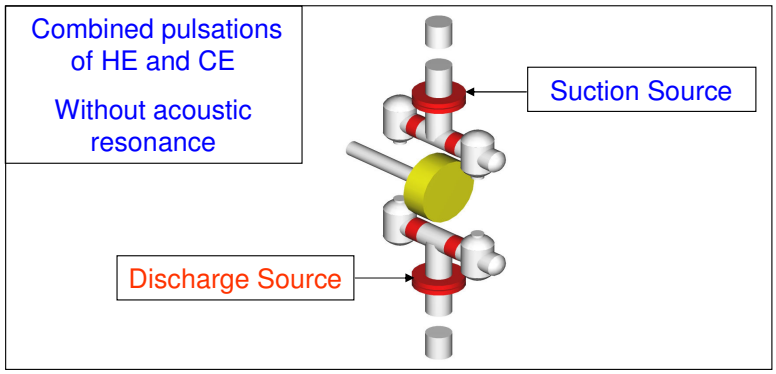
Contents

- Introduction
- Effect of capacity control systems
  - Flow pulses (amplitudes and frequencies)
  - Damper sizing
- Pulsation Dampers
- Restriction Orifices (single and multiple)
- **Prevention of Noise**
- Conclusions & Recommendations

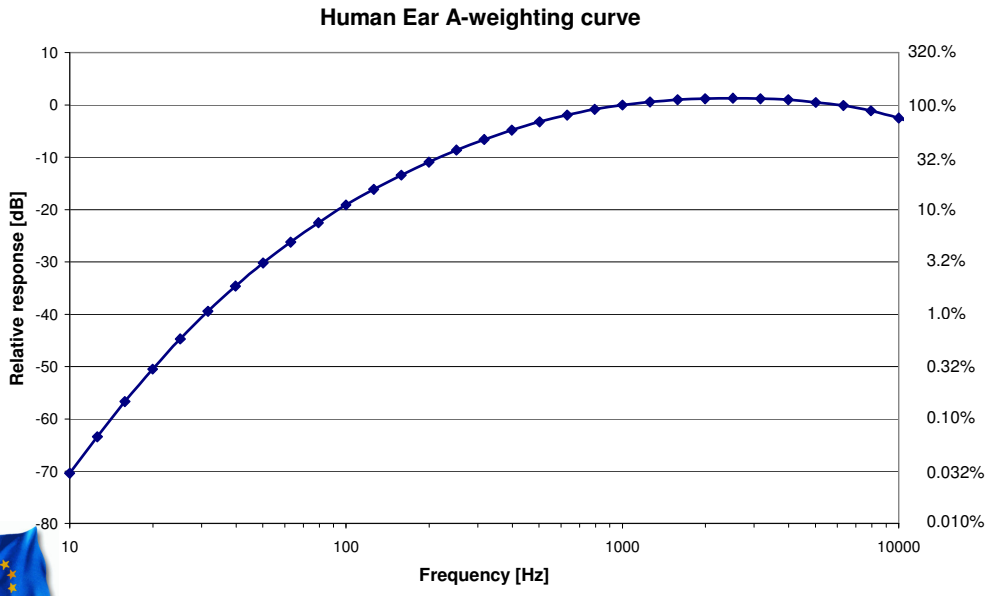
Prevention of Noise

Nowadays more emphasis on noise due to:

- more strict HSE legislation
- higher compressor speeds
- use of reverse flow control



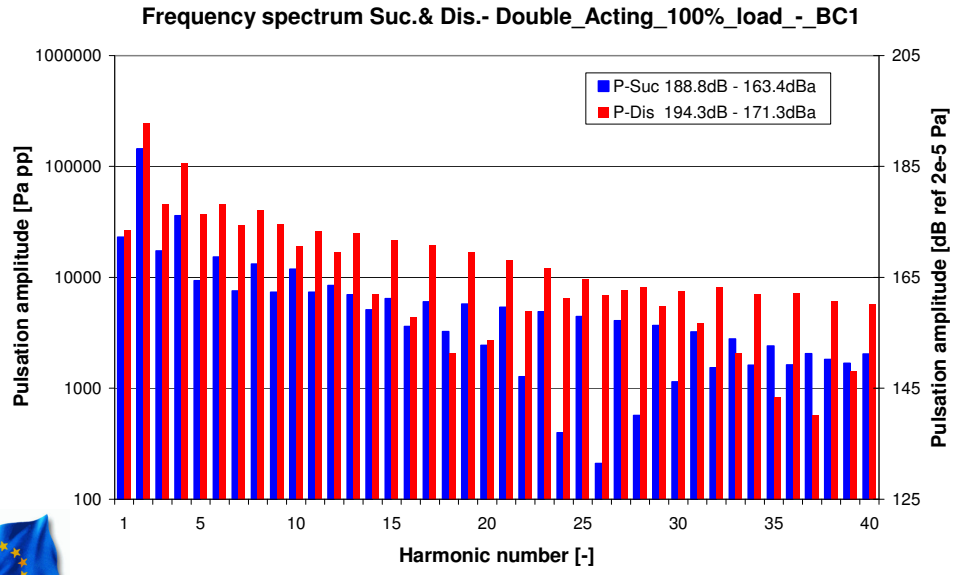
Prevention of Noise



EFRC

Compressor Control Workshop 21 March 2007

Prevention of Noise

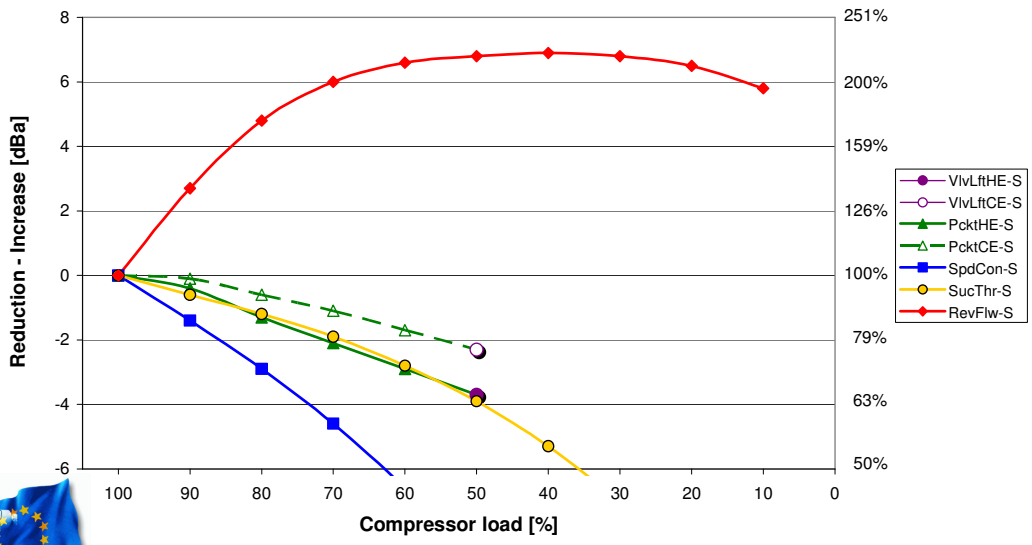


EFRC

Compressor Control Workshop

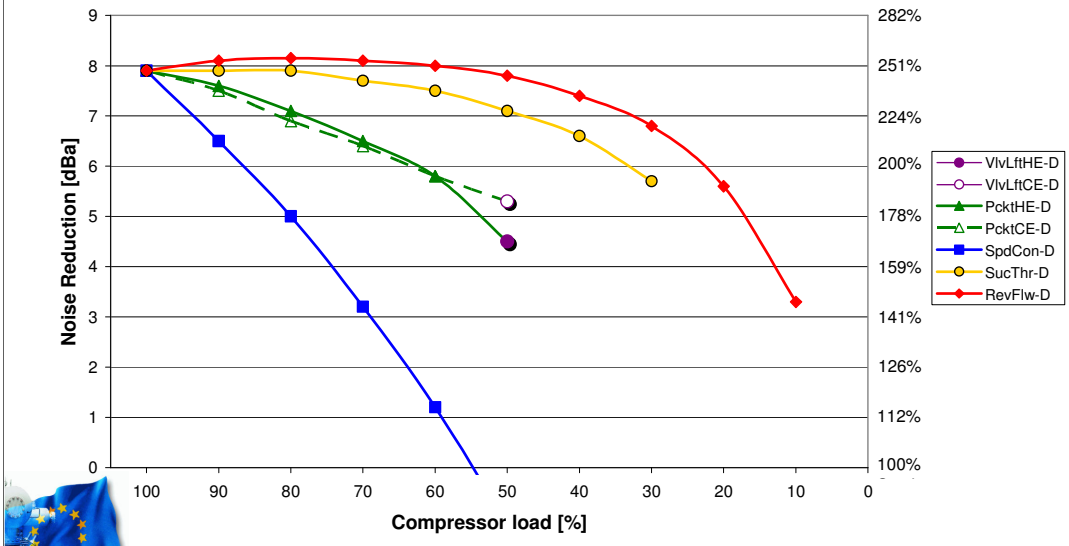
21 March 2007

Prevention of Noise



EFRC

Prevention of Noise



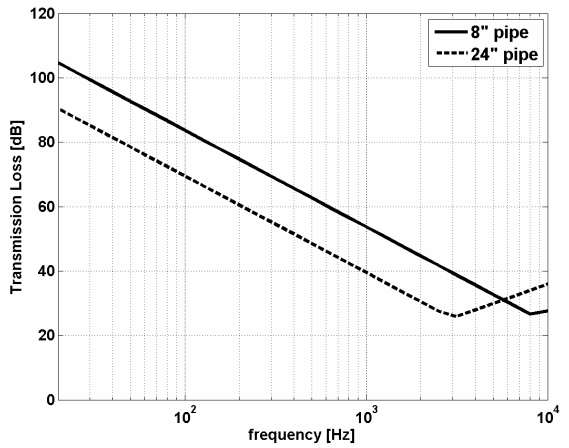
EFRC

Compressor Control Workshop

21 March 2007

Prevention of Noise

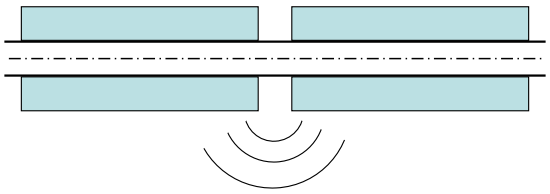
Pipe walls provide a very effective damping for low frequencies, but are more transparent for higher frequencies



(from VDI 3733)

Prevention of Noise

- Pulsations and noise should be attenuated to acceptable levels by the damper (and RO's) at the cylinder and line connections
- Additional measures to reduce noise are:
  - Use of acoustical filter type of damper (2 volumes connected with a choke)
  - Use of MRO's in stead of SRO's
  - Pipe insulation (if well applied, also thermal insulation can be effective for higher frequencies)



Conclusions

Control system	Damper sizing	Pipe systems	Audible Pulsations
Double acting	±	++	±
Valve lifting	--	±	++
Clearance Pockets	--	±	++
Speed control	±	-- (1	++
By-passing	±	++	±
Suction throttling	±	±	±
Reverse flow	--	± (2	--

1) Caused by the fact that mechanical and acoustical natural frequencies will coincide
2) Shift towards higher frequencies (pulsation analysis up to 64th harmonic)

Conclusions

- Every capacity control system has its own distinct effect on the way the suction and discharge systems are excited.
- Capacity control systems influence the requirements put to the dampers. They can affect size and frequency requirements
- Dampers, RO's and other pulsation reducing measures should be optimised to obtain acceptable pulsation levels at all occurring conditions (part loads)

The effect of capacity control systems can best be understood by looking at the differences in the compressor's flow pulses

Recommendations

- Solve pulsation, vibration and noise problems in the design phase (easier and cheaper)
- In a pulsation analysis the volume of the damper should be sized for the worst case (this could be during part load)
- A pulsation analysis should include the complete operating envelope of the compressor (incl. all occurring part loads, duties, configs). In case of reverse flow, carry out a pulsation analysis up to the 64th harmonic
- In case of stringent noise levels, the use of acoustic filters, MRO's and insulation could be considered.

Solve your problems on the drawing board!