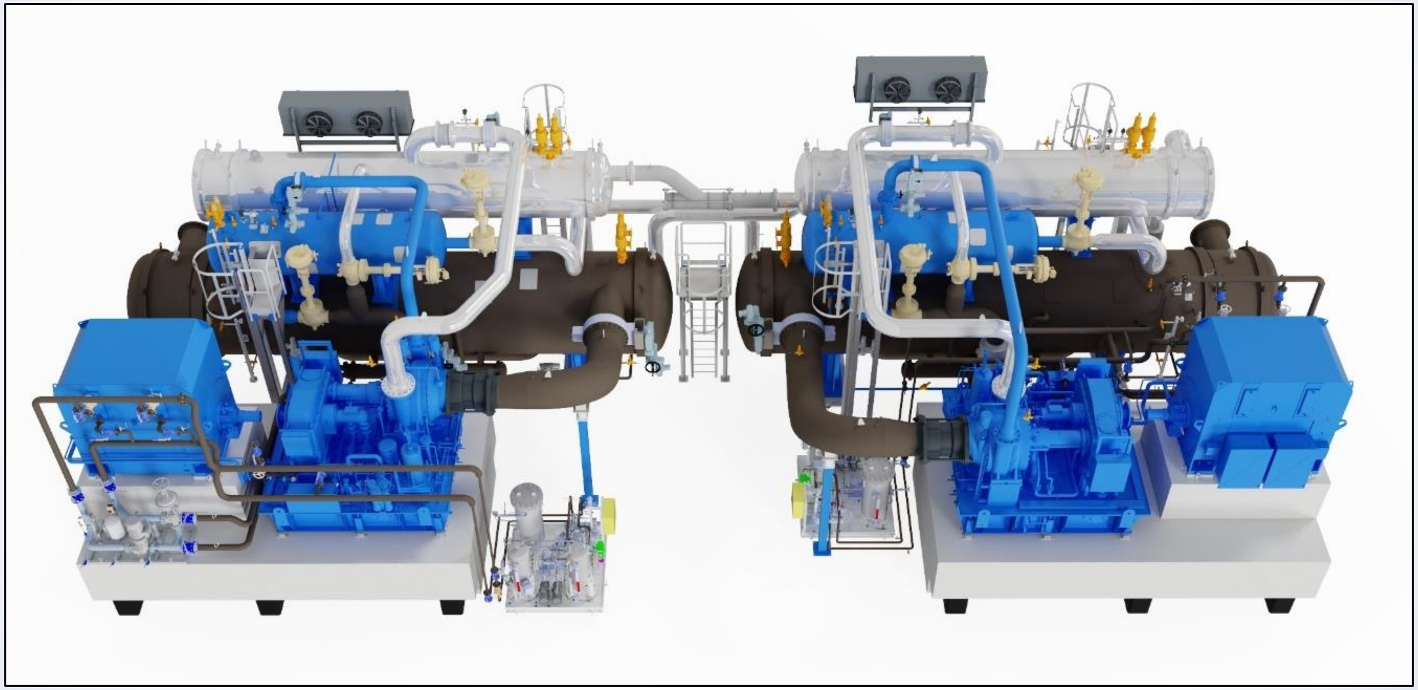
Machine-Induced Vibrations

MACHINE FOUNDATIONS



Exercise: Moto-Compressor Foundation - Basic Design

EPFL, Civil – Dynamics of Structures

Introduction / Basic Design

A motor-compressor foundation must be pre-dimensioned / key parameters must be studied, determined and proved. The aim of the exercise (as part of the lecture “Machine-Induced Vibrations”) is to deal with essential dynamic aspects of a machine foundation. Not all aspects of a basic design are covered within this exercise; focus is laid on Serviceability Limit States (SLS).

The purpose of a basic design is to finalise overall main dimensions of the foundation and – in this case - the spring layout (position, stiffness, etc.), excluding substructure. Such a design step consists „simplified“ design calculation, i.e. not as detailed as the final design and neither reinforcing drawings nor detailed formwork drawings will be issued during this phase, only overall layout drawings.

Structure-Borne Noise Protection

The moto-compressor is installed in an urban environment and the decoupled foundation is intended to counteract the radiated structure-borne noise.

► Concept: Spring Mounted Machine Foundation

Installation of Spring Elements / Lifting of the Foundation

Machine Data

	Total Mass [kg]	Rotating Mass [kg]	Operational Speed [rpm]	Balancing Quality [mm/s]
Drive engine	**15'500**	**3'775**	**1'489**	**G 1.00**
Low-speed Clutch	**20’100**	352.5	1'489	G 0.66
Gearbox: Gearwheel		1'956	1'489	G 0.67
Gearbox: Pinion		101.5	9'238	G 0.67
High-speed Clutch		35	9'238	G 0.67
Compressor		**177**	**9'238**	**G 6.3**
Steel Frame		-	-	-
Cooling Unit	400	-	-	-

Further Information

Construction Materials

Concrete: Grade C 25 / 30
Reinforcement: Grade BSt 500 SB

One Continuous Foundation

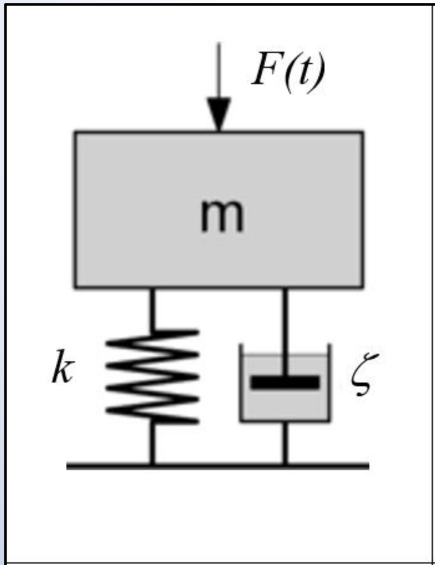
Compressor and Motor must be installed on one continuous foundation (‘no’ relative deflections between the components are allowed).

Acknowledgements

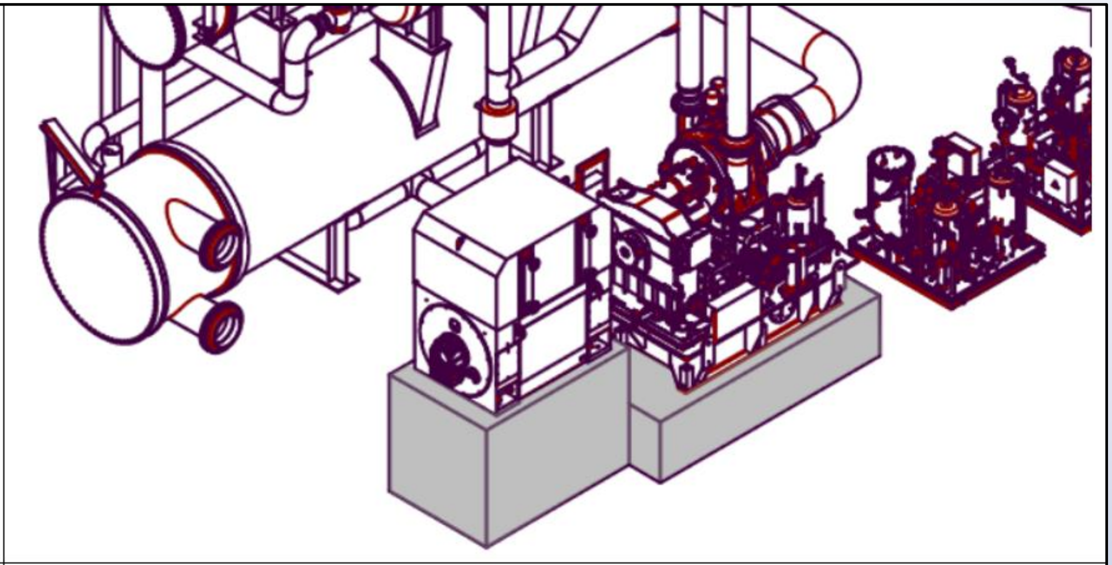
Many thanks to Friotherm AG, Switzerland for providing the case study (e.g. machine data, visualisations, pictures).

Exercise Harmonic Oscillator

Simplifications: For this exercise, the spring mounted foundation (elastic decoupling: low-pass filter) can be considered as a harmonic oscillator (harmonic excitation by the machine) and only the vertical direction must be examined. As a maximum isolation is aimed for, damping can be set to zero.



Harmonic Oscillator



Manufacturers Proposal

Simplifications / Initial Situation

Tuning Frequency

<u>Question 1</u>: Define the tuning frequency

First draft of the foundation in relation to the machine manufacturers proposal (width x length x height):

- Compressor Plinth: 3.20 x 7.08 x 0.88 m
- Motor Plinth: 1.95 x 2.87 x 1.86 m

The spring mounted foundation should be designed for an **isolation ratio 0.05 (**maximum force transmission of 5%), meaning $(F_d + F_k) / F_0 < 0.05$.

Tuning Frequency

Spring Stiffness

<u>Question 2</u>: Define the (overall vertical) spring stiffness.

Note: The effective stiffness is obtained by specifying the spring type according to the manufacturer's product range. 6 pieces of the following spring type were used for this project:

Spring Element Type 4B-50-40-4x1

- Load Bearing Capacity: 400 kN
- Operational Load: 320 kN
- Vertical Spring Constant: 22.0 kN/mm
- Installation Height: 450 mm
- Size in plan: 350 x 350 mm
- Vertical Range of Regulation: -25 / +150 mm

Spring Stiffness

Vibration Velocities

<u>Question 3</u>: Calculate the operational vibration amplitudes (velocities and deflections) due to the motor unbalance and – separately – due to the compressor unbalance.

The unbalance forces must be calculated based on the balancing quality: $F = m * e * \Omega^2$; whereas the balancing quality is equal to $G = e * \Omega$.

The allowable vibration velocities must be compared with values specified as per ISO 10816-3 for Zone A, Group 2 and Soft Support: The value v_{eff} = 2.3 mm/s should not be exceeded.

Vibration Velocities

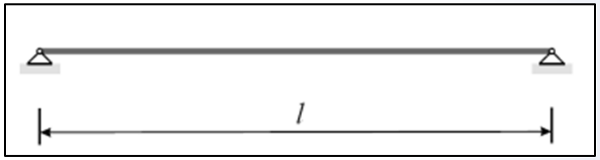
Vibration Velocities

Structural Eigenmode(s)

<u>Question 4</u>: Calculate / estimated the first flexural mode of the foundation by simplifying the foundation to a representative cuboid.

The first natural frequency of a simple beam is as follows:

$$f_1 = \frac{\pi}{2 * l^2} * \sqrt{\frac{EI}{\mu}}$$



μ: Mass per unit length

Structural Eigenmode(s)

Discussions

<u>Question 5</u>: Discuss the following topics

- Modelling: What do you think of the simplifications? Are the calculations still realistic? Which model parameters do you consider to be particularly important?

- Calculation Results: Do you consider the structural eigenmodes to be critical for the present situation? Evaluate the deflections (e.g. regarding the connecting pipes)

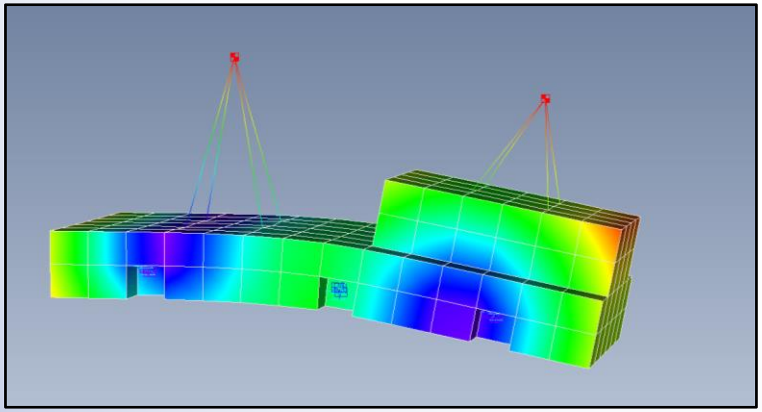
- Next steps: Which optimisations do you suggest? Which further checks should be carried out (as part of the basic design)?

Discussions

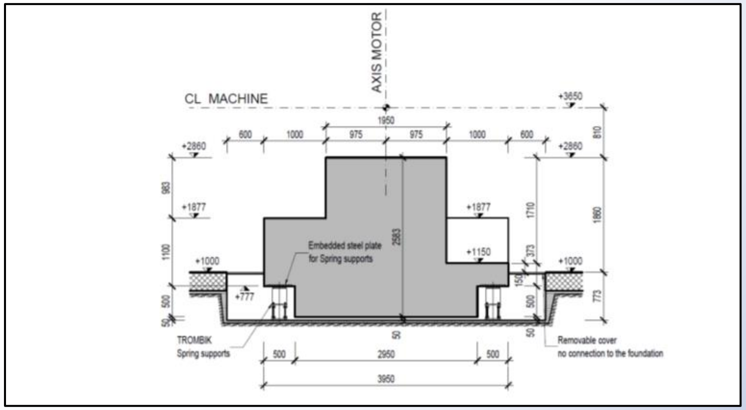
Final Outline

The machine manufacturer's initial design showed that the inertia mass was too low and that there were critical eigenfrequencies (torsional and bending). The optimisation led, among other things, to a widening and also to a thickening of the foundation. To maintain the tuning ratio of the overall system, the type of springs also had to be adapted.

Note: As a rule, the foundation weight should be 5 to 6 times heavier than the machine.



Critical Flexural Mode next to the operation Speed

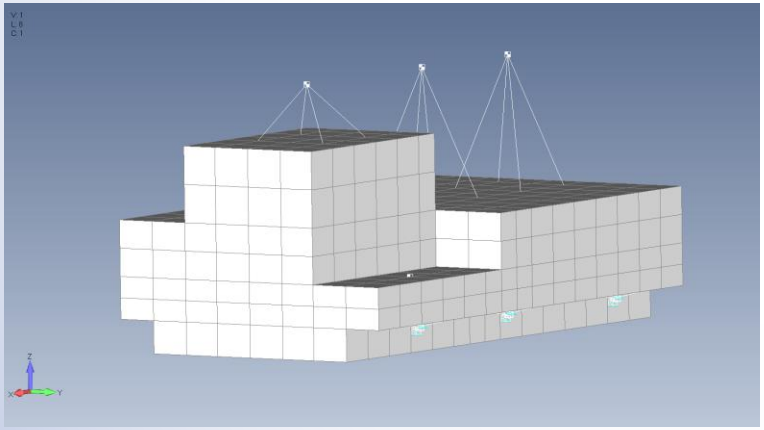


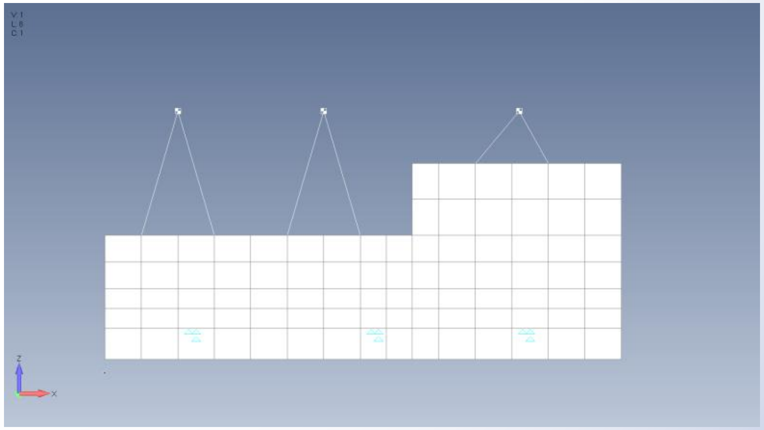
Typical Cross Section

Numerical Modelling

The foundation structure is replaced by a three-dimensional finite element structure. A number of reasonable simplifications have to be applied, to keep the complexity of the model within reasonable limits. Main focus to be laid on mass and stiffness distribution:

- Use of volume elements
- Machine masses at the exact positions (by ‘dummy’ beams)

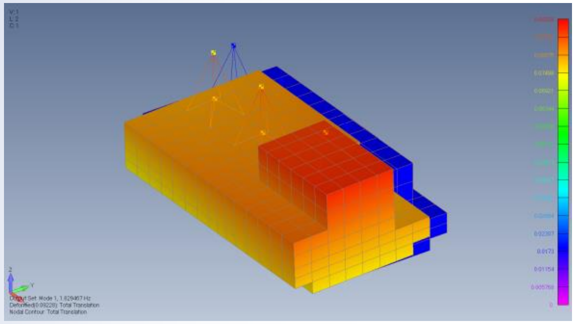




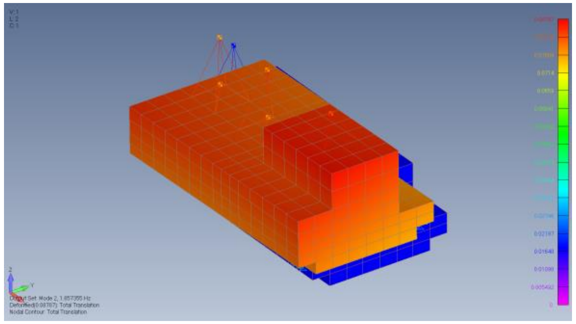
Overview FE-Model

Eigenvalues - Selected Eigenmode Plots

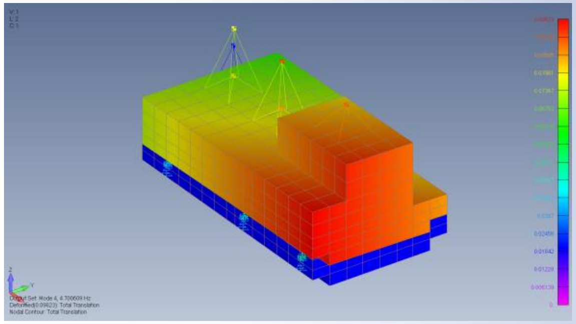
Basic eigenfrequencies (rigid body motions)



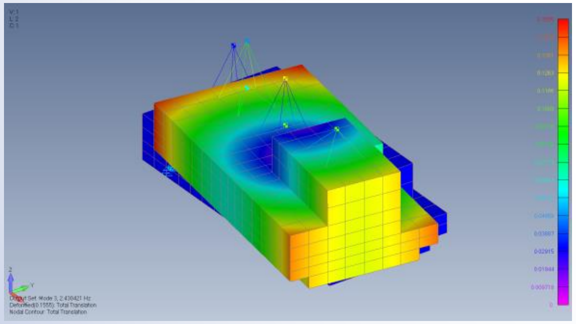
$f_1 = 1.8\ Hz$



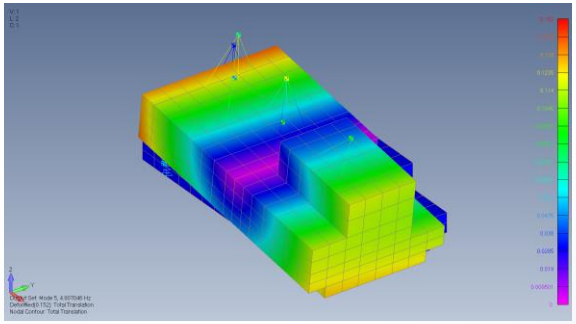
$f_2 = 1.9\ Hz$



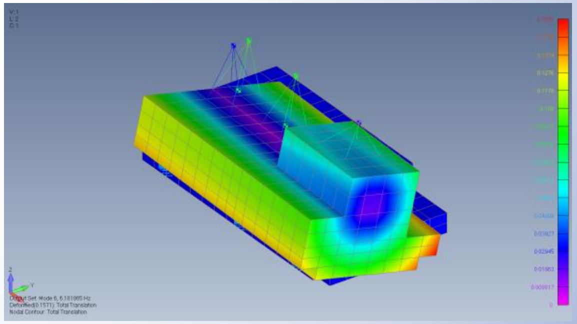
$f_4 = 4.7\ Hz$



$f_3 = 2.4\ Hz$



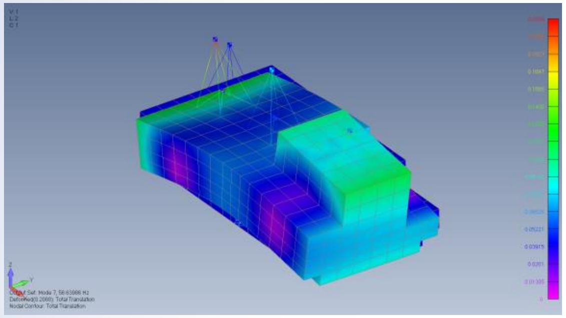
$f_5 = 4.8\ Hz$



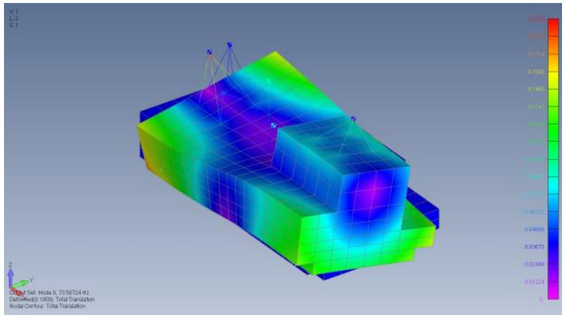
$f_6 = 6.2\ Hz$

Eigenvalues - Selected Eigenmode Plots

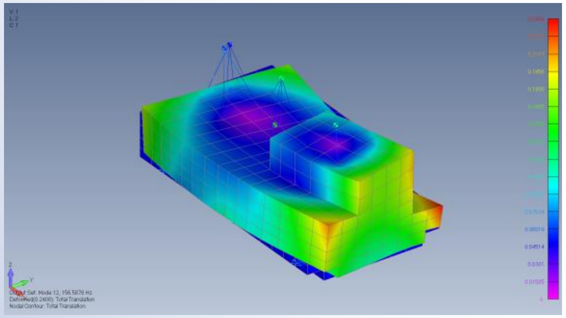
Main bending and torsional eigenfrequencies



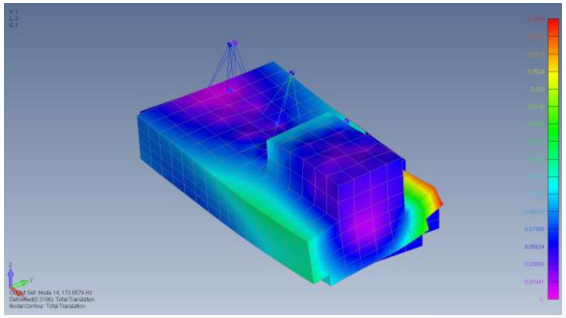
$f_7 = 56.6\ Hz$



$f_8 = 73.6\ Hz$



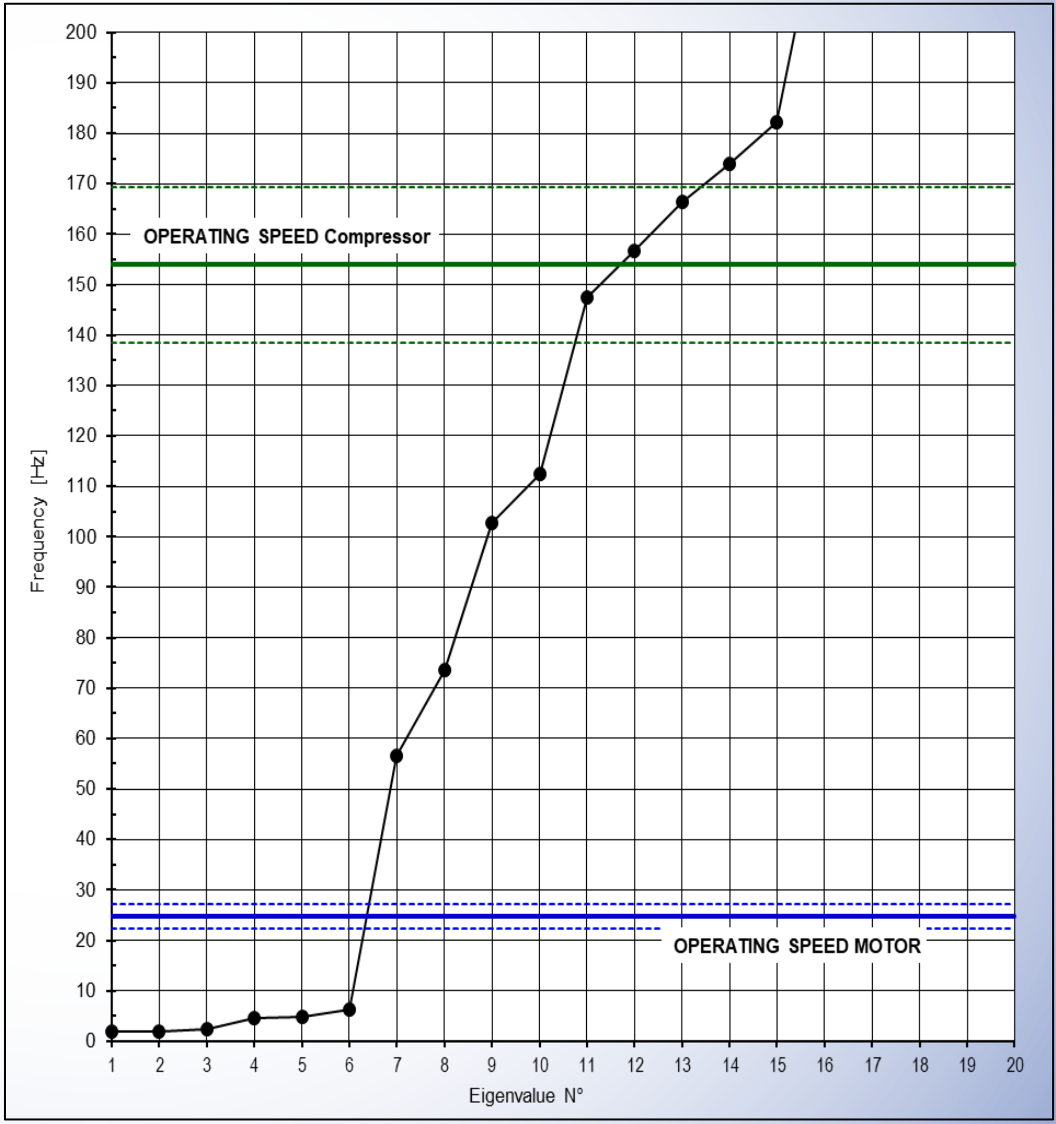
$f_{12} = 156.6\ Hz$



$f_{14} = 173.9\ Hz$

Eigenvalues

The Eigenvalues are appropriately distributed. Only 3 Eigenvalues (N° 11 to 13) are situated within a +/-10 % Zone of the operating speed (of the compressor). These 3 Eigenvalues, situated closest to the operating speed, are Eigenvalues of high order, where the influence of the material damping is considerable. Additionally, the corresponding mode shapes show that the machines (machine masses / anchorages) are not primarily affected. Also, it is recorded that the rigid body motions (lower order Eigenvalues) are located lower than 90 % of the motor operating speed.



Normal Operation (Unbalance)

Excitation Forces: The horizontal and vertical unbalance forces due to normal operational at the bearing supports have been applied separately at the bearings. The unbalance loads were calculated based on the balancing quality.

Vertical and horizontal operational unbalance loads

Bearing	Motor	Gearbox	Compressor
Rotormass M [t]	3.775	1.956	0.177
Unbalance Loads [kN] [1]	0.59	0.20	1.08
Mass Amplitude [t m] [2]	2.42E-05	1.25E-05	1.15E-06

[1] $F = M * e * \Omega^2$ [kN]   [2] used for computer input

The unbalance force amplitudes are applied as sinusoidal excitation forces at the bearing pads. The unbalance forces have been swept in the frequency range from -10% to +10% of the operation speeds.

Vibration Velocities

The maximum resulting vibration amplitudes v_{peak} have been taken in the range of 22.3 to 27.3 Hz for the Motor and the Gearbox and in the range of 154 to 169 Hz for the Compressor (± 10% of the operating speed). The resulting maximum vibration velocities for all operational unbalance cases are given in the following table.

Operational Unbalances **[mm/s]**

Bearing	Motor	Gearbox	Compressor
Vertical Vibrations	0.09	0.02	0.03
Horizontal Vibration	1.14	0.26	0.37

Conclusion: The allowable vibration velocities on each bearing point have been compared with values specified as per ISO 10816-3 (refer to Chapter 2.1) for Zone A, Group 2 and Soft Support: The value v_{eff} = 2.3 mm/s will not be exceeded (horizontal and vertical).