2.4. Solutions

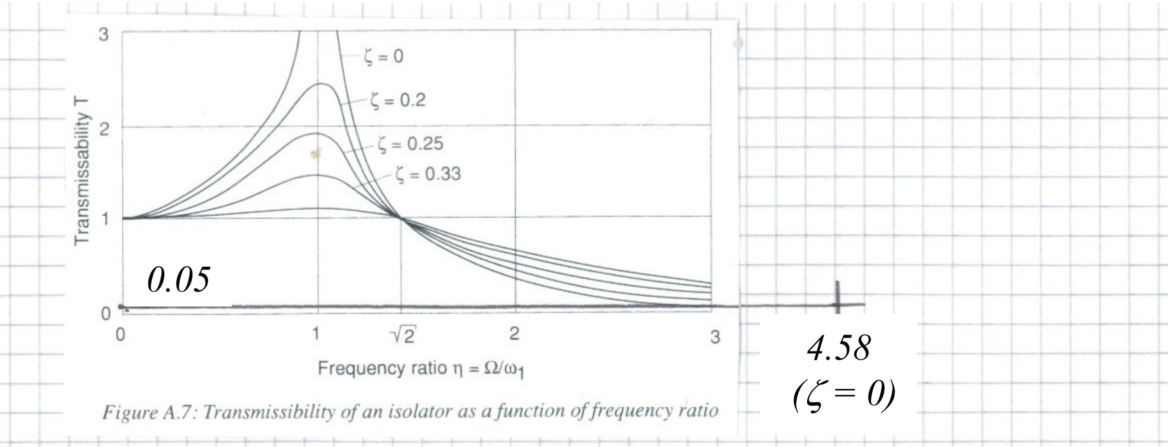
A) Tuning Frequency

- Isolation ratio: 5% (Transmissibility)
- Minimal Damping: $\zeta = 0$
- $T = |F_d + F_k| / F_0 = \sqrt{\frac{1}{(1-\eta^2)^2}} = \frac{1}{|1-\eta^2|} \leq 0{,}05$

  $\hookrightarrow \eta = 4{,}58 \quad = \Omega/\omega = F/f_1$
- Motor: 1'489 rpm ≙ 24,8 Hz → $f_1 \leq 5{,}4$ Hz

  Compressor: 9'238 rpm ≙ 154 Hz → $f_1 \leq 33{,}6$ Hz

  ↳ Tuning Frequency ≤ 5,4 Hz



Figures 2.2 Transmissibility T

B) Spring Stiffness

- Machine mass: 36,0 t
- Concrete: V = 30,3 m³ → 75,9 t

  $\}$ $m_{tot} = 111{,}9$ t
- $f = 1/2\pi \cdot \sqrt{k/m} \leq 5{,}4$ Hz

  ↳ $k_{tot} \leq 128'818$ kN/m ≈ 129'000 kN/m

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 (recommendation):* 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

C) Vibrations Amplitudes

- Balancing Quality: Motor: $G = e \cdot \Omega = 1{,}0\ mm/s \rightarrow e = 6{,}41 \cdot 10^{-6}\ m$
  Compressor: $= 6{,}3 \rightarrow e = 6{,}51 \cdot 10^{-6}\ m$
- Unbalance Force: Motor: $m = 3{,}775\ t \rightarrow F = 0{,}59\ kN$
  Compressor: $0{,}177\ t \rightarrow F = 1{,}08\ kN$
- Static Deflection Motor: $x = 0{,}59/129'000 = 4{,}57 \cdot 10^{-6}\ m$
  Compressor: $= 8{,}37 \cdot 10^{-6}\ m$
- $DMF\ (\zeta = 0) = \frac{1}{1-\eta^2}$ Motor: $DMF = 0{,}050 \rightarrow x_{max} = 2{,}29 \cdot 10^{-7}\ m$
  Compressor: $= 0{,}0012 \rightarrow x_{max} = 1{,}00 \cdot 10^{-8}\ m$
- Velocities: $v = 2 \cdot \pi \cdot f \cdot x_{max}$ Motor: $v_{max} = 0{,}036\ mm/s$
  Compressor: $v_{max} = 0{,}010\ mm/s$
- $v_{eff,adm} = 2{,}3\ mm/s \rightarrow v_{max,adm} = 3{,}25\ mm/s > v_{max}$ ✓

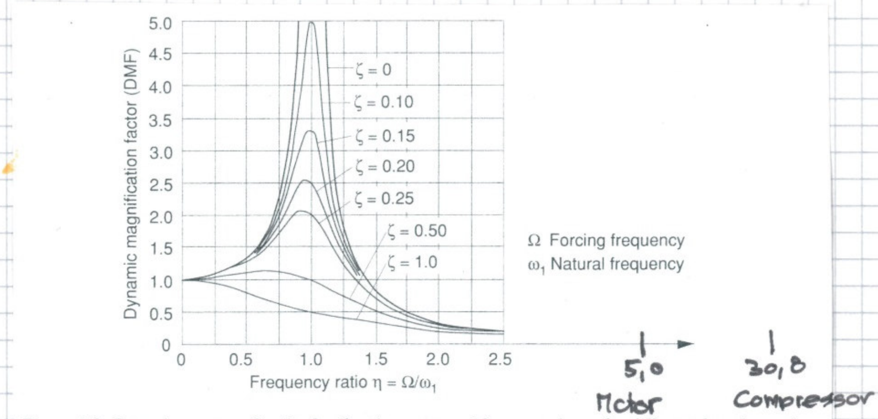


Figure A.2: Forced response of a simple vibrating system with curves shown for different damping ratios

Figures 2.3 Dynamic Magnification Factor DMF

D) Structural Eigenmode

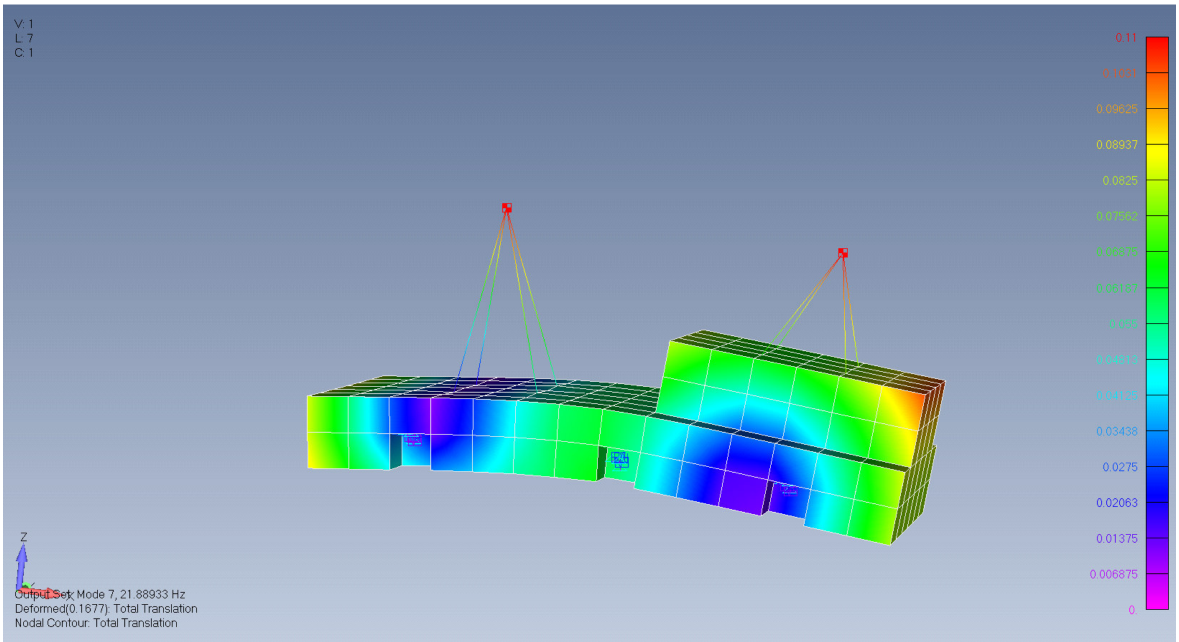
- Governing cross section $3{,}2\ m \times 0{,}88\ m$ $I = 0{,}182\ m^4$
- Concret $E_{dyn} = 30\ GPa = 30 \cdot 10^6\ kN/m^2$
- mass $= 111{,}9\ t / 7{,}08\ m = 15{,}8\ t/m = \mu$
- μ, EI, ℓ: $f = \frac{\pi}{2 \cdot \ell^2} \cdot \sqrt{EI/\mu} \cong \underline{18\ Hz}$

3. Basic Design

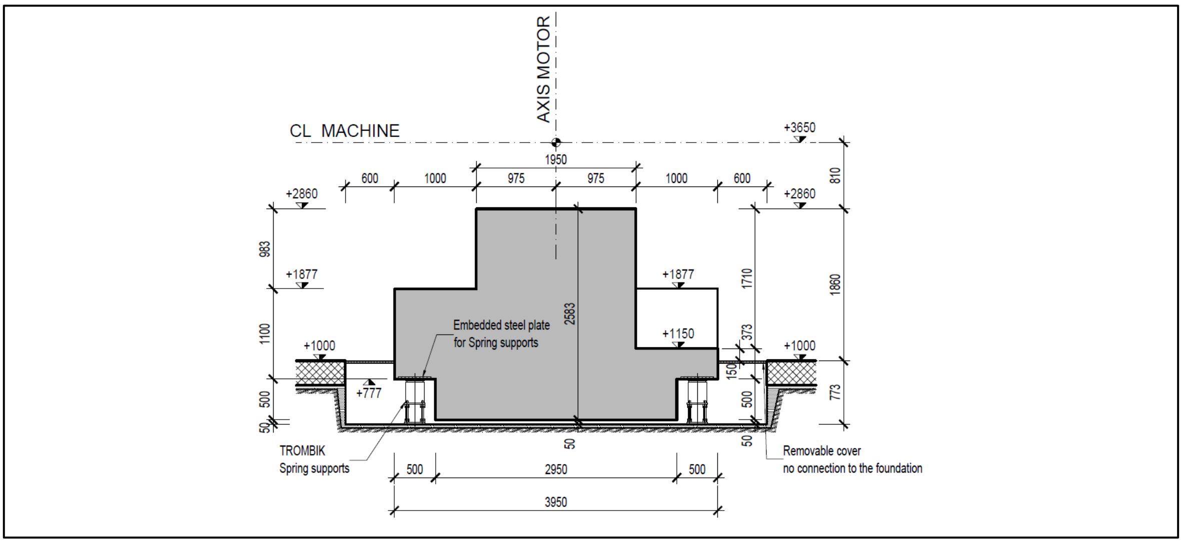
3.1. Final Outline

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. In order 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.



Figures 3.1: Critical Flexural Mode next to the operation Speed



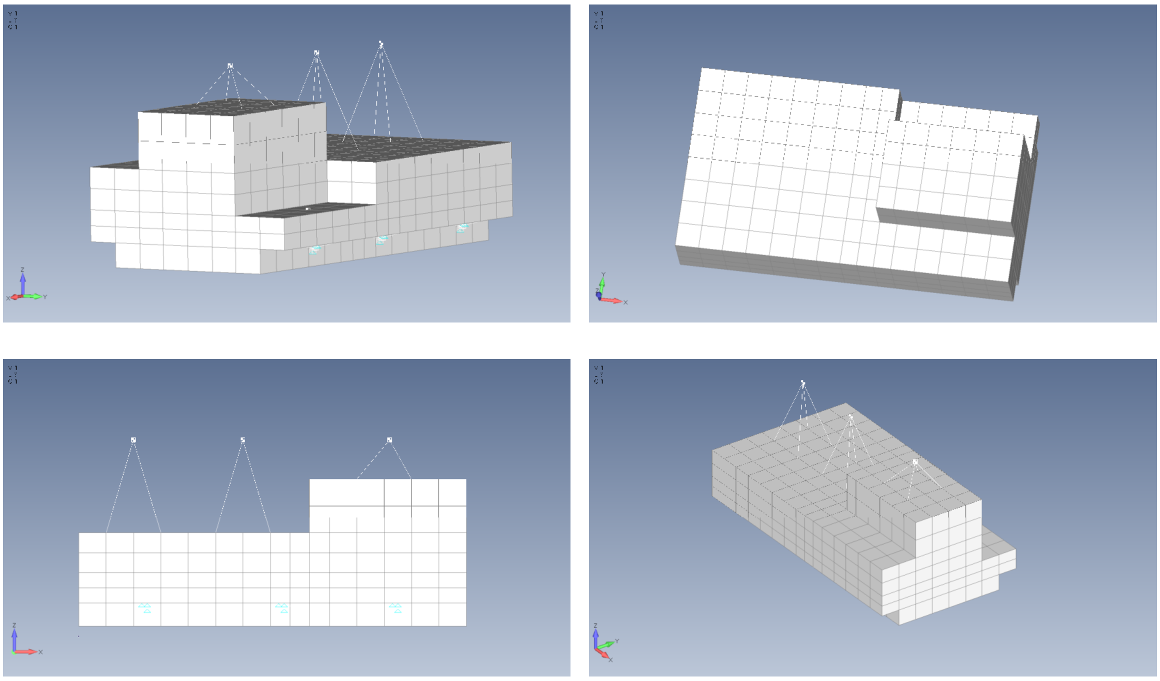
Figures 3.2: Typical Cross Section

3.2. Numerical Modelling

The foundation structure is replaced by a three-dimensional finite element structure. A number of reasonable simplifications have been 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

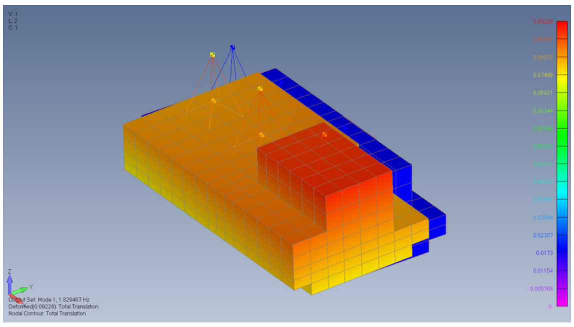
➔ Machine masses at the exact positions (by 'dummy' beams)



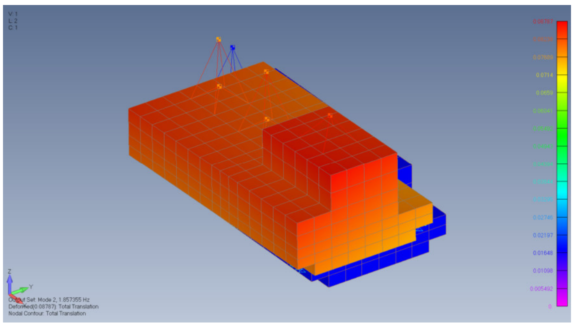
Figures 3.3: Overview FE-Model

3.3. Eigenvalues

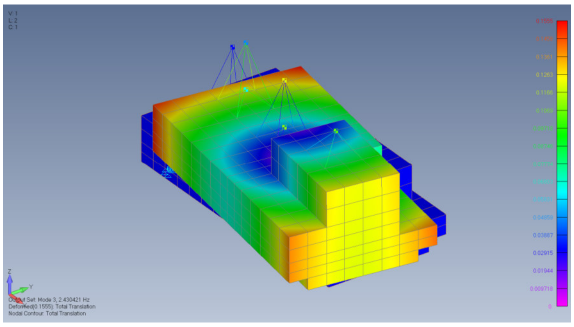
<u>Selected Eigenmode Plots</u>



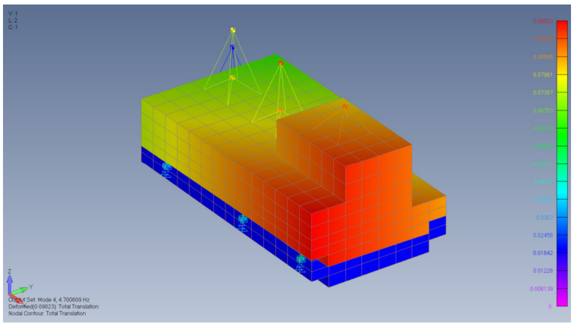
$f_1 = 1.8$ Hz



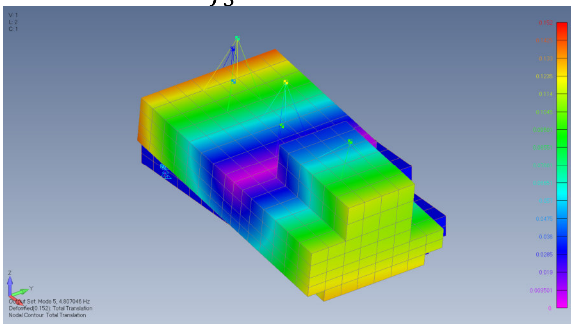
$f_2 = 1.9$ Hz



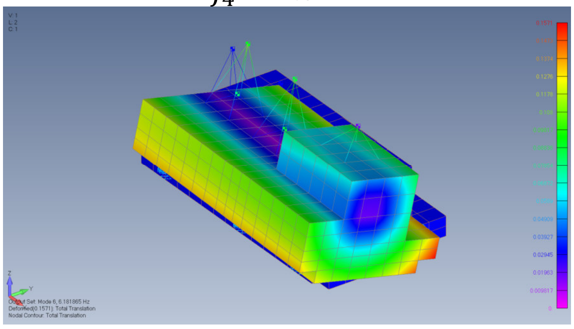
$f_3 = 2.4$ Hz



$f_4 = 4.7$ Hz

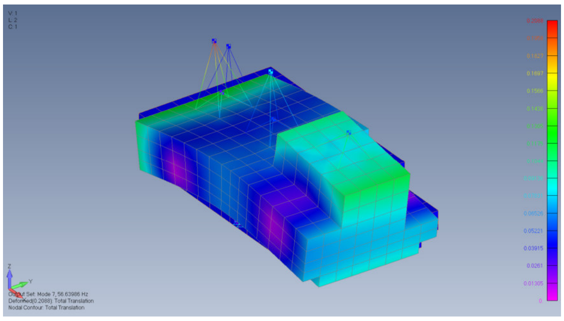


$f_5 = 4.8$ Hz

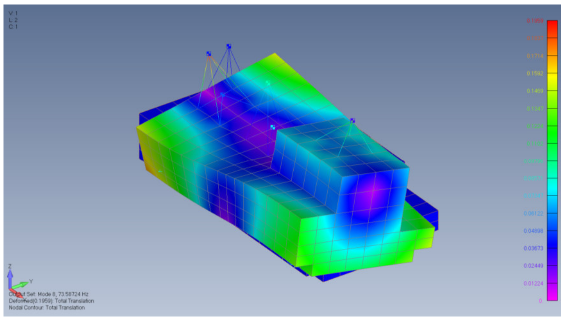


$f_6 = 6.2$ Hz

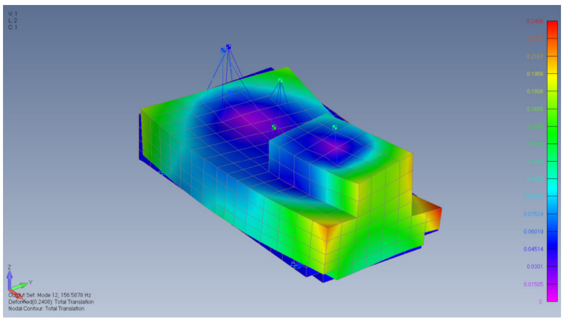
Figures 3.4: Basic eigenfrequencies (rigid body motions):



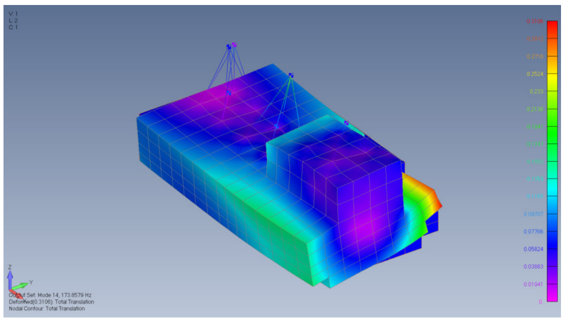
$f_7 = 56.6$ Hz



$f_8 = 73.6$ Hz

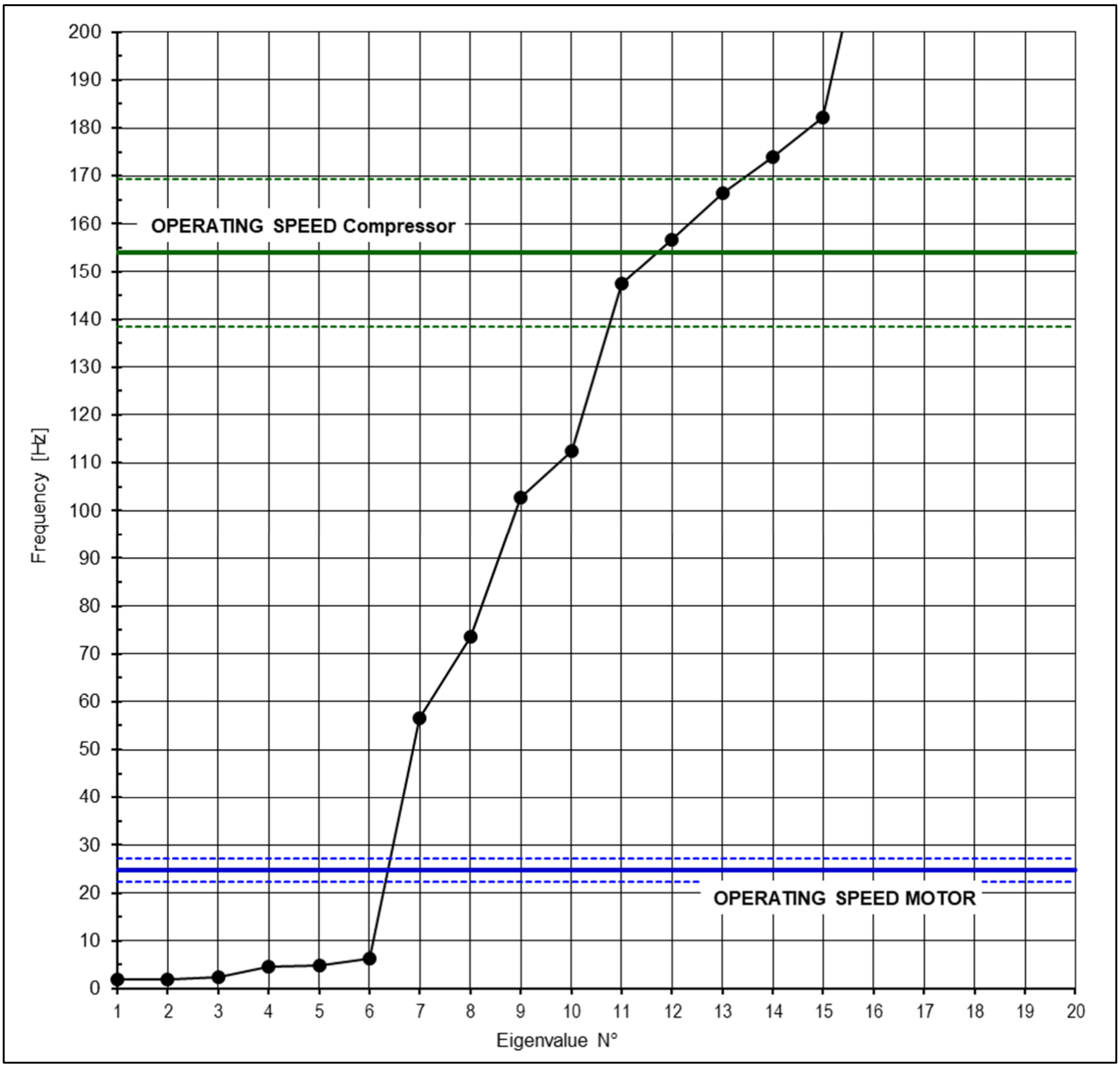


$f_{12} = 156.6$ Hz



$f_{14} = 173.9$ Hz

Figures 3.5: Main bending and torsional eigenfrequencies:



Figures 3.6: Eigenvalues vs. Operating Speeds

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.

3.4. 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

Calculation Method / Modell Uncertainty

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. By performing sweeping calculation and studying the range around the operational speed, variations (Young's Modulus and other modelling uncertainties as e.g. geometrical simplifications, differences in mass and stiffness distribution) have been considered.

Vibration Velocities

The maximum resulting vibration amplitudes $\mathbf{v_{peak}}$ 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).