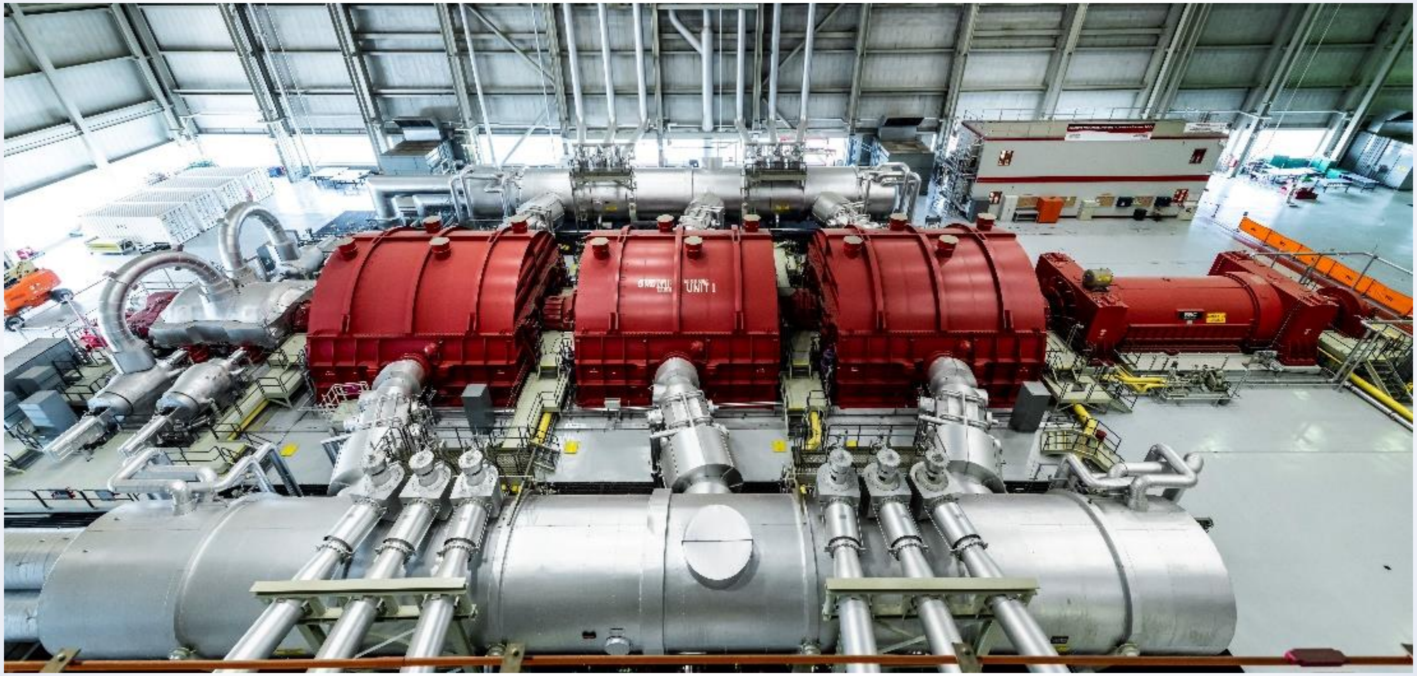
Machine-Induced Vibrations

MACHINE FOUNDATIONS



Pascal Fleischer, TROMBIK Ingenieure AG

EPFL, Civil – Dynamics of Structures

Foundation Types

Slabs: For common workshops, base plates preferred

(Rigid) Blocks: Heavy inertia mass needed

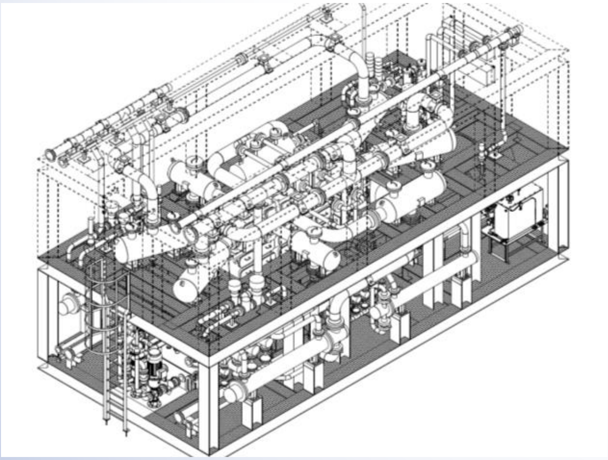
Frames / Tables: Space needed below the machine

Decoupled Blocks or Tables: Low tuned systems, control of the dynamic behaviour, alignment possible

Machine Types:
- Rotating parts, oscillating parts, impacting parts
- harmonic, periodical, transient or stochastic excitation

Tables / Frames

Turbo Generator



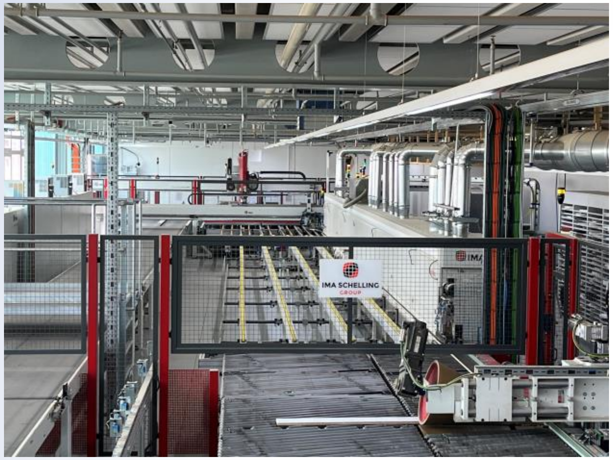
Compressor

Blocks

Compressor

Coal Mill

Slabs

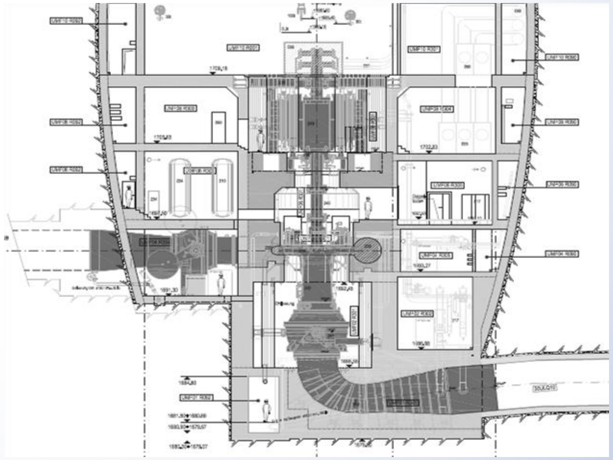


Production Line

Workshop (test plate)

Various

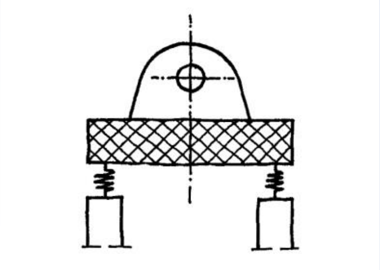
Fan (Cement Mill)



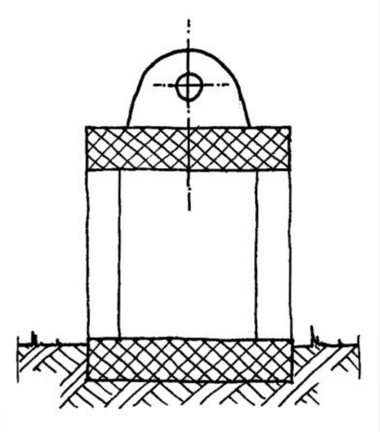
Pump-Storage Power Plant

Mounting / Tuning

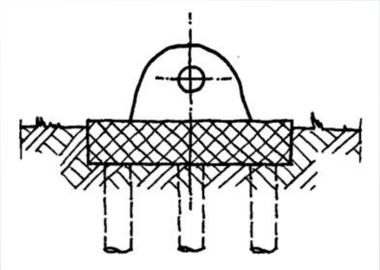
<u>*Spring Mounted Foundations:*</u>
Very low tuned, dynamical decoupled
(e.g. supported by “soft” spring elements)



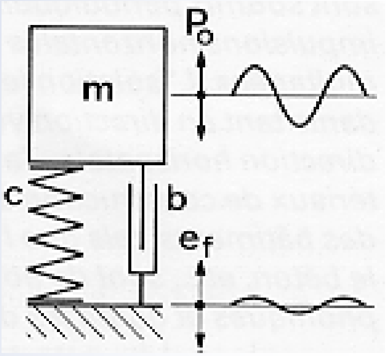
<u>*Table Mounted Foundations:*</u>
Low tuned (e.g. supported by “elastic”,
slender columns)
High tuned (e.g. supported by “rigid”
columns)



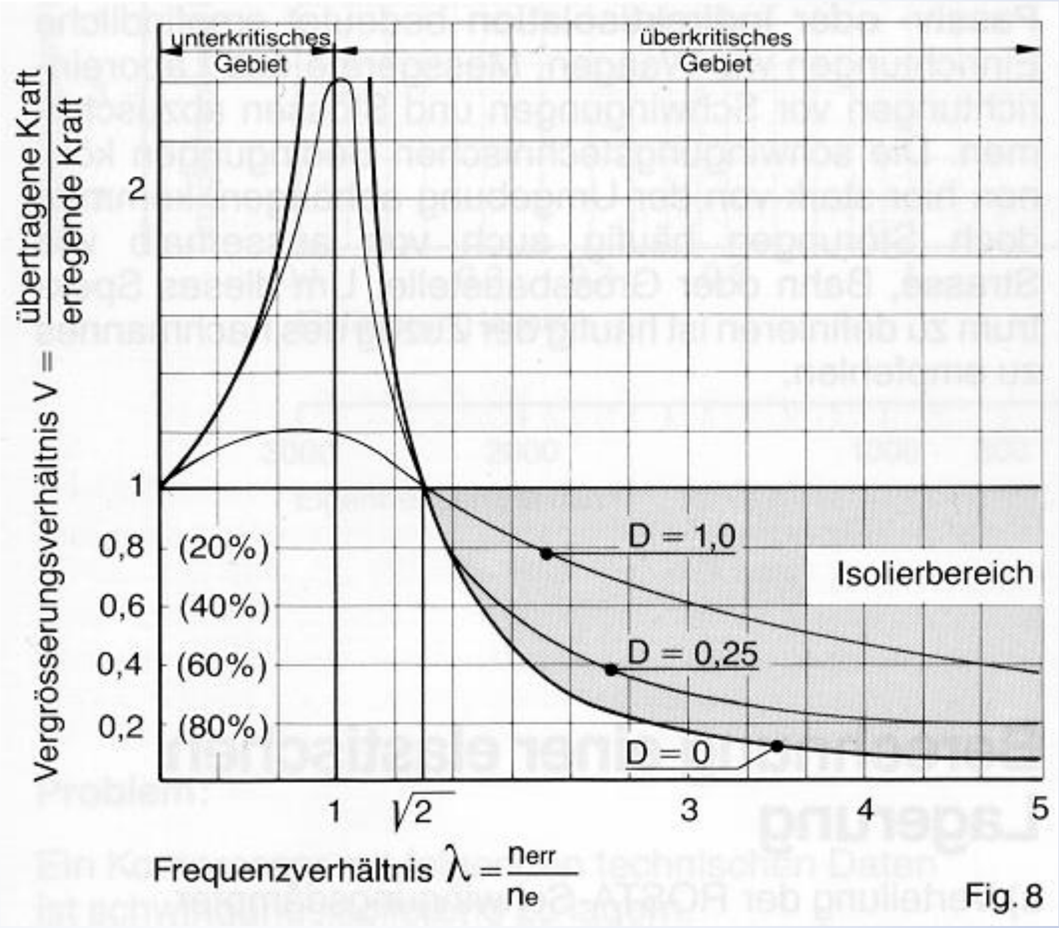
<u>*Raft Foundations:*</u>
Soil mounted foundations,
if needed on piles



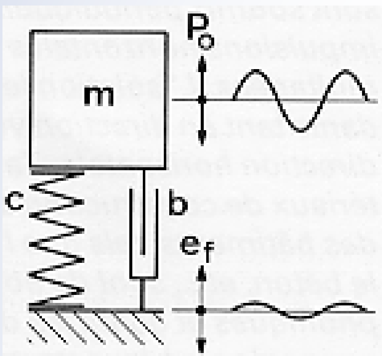
Design: Avoiding Resonances



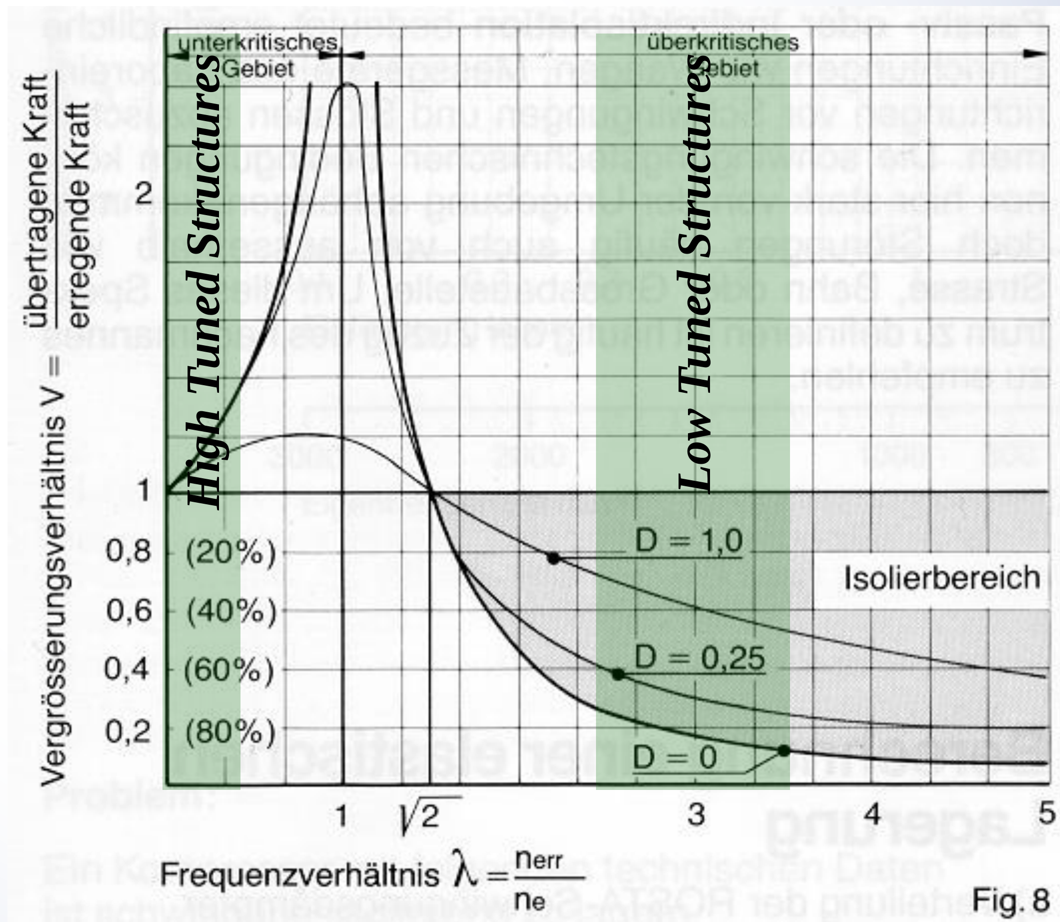
Spring-Mass-System



Tuning / Vibration Isolation

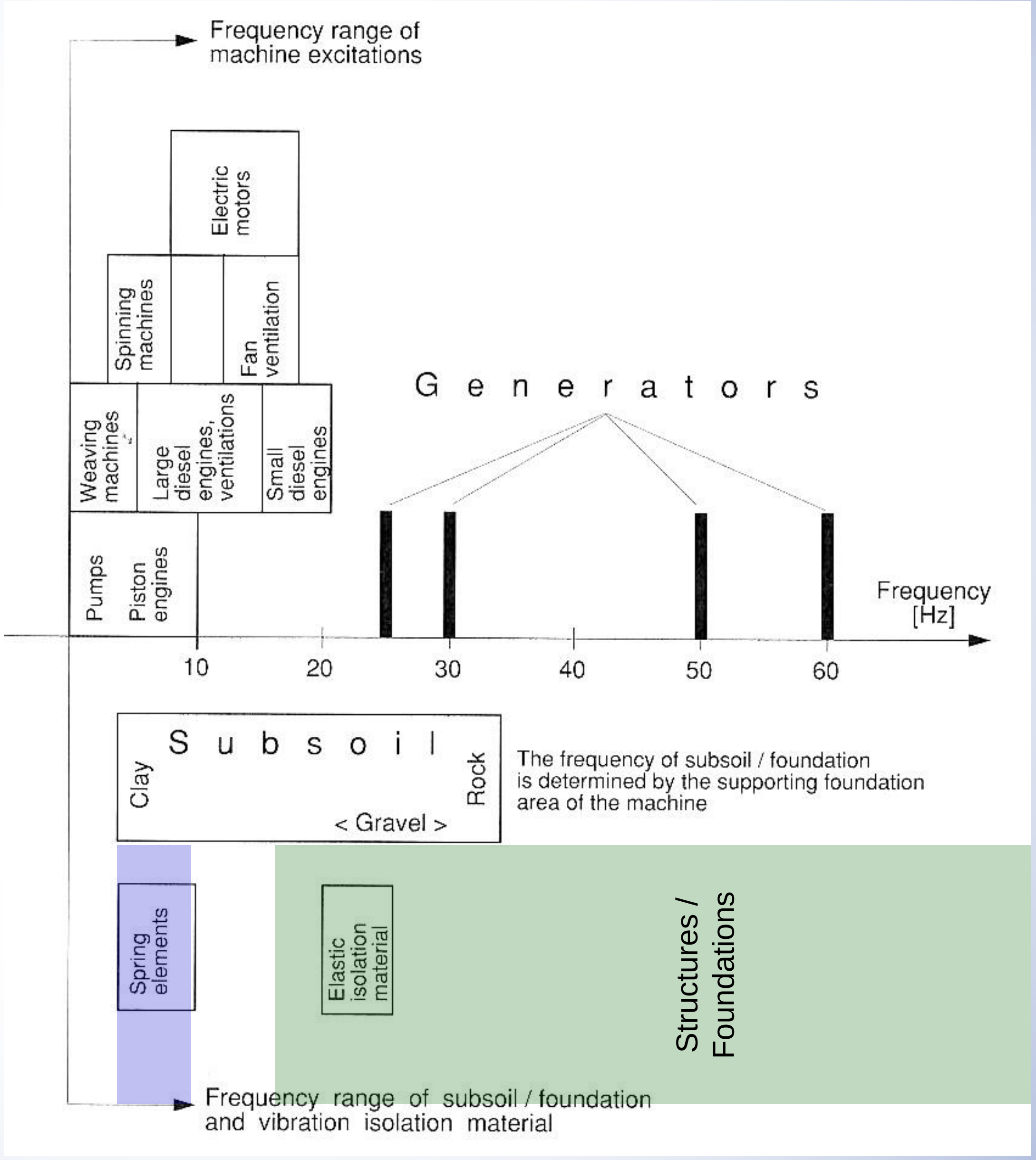


Spring-Mass-System

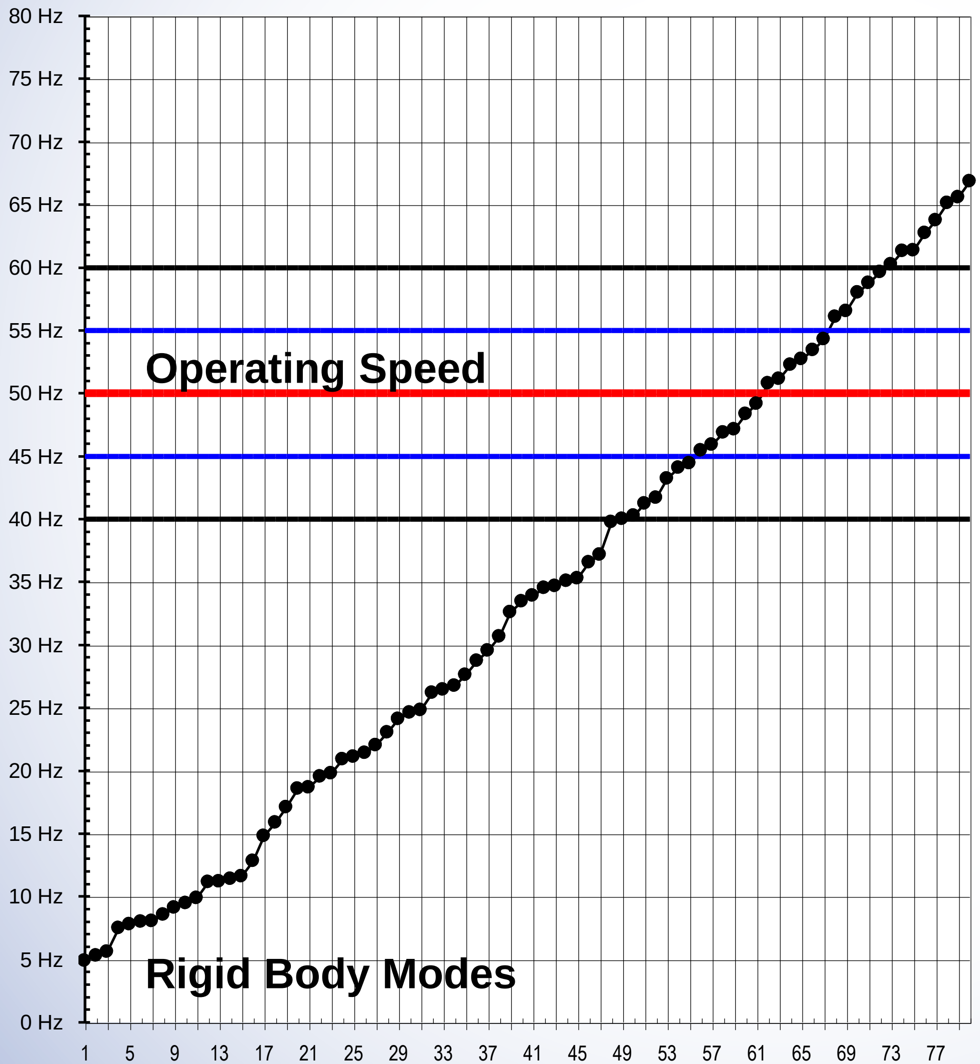


Spring Mounted Foundations

Operation Frequency vs. Mounting System

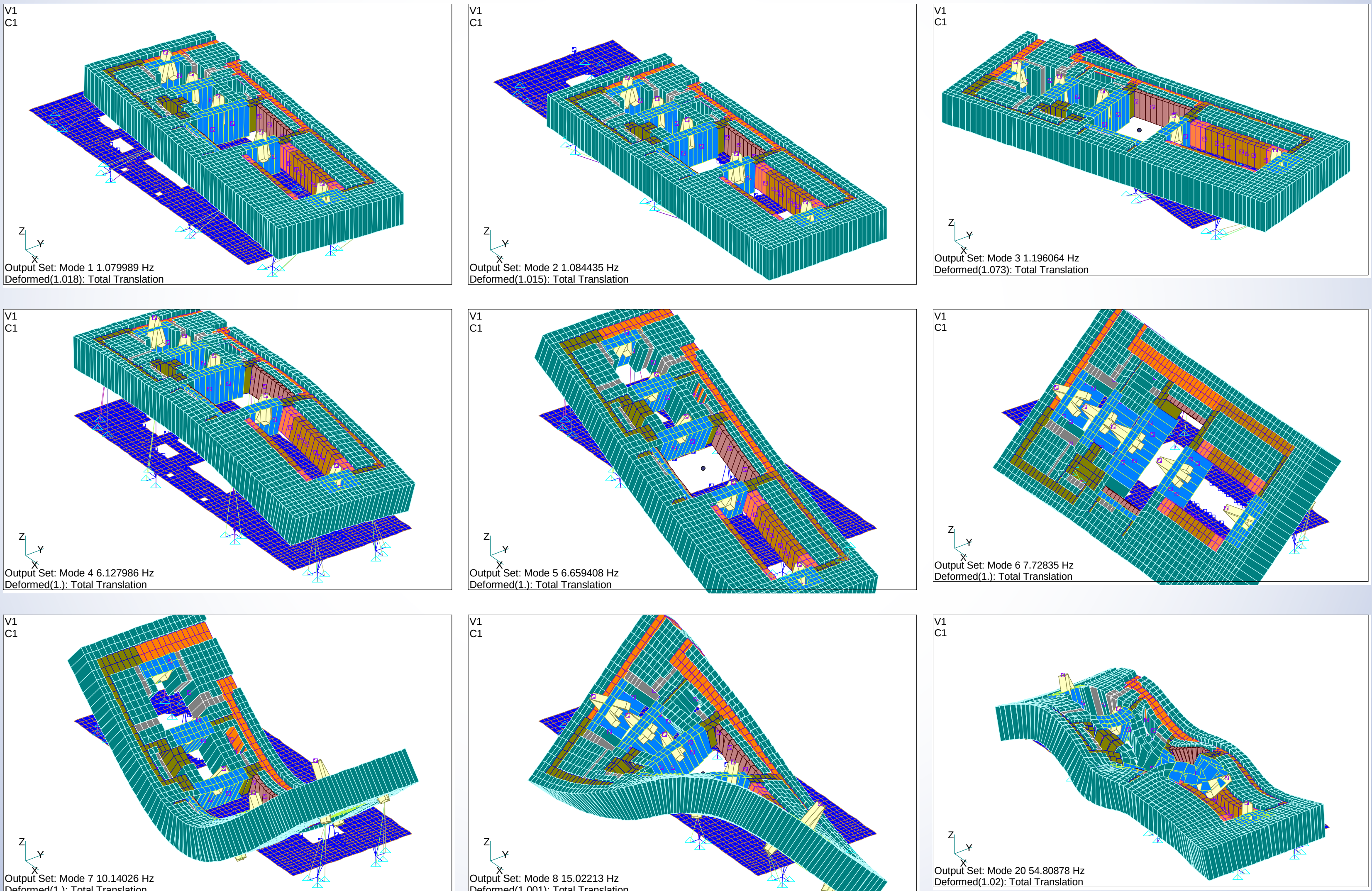


Structural Eigenfrequencies

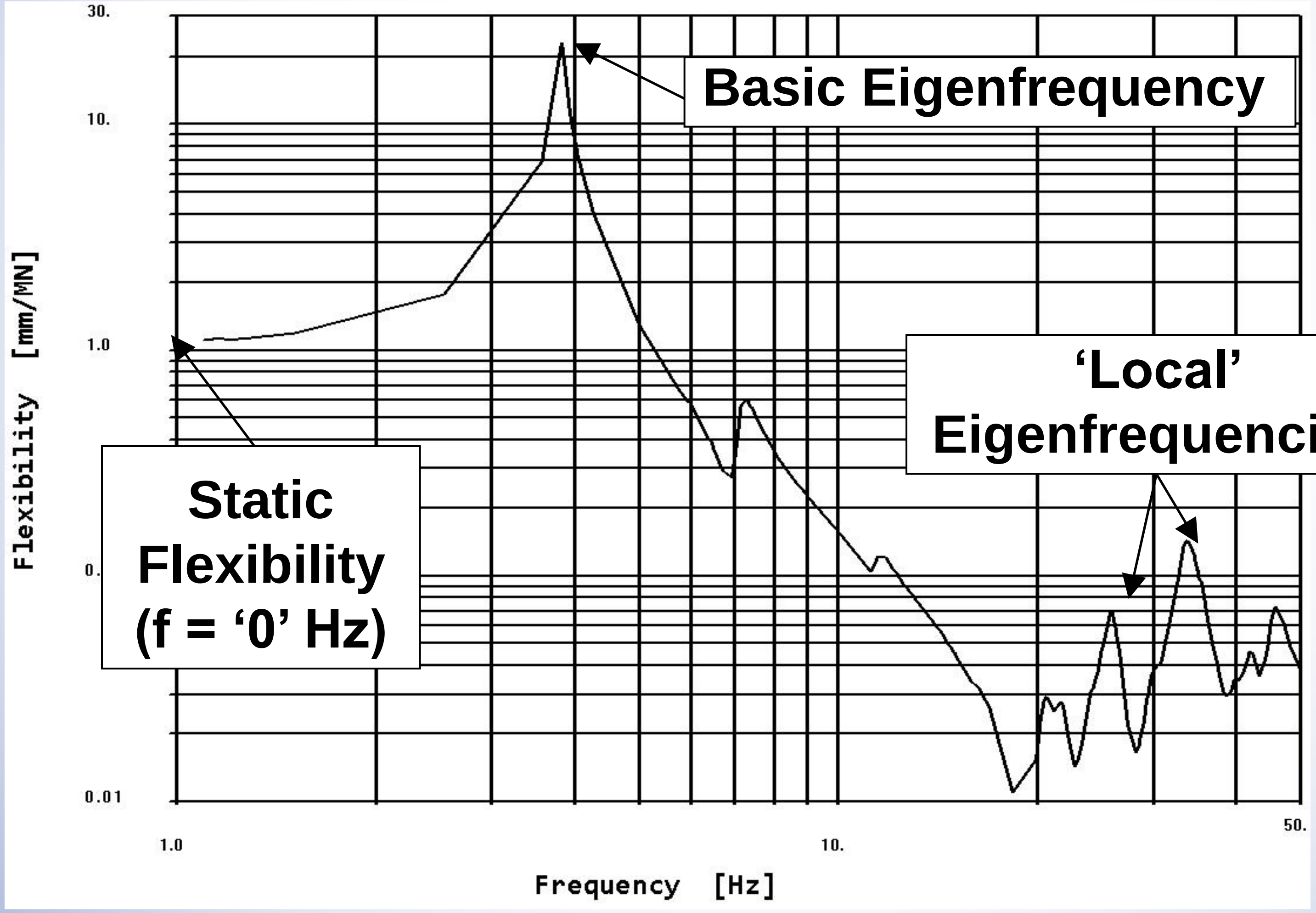


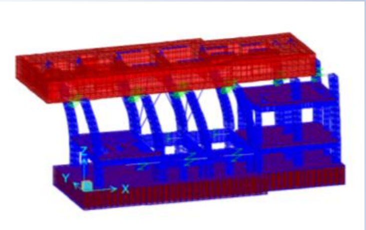
MODE	NATURAL		PARTICIPAT ION FACTORS		
NO	FREQUENCY	PERIOD	X1	X2	X3
1	4.9	0.2041	519.6	39412.6	1.1
2	5.3	0.1901	54113.6	1791.3	13.6
3	5.6	0.1787	2345.8	12369.9	2.2
4	7.5	0.1342	285.1	36.3	7409.0
5	7.8	0.1288	335.2	9.1	13512.6
6	8.0	0.1255	1047.9	373.8	207.1
7	8.1	0.1242	129.8	4132.7	88.1
8	8.5	0.1171	260.1	15.7	35691.0
9	9.1	0.1100	14.9	0.0	5.9
10	9.5	0.1057	5.4	1087.6	40.1
11	9.9	0.1012	3.9	3.5	1399.3
12	11.1	0.0898	0.0	4.7	0.0
13	11.2	0.0892	51.3	0.0	196.1
14	11.4	0.0878	0.0	0.0	0.3
15	11.6	0.0864	0.8	221.3	5.5
16	12.8	0.0781	2.7	11.4	1.4
17	14.8	0.0677	308.6	0.0	151.6
18	15.8	0.0631	7.5	0.2	5.6
19	17.1	0.0585	0.3	0.6	2.2
20	18.5	0.0539	0.1	0.0	0.0
21	18.7	0.0536	0.1	0.0	0.0
22	19.5	0.0513	17.1	0.0	11.9
23	19.8	0.0505	2.8	0.0	78.7
24	20.9	0.0478	17.7	0.0	51.7
25	21.1	0.0475	5.0	0.3	15.0
26	21.4	0.0468	2.8	1.1	222.6
27	22.0	0.0455	0.7	1.0	159.2
28	23.0	0.0434	0.0	0.9	3.7
29	24.1	0.0415	2.3	1.4	49.2
30	24.6	0.0406	0.0	4.0	56.3
31	24.8	0.0403	0.1	0.8	1.8
32	26.2	0.0382	2.4	0.1	4.6
33	26.4	0.0378	0.5	0.4	72.1
34	26.7	0.0374	0.1	5.9	6.3
35	27.6	0.0362	0.7	0.0	0.4
36	28.7	0.0348	0.1	0.3	5.3
37	29.5	0.0339	0.1	0.5	0.0
38	30.6	0.0326	1.6	0.0	1.9
39	32.6	0.0307	0.5	1.3	0.2
40	33.4	0.0299	0.2	0.6	3.3
41	33.9	0.0295	0.0	0.0	0.0
42	34.5	0.0290	0.2	0.6	0.8
43	34.7	0.0289	0.2	0.1	0.0
44	35.1	0.0285	0.3	0.0	1.3
45	35.3	0.0283	0.1	0.8	0.0
46	36.5	0.0274	0.0	0.0	0.0
47	37.2	0.0269	0.6	0.0	0.2
48	39.7	0.0252	0.1	0.1	0.2
49	40.0	0.0250	0.3	0.1	0.0
50	40.3	0.0248	0.0	0.1	0.6
51	41.2	0.0243	0.1	0.0	0.1
52	41.7	0.0240	0.1	0.2	1.7
53	43.2	0.0231	0.0	0.0	0.0
54	44.1	0.0227	0.0	0.0	0.0
55	44.4	0.0225	0.0	0.0	0.0
56	45.5	0.0220	0.0	0.4	0.1
57	45.9	0.0218	0.0	0.6	0.1
58	46.8	0.0213	0.0	0.2	0.0
59	47.1	0.0212	0.2	0.1	0.5
60	48.3	0.0207	0.5	0.1	0.1
61	49.2	0.0203	0.9	0.1	0.0
62	50.8	0.0197	0.2	0.0	2.0
63	51.1	0.0196	0.0	0.0	0.2
64	52.2	0.0191	0.0	0.0	0.2
65	52.7	0.0190	0.0	0.0	0.3
66	53.4	0.0187	1.1	0.1	0.0
67	54.3	0.0184	0.0	0.0	0.0
68	56.0	0.0178	0.0	0.0	0.1
69	56.5	0.0177	0.4	0.0	0.0
70	58.0	0.0172	0.0	0.0	0.0
71	58.8	0.0170	0.0	0.0	0.0
72	59.6	0.0168	0.0	0.0	0.0

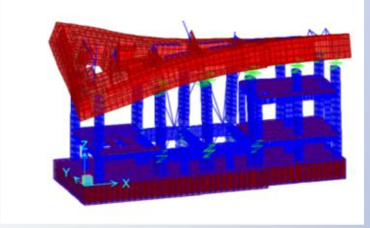
Selected Eigenmodes “Toptable”



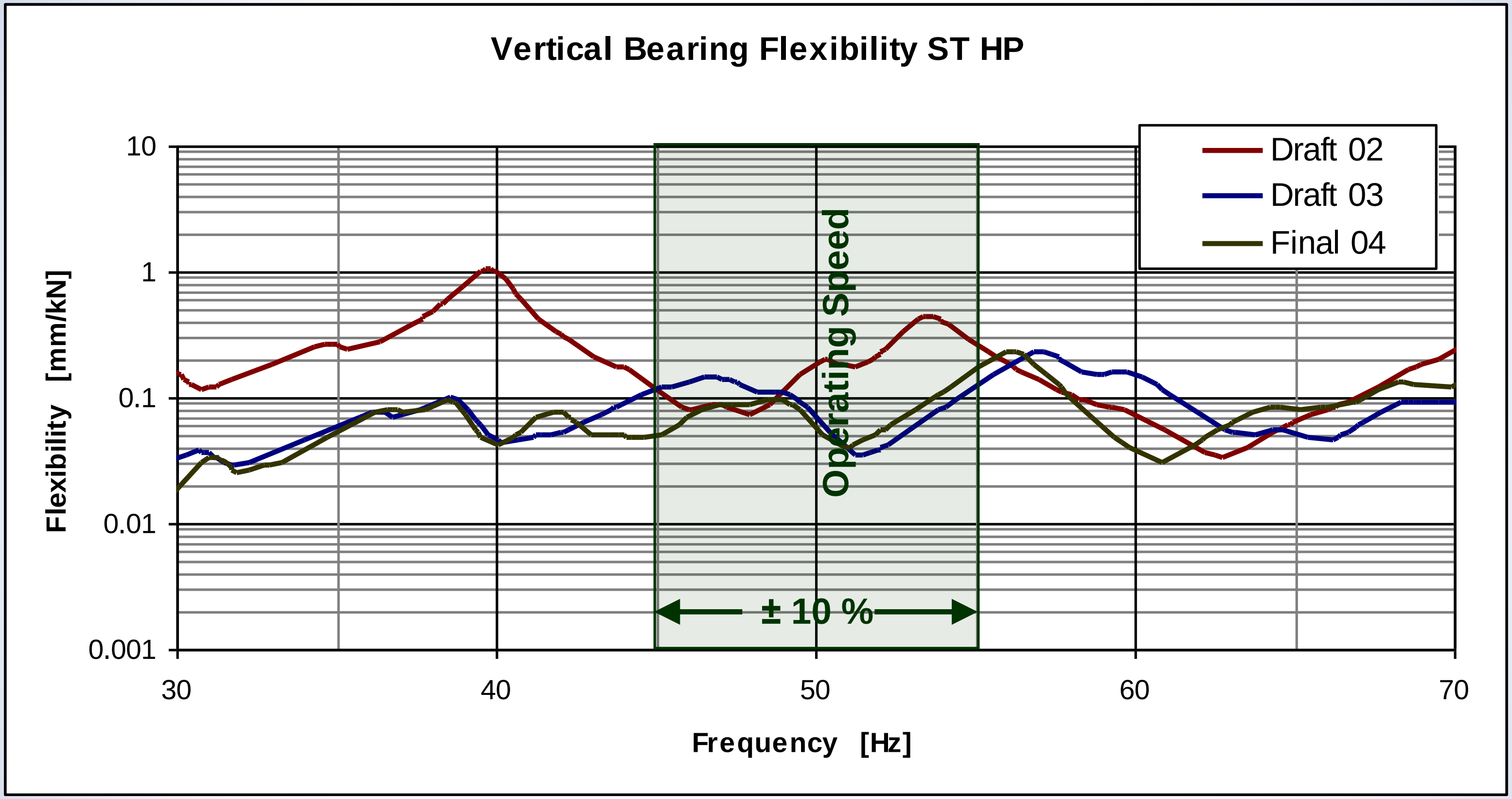
(Dynamic) Bearing Flexibility



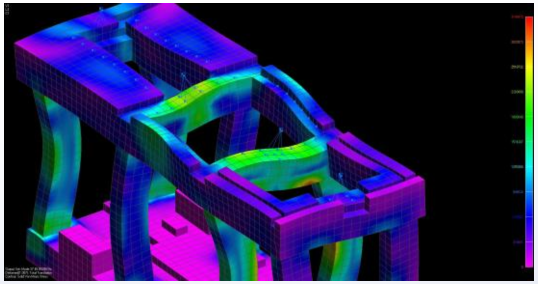


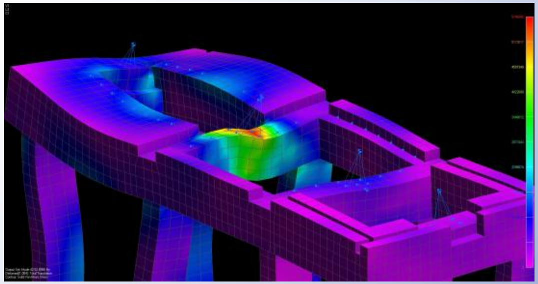


Frequency Tuning of the Foundation Structure



-> Avoiding local resonances / critical eigenfrequencies next to the operation speed





Requirements

- ***Fundamental <u>eigenfrequencies</u> not near the range of the operational speed.***
  → *low tuned systems (eigenmodes < operational speed)*
  → *heavy mass on soft support*

- ***<u>Forced vibrations</u> of the foundation within the limits defined by codes or machine manufacturer.***
  → *high stiffness and heavy mass*

- ***The <u>design of the foundation structure</u> has to include all sections forces like bending, distortional moments, shear forceas and axial stresses <u>for operational, accidental and seismic states</u>***
  → *material strength and thickness (inner lever arm)*

Foundation Requirements (Cont.)

- ***The overall stiffness of the foundation structure has to limit the <u>deflections of the rotor shaft axis</u> for the operational states, respectively the <u>bearing flexibility</u>. Limits defined by codes or machine manufacturer.***
  → *high foundation stiffness to prevent deflections, twisting and warping*

  → *avoiding local resonances*

- ***The sensitivity to <u>differential settlements</u> has to be minimised.*** → *high stiffness required*

- ***<u>Temperature effects</u> has to be minimised.***
  → *et al. high thermal inertia (= mass of concrete) required.*

Foundation Requirements (Cont.)

- ***<u>Vibration isolation</u> has to guaranty that external vibrations will not affect / reduce the functional efficiency of the machine. On the other hand, the vibrations caused by the machine itself has to be absorbed mostly by the foundation itself so that no uncontrolled vibration propagation will affect adjoined structures / machines.***
  → low tuned systems, high structural masses (= fundamental eigenmodes low below the operational speed).

- ***Additional space for <u>secondary elements</u> below and around has to be provided by the foundation (pipes, oil channels, condenser, etc.***
  → limited maximum dimension of the foundation
  → restricted size and position of the columns

Further Considerations

- ***Allowable operational deflections:***
  "Misalignment Tolerance Matrix MTM„ relative or absolute bearing deflections or curvature of the rotor axis. -> „No“ deflections allowed.

- ***Differential subsoil settlements:***
  Difficult to predict, additional stiffness capacities of the foundation

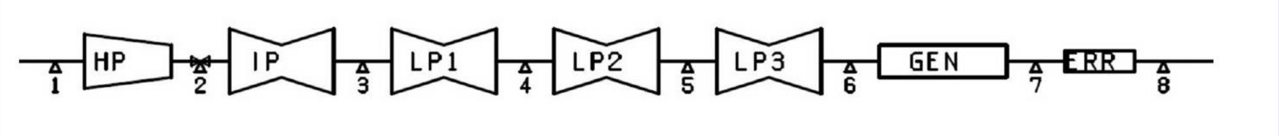
- ***High accidental load cases***
  Blade loss (acc. DIN 4024 „Machine Foundations“: up to 18 times the rotor weight – static equivalent), short circuit, deflagration, etc.

In general: A foundation has to be <u>stiff</u>, <u>heavy</u> and <u>softly supported</u>!

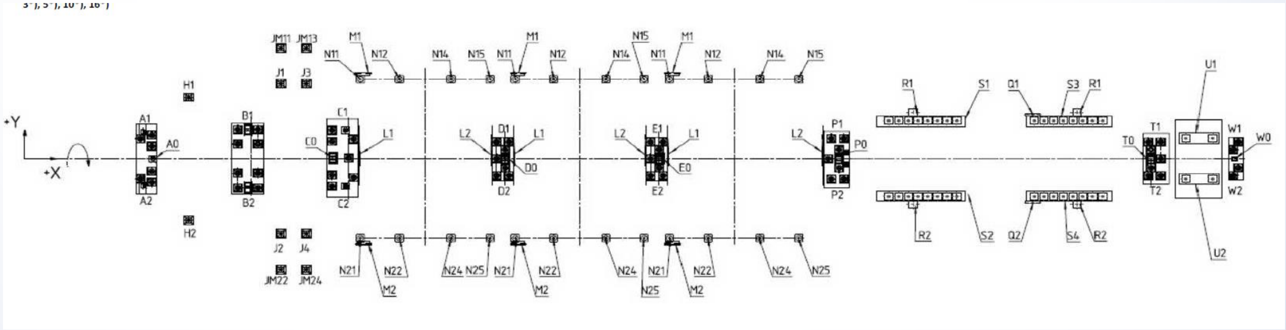
Machine-Foundation Interaction

In general the machine is only considered as mass for the foundation design, where a distinction is made between rotor and casing. This means that mainly the casing stiffness and the impact of the rotor are neglected.

Rotor:



Casing:



Machine and foundation uncertainties: Sweep calculations

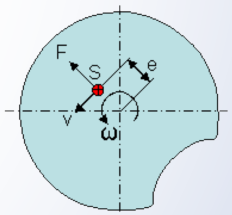
Machine Forces / Load Cases

Load Combination N°	Load Combination	Loading Case
ULTIMATE LIMIT STATE		
1001	Operating State	
1002	Unbalance Turbine Vertical	
1003	Unbalance Turbine Vertical	
1004	Unbalance Turbine Horizontal	
1005	Unbalance Turbine Horizontal	
1006	Generator Short Circuit	
1007	Generator Short Circuit	
1008	Vacuum Break	
1009	Earthquake Longitudinal	
1010	Earthquake Longitudinal	
1011	Earthquake Transversal	
1012	Earthquake Transversal	
1013	Earthquake Vertical	
1014	Earthquake Vertical	
SERVICEABILITY LIMIT STATE Relative Deflections		
1015	Operating State	
1016	Operating State + Therm. Ext.	
Spring Supports		
1017	Machine Weight	
1018	Dead Load	
Operating		
1019	Operating State	

Main parameter: Operational Speed(s)

ULS:

- Governing: Accidental States
- In general: Equivalent static forces
- Blade Loss
  (up to 18x rotor weight)
  acting at the bearings

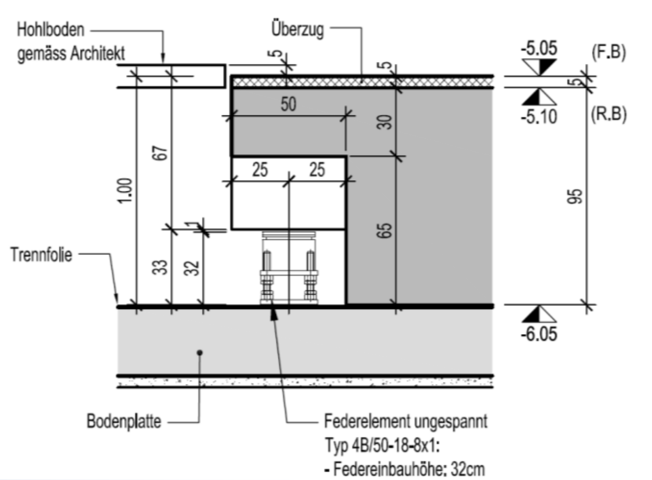


- Generator Short Circuit
- Vacuum Break

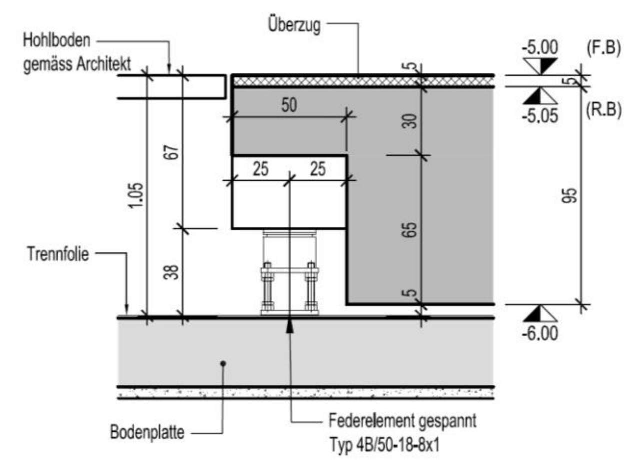
Comment*:* Seismic Design regarding “Safe Operation Earthquake” and “Safe Shutdown Earthquake”

Construction Process

Spring Mounted Foundation: Loading procedure? Lifting?



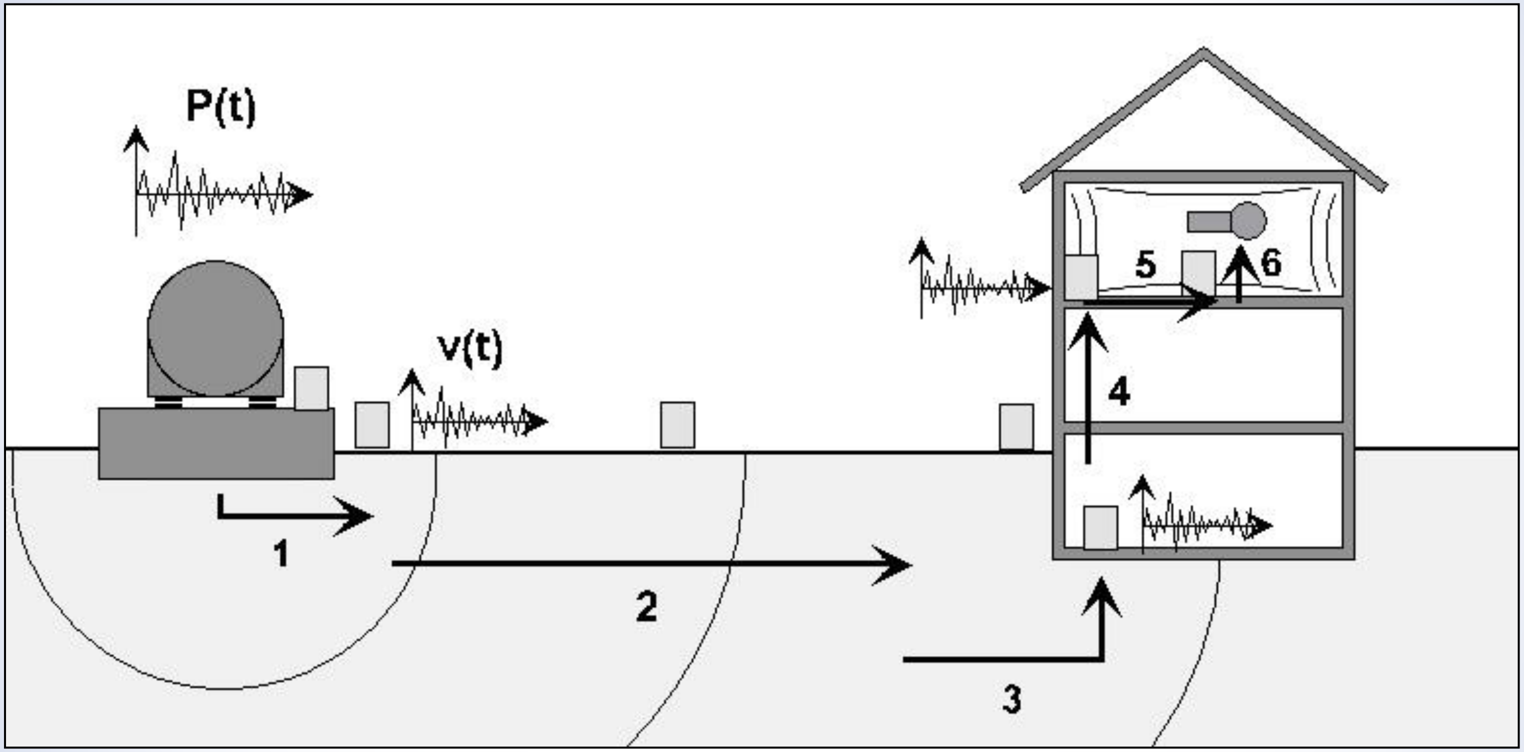
Concreting of the foundation directly onto the floor / separating layer



Final state after lifting of the foundation

- *Excavation work, construction of a floor slab.*
- *Placement of the separation layer.*
- *Placement of formwork steel, embedded steel parts, anchor boxes, etc.*
- *Concreting of the entire foundation.*
- *Placing of the spring supports by the contractor.*
- *Installation of the machine.*
- *Loading of the spring supports and lifting of the foundation, fine adjustment*

Vibration Propagation



1: Machine-Foundation-Soil-Interaction

2: Free-Field-Propagation *3: Building Coupling*

4: Bearing-Structure-Propagation

5: Local Resonances *6: Radiation of Structure-Bound Sound*

Requirements / Codes (Switzerland)

People:

- Health Hazard: Labour Law

- Nuisance:

. DIN 45680: Measurement and assessment of low-frequency noise in the neighbourhood

. BEKS (and DIN 4150-2)

- Comfort: SIA 181 and VDI 2038 (recommendation)

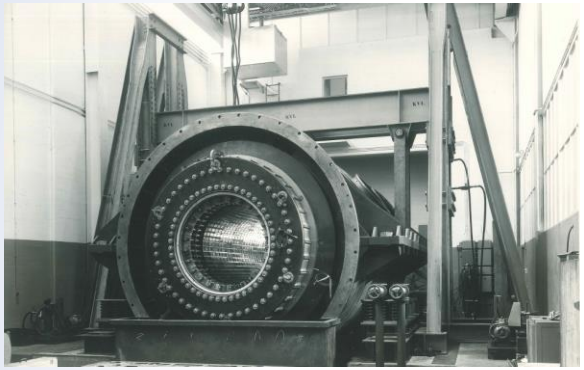
Equipment: *ISO and VC criteria (permissible vibration velocities: RMS, Third Octave Band Spectra)*

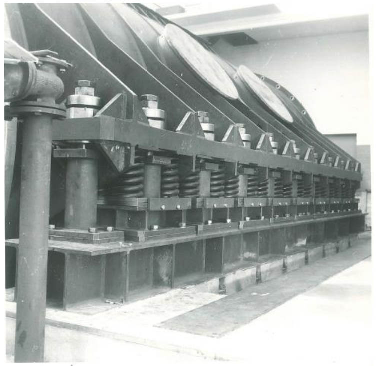
Buildings: *VSS 40 312 Vibrations Effects on Structures*

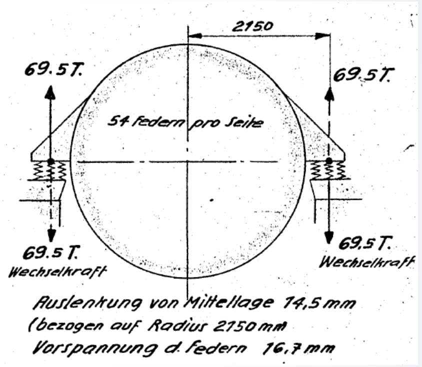
Selected Case I:

Short Circuit Generator

Short-circuit generator replacement
Change: Tests at 60 Hz also to be considered







The bearing system has to be checked:
- Springs of the stator to be tested
- Verifications of the elastic bearing system

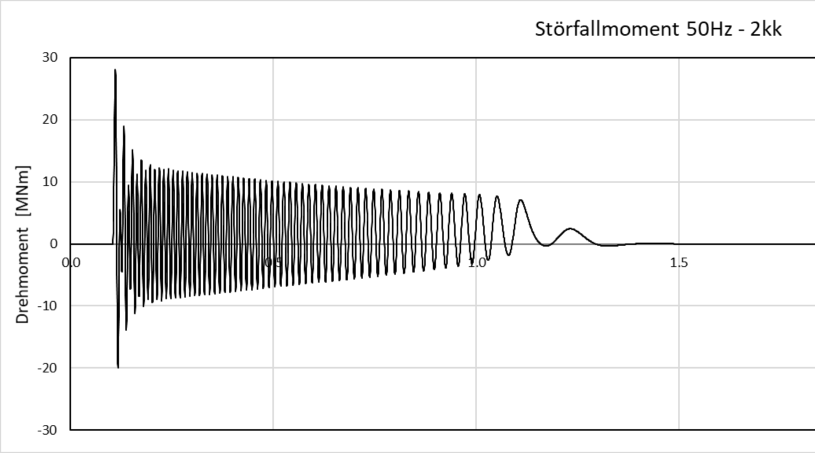
Testing frequencies: 16.7 Hz, 50 Hz and 60 Hz (incl. "2f oscillations")

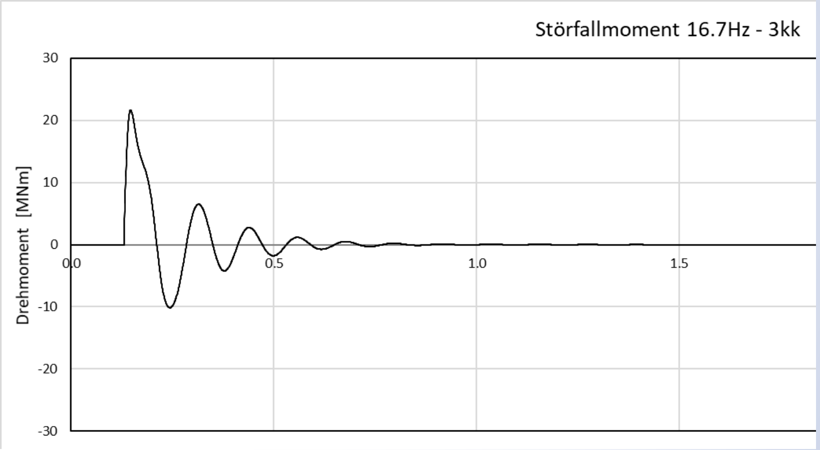
Selected Case I:

Short Circuit Loads

Accidents on purpose: Testing of electrical devices / components

Loading examples (time history plots):





Several loading situations to be checked:
- decreasing (amplitudes)
- frequency drops
- impulse-like loading

Selected Case I:

Specialities / Comments

Low tuned system: Rotational eigenfrequency around 6.1 Hz

But: Natural frequency of the (helical compression) spring itself was critical. At 104 Hz (measured value), the spring fundamental frequency is within a critical range with regard to the planned 60 Hz tests: Run-through at the drop in speed of the "2f excitation frequency".

Conclusions: A minimal effect of the falling speed and the excitation of the spring fundamental frequency is to be expected. However, the critical range is passed through relatively quickly and a strong / significant amplification is not to be expected. The effect is therefore negligible for the design of the springs (e.g. regarding superimposed stress changes).

Selected Case II:

Wind Tunnel Upgrade

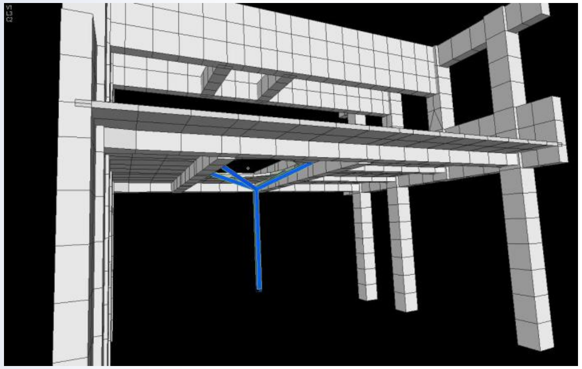
A new model manipulator (AMM) was installed on the ceiling of an existing Wind Tunnel with the aim of studying not only the static but also the dynamic behaviour of various objects under wind load: The models are also excited dynamically by means of a built-in exciter (shaker). This means, among other things, that the existing wind tunnel ceiling and also the new manipulator panelling are subjected to relatively high dynamic forces.

Preliminary investigations showed that the structural situation next to the manipulator did not fulfil the requirements for "shaker operation" and that operational safety was not guaranteed. This primarily concerned fatigue safety as well as the natural vibration behaviour and dynamic stiffness requirements of the reinforced concrete ceiling.

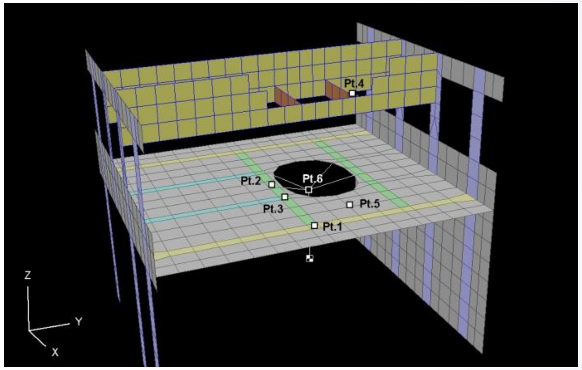
Selected Case II:

System Identification

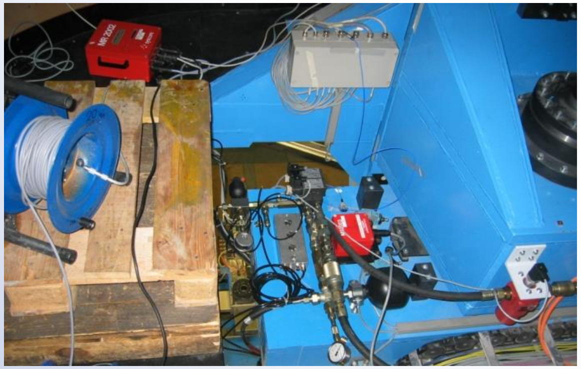
Dynamic analysis: Measurements and model calibration



Numerical FE-Model



Overview Measuring points

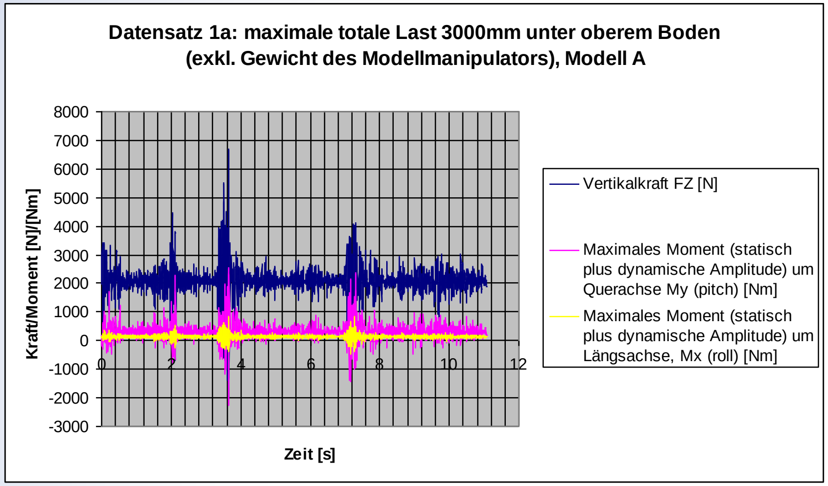


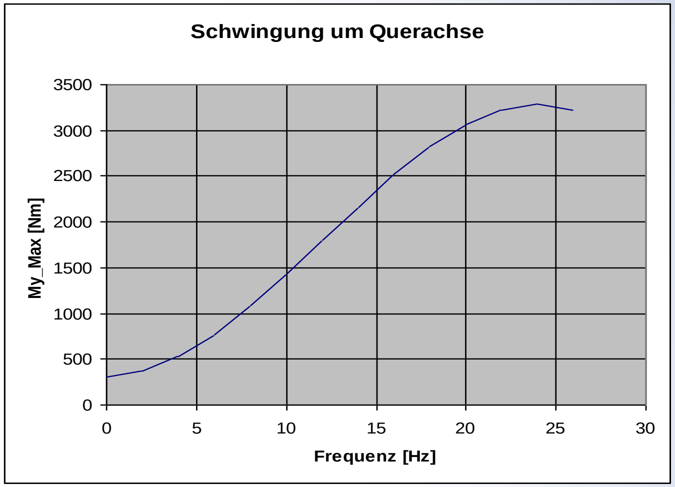
Measuring Point
on the Model Manipulator

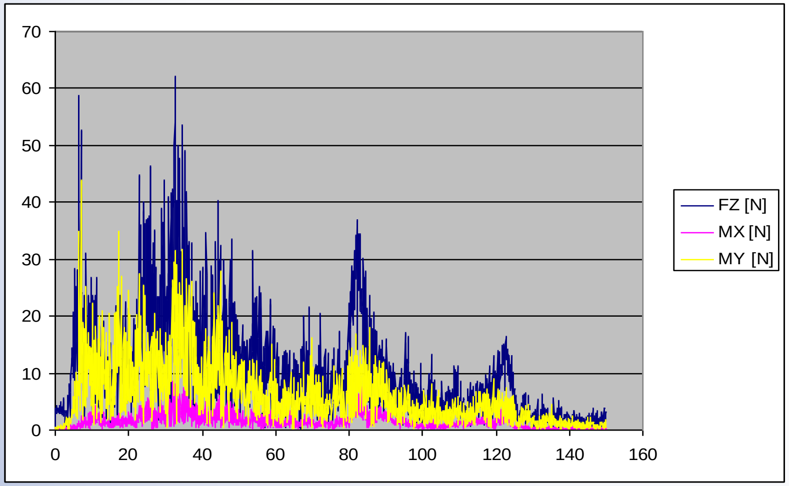
Exciter for structures (Shaker)

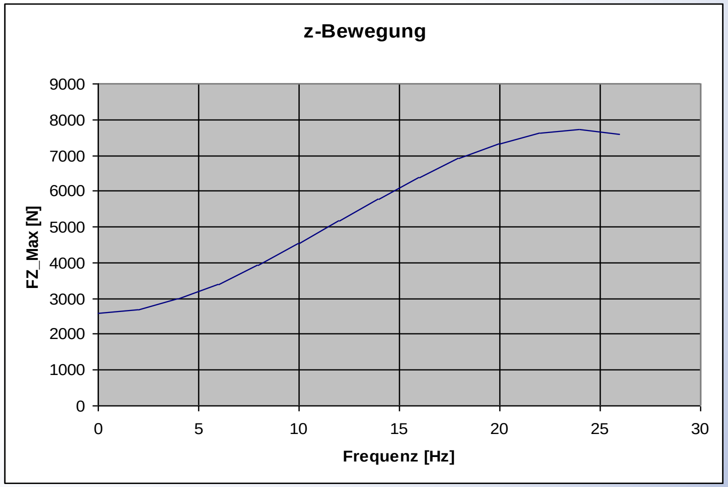
Selected Case II:

Detailed Load Definitions









Selected Case II:

Upgrading Concepts in General

Frequency tuning: mass, stiffness, operating speed

Dynamic stiffening: stiffening the structure, increasing the inertia mass

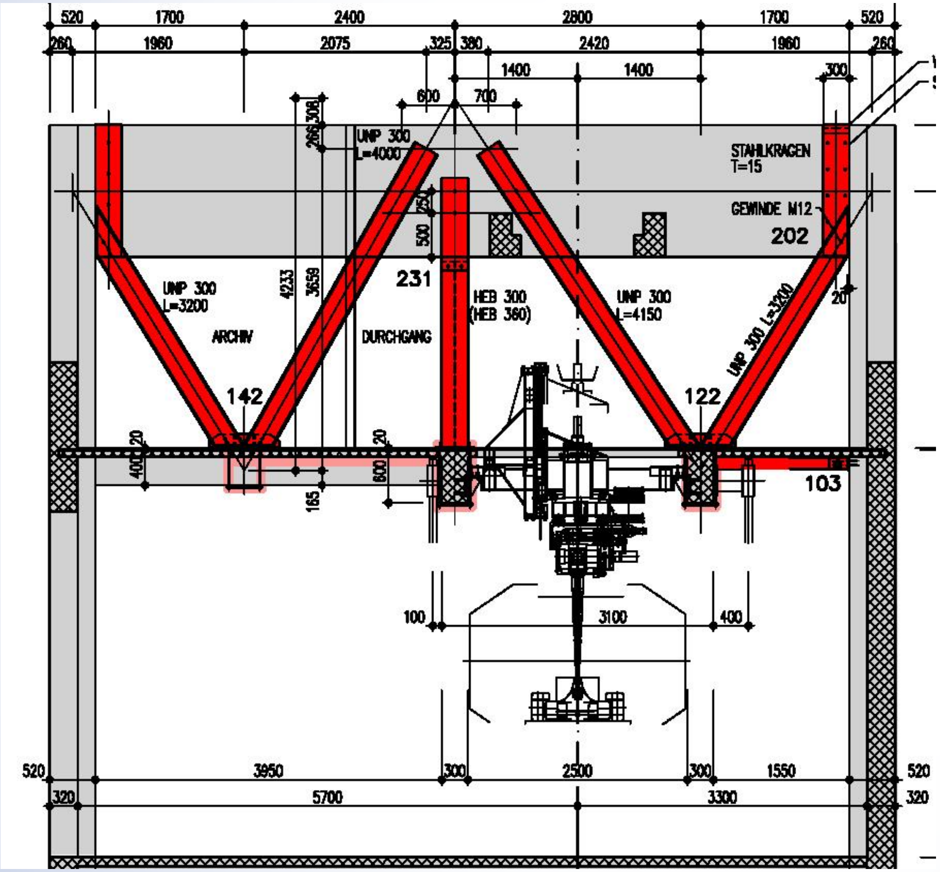
Increasing damping: additional damping elements

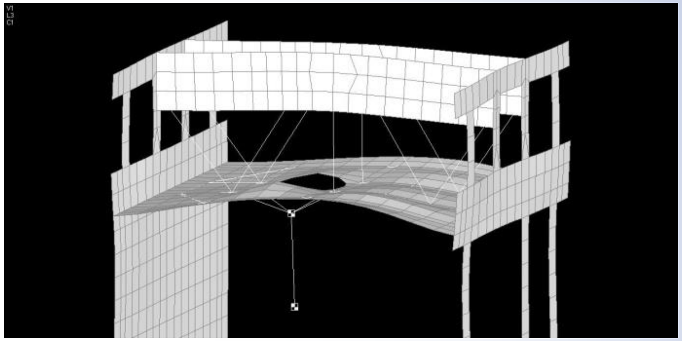
Installation of vibration absorbers: counteract the interfering vibrations

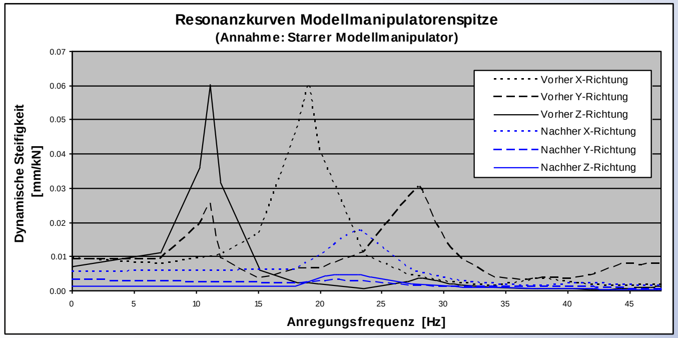
Decoupling: installation of an elastic separating layer

Selected Case II:

Solution: Steel Frame







Selected Case II:

Specialities / Comments

Load-bearing safety of the supporting structure: design for full shaker operation (fatique safety)

Serviceability of shaker tests: reduction of vibration amplitudes, increase of the relevant natural frequencies, stiffening

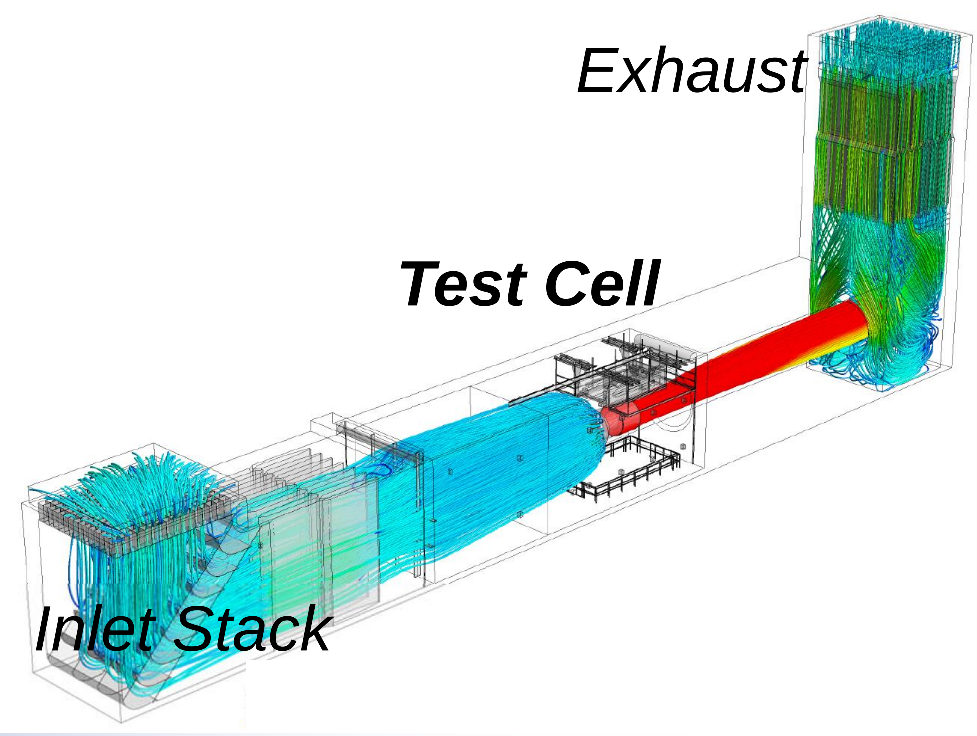
Boundary conditions: costs, downtime AWTE, installations / space conditions, relocation options AMM

Structural conditions: Element weights, access, connections / force transmission

Natural frequency model manipulator (modelled as rigid element)

Selected Case III:

(Aircraft) Turbine Test Cell

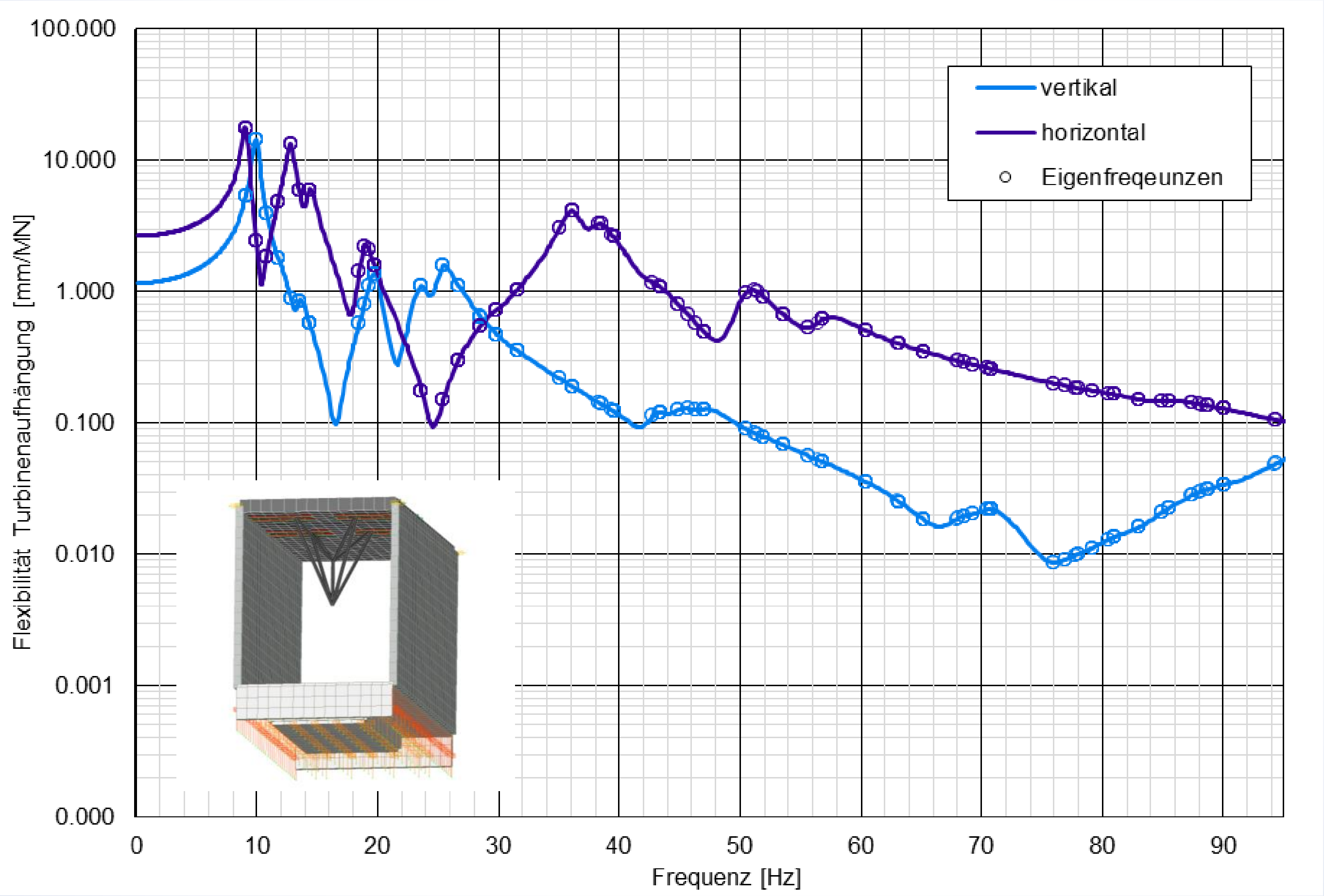


Key figures

- Operational speeds:
  - Fan 10 – 86 Hz
  - Core 241 – 372 Hz
- Turbine weights:
  up to 3‘150 kg
- Total weight:
  up to 37'430 kg

Selected Case III:

Dynamic Flexibility



For the dynamic flexibility in vertical and horizontal (transverse) direction, the steady state response (displacements) of forced vibrations due to a concentrated load unit was determined. The load unit simulates a sinusoidal excitation in the centre of mass, which was swept over a frequency range from 1 to 500 Hz.

Selected Case III:

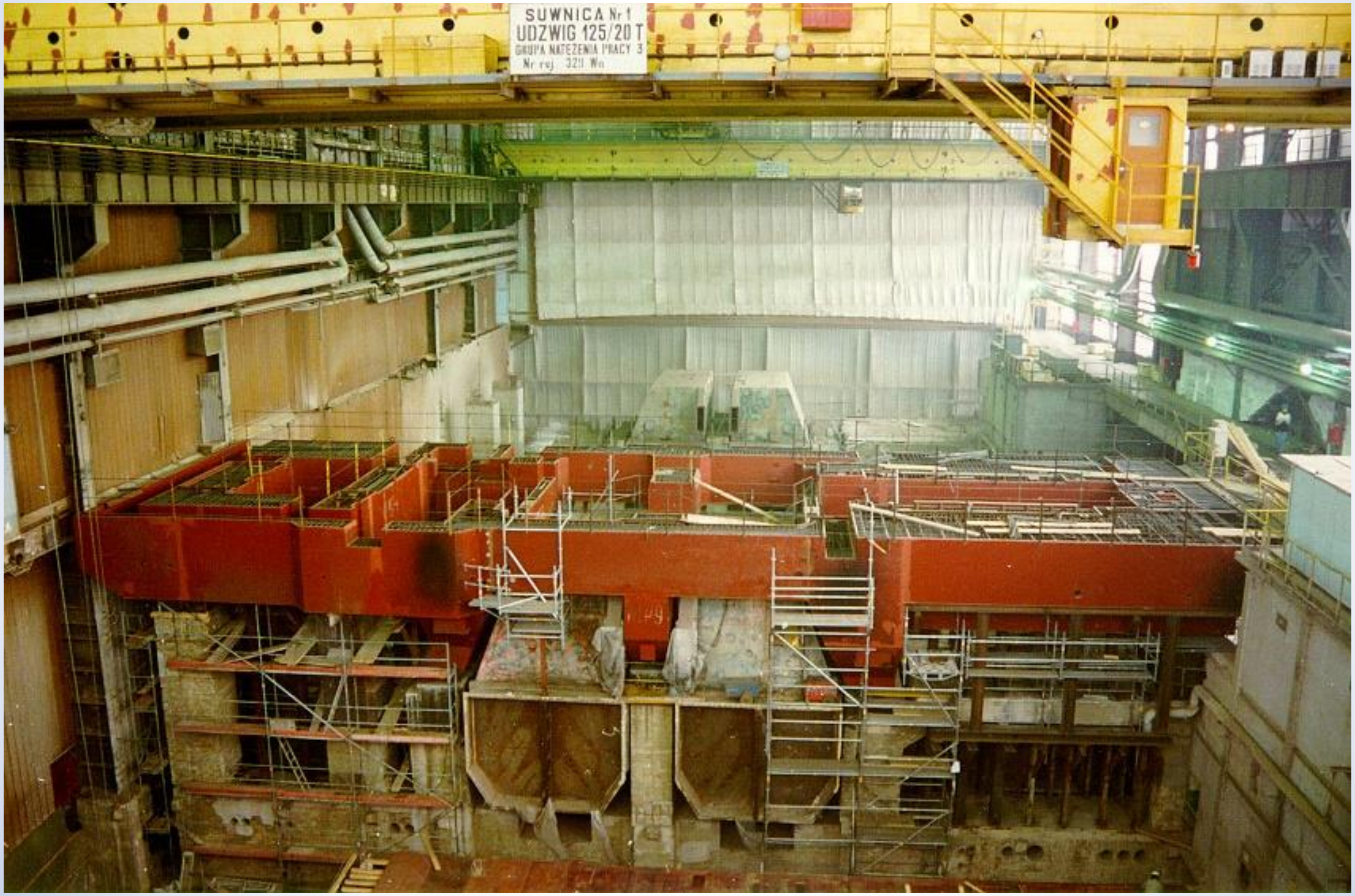
Specialities / Comments

Verifications: Usually, operating unbalance forces are specified by the machine operator and checked for permissible vibration amplitudes using structural dynamic analyses. For the present case, an enveloping unbalance force of 1 kN was defined over the frequency range from 1 to 500 Hz and the resulting vibration velocities were compared with "Engine Unbalanced Limits".

House-in-house Construction: Soft layer between the base plate and the piles (vertical tuning frequency of < 10.0 Hz) and ceiling bearings / springs at each corner.

Selected Case IV:

‘Reconstruction Toptable’



Lost steel formwork / new spring mounted toptable on existing substructure

Selected Case IV:

Specialities / Comments

Before: High tuned structure

After: Low tuned structure
- Substructure to be designed for static loads only, governing dynamic forces ‘staying’ within the toptable

Lost steel formwork, to reduce overall construction time

These Days: More retrofits than new ones (in western country)
-> foundation assessments and adjustments

Machine-Induced Vibrations

MACHINE FOUNDATIONS

Thank you for your attention!

Pascal Fleischer, TROMBIK Ingenieure AG

EPFL, Civil – Dynamics of Structures

(Criteria in favour to a spring mounted foundation)

Spring Mounted vs. Conventional

- ***Vibrational isolation:*** *The passive vibration isolation protects the T/G-Set against vibrations coming from the surrounding area and the active vibration isolation absorbs the vibrations caused by the T/G-Set, resp. prevents the vibrations from being spread out into the surrounding area.*

- ***Low tuned systems:*** *Separating the frequencies by (low) tuning of the foundation is the most effective measure against machine-induced vibrations and to avoid any state of resonance. For conventional STP the obtainable basic natural frequencies are not very low, as the supporting columns cannot be constructed infinitely slender (due to structural and constructive requirements) and often a spring mounted STP is the only solution to have the control on the (basic) eigenfrequencies.*

(Criteria in favour to a spring mounted foundation)

Spring Mounted vs. Conventional

- ***Geotechnical situation:*** *STG are very sensitive against (differential) <u>settlements</u> of the subsoil; settlements directly affect the shaft alignment and depend mainly on the subsoil classification and material parameters, position of different subsoil-layers, groundwater level and the baseplate itself - for conventional STP massive baseplates (with or without piles) are necessary. Spring mounted STP are considerably less sensitive to such differential settlements of the substructure due to the built-in elastic bedding conditions for the toptable. If a reduction of the total mass is required to reduce the <u>soil pressures</u> / soil settlements (when piles not possible or not effective) or the soil is sensitive to <u>dynamic stresses</u> (alternating stresses) a spring mounted STP has to be chosen. A complete separation between foundation structure and surrounding structures is strictly required for conventional STP due to vibration transmission aspects; if the groundwater level lies within or above the foundation additional measures has to be taken into account in regard to the watertightness.*

(Criteria in favour to a spring mounted foundation)

Spring Mounted vs. Conventional

- ***Height level adjustments of the toptable:*** *By major adjustments on the spring supports a close to the origin foundation elevation can be reached: Readjusting of normal long time deformations of the reinforced concrete foundation table (creeping / shrinkage of the concrete or settlements), which can affect the machine operation (misalignment of the machine shaft line).*

- ***Bill of Quantity (Concrete & Reinforcement):*** *Overall size and weight of spring mounted foundations are considerably smaller compared with conventional foundations: Slender columns and thin baseplate (less excavation work), resp. columns and baseplate can be part of / can be integrated into the building. Further on a shorter construction time of the base plate can be expected.*

- ***Seismicity / Base Isolation:*** *Protection of the T/G-Set against earthquake forces by a very low tuned system. Horizontal stiffness for the decoupled toptable to be very low.*

(Criteria in favour to a spring mounted foundation)

Spring Mounted vs. Conventional

- ***Long-term behaviour:*** *As a more theoretical, but also very important factor it must be mentioned that due to the "soft" support of the T/G-Set the operating conditions are positively influenced. Long-time experience with spring mounted foundations show an optimum of performance and smooth running behaviour.*

- ***Dimensions of the substructure (only static loads):*** *The substructure is dynamically decoupled, therefore the substructure has only to be designed for static loading situations. This leads to slender columns and a thinner baseplate and allows more space for secondary equipment below the foundation table as condenser, pumps, pipes, etc.*
  . usable space below the foundation table
  . New toptable on existing substructure