Burns & McDonnell

Dynamic Foundations:

Basics of Analysis & Design

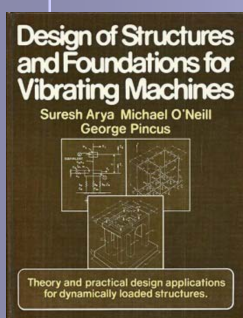
Agenda

- Resources
- Types of Machines & Foundations
- When is Dynamic Analysis Required?
- What is Dynamic Analysis?
  - Basics of Dynamics
  - Preliminary Design
  - Machine Manufacturer Criteria
  - Detailed Analysis & Design
- Construction Considerations
- Questions

Resources

- ACI 351.3R-04. “Foundations for Dynamic Equipment.” American Concrete Institute, 2004.

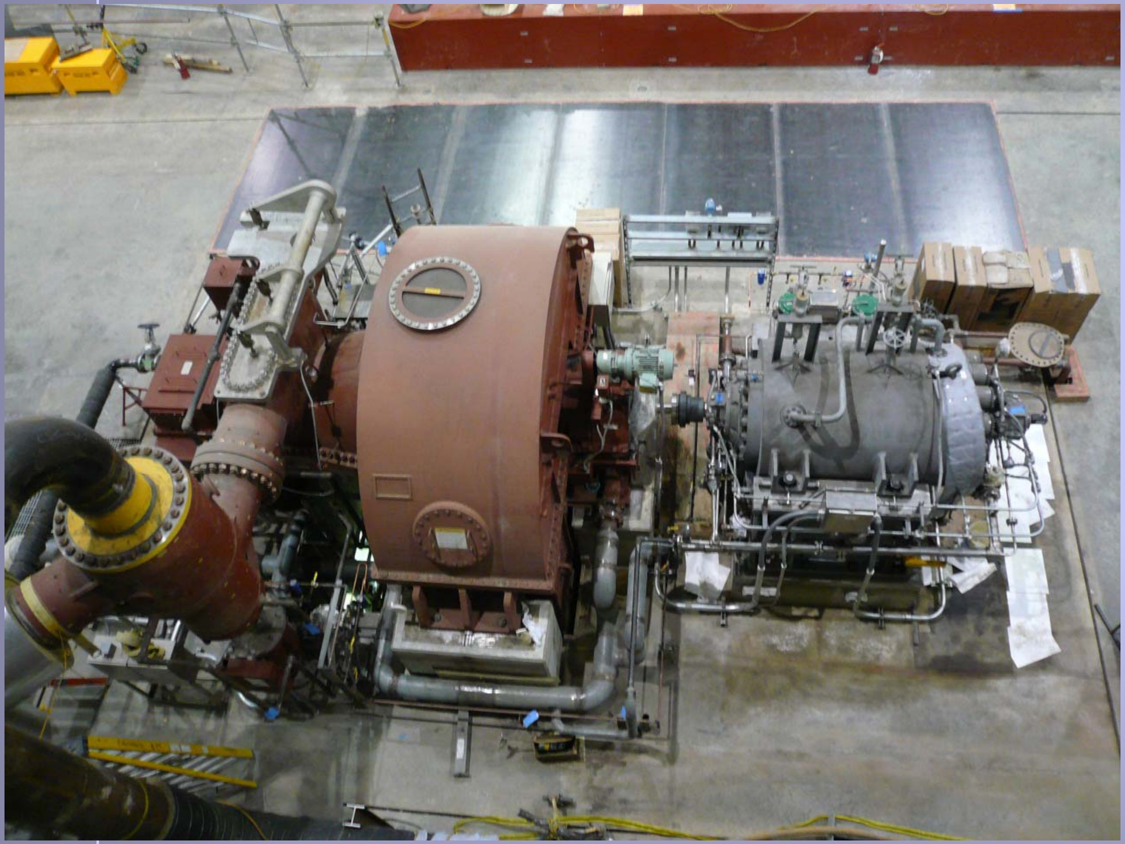
- El Naggar, M.H. “Design of Machine Foundations-Lecture Notes.” Geotechnical Research Center, Department of Civil and Environmental Engineering, University of Western Ontario. http://www.engga.uwo.ca/People/helnaggar/default.htm



- Arya, Suresh; O’Neil, Michael, & Pincus, George. “Design of Structures and Foundations for Vibrating Machines.” Gulf Publishing Co, June 1979.

Types of Dynamic Machines

Pumps



Types of Dynamic Machines

Fans

Types of Dynamic Machines

Turbine Generators

Types of Foundations

Block vs. Table Top
Piles vs. Soil supported

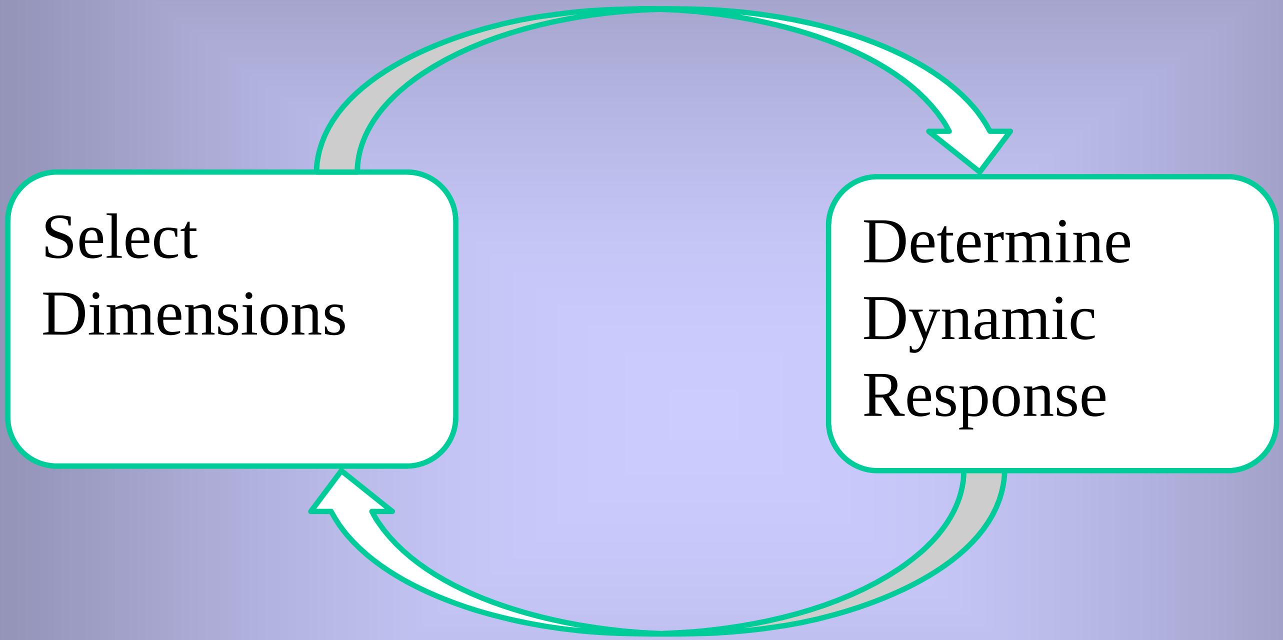

When is dynamic analysis required?

The level of analysis required is primarily dictated by the design requirements and performance parameters provided by the machine manufacturer.

Varying levels of dynamic analysis include:

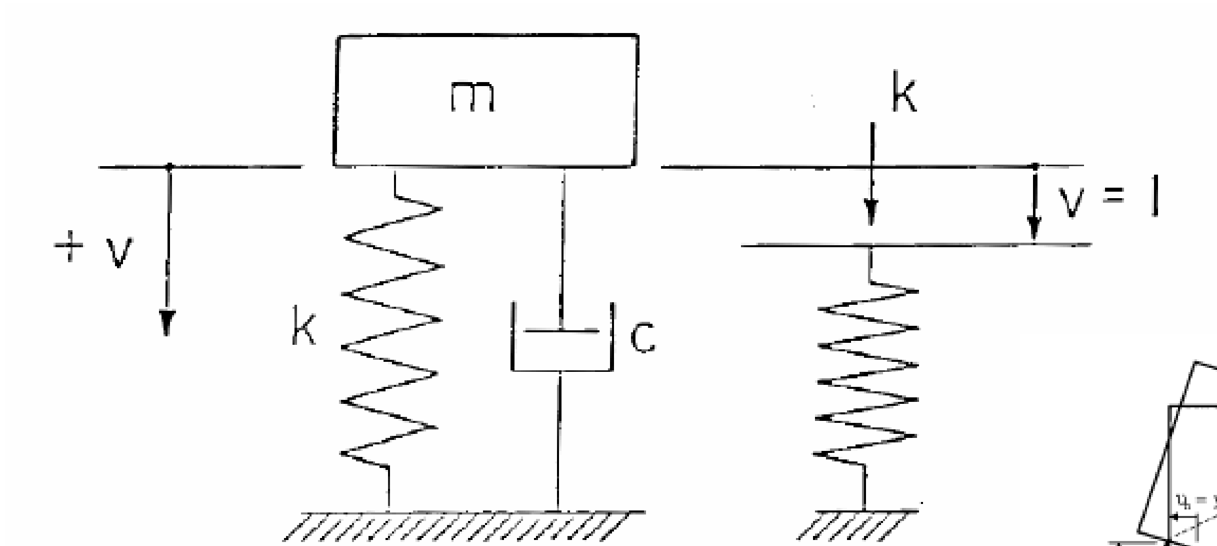
1. Mass Ratio (Fdn wt : equipment wt)
2. Frequency Analysis
3. Forced Response Analysis

What is the approach to dynamic analysis?



Basics of Dynamics

Figure 2.1: Basic Model of Single Degree of Freedom System



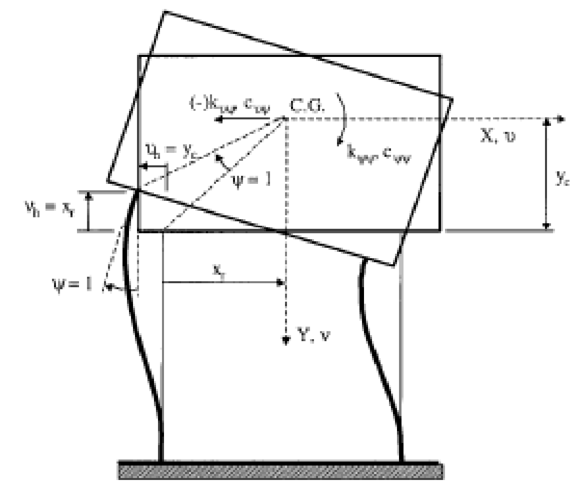
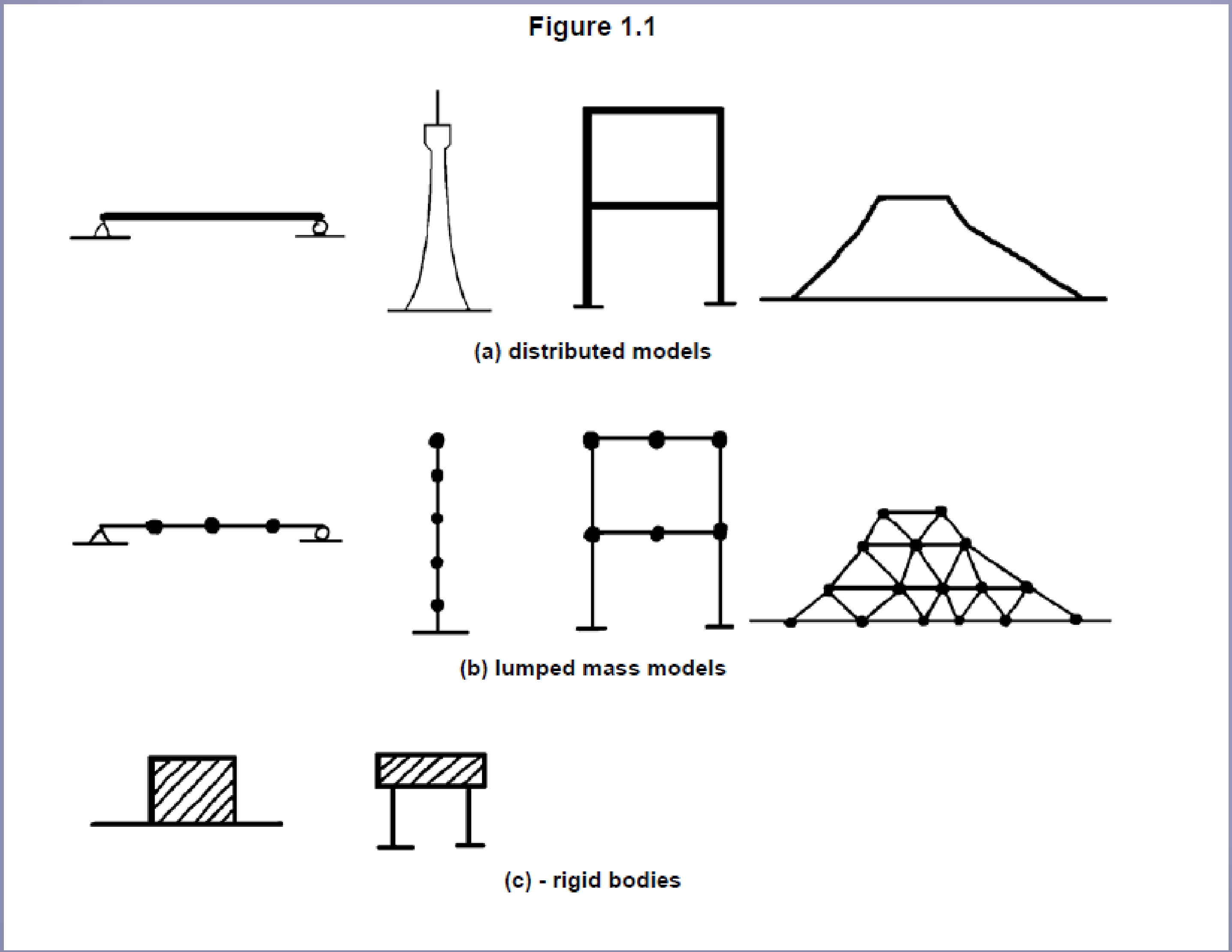


Fig. 4.8—Pile displacements for determination of group stiffness and damping related to unit rotation ψ.

Source: El Naggar, M.H. "Design of Machine Foundations."

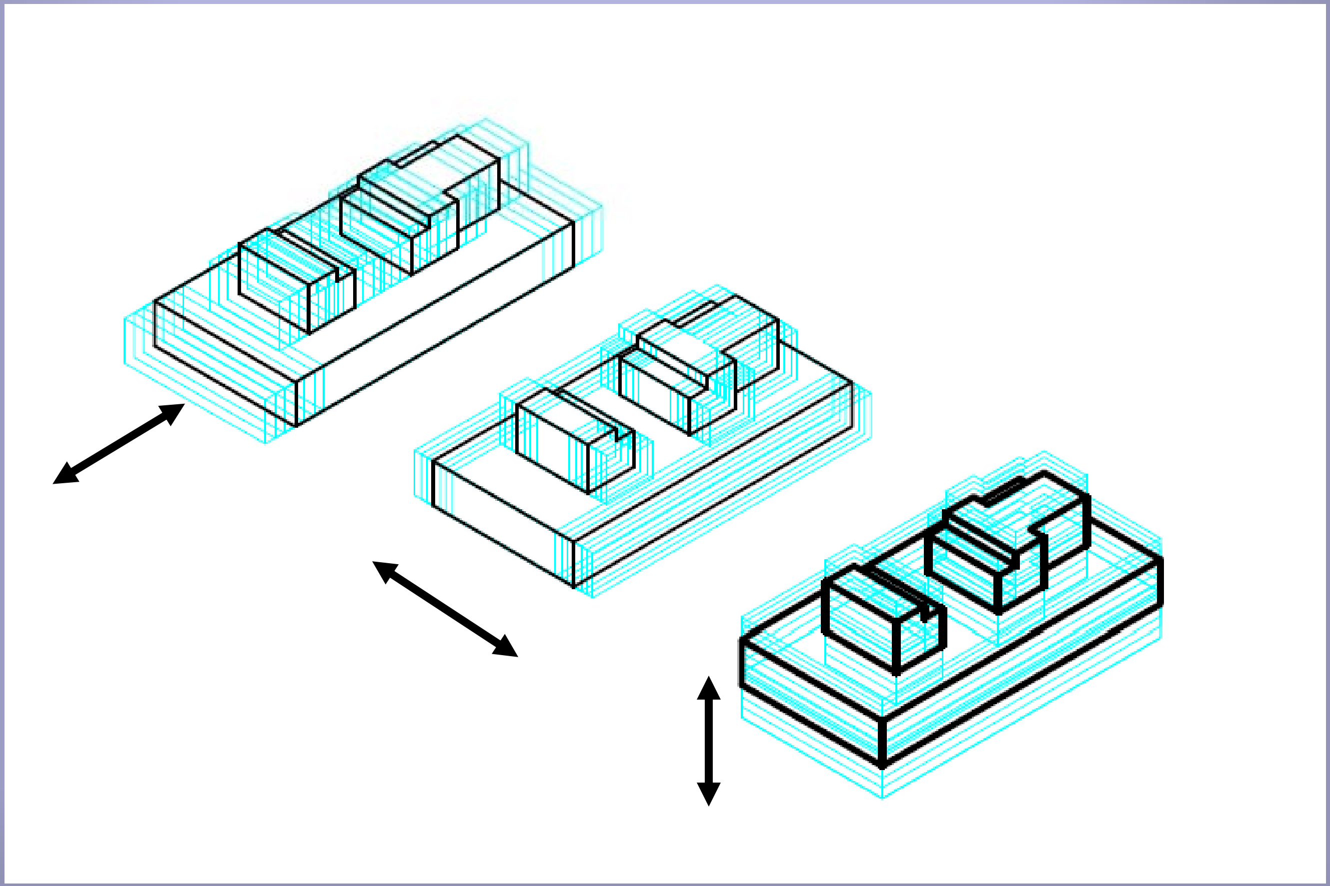
Basics of Dynamics – Types of Models



Source: El Naggar, M.H. “Design of Machine Foundations.”

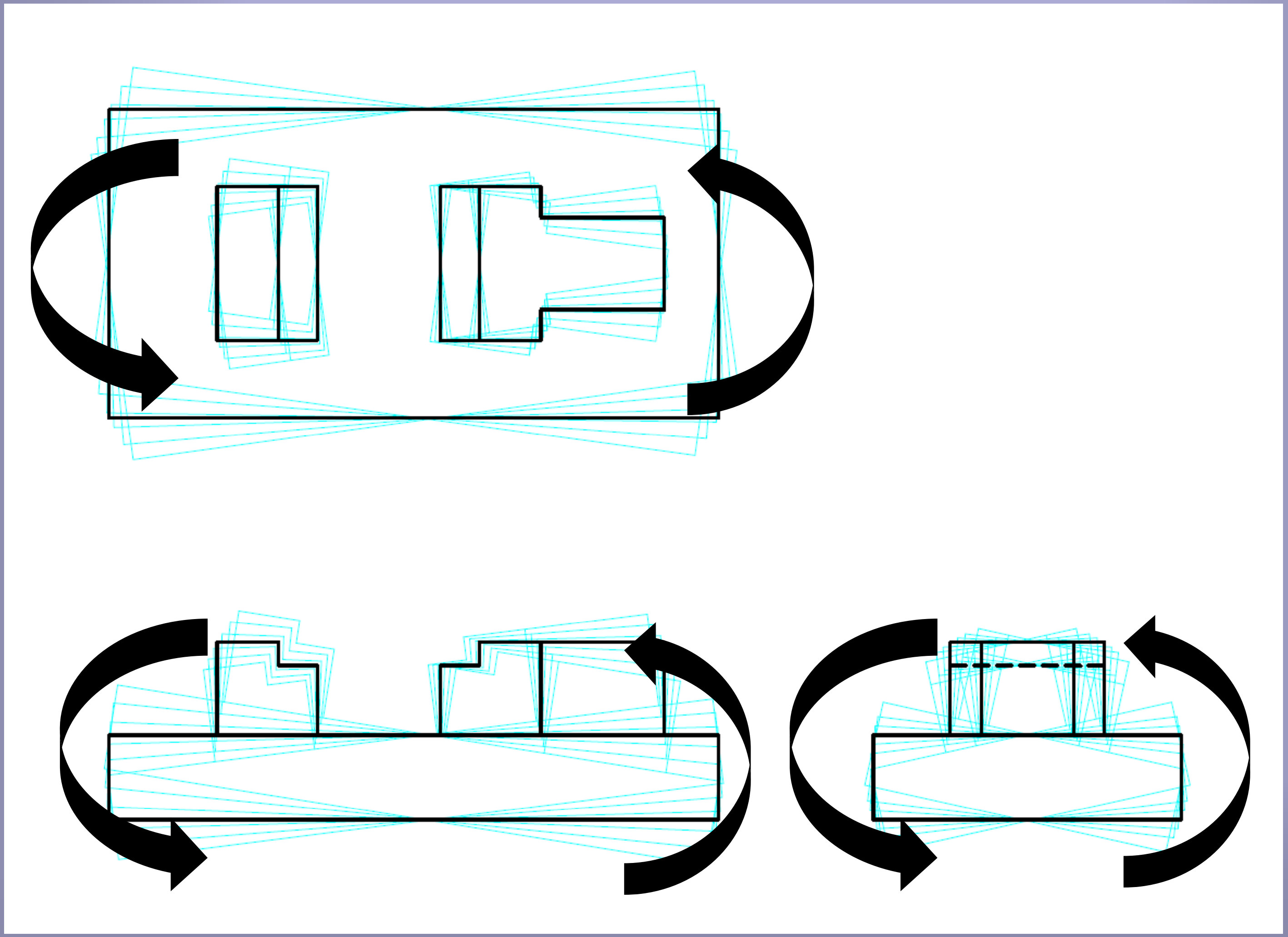
Basics of Dynamics – Rigid Body Modes

RIGID BODIES (Translational):



Basics of Dynamics – Rigid Body Modes

RIGID BODIES (Rotational):



Basics of Dynamics – Mode Shapes

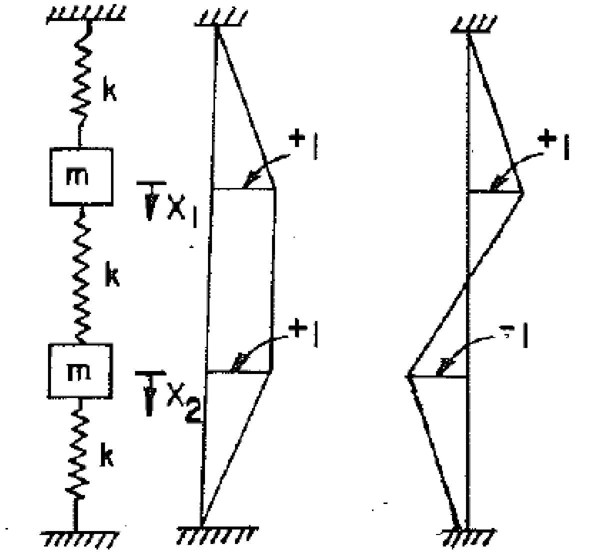


Figure 1-51. Normal modes of vibration.

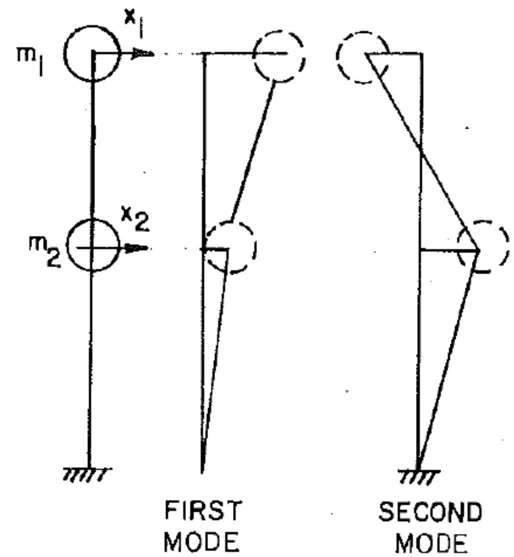


Figure 1-52. Modes of vibration of a two-degree-of-freedom system.

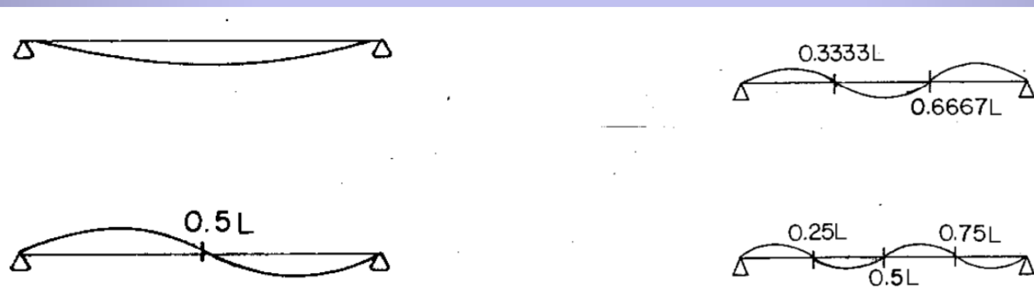
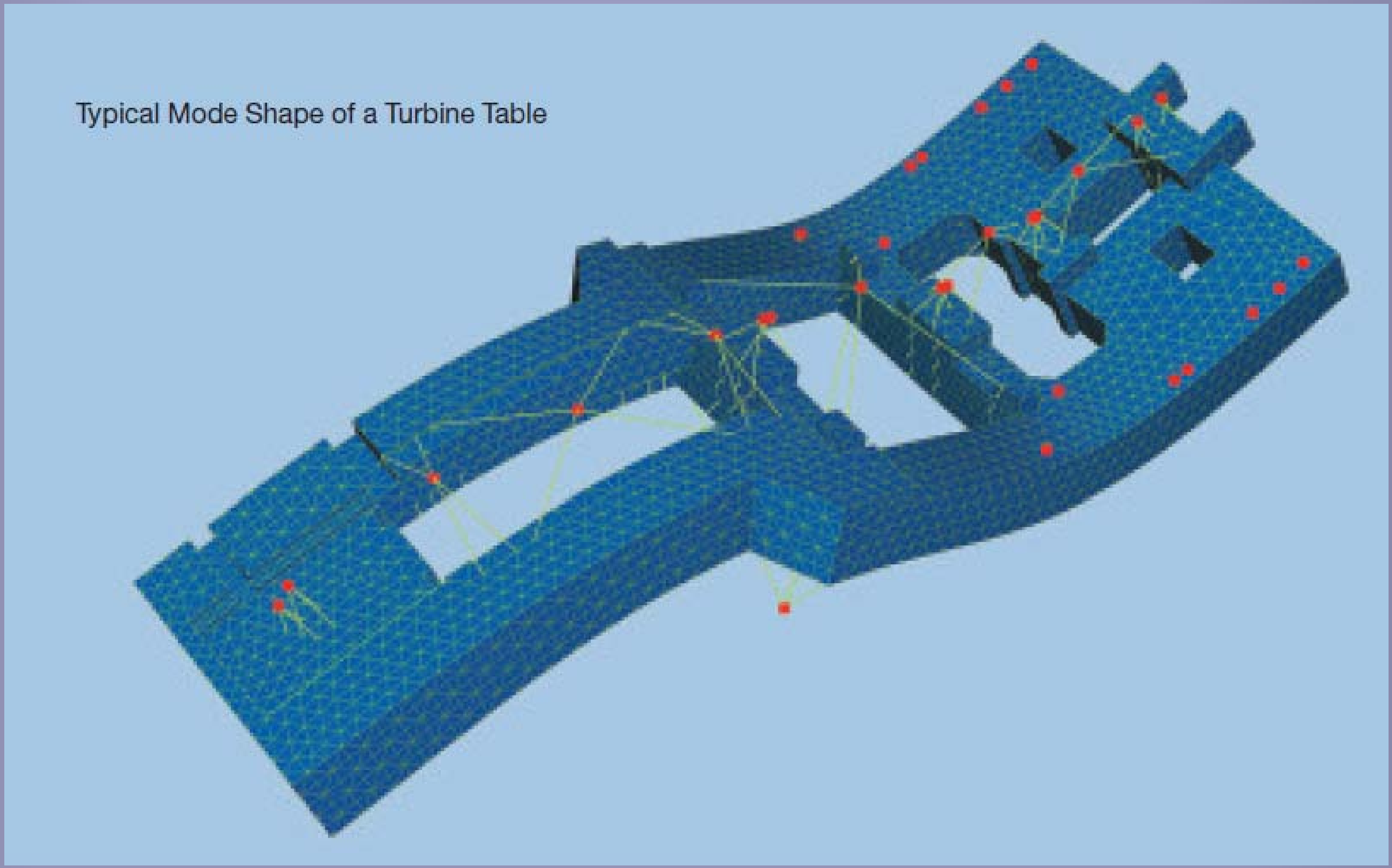


Figure 1-49. Various mode shapes of a hinged-hinged beam.

Source: Arya, O'Neill, & Pincus, "Design of Structures and Foundations for Vibrating Machines."

Basics of Dynamics – Mode Shapes



Source: GERB Vibration Control systems

Basics of Dynamics

SDOF Equation of Motion:

$$m\ddot{v} + c\dot{v} + kv = P(t)$$

Forcing function

m =mass

$\ddot{v}$ = *acceleration*

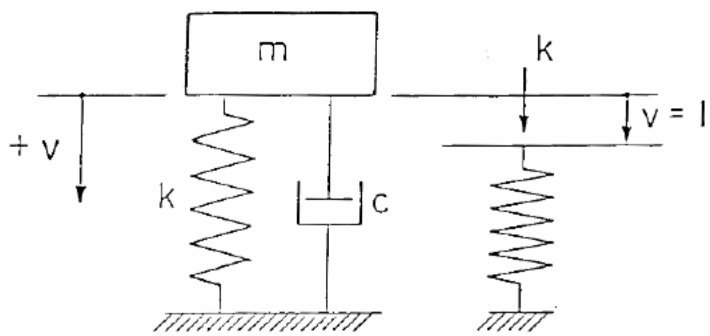
c = *damping*

$\dot{v}$ = *velocity*

k = *stiffness*

v = *displacement*

Figure 2.1: Basic Model of Single Degree of Freedom System



Basics of Dynamics

For a rotating machine:

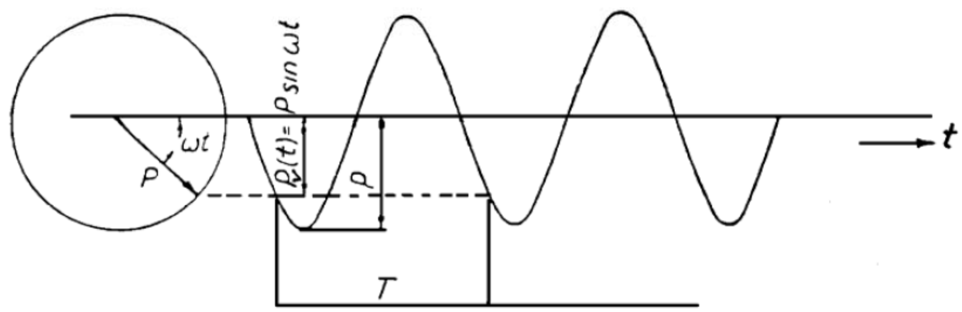
$$P = m_e e \omega^2$$

m_e = rotating mass

e = eccentricity

ω = circular frequency of rotation

Figure 1.2: Harmonic time history



$$P_V(t) = P\sin(\omega t)$$

$$P_h(t) = P\cos(\omega t)$$

Source: El Naggar, M.H. "Design of Machine Foundations."

Basics of Dynamics

For a rotating machine:

$$F_o = m_r e_m \omega_o^2 S_f / 12 \quad \text{lbf} \qquad (3\text{-}3)$$

$$F_o = m_r e_m \omega_o^2 S_f / 1000 \quad \text{N}$$

where

F_o = dynamic force amplitude (zero-to-peak), lbf (N);
m_r = rotating mass, lbm (kg);
e_m = mass eccentricity, in. (mm);
ω_o = circular operating frequency of the machine (rad/s); and
S_f = service factor, used to account for increased unbalance during the service life of the machine, generally greater than or equal to 2.

Source: ACI 351

Table 3.1—Balance quality grades for selected groups of representative rigid rotors (excerpted from ANSI/ASA S2.19)

Balance quality guide	Product of $e\omega$, in./s (mm/s)	Rotor types—general examples
G1600	63 (1600)	Crankshaft/drives of rigidly mounted, large, two-cycle engines
G630	2.5 (630)	Crankshaft/drives of rigidly mounted, large, four-cycle engines
G250	10 (250)	Crankshaft/drives of rigidly mounted, fast, four-cylinder diesel engines
G100	4 (100)	Crankshaft/drives of fast diesel engines with six or more cylinders
G40	1.6 (40)	Crankshaft/drives of elastically mounted, fast four-cycle engines (gasoline or diesel) with six or more cylinders
G16	0.6 (16)	Parts of crushing machines; drive shafts (propeller shafts, cardan shafts) with special requirements; crankshaft/drives of engines with six or more cylinders under special requirements
G6.3	0.25 (6.3)	Parts of process plant machines; centrifuge drums, paper machinery rolls, print rolls; fans; flywheels; pump impellers; machine tool and general machinery parts; medium and large electric armatures (of electric motors having at least 80 mm shaft height) without special requirement
G2.5	0.1 (2.5)	Gas and steam turbines, including marine main turbines; rigid turbo-generator rotors; turbo-compressors; machine tool drives; medium and large electric armatures with special requirements; turbine driven pumps
G1	0.04 (1)	Grinding machine drives
G0.4	0.015 (0.4)	Spindles, discs, and armatures of precision grinders

Preliminary Design – Rules of Thumb

The following guidelines may be used for the trial dimensions of the foundation block:

1. Generally, the base of the foundation should be above the ground water table. It should be resting on competent native soil (no backfill or vibration-sensitive soil).

2. The mass of the block should be 2-3 times the mass of the supported rotating machine, and 3-5 times the supported reciprocating machine.

Source: El Naggar, M.H. “Design of Machine Foundations.”

Preliminary Design – Rules of Thumb

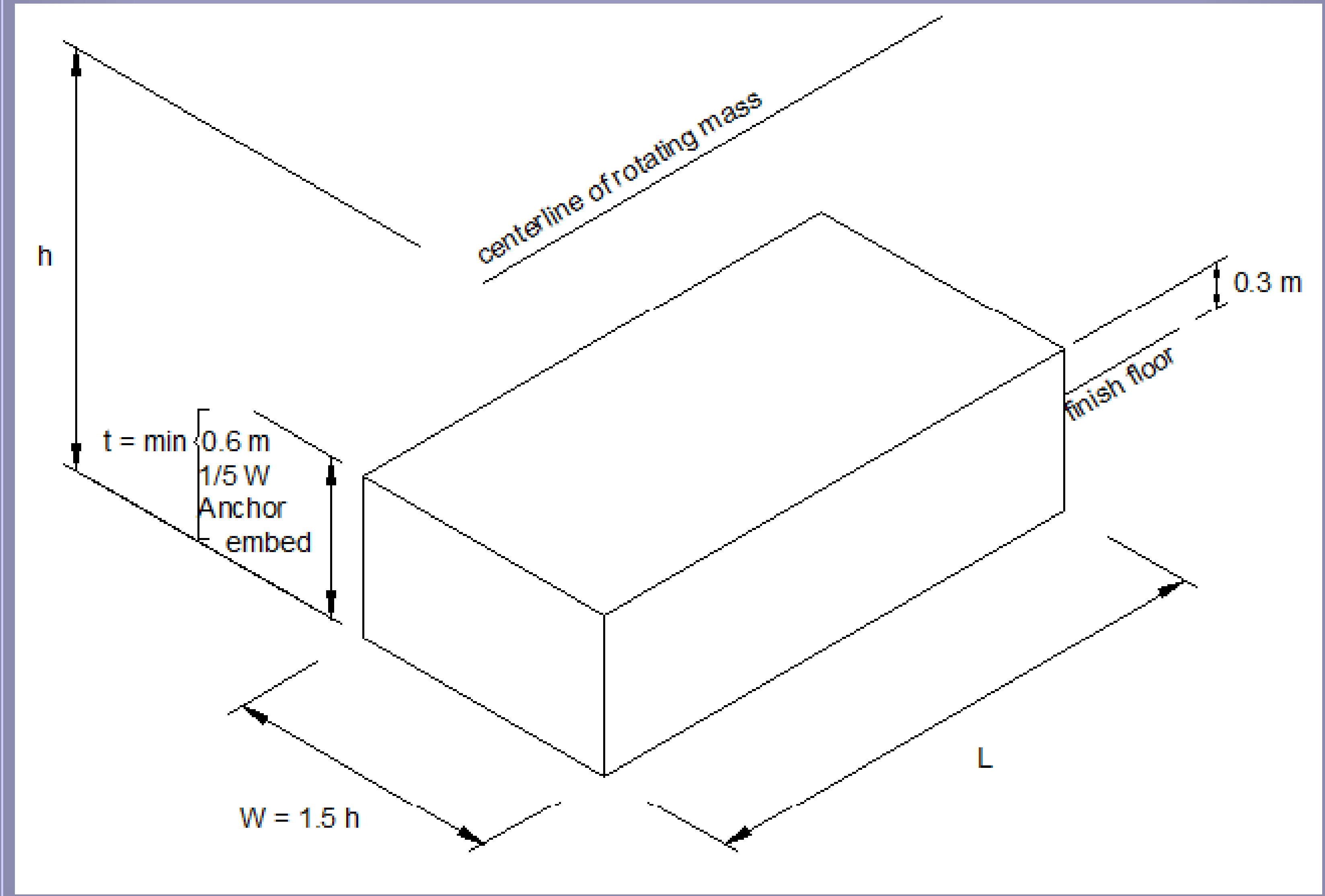
3. The top of the block should be 0.3 m above the elevation of the finished floor.

4. The thickness of the block should be the greatest of 0.6 m, the anchorage length of the anchor bolts and 1/5 the least dimension of the footing.

5. The width should be 1-1.5 times the vertical distance from the base to the machine centerline to increase damping in rocking mode.

Source: El Naggar, M.H. "Design of Machine Foundations."

Preliminary Design – Rules of Thumb



Preliminary Design – Rules of Thumb

6. The length is estimated from the mass requirement and estimated thickness and width of the foundation. The length should then be increased by 0.3 m for access maintenance purposes.

7. The length and width of the foundation are adjusted so that the center of gravity of the machine plus equipment lies within 5% of the foundation dimension in each direction, from the foundation center of gravity.

Source: El Naggar, M.H. "Design of Machine Foundations."

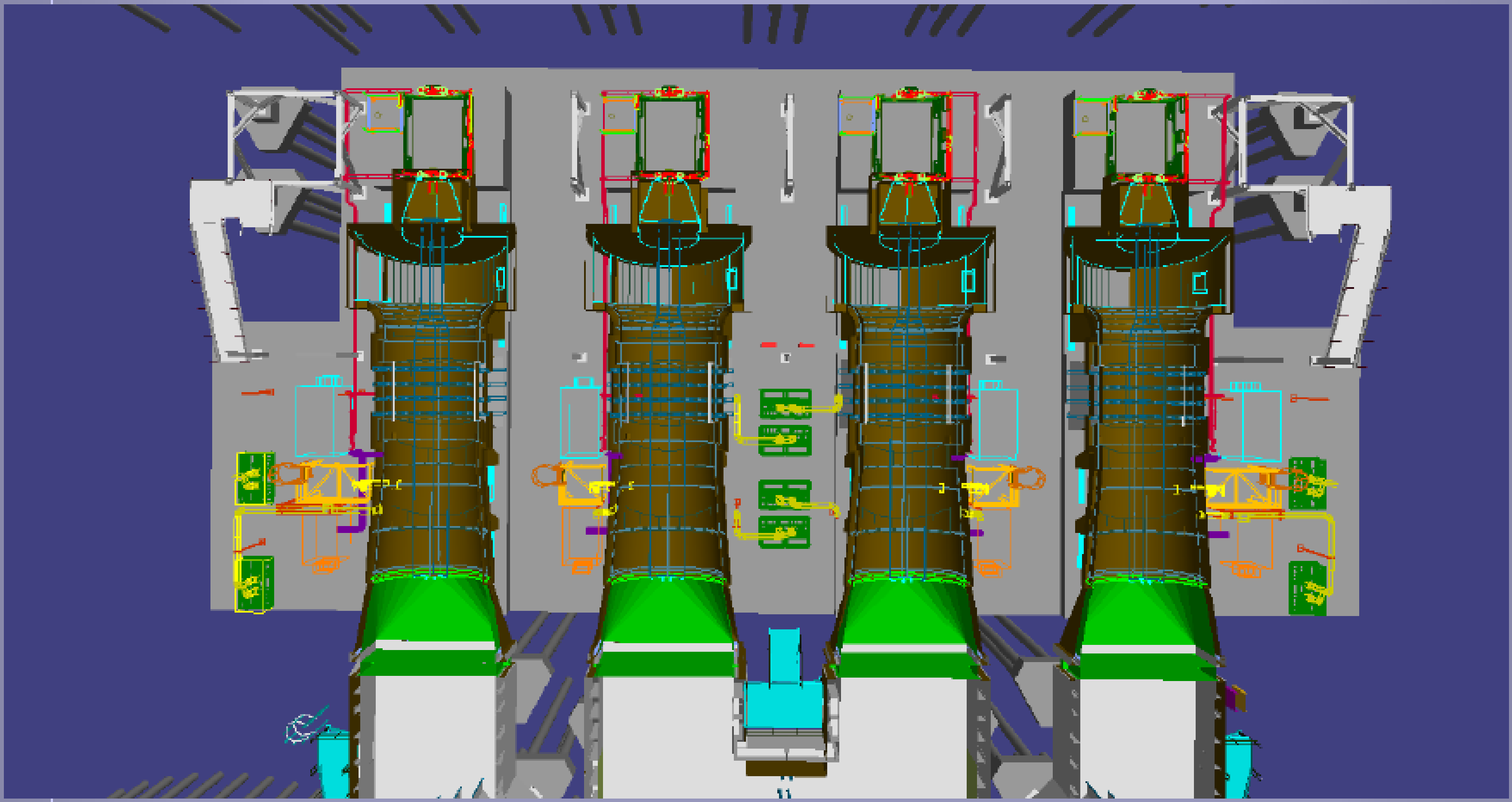
Preliminary Design – Rules of Thumb

8. It is desirable to increase the embedded depth of the foundation to increase the damping and provide lateral restraint as well.

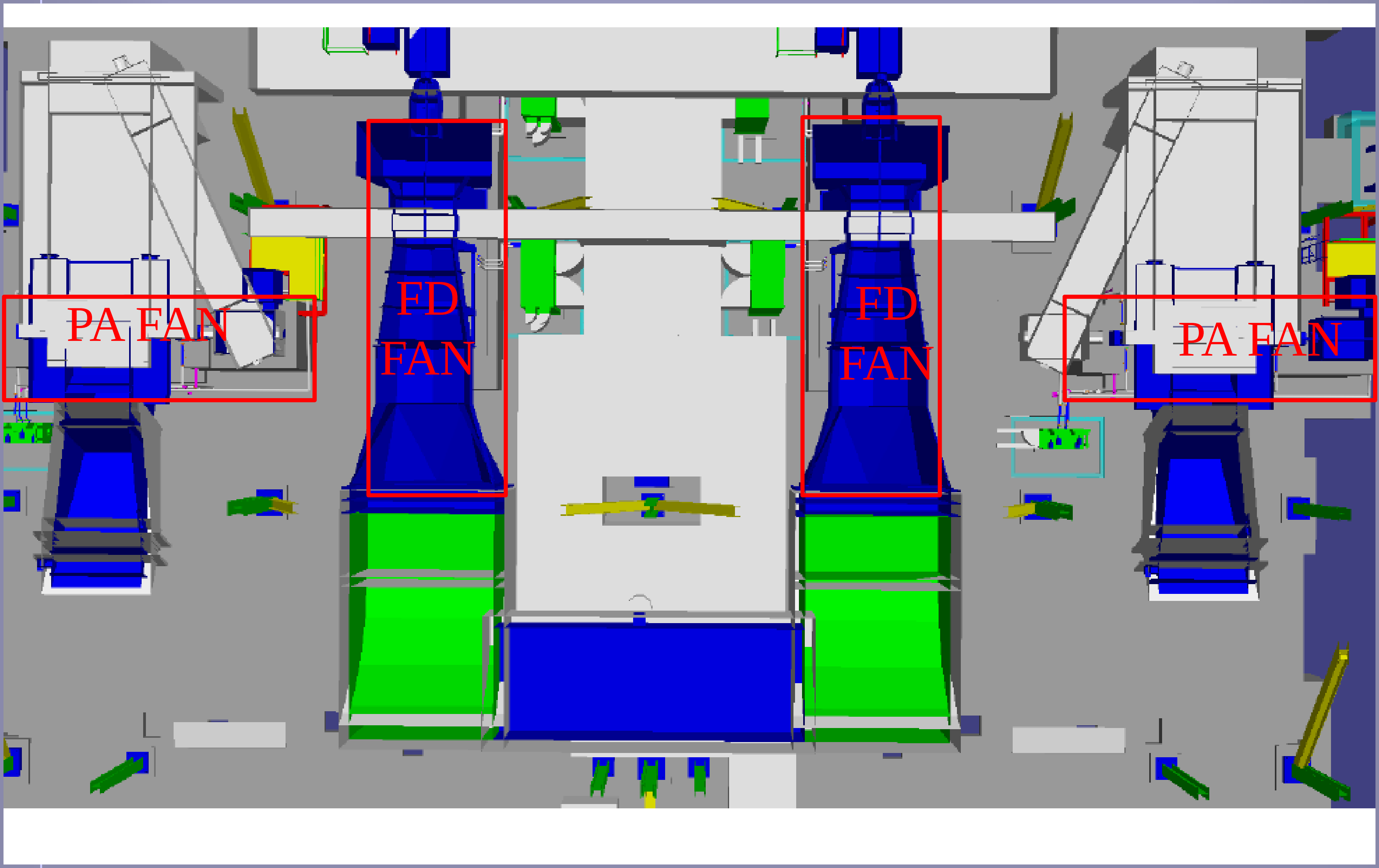
9. Ensure dimensions fit with all physical constraints.

Source: El Naggar, M.H. “Design of Machine Foundations.”

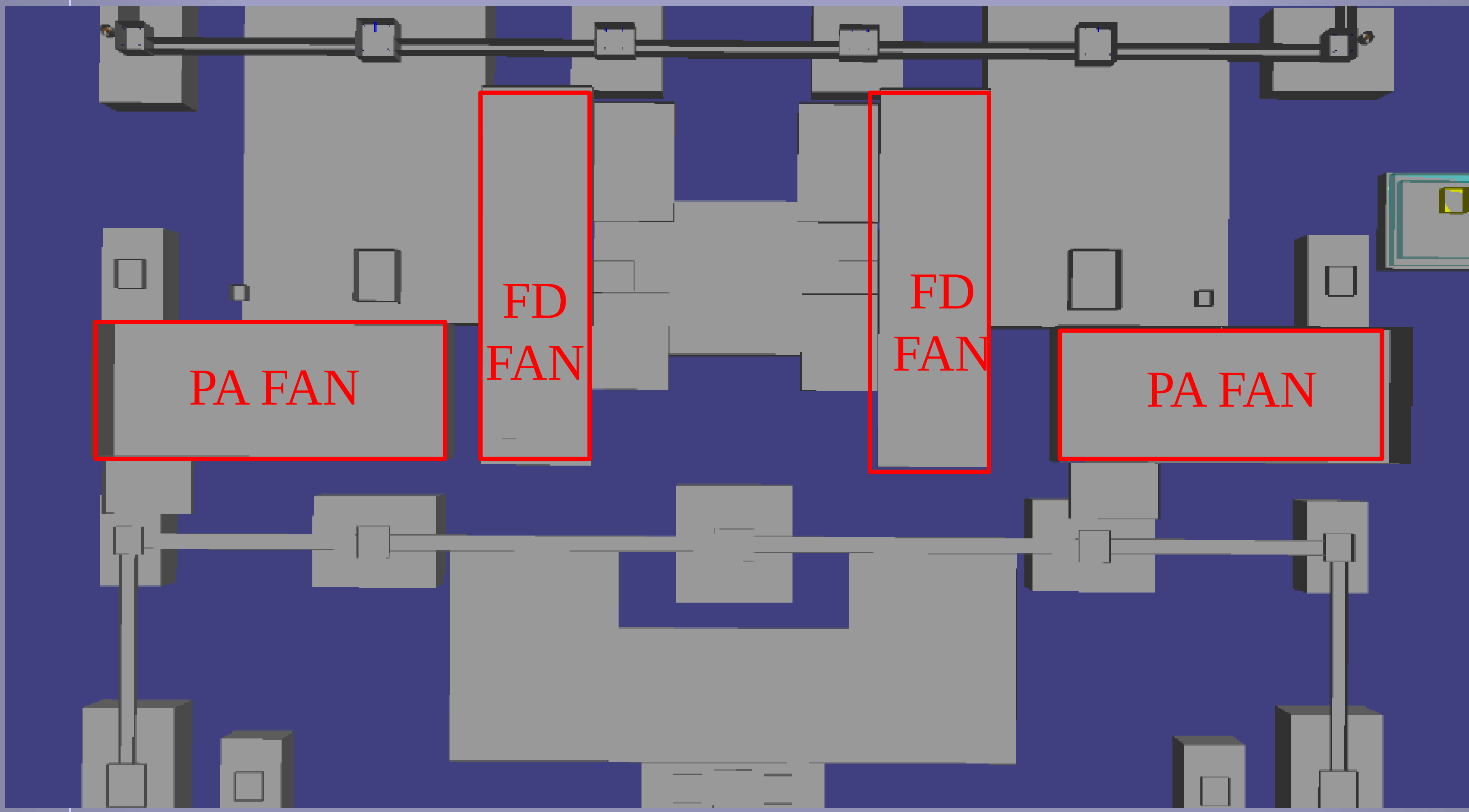
Preliminary Design – Physical Constraints



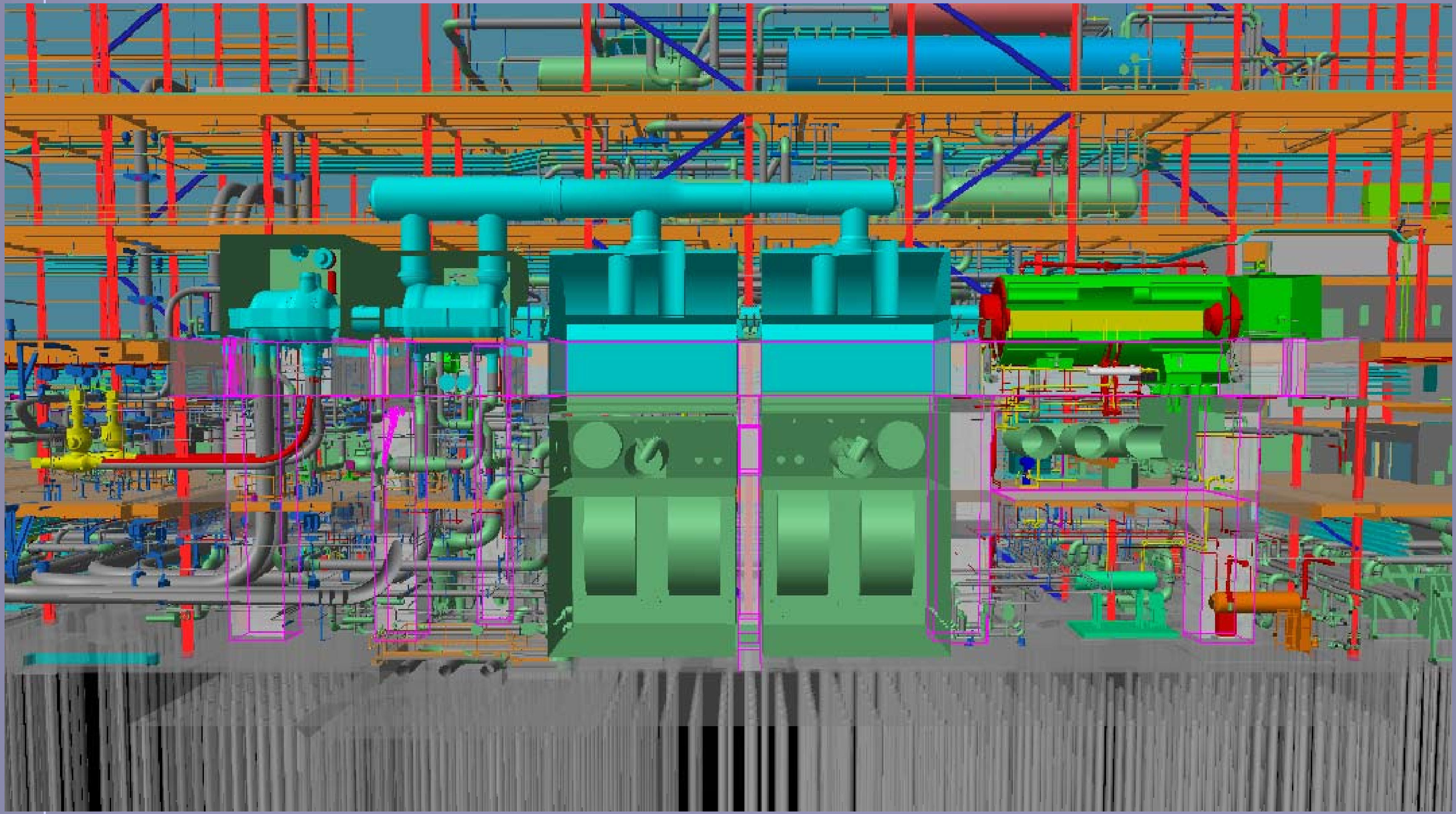
Preliminary Design – Physical Constraints



Preliminary Design – Physical Constraints



Preliminary Design – Physical Constraints



Detailed Dynamic Analysis

Design Checks:

Preliminary
- Mass ratio

Frequency (Modal) Analysis
- Natural frequency outside of a range the of operating frequency

Forced Response (Time History)
- Maximum displacement amplitude
  - Min foundation stiffness in all directions
  - Relative displacements between bearings (multiple rotors)
- Maximum velocity
- Maximum acceleration

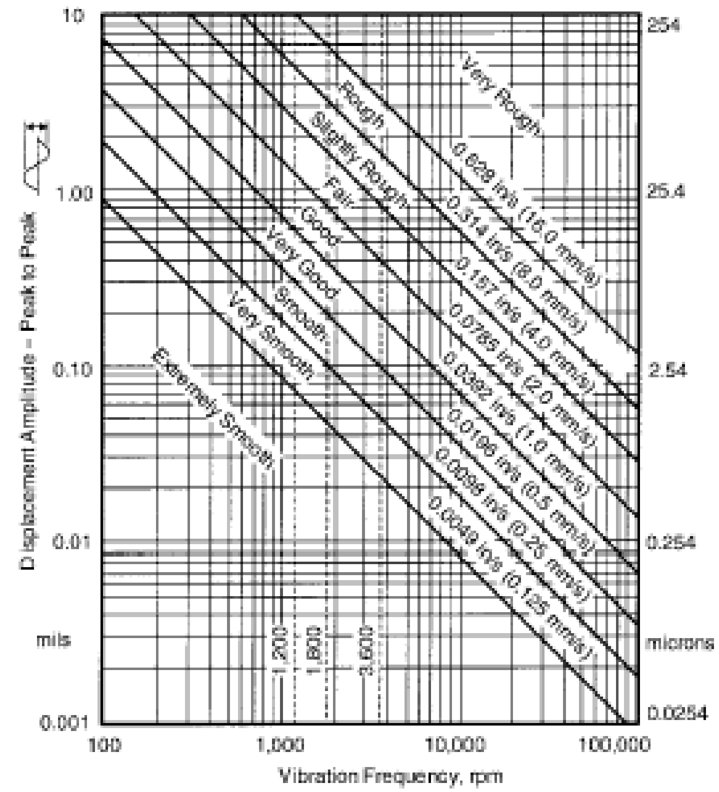


Fig. 3.10—General Machinery Vibration Severity Chart (Baxter and Bernhard 1967).

Source: ACI 351

Dynamic Amplification

Amplification Factor & Natural Frequency Avoidance

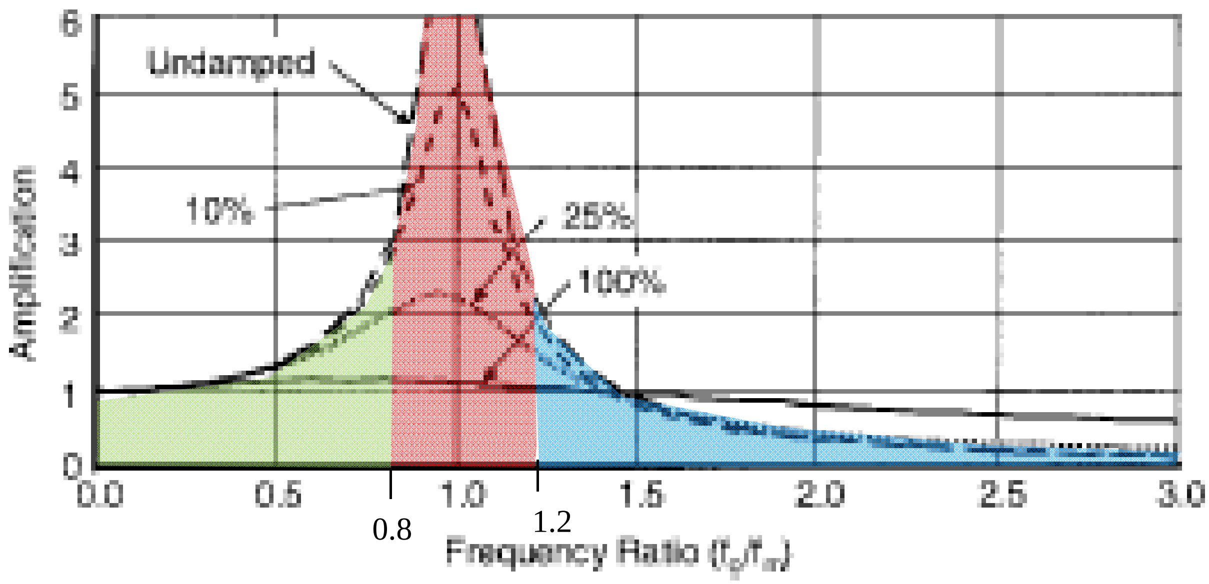


Fig. 3.14—Force transmissibility.

Source: ACI 351

Dynamic Amplification – Natural Frequency

Natural Frequency Equation

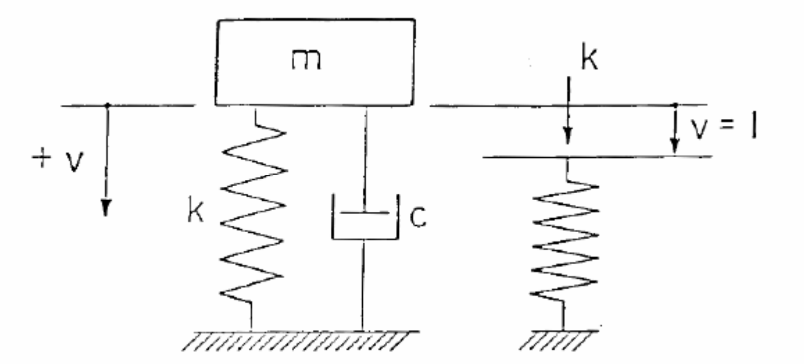
$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

$f_n = natural\ frequency$

$k = stiffness$

$m = mass$

Figure 2.1: Basic Model of Single Degree of Freedom System

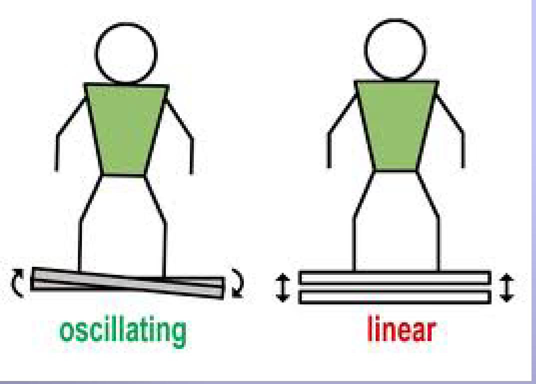


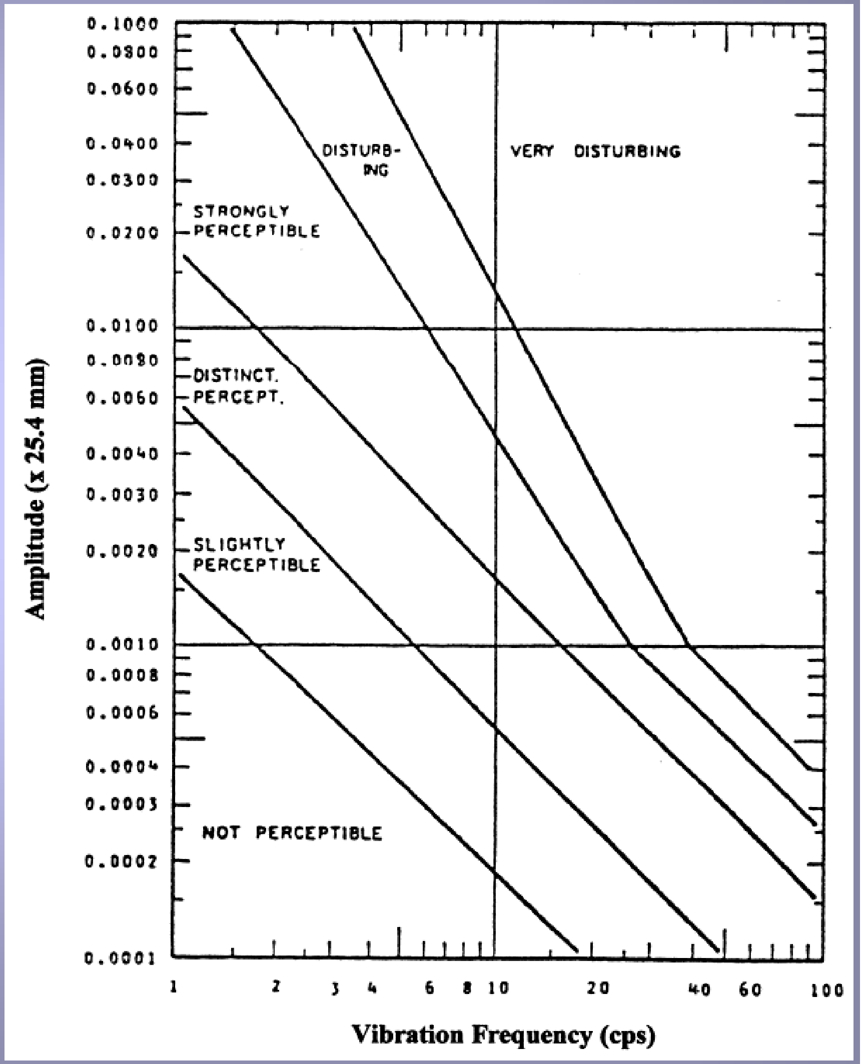
Source: Pincus & GERB Vibration Control systems

Other Design Considerations

Interesting fact:

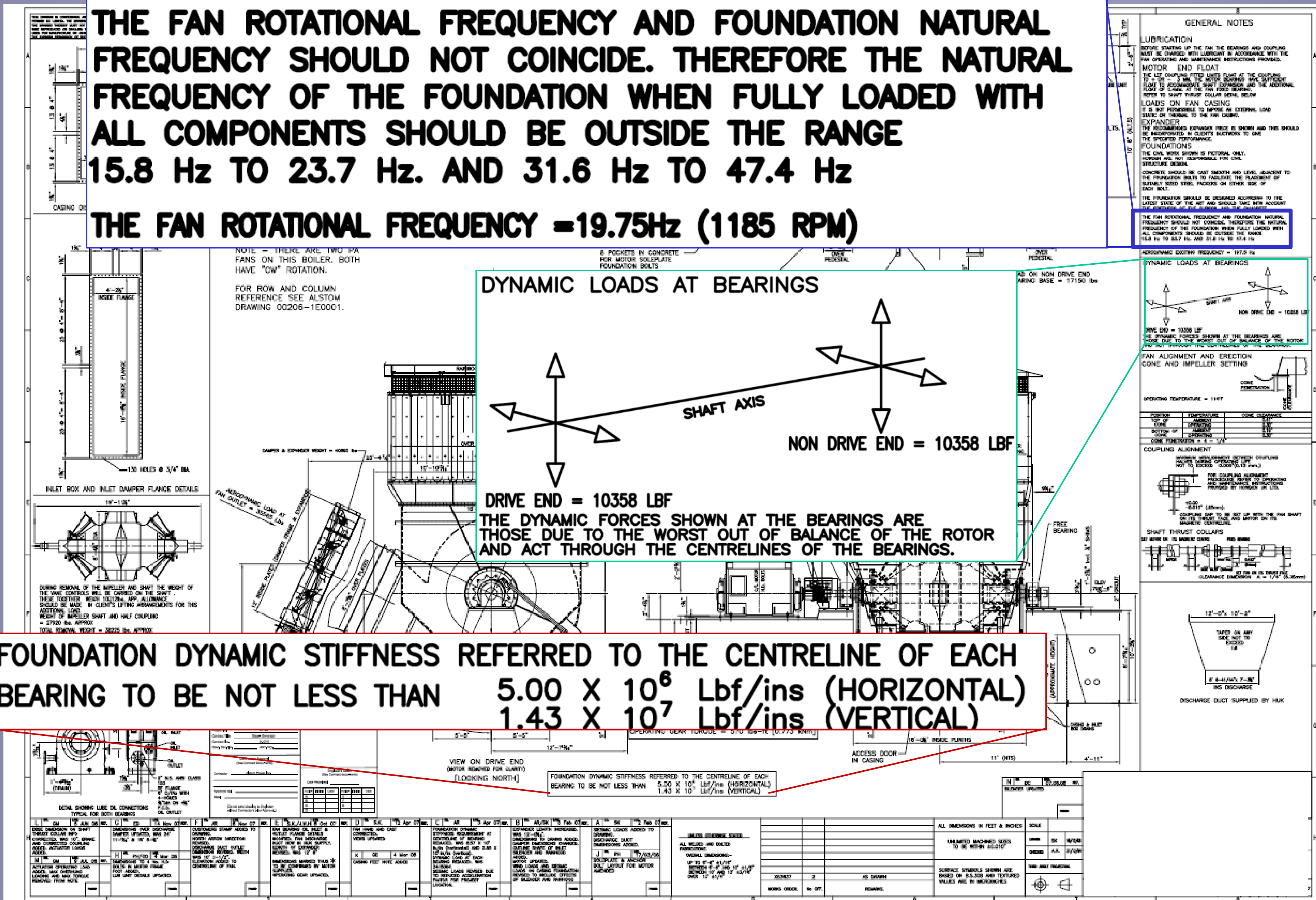
Motion which may be noticed by persons is on the order of 1/100 of that which is likely to cause damage to machines.





Source: Whitman & Richart. "Design Procedures for Dynamically Loaded Foundations"

Machine Manufacturer's Design Criteria



Machine Manufacturer's Design Criteria

For a rotating machine:

$$F_o = m_r e_m \omega_o^2 S_f / 12 \quad \text{lbf}$$

Design Input: Common

$\omega := 1185\,\text{rpm}$

$g = 32.174 \dfrac{\text{ft}}{\text{s}^2}$

$Q := 0.25 \cdot \dfrac{\text{in}}{\text{s}}$ — Product of eccentricity and operating frequency. Designated as "Q" in Table 3.1, ACI 351.3R (Based on ANSI/ASA S2.19). Industry standard Q=0.25 per table.

$e := \dfrac{Q}{\omega} = 2.015 \times 10^{-3} \cdot \text{in}$

$S_f := 6.75$ — Service factor

Design Input:

$w_{rotor} := 38.225 \cdot \text{kip}$

$m_{rotor} := \dfrac{w_{rotor}}{g} = 3.822 \times 10^{4}\,\text{lb}$

$F_{rotor} := S_f \cdot m_{rotor} \cdot e \cdot \omega^2 = 20.732 \cdot \text{kip}$ — Total imbalance force @ rotor

$F_{bearing} := \dfrac{F_{rotor}}{2} = 10.366\,\text{kip}$ — Imbalance force per bearing

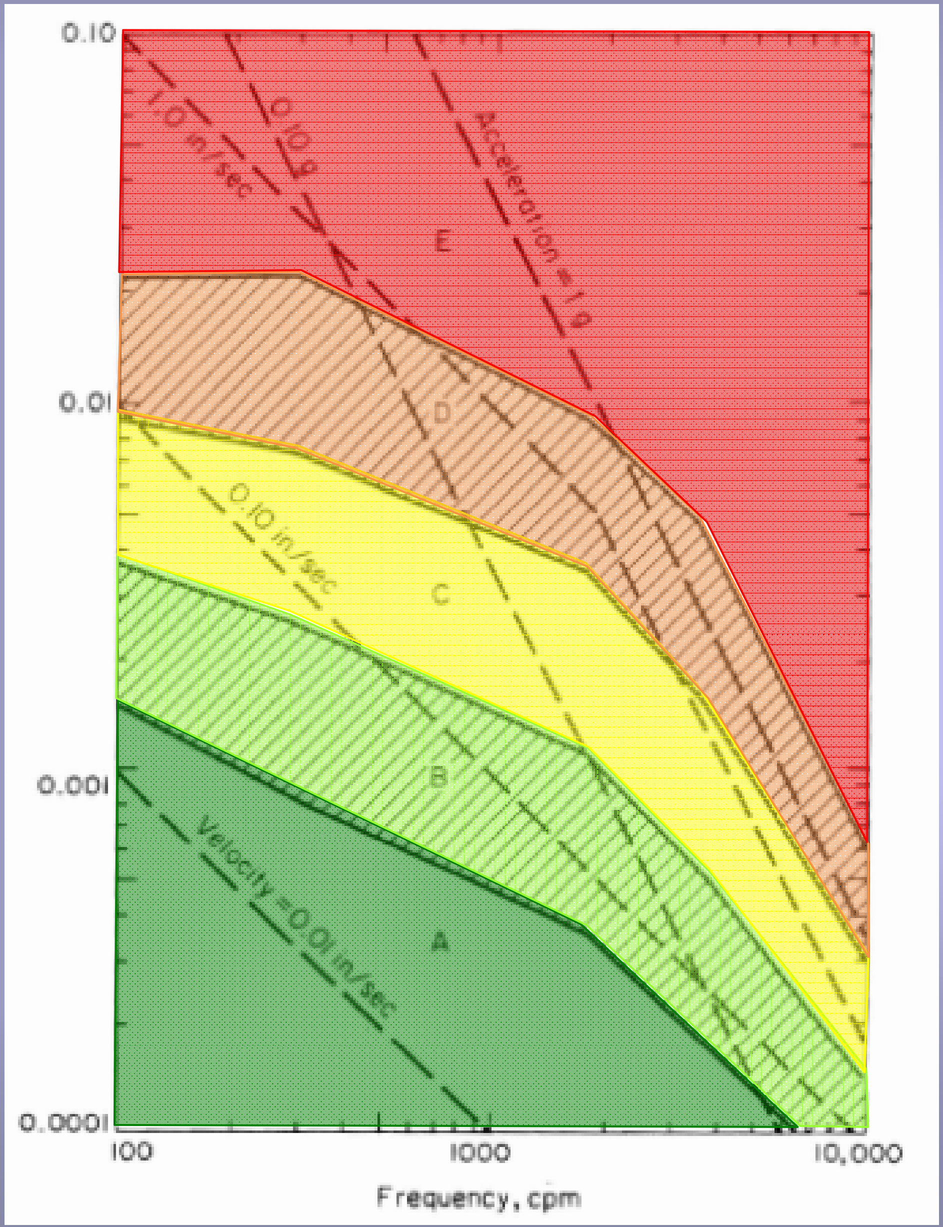
Source:ACI 351

Machine Manufacturer's Design Criteria

Additional loads for a turbine:

- Bowed rotor
- Loss of blade
- Generator short circuit
- Condenser vacuum
- Valve trips

Machine Performance



Performance Zones

A=No Faults, New

B=Minor Faults, Good Condition

C = Faulty, Correct In 10 Days To Save $$

D = Failure Is Near, Correct In 2 Days

E = Stop Now

Source: ACI 351 & Richard P. Ray, Ph.D., P.E., University of South Carolina

Computer Modeling - Soil Considerations

To accurately account for soil-structure interactions for damping and stiffness effects on the system, a program which accounts for the geotechnical analysis is necessary.

Geotechnical parameters required for analysis include:

-G, shear modulus

-mass density

-Poisson’s ratio

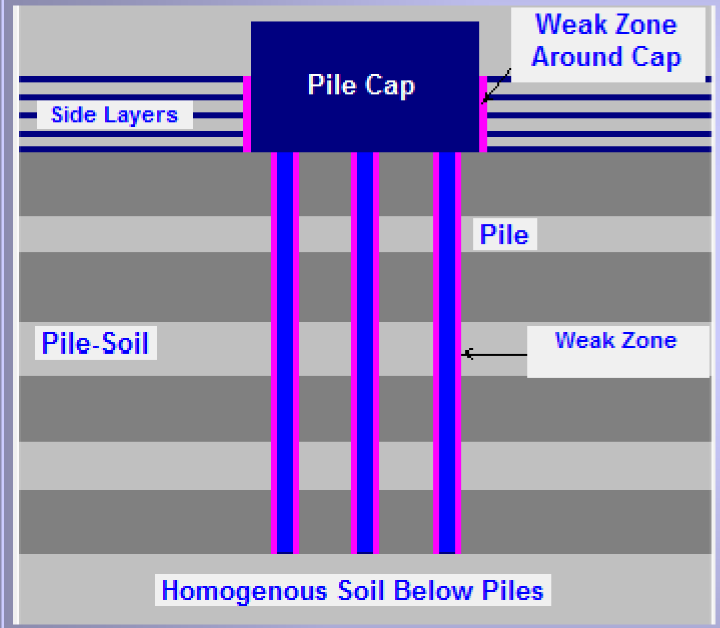
-damping ratio

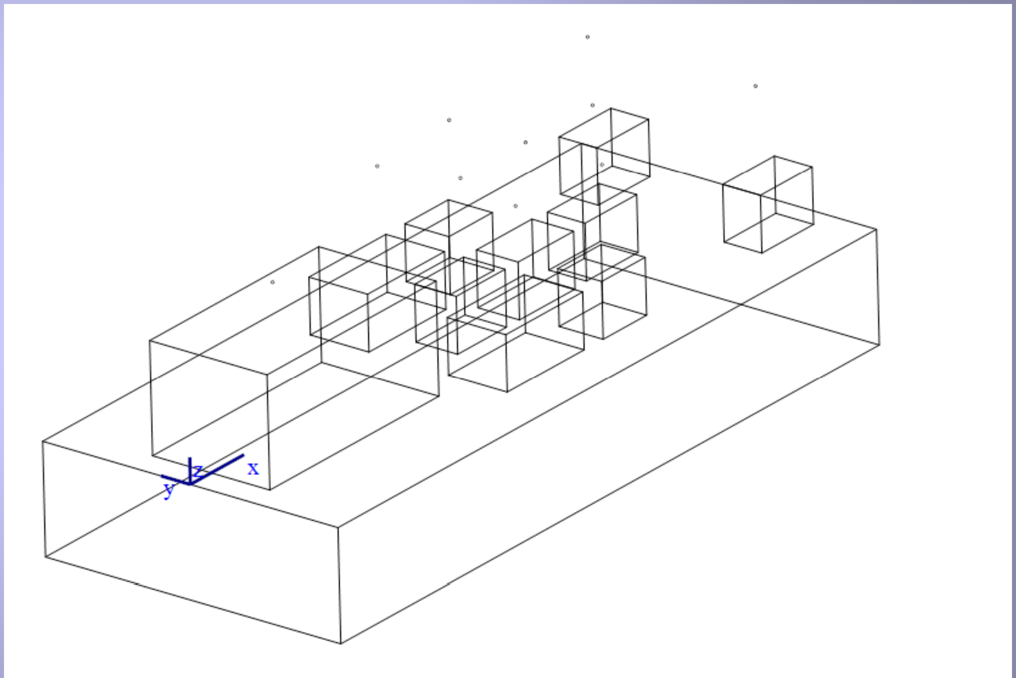
-depths and thickness of soil layers

Computer Modeling - Soil Considerations

Input:

Geotechnical parameters, Physical characteristics, Dynamic load





Computer Modeling - Soil Considerations

Response Output: Stiffness and Displacements

	Frequency (rpm)	Horizontal Stiffness X (lb/ft)	Horizontal Damping X (lb/ft/S)	Horizontal Stiffness Y (lb/ft)	Horizontal Damping Y (lb/ft/S)	Vertical Stiffness Z (lb/ft)	Vertical Damping Z (lb/ft/S)	Rocking Stiffness X (lb.ft/Rad)	Rocking Damping X (lb.ft/Rad/S)	Rocking Stiffness Y (lb.ft/Rad)	Rocking Damping Y (lb.ft/Rad/S)	Torsional Stiffness Z (lb.ft/Rad)	Torsional Damping Z (lb.ft/Rad/S)
1	0.00	1.77E+08	3.98E+06	1.84E+08	4.13E+06	2.90E+08	6.95E+06	6.56E+10	3.58E+08	2.01E+11	9.81E+08	1.65E+11	7.12E+08
2	50.00	1.78E+08	3.71E+06	1.84E+08	3.84E+06	2.95E+08	6.06E+06	6.51E+10	2.74E+08	1.98E+11	8.36E+08	1.62E+11	6.16E+08
3	100.00	1.78E+08	3.41E+06	1.85E+08	3.53E+06	2.97E+08	5.79E+06	6.39E+10	2.63E+08	1.90E+11	9.21E+08	1.58E+11	6.53E+08
4	150.00	1.82E+08	3.27E+06	1.90E+08	3.38E+06	2.96E+08	5.68E+06	6.25E+10	2.71E+08	1.80E+11	1.04E+09	1.53E+11	7.06E+08
5	200.00	1.84E+08	3.19E+06	1.93E+08	3.30E+06	2.92E+08	5.65E+06	6.10E+10	2.84E+08	1.71E+11	1.16E+09	1.49E+11	7.56E+08
6	250.00	1.85E+08	3.15E+06	1.95E+08	3.24E+06	2.88E+08	5.66E+06	5.96E+10	2.97E+08	1.63E+11	1.26E+09	1.45E+11	8.01E+08
7	300.00	1.85E+08	3.13E+06	1.98E+08	3.20E+06	2.82E+08	5.69E+06	5.84E+10	3.10E+08	1.56E+11	1.35E+09	1.42E+11	8.39E+08

Center of Gravity | Resultant Points

	Frequency(rpm)	Translational Response at CG - X (ft)	Translational Response at CG - Y (ft)	Translational Response at CG - Z (ft)	Rotational Response at CG - X (Rad)	Rotational Response at CG - Y (Rad)	Rotational Response at CG - Z (Rad)
1	0.00	2.11E-16	7.72E-15	3.46E-15	3.30E-16	3.18E-17	4.50E-17
2	50.00	5.96E-09	2.13E-07	9.33E-08	9.19E-09	8.91E-10	1.26E-09
3	100.00	2.57E-08	8.70E-07	3.72E-07	3.82E-08	3.76E-09	5.26E-09
4	150.00	6.39E-08	2.01E-06	8.47E-07	9.08E-08	9.10E-09	1.25E-08
5	200.00	1.30E-07	3.77E-06	1.53E-06	1.73E-07	1.76E-08	2.37E-08
6	250.00	2.35E-07	6.32E-06	2.44E-06	2.94E-07	3.01E-08	3.97E-08
7	300.00	3.98E-07	9.87E-06	3.56E-06	4.64E-07	4.77E-08	6.17E-08

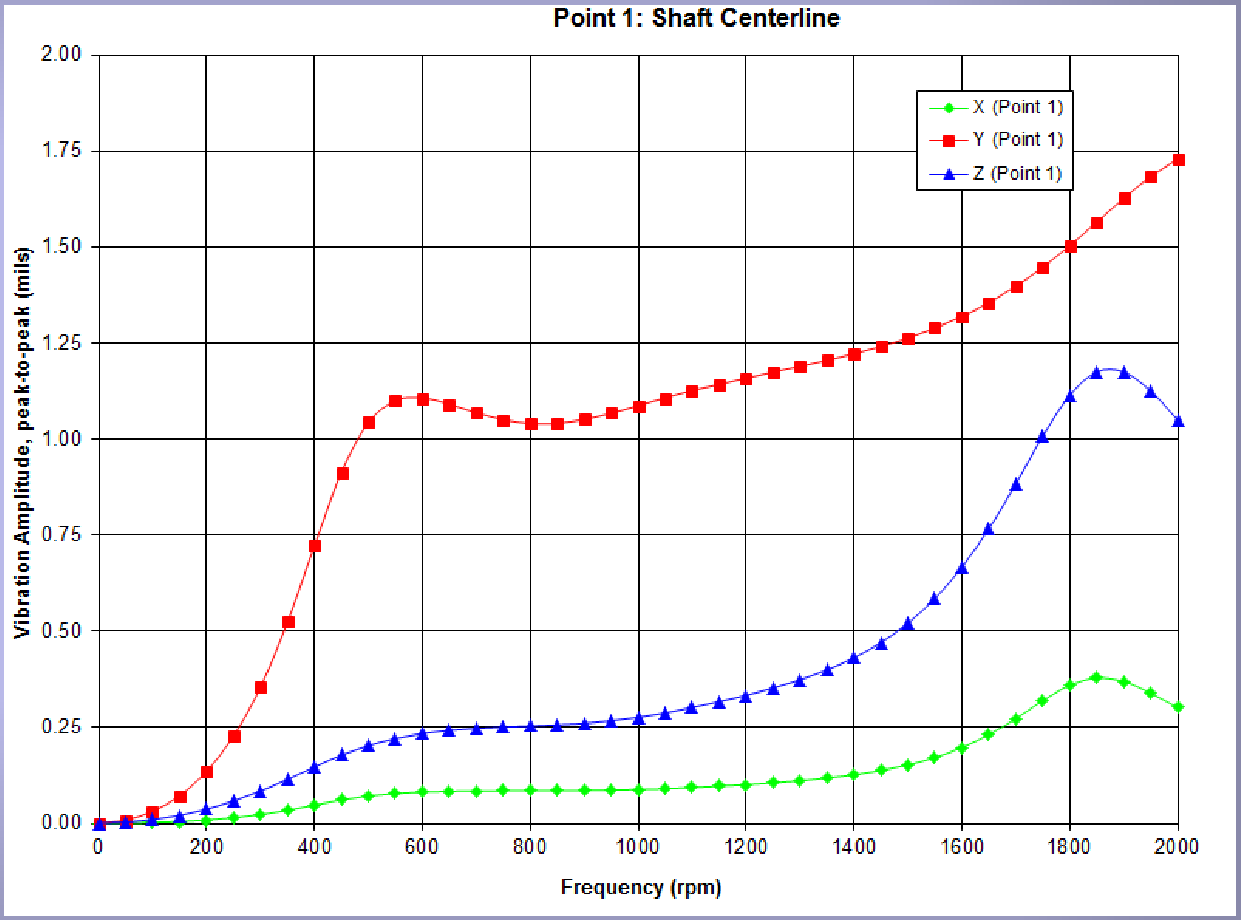
Computer Modeling - Soil Considerations

<u>Check against Machine Requirements:</u>

- Vibration Amplitudes

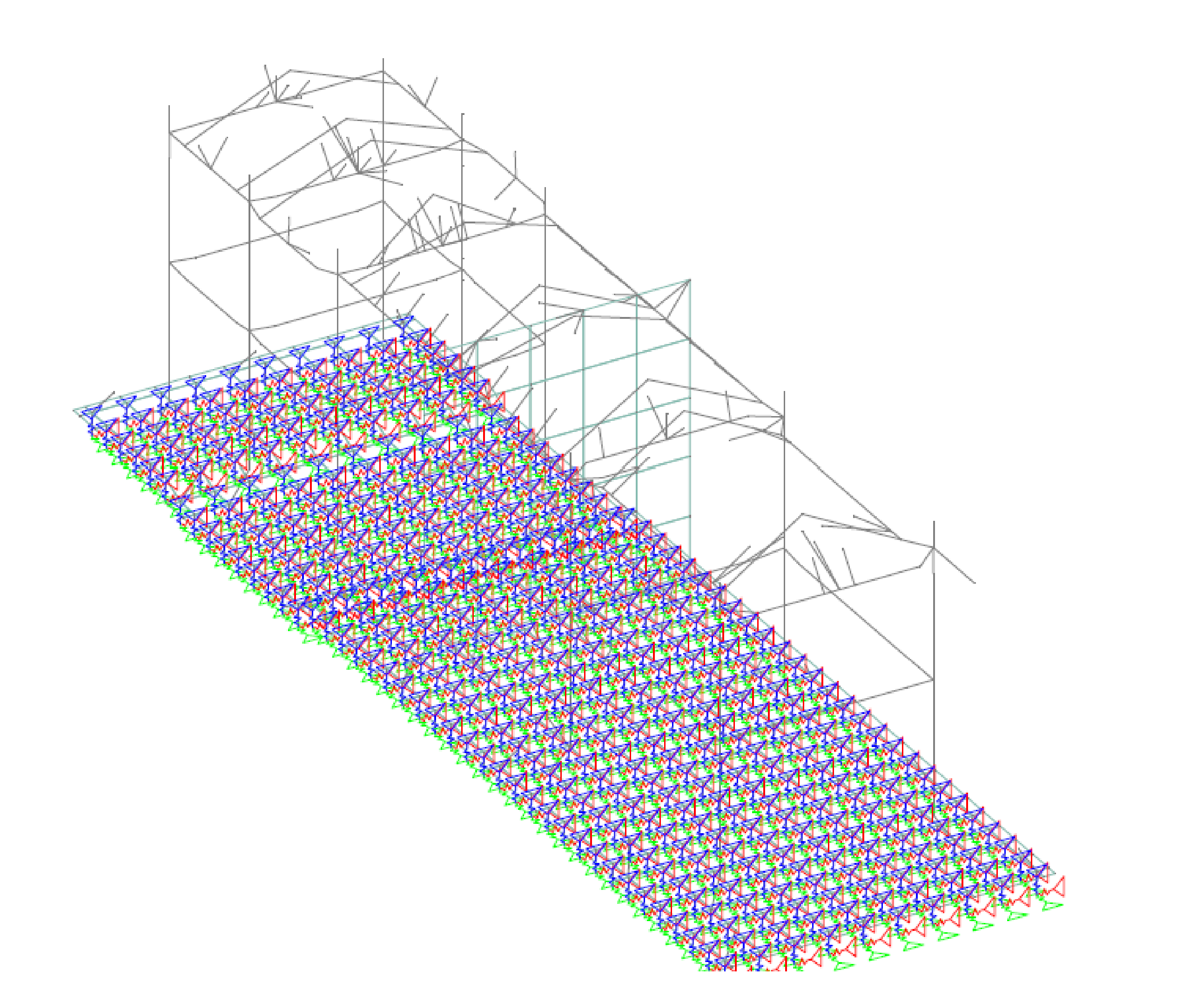
- Vibration Velocities

- Foundation Stiffness



Computer Modeling - Structural

Structural modeling – Steam Turbine-Generator



Construction Considerations

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Dynamic Foundations:

Basics of Analysis & Design

Thanks for Attending.
Have a Great Day.