1. General information about the foundation

The gas turbine (GT) foundation consists of a simple concrete block as one unit without any joints. Also, with purpose to avoid distribution of vibrations generated by the machines, the foundation must be disconnected from the surrounding structure.

When designing a GT foundation, following inputs are supplied by Siemens:

1) Project design basis
2) Soil parameters (*)
3) Foundation layouts and loadings

(*) not supplied by Siemens when the customer designs the GT foundation themselves

1.1 Project design basis

The following are the major inputs for design of a GT foundation:

a) Material requirements

- All concrete work shall comply with the applicable legal and official laws and corresponding acceptance codes.
- All concrete shall be controlled concrete, mixed and placed under the supervision of an approved control engineer.
- All concrete shall attain a minimum compressive strength of:
  25 MPa (3500 psi) on cylinders with dimensions ø150 x 300 mm (6" ø by 12") or
  30 MPa (4200 psi) on cubes with dimension 150 mm (6") at 28 days, and shall be normal weight aggregate concrete.
  No horizontal or vertical casting joints are allowed.

b) Cleanliness

- Sleeve must be cleaned inside and to be protected from penetration of concrete during the pouring.
- Surface of embedded details to be cleaned after removal of the mould.
- Foundation to be clean and treated with a suitable concrete sealant.

c) Criteria for static analysis (see chapter 2.1)

d) Criteria for dynamic analysis (see chapter 0)

e) Additional recommendations

If the GT includes liquid fuel and the liquid fuel unit is located outside the turbine sound enclosure, Siemens recommends a walled in foundation with suitable drain equipment to handle any possible fuel oil spill or rain water.

1.2 Soil parameters

Soil has a specific importance in the analysis of GT foundations. For determining the static and dynamic characteristics of the soil, a geotechnical investigation on the site must be done. Soil dynamics deals with engineering properties and behaviour of soil under dynamic stress. For the dynamic analysis of machine foundations, soil properties, such as poisson's ratio, dynamic shear modulus, and damping of the soil, are generally required.

Special treatment shall be taken when founding a GT foundation directly into the soil. In such case the depth to the firmer ground under the foundation must be known. If the elevation of the firmer ground varies i.e. the thickness of the soil layers under the foundation varies, then the soil spring stiffness along the foundation is going to vary. This will cause unwanted settlements under the foundation. Therefore, if it is economically and technically reasonable, the backfill stiffness should be made more uniform by excavating to the firmer ground and levelling it off. As results, the settlement under the foundation will be more even.

1.3 Foundation layouts and loadings

For designing of a GT foundation Siemens, as machine supplier provides foundation layouts and several loading cases for each component of the package.

2. Design of GT foundation

For maintaining the functionality of the GT foundation i.e. trouble free operation, Siemens has indicated permissible boundary values for the deformations and the vibration amplitudes of the foundation.

When designing and analyzing a GT foundation, Siemens' demands can be structured in four main parts:

- Design of the GT foundation with regards to the static loads including earthquake, seen as a high g-force
- Design of the GT foundation with regards to the dynamic loads
- Minimum data in the reports for documentation of the results
- Responsibilities

2.1 Design of GT foundation with regards to the static loads

Static dimensioning of the GT foundation shall be performed, including check for strength of the foundation, stability of the foundation and check for soil (pile) bearing capacity. For this purpose Siemens, as machine supplier, provides foundation layouts and a document with foundation loads Intensity. In the calculation and dimensioning of the foundation the characteristics of the soil must be taken into account.

When designing the foundation for the whole plant, the customer shall consider the tolerances for potential settlements between different concrete blocks, e.g. GT on one and boiler on another.

Since the GT foundation behaves like a rigid body on a soft media like soil, piles or vibration springs, the block foundation should always prove to be sufficient against the forces generated by the machines.

The Strength design shall be performed considering the forces and moments on the foundation due to:

- Static loads (dead weight, torque, thermal forces, erection loads and maintenance)
- Emergency loads (short circuit and loss of blade)
- Wind and Snow loads
- Earthquake

2.1.1 Limits on deflection

All criteria stated below for the deformation of the GT foundation must be met. When designing the foundation the characteristics of the soil must be taken into account.

2.1.2 Dead load deflections and settlements

Following application and adjustment of all dead loads, the inclination of the foundation surface to the horizontal, as measured between machinery supports, shall at no point exceed 1 in 1000.

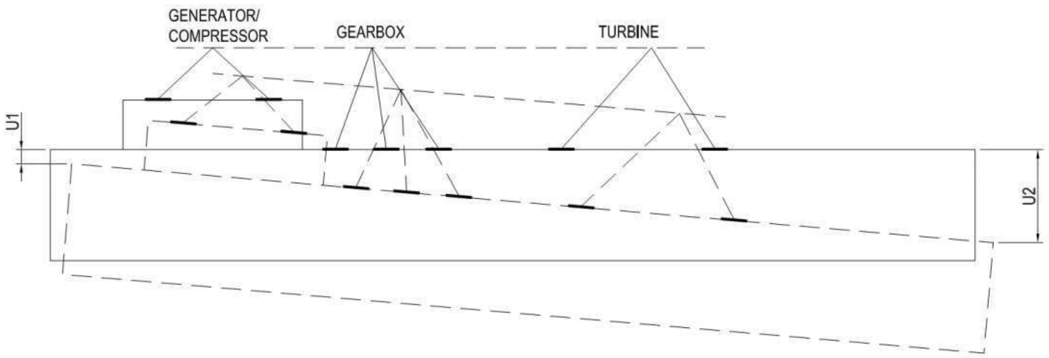


Figure 1: Schematic view of foundation inclination

Reference: SIT AB/2016-02-22

$$U = U2 - U1$$

$U : A \leq 1:1000$ i.e. $U \leq 0{,}001 \cdot A$

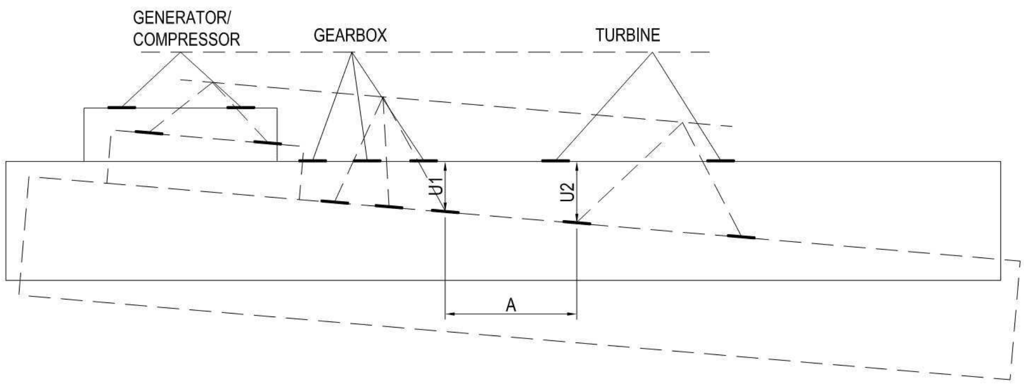
2.1.3 Live load deflections

Forces related to operation torque, external pipes, thermal forces etc. are not allowed to cause more vertical deflection than stated below (see also Figure 1):

- 0,5mm as total deflection for the whole foundation.

$U1 \le 0{,}5mm \qquad U2 \le 0{,}5mm$

- Between each component the embedded steel plates are not allowed to deflect more than 0,15mm/m.

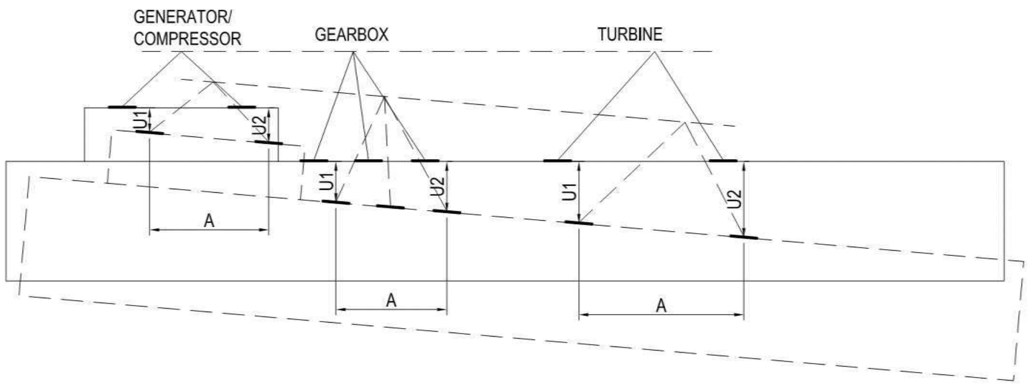


Reference: SIT AB/2016-02-22

Figure 2: Schematic view of deflection between two components

$U = U2 - U1$, $\frac{U}{A} \le 0{,}15 mm/m$ i.e. $U : A \le 0{,}15 : 1000$

- Two adjacent embedded steel plates (in axial or perpendicular direction of the driven equipment set) should not deflect more than 0,05mm/m relative to each other within each component.
  This requirement is not applicable for a three-point installed package, since it does not have adjacent steel plates.



Reference: SIT AB/2016-02-22

Figure 3: Schematic view of deflection within each component

$$U = U2 - U1 \quad \frac{U}{A} \leq 0{,}05mm/m \text{ i.e. } U : A \leq 0{,}05mm : 1000mm$$

2.1.4 Emergency load deflections and settlements

The deflection and settlements caused by emergency loads (driving and/or driven equipment failure) shall not exceed three times the values that could have been acceptable as corresponding live-load deflections and settlements.

2.1.5 Reinforcement

The structural design of the GT reinforced concrete foundation should be in accordance with valid standards and codes in the country where the equipment is installed. The engineer may use allowable stress methods for non-prestressed reinforced concrete.

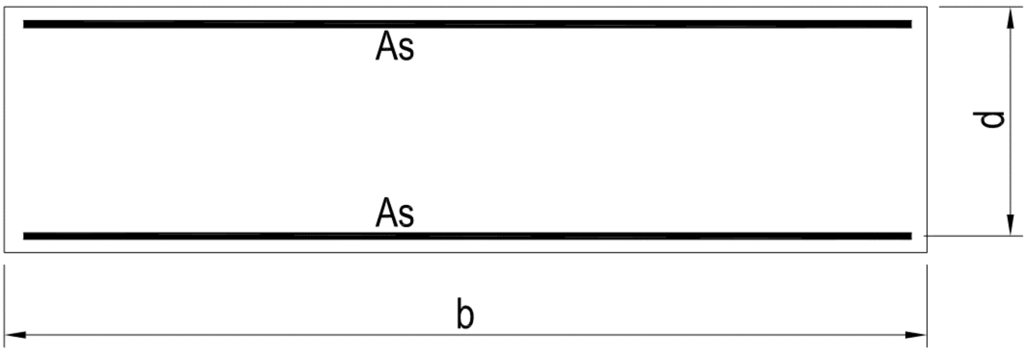
Cracking should be minimized to ensure protection of reinforcing steel. Therefore, minimum reinforcing steel shall be applied, if the reinforcement obtained with calculation is less than the minimum reinforcing steel suggested by the valid standards and codes. According to Eurocode 2, 1991-1-1, section 9.2.1.1 [5], the minimum cross section area of the primary reinforcement is:

$$A_{s,\min} = 0{,}26 \cdot \frac{f_{ctm}}{f_{yk}} \cdot b \cdot d \quad \text{(but not less than } 0{,}0013 \cdot b \cdot d\text{)}$$

f_{ctm} - is the mean value of axial tensile strength of concrete

f_{yk} - characteristic yield strength of reinforcement

The higher of the two $A_{s,\min}$ values shall be chosen, which are calculated in accordance with both, Eurocode 2 and the valid standards and codes concerning the country in which the equipment shall be installed.



Reference: SIT AB/2016-02-22

Figure 4: Cross section of the concrete block

The same primary reinforcement quantity shall be applied at the bottom and at the top of the concrete block.

2.2 Design of GT foundation with regards to the dynamic loads

The dynamic calculation of the GT foundation has the objective of assessing the vibration behavior of the machines and the surrounding.

For the vibration calculation the entire system (package, foundation and soil) is mapped by a computational model that takes into account the position of the application points of the excitation and of the system characteristics of mass, stiffness and damping. It should be so detailed that the vibration behavior of the entire system can be assessed with sufficient accuracy.

For this purpose Siemens, as machine supplier, provides foundation layouts and the applied masses (dead weights) on the foundation.

When designing the GT foundation, as a thumb rule, that the thickness of the concrete block can be assumed to L/15 to L/12, there L is the length of the concrete block. Another guideline is that the mass of the foundation is approximately 5 to 8 times of the machines which contain rotating masses.

In the following paragraphs: damping, the procedure for verification of sufficient vibration stability, the dynamic loads to be taken into account as well as the stipulated permissible limits to be maintained are described in further details.

2.2.1 Damping

Damping is a phenomenon of energy dissipation that opposes free vibrations of a system. Like the restoring forces, the damping forces oppose the motion, but the energy dissipated through damping cannot be recovered. A characteristic feature of damping forces is that they lag the displacement and are out of phase with the motion. The effect of damping in forced vibration reduces the amplitude but does not affect the frequency.

When no information about the damping characteristics of the machines and the concrete is available, the damping of the machines and the foundation together, suggested by DIN 4024 Part 1 (chapter 3.1) [4], can be assumed as 2% of the critical damping, under normal operating condition. The effect of damping may be neglected for free vibration analysis (calculation of the natural frequencies) but shall be considered for forced vibration analysis.

Additionally, the soil damping, estimated by the Geotechnical investigation, shall be also added to the entire system (package, foundation and soil).

2.2.2 Procedure

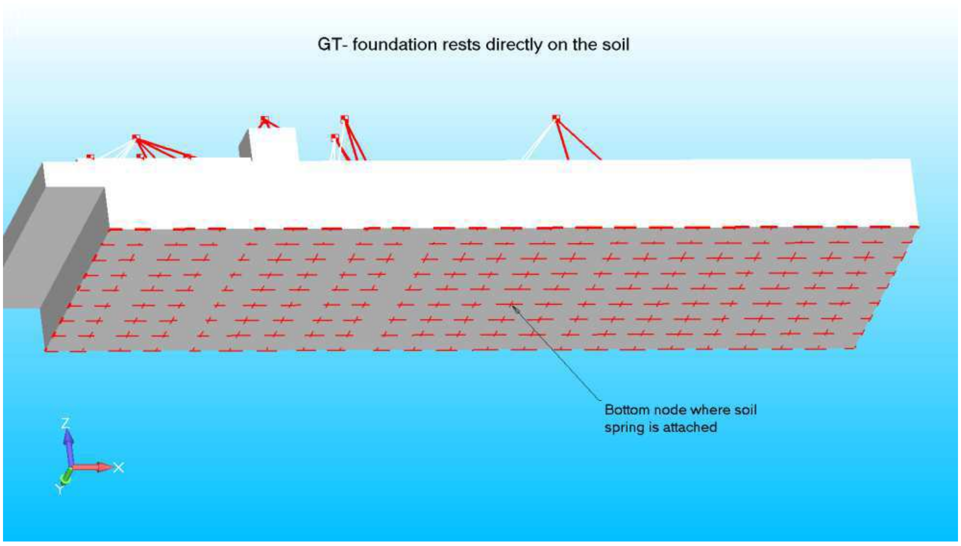
For verification of the vibration stability, first it shall be calculated the natural frequencies of the entire system (package, foundation and soil).

The machine parts are generally modelled with mass elements at adequate position, which are coupled with rigid beam elements to the foundation. The stiffening effect of the technological equipment shall not be considered in the analysis. The foundation is generally modelled with volume elements.

If the influence of the foundation subsoil is to be taken into account (GT foundation onto soil or piles), then the foundation subsoil resilience can be replaced by springs with soil stiffness and damping. If possible use frequency dependent soil stiffness and damping.

In that way the springs shall perform the function of the boundary elements for the entire system.

The static and dynamic properties of the soil are represented by springs and can be attached in nodes obtained by equally dividing the bottom plan.

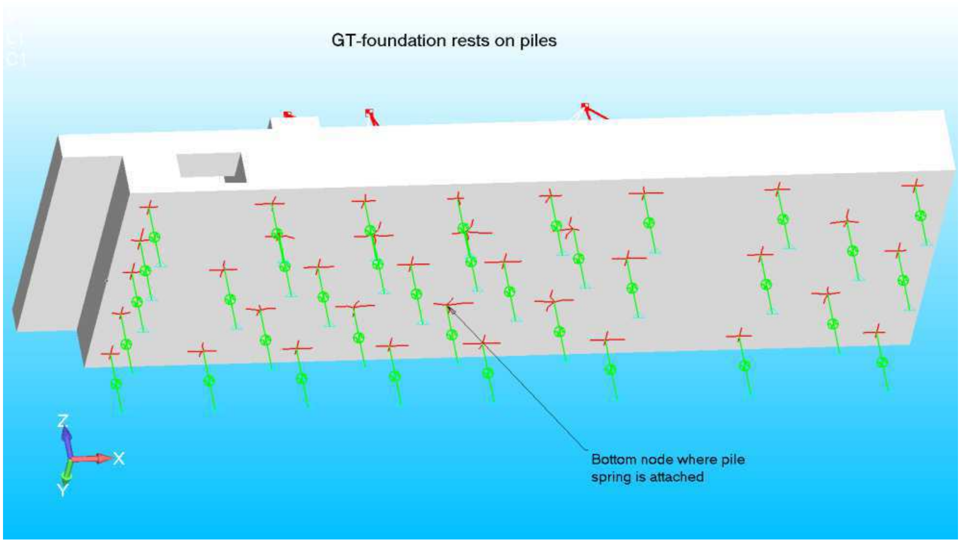


Reference: SIT AB/2016-02-22

Figure 5: Schematic view of a GT foundation which rests directly on the soil

As an example, within Figure 5 is shown the bottom of a GT foundation block with proposed nodes where the soil springs are attached. The number of the attached soil springs at the bottom of the concrete block shall be sufficient and in the judgment of the engineer.

If the soil properties are such that piles must be used, then the spring elements shall be attached there the piles are intended to be placed (see Figure 6). The number of the springs is equal to the designed number of piles. The spring shall contain dynamic properties for both, the pile and the soil.



Reference: SIT AB/2016-02-22

Figure 6: Schematic view of a GT foundation which rests on piles

The number of the natural frequencies and mode shapes to be determined must, in principle, be selected so that the maximum calculated natural frequency is at least 10 % higher than the highest exciter frequency.

When the natural frequencies have been determined, then it shall be verified their sufficient margin from the given exciting frequencies of the generator/compressor and the turbine in order to avoid major resonance effects.

The judgement of the dynamic behaviour of a machine foundation can be done by comparing its natural frequencies, f_n, with the operation frequencies of the machine, f_0. According to DIN 4024 Part 1 (5.3.2) [4], the first order natural frequencies shall be at least 25% above or 20% below the operating frequency, and the higher order natural frequencies shall be at least ±10% above/below the operating frequency:

- First order natural frequency

  $$f_1 \leq 0{,}8 \cdot f_0$$

  $$f_1 \geq 1{,}25 \cdot f_0$$

- Higher order natural frequency

  $$f_n \leq 0{,}9 \cdot f_0$$

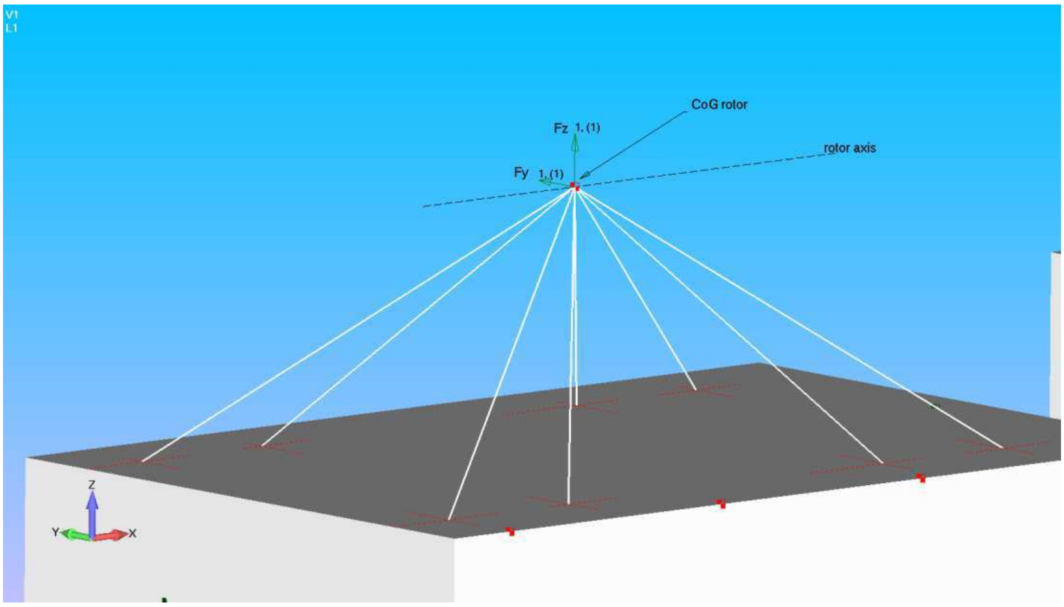
$$f_{n+1} \geq 1{,}1 \cdot f_0$$

This shall be checked for both operating speed of turbine and generator (or compressor).

However it is often impossible economically and technically to meet the above requirement. It is therefore recommended that a forced vibration analysis (Frequency/Harmonic response analysis) be performed on the entire system (package, foundation, soil) for determination of the vibration amplitudes.

2.2.3 Dynamic loads

Unbalanced forces in rotating machines are created during operation due to rotor unbalance, i.e. when the mass of the rotating part does not coincide with the center of rotation. These exciting (centrifugal) forces are assumed to be applied at the center of gravity of rotor (CoG), perpendicular to the rotor axis, as it shown with the figure below.



Reference: SIT AB/2016-02-22

Figure 7: Applied centrifugal forces at the CoG of the rotor, where the rigid body (white lines) has one independent node (CoG of the rotor mass) and eight dependent nodes (connection points to the foundation). This is also valid for a three-point supported package, but with only three dependent nodes.

The unbalanced forces from one rotating part at the CoG of the rotor are represented as a pair of forces with 90° phase shift, one horizontal force F_y and one vertical force F_z, acting at the corresponding operating frequency f_0.

According to ISO 1940-1 [3], the balance quality grade for turbines and generators shall be G=2,5mm/s. However, the increasing of the unbalance in the course of the operation has to be taken into account. Therefore, the balance quality grade is assumed to be one step worse i.e. G=6,3 instead of 2,5 (see DIN 4024 Part 1 [4], chapter 5.4.2).

Replacing angular speed with operation revolutions per minute gives centrifugal force:

$$F = \frac{m \cdot g \cdot n}{15000}$$

m → rotor mass [kg]

g → gravitational constant (g=9,81) [m/s2]

n → operation revolution per minute [RPM]

F → centrifugal force [N]

Let $F_{(f)}$ represents the unbalanced force for any rotor as a function of the frequency. The charting of this force shall be presented and applied in the analysis for the frequency range $0{,}85 f_0 \leq f \leq 1{,}2 f_0$, where f_0 is operating frequency.

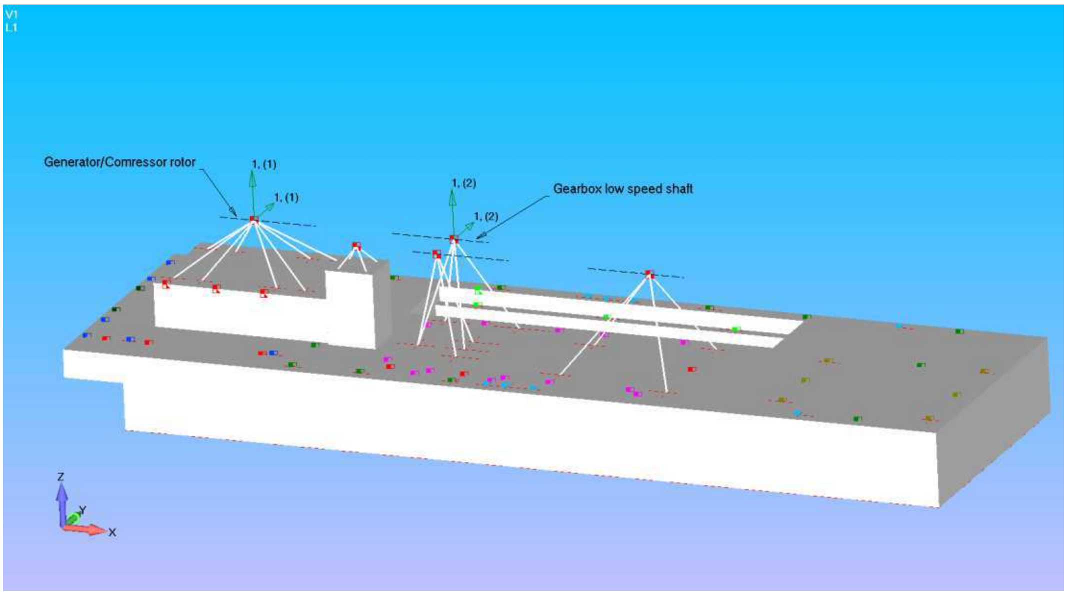
Generally, there are four exciters on the GT foundation:

- Generator rotor or compressor rotor
- If any, gearbox – low speed shaft (same revolution per minute as the generator rotor/compressor rotor)
- Turbine
- If any, gearbox – high speed shaft (same revolution per minute as the turbine)

Modal frequency response analysis can be used to determine a structure's response to harmonic (oscillatory) excitation where all forces at each forcing frequency (loading case) are known and defined within a frequency domain.

Since the generator rotor/compressor rotor and gearbox with low speed shaft has the same revolution per minute then their unbalanced forces can be applied in the same loading case (see Figure 8).

The low speed side is one rotor with generator and low speed gear wheel. Unbalance in the generator and gear wheel shall have the same phase (direction) and responses shall be added linearly. See Figure 8 for how the forces are applied to the foundation. The sum of the two excitation forces is the same as would result if the two rotor masses would have been added before calculation of *F* above.



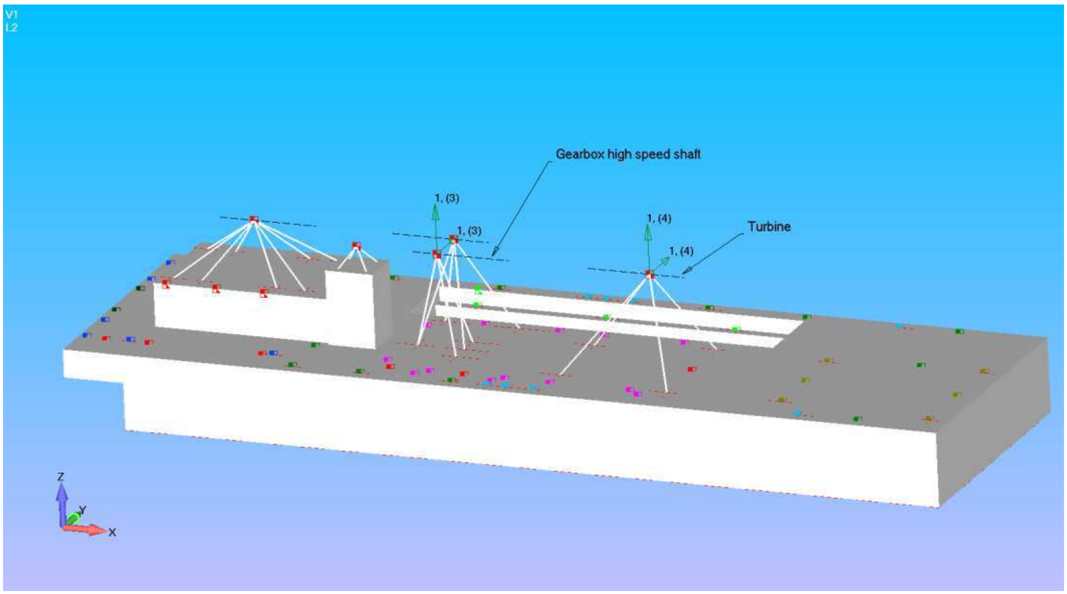
Reference: SIT AB/2016-02-22

Figure 8: Schematic view of applied unbalanced forces at generator/compressor and gearbox low speed shaft

Similarly, the unbalanced forces from the turbine and gearbox high speed shaft can be applied in another loading case since they have a same rotation speed (see Figure 9).

The high speed side with GT and high speed gear wheel shall be handled in the same way. It is one rotor with GT and high speed gear wheel. Unbalance in the GT and gear wheel shall have the same phase (direction) and responses shall be added linearly. See Figure 9 for how the forces are applied to the foundation.

If a compressor is driven with the same speed as the GT then the compressor shall be treated as the gear wheel above (added to the GT).



Reference: SIT AB/2016-02-22

Figure 9: Schematic view of applied unbalanced forces at turbine and gearbox high speed shaft

2.2.4 Vibration requirements

For the determination of the harmonic vibration amplitudes in the resonance case with modal frequency response analysis, the exciter forces recommended by Siemens shall be used with the exciter frequency at the associated load points in the dynamic model. The induced vibrations shall be determined at several points of the GT foundation for evaluation.

Loading cases on the foundation:

1) Generator/Compressor/ + if any, gearbox with low speed shaft
2) Turbine + if any, gearbox with high speed shaft (plus compressor if at same speed as turbine)

For the selected evaluation points of the foundation the vibration amplitude curve shall be calculated and presented versus the exciter frequency for frequency range $0{,}85 f_0 \le f \le 1{,}2 f_0$ i.e. *Amplitude vs. Frequency*.

$\{v_{i,x}\ ;\ v_{i,y}\ ;\ v_{i,z}\}$ → calculated all three space components (peak value) of the velocity vector for each loading case at several evaluation points of the GT foundation for the frequency range $0{,}85 f_0 \le f \le 1{,}2 f_0$

Use these data to calculate:

$$v_{x,RMS} = \frac{v_{x,peak}}{\sqrt{2}} \qquad v_{y,RMS} = \frac{v_{y,peak}}{\sqrt{2}} \qquad v_{z,RMS} = \frac{v_{z,peak}}{\sqrt{2}}$$

$$V_{RMS} = \sqrt{v_{x,RMS}{}^2 + v_{y,RMS}{}^2 + v_{z,RMS}{}^2}$$

The vibration velocity components resulting from one separate rotor string (unbalanced forces acting with same operating frequency f_0) within the frequency range $0{,}85 f_0 \le f \le 1{,}2 f_0$ shall, at no point within a radius of 1,0m of one machine support, exceed values corresponding to a mean effective velocity $V_{RMS} \le 1{,}0 mm/s$.

Exceptions from this can be accepted for start motor (in package configurations with start motor installed direct on foundation) that not is in continuous operation. If so, 1,8 mm/s is applicable.

For the rest of the GT foundation the total effective vibration velocity shall not exceed 1,8 mm/s.

These values on V_{RMS} indicate a trouble free operation and is based on achieving low vibrations in the machine bearings. Foundation vibrations shall be lower than bearing vibrations. For bearing vibration limits see ISO10816-1 [1] and ISO10816-4 [2].

3. Responsibilities

The commissioned civil engineer is responsible for the calculation of the GT foundation for strength, suitability for use and vibration stability.

The commissioned civil engineer has to ensure that the calculated deformations and vibration amplitudes are maintained under the stipulated permissible values stated by Siemens.

The loads and load cases indicated by Siemens are to be taken into account additionally to the loads from the applicable standards and codes. The commissioned civil engineer is responsible for the application of the valid standards and codes in the country where the equipment is installed.

4. References

[1] ISO 10816-1 Mechanical vibration – Evaluation of machine vibration by measurements on non-rotating parts - Part 1: General guidelines

[2] ISO 10816-4 Mechanical vibration – Evaluation of machine vibration by measurements on non-rotating parts - Part 4: Gas turbine sets with fluid-film bearings

[3] ISO 1940-1 Mechanical vibration – Balance quality requirements of rigid rotor

[4] DIN 4024 Machine foundations – Part 1: Flexible structures that support machines with rotating elements

[5] Eurocode 2. 1992-1-1 Design of concrete structure