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DIMENSIONING MACHINE STRUCTURE FOR EARTHQUAKE RESISTANCE IN DESIGN STAGE

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1. Introduction

In the course of the design of power plants and large chemical plants up to the middle of 20th century, the equipment has been designed and calculated taking into account standard and predictable loads (temperature, pressure, rotational speed, wind). Through the design of large fossil and nuclear power plants and large chemical and petrochemical plants, mechanical and electrical engineers have encountered the need to evaluate the construction regarding possible earthquake. Designers started to perform earthquake calculations as well, significantly improving knowledge about earthquakes and response of different structures and machines [Singh 1992].
Requirements on the safe operation of large plant equipment have became more strictduring the last several years. The designers are faced with the demands of continuous operation or slight damages of the equipment during excess situations, which include earthquake.
Gas turbines and steam turbines are mostly standardised products, which are installed in various locations in the world, and redesign to accommodate to local earthquake requirements can be expensive and time consuming.
However, earthquakes are partially random events, and there is no deterministic method, which fulfils all demands thoroughly.
National and international bureaus of standards in different countries of the world try to overcome these problems [UBC 1977], [EUROCODE 1994]. Because earthquakes are basically statistical events, buildings and plants are only statistically (probabilistically) safe to earthquakes. Risks of earthquake are classified for different constructions and purposes of construction, such as: apartments, workshops and office buildings, public buildings, and infrastructure constructions.
Most of the previously mentioned is the reason to design machines which would satisfy earthquake requirements of most locations over the world, but at the same time will not be too expensive to cover all the locations.
In this paper an optimal seismic intensity for calculations is proposed, as well as the method of earthquake response calculation of the machinery structure.

2. Methods used for calculation of structure response to earthquake

Gas and steam turbine parts are designed to retain required operational functionality, integrity, to be safe to human operator and the environment, taking into account loads due to normal operating conditions as well as in excess situations such as earthquake. Significant portion of excess situations is predictable and the designer can take into account their influence and magnitude during the design process. Examples of such events are: exceeding the pressure, temperature, rotational speed, and imbalance.
However, as already said in the introduction, earthquake is statistical event with several unknown characteristics :

- time of duration is unknown
- frequency content of earthquake movements is unknown
- direction of earthquake movements is unknown

Because of statistical nature of earthquake gathering the earthquake data improves quality of values but it is impossible to have deterministic earthquake data.

Regarding the required operational safety and functionality of the driving engine during the earthquake, design of structure has to satisfy increased load due to earthquake. There are three basic methods for calculation of earthquake response: statistical, deterministic and methods mixed of the two.

Mixed methods are included in national and international earthquake standards. Because no method is exact there is variety of methods which are approximate with some advantages and some disadvantages. The choice of the metod depends on the importance of the construction and available data.

2.1 Static methods

This is a fairly simple method. Structures can be considered as stiff if natural frequencies are above 33 Hz [Butković 2000] . Earthquake load can be considered as an additional static load

$$F_{ES} = C_S \cdot W = (D \cdot a_0) \cdot W \tag{1}$$

where :
F_{ES} = additional earthquake force in horizontal or vertical direction, (N)
C_S = seismic coefficient, (-)
W = weight of construction, (N)
D = risk factor (importance factor, safety factor etc.) for the structure, depending on the purpose and importance of the structure, (-)
a_0 = basic seismic acceleration (effective peak ground acceleration) for seismic region and site, in portion of gravity acceleration g , for horizontal or vertical direction, (-)

With additional seismic force strength of the structure is assessed as by usual static calculations.

2.2 Quasi static methods (QSM)

This method applies for structures with natural frequencies under 100 Hz [UBC 1977]

$$F_{EQS} = C_{QS} \cdot W = (D \cdot M \cdot a_0) \cdot W \tag{2}$$

where :
F_{EQS} = additional static force on the structure foundation or on the floors of the structure, (N)
C_{QS} = quasi static seismic coefficient, (-)
W = weight of construction, (N)
M = magnification factor which includes natural frequency of structure, its damping behaviour, ground characteristics and duration, (-)

Figure1. shows the magnification factors for elastic response of structure as a function of its natural frequencies according to preposition of Eurocode 8 [EUROCODE 1994]. There are other prepositions as well [ISO3010 1988]. Strength of the construction is calculated on the basis of equation (2) the same as if it would be statically loaded. Additional earthquake forces are calculated in one horizontal direction and one vertical direction with or without adding of forces as vectors.

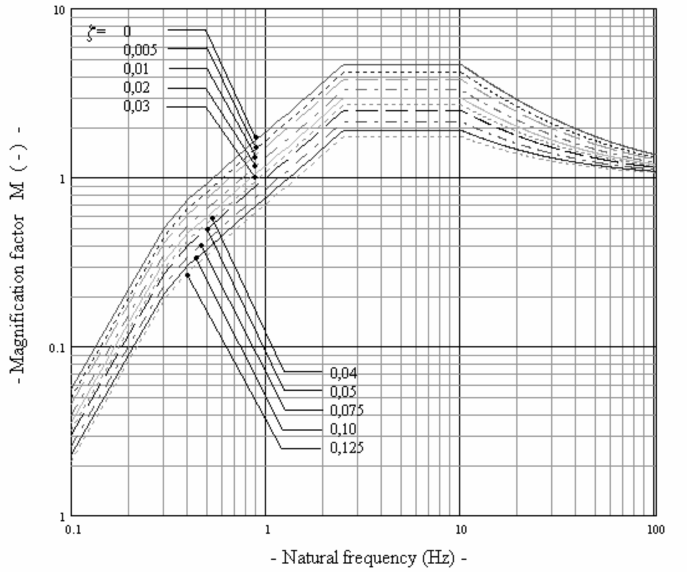

Figure 1. Equivalent magnification factor for linear response spectrum of structure for subsoil class A as a function of natural frequency and damping [EUROCODE 1994]

2.3 Dynamic methods

Two methods are commonly used. One is deterministic, where response is calculated and stresses and deformations are obtained from the exact time domain (time history) of one particular earthquake. Calculations can be linear or nonlinear [EUROCODE 1994]. Second approach is statistical where characteristics of the earthquake are random and response is being calculated. The problem with deterministic approach is that one particular oscilogram will never be exactly repeated in reality and one can not wait during the design process to obtain the histogram that will not repeat itself. This can be partially overcome using at least three to five different oscilograms [EUROCODE 1994] and applying the worst response. There is development of synthesized earthquakes in time domain [Bachmann 1995] which, for the same maximum acceleration, are much closer to worst earthquakes.

2.4 Quasi dynamic methods (QDM)

Quasi dynamic methods (QDM) are utilizing calculations of response to stationary (steady state) excitations. Quasi static methods have erroneous results mainly in positions of maximal stresses.
QDM is using two approaches to achieve correct response values:

- Increase of damping values to the equivalent ones which will give, in steady state conditions, the same response as transient excitation
- Decrease of acceleration excitations to the equivalent ones, which will give the same response as transient excitation for stationary state excitations

An advantage of QDM in comparison to dynamic method (DM) is simplicity of calculations and existance of vast quantity of data on spectral dynamic coefficient of magnifications of structures (response spectrum [Newmark 1976]). Third advantage of these methods is that the designer can design the structure, early in the design stage, that will satisfy earthquake requirements in over 90% of situations.
Proposed QDM uses the reduction of the response spectrum to calculate equivalent acceleration coefficients for calculation of stationary excitation of the structure.
Method can be explained on the system with one degree of freedom based on EUROCODE 8 [EUROCODE 1994].

$$a_{0_i\,red} = \frac{M_i}{Q_i} \cdot a_{0_i} = K_i \cdot a_{0_i} \tag{3}$$

where :

a_{0_i} = maximum value of ground acceleration, <u>for location and direction</u> ?? and "i" natural frequency - nonstationary, (ms^{-2})

$a_{0_i\,red}$ = reduced ground acceleration, for "i" natural frequency of structure – stationary, (ms^{-2})

M_i = magnification factor of spectral response of structure, for "i" natural frequency - nonstationary, (-)

Q_i = magnification factor, for "i" natural frequency – stationary, (-)

K_i = correction factor, for "i" natural frequency, (-)

Figure 2. shows the correction factors for earthquake excitation as a function of natural frequency of structure, damping and quality of ground (class A).
Correction diagrams are shown in frequency range from 0.1 to 100 Hz for which QDM can be applied. For QDM resonance response values are calculated using equation (3) and equations (1) and (2) are not needed.

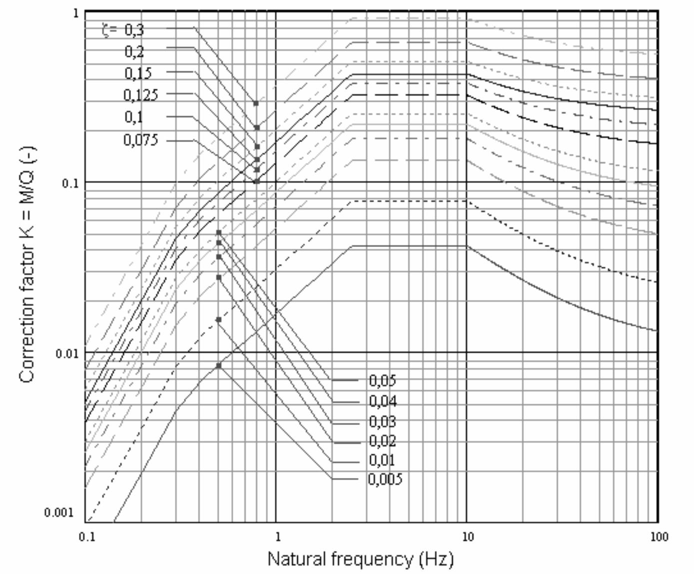

Figure 2. Correction factor for linear earthquake spectrum, for stationary response calculation, subsoil class A, for different natural frequencies and damping [Butković 2000]

If the structure has more than one natural frequency under 100 Hz , calculation (3) is performed for each natural frequency. Stresses for particular points are summerized using the method of effective stress

$$\sigma_{ef} = \sqrt{\Sigma\sigma^2{}_i} \tag{4}$$

This is valid for horizontal and vertical direction. For vertical direction 2/3 of horizontal excitation is used as a value.

3. Procedure for designers

When machine structure is designed by using design tools such as CATIA, PROENGINEER, Solid Works, AUTOCAD etc. natural frequencies of a structure have to be calculated upon some of codes in the range of frequencies from 0 to 100 Hz. If a structure has the first natural frequency under 5 or 10 Hz it is not necessary to calculate natural frequencies over 30 Hz. (response of a structure to the first natural frequency is most severe).

The next step is calculation of forced response calculation of structure using quasi dynamic method (QDM) of calculation (steady state response). Ground acceleration a_0 depends on site of installation, but this is not known in the design stage and it is recommended to use values of seismic zone 4 of UBC [UBC 1977] which gives $a_0 = 0.4 \cdot g$ in horizontal direction and $0.27 \cdot g$ in vertical direction.

Correction of acceleration (factor K_i), equation (3), has to be found based on EUROCODE 8 [EUROCODE 1994] for known damping factor of structure ζ and for ground quality A on Figure 2.

For overview of damping factors for various structures see Table 1. If values of ζ are not known, use ζ = 5%.

Table 1. Damping values for various structures and stresses

Nr.	Type and condition of structure		Damping rate ζ (*)	
			Stresses in the range of $0.5R_y$	Stresses in the range of yielding stress (R_y)
1	Vital pipelines		1÷2	2÷3
2	Welded steel structure		2÷3	5÷7
3	Reinforced concrete	without cracks	2÷3	7÷10
		with cracks	3÷5	7÷10
4	Prestressed concrete	normal	2÷3	
		with partial loss of prestress		5÷10
		with loss of prestress		7÷10
5	Steel structure connected with screws and rivets		5÷7	10÷15
6	Wooden construction	screw connected	5÷7	10÷15
		nail connected	5÷7	10÷20

Steady state forced vibrations are calculated for each natural frequency and stresses (Von Mises) and deformations are calculated using linear method. Sumation of earthquake stress for each excitation direction is performed according to (4). This additional stresses have to be added to the operational stresses and redesign of structure has to be perfomed, if necessary.

4. Examples

4.1 Redesign of gas turbine intake manifold due to the influence of an earthquake

Figure 3. shows a gas turbine air intake manifold designed with CAD software and calculated by finite element method package.

Natural frequencies are: f_1 = 3.07 Hz, f_2 = 10.5 Hz, f_3 = 14.6 Hz, etc.

QDM method of forced vibration calculation is used. The only calculations performed are those in horizontal x direction and for the first three natural frequencies.

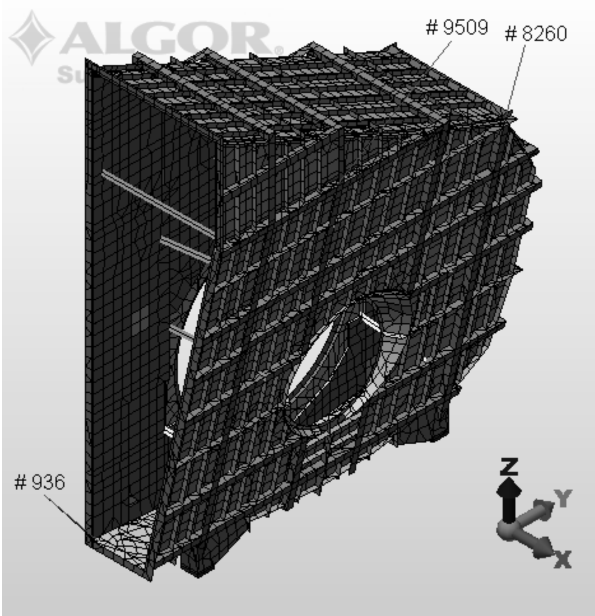

Figure 3. Gas turbine air intake manifold FEM mesh

Ground acceleration is 0.4g. Damping factor is $\zeta = 5\%$. Correction factors are: $K_1 = 0.25$, $K_2 = 0.245$, $K_3 = 0.2$ (see Figure 2.).

Results of the calculation are shown in Table 2. Highest stress is at node 8260, $\sigma_{QDM} = 85.9$ MPa. For comparison of the results obtained using QDM with time domain history calculation, a time domain diagram of the earthquake Taranaki [ATH 1997] has been analyzed using the same damping and maximum acceleration of $a_0 = 0.4 \cdot g$. Results are shown in the Table 2.

Table 2. Comparison of stresses in gas turbine air intake manifold excited with normed earthquake of 0.4g and calculated with quasi dynamic and time history methods

Node	First natural frequency 3.075 Hz			Second natural frequency 10.51 Hz			Third natural frequency 14.6 Hz		
	σ_{QDM} (MPa)	σ_{TH} (MPa)	$\frac{\sigma_{QDM}}{\sigma_{TH}}$ (-)	σ_{QDM} (MPa)	σ_{TH} (MPa)	$\frac{\sigma_{QDM}}{\sigma_{TH}}$ (-)	σ_{QDM} (MPa)	σ_{TH} (MPa)	$\frac{\sigma_{QDM}}{\sigma_{TH}}$ (-)
8260	85.5	95.0	0.90	2.1	3.3	0.63	7.8	1.1	6.4
9509	67.7	75.0	0.90	1.5	4.5	0.33	4.7	1.1	4.3
936	17.8	19.3	0.92	2.4	1.4	1.73	2.2	1.9	1.18

Node	Summ of stresses1		
	$\sqrt{\sum \sigma_{QDM}^2}$ (MPa)	$\sqrt{\sum \sigma_{TH}^2}$ (MPa)	$\frac{\sqrt{\sum \sigma_{QDM}^2}}{\sqrt{\sum \sigma_{TH}^2}}$ (-)
8260	85.9	95.1	0.90
9509	67.9	75.1	0.90
936	18.1	19.4	0.93

Maximum stress is also at the node 8260, $\sigma_{TH} = 95.1$ MPa, which is 10% higher than using QDM of calculation.
Strength of the structure has been calculated taking into account loads due to structure's own weight, operating underpressure and earthquake. Total stress according to the more conservative method is algebraic sum of the stresses due to structure's weight, underpressure and earthquake, which is 118.5 MPa (21+12+85.5) at the node # 8260.
Allowable stress, depending on the safety of calculation variables, is close to the yield strength of the matierial. In our case that is, due to the welding, 160 MPa. The calculation has shown that the redesign of the gas turbine air intake manifold is not needed.
In this case, however, forces acting on anchor screws were 450 kN which required an increase in the prestress of the screws in order to prevent detachment of the AIM foot from the ground, as well as changing the material of the anchor screws. This changes were incorporated into standard design of the gas turbine air intake manifold.

4.2 Redesign of Auxiliary Block

Figure 4.shows the part of the FEM model of an auxiliary block. Strength verification has been done by QDM.The model is subjected to the own dead weight of the block filled with oil and the earthquake conditions as in the chapter 4.1.
The maximum stress value is at the node #14 is $\sigma_{QDM} = 212$ MPa..This calculated stress is higher than alowable σ_{all} = 160 MPa and the supports have been strenghted by increasing the thickness of plates from 8 up to 10 mm. This changes were incorporated into standard design of the auxiliary block.

Figure 4. Auxiliary block FEM model

5. Conclusion

Taking into account more strict regulations regarding the operational safety of power plants, as well as shorter deadlines and reduced expenses of design and manufacturing, a method for calculating the load due to the earthquake acting on mechanical constructions have been proposed. Also the optimal earthquake level.,. The advantages of such approach for the design are the following:

- The accuracy of the method is satisfactory, deviation from more accurate methods is below 10%
- Propopsed earthquake level of 0.4 *g* satisfies 95% of site equipment over the world. Since the year 2000, when this method was first applied, none of site redesign in over 20 deliveries was required.

- Total expenses of design, manufacturing and assembly of machinery are lower then before the application of this method
- Application of QDM is simple for desingners, as it is shown in the flow chart in Figure 5.

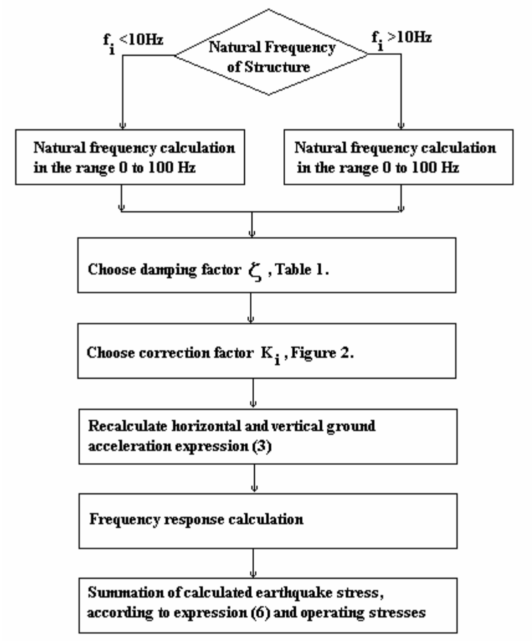

Figure 5. Flow chart of QDM application

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