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DAMPING OPTIMIZATION OF BASE ISOLATED COMPONENTS

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ABSTRACT

The design of mechanical and electrical components and systems in nuclear facilities is based on their dynamic response, exposed to load cases such as design basis earthquake (DBE) and airplane crash (APC). Base isolation of components by means of a spring-damper system is a common method to reduce the mechanical vibrations during operation as well as seismic and APC induced forces (JNES (2013)). It is generally accepted that higher damping is favorable because it reduces the dynamic response. However, in order to achieve redundancy in case a damper fails, in the design process of two currently build Main Control Rooms of nuclear power plants it has been neglected that in case of too high damping, the opposite effect occurs and further increase of damping leads to a coupling effect, annihalating the positive effects of the spring-damper system.

The focus of this work is to emphasize the negative effects of overdamping and to sensitize designers for damping optimization in order to achieve optimal effects of base isolation.

INTRODUCTION

Systems which implement base isolation are highly variable, ranging from low to high damping, pseudo-linear or completely non-linear behavior. The general principle is to modify the dynamic behavior of the base isolated structure in order to increase the level of tolerable DBE or APC loading. In the case of nuclear components design, the modification is meant to uncouple the main building’s modes from the internal components’ modes, to avoid resonance phenomena and preserve the safety-critical interior components even in the presence of exterior damage. As the eigenfrequencies of components generally range between 3 and 20Hz, the isolation systems are classically designed to shift the main horizontal building modes to the lower frequency range. This is achieved by introducing “soft” elements between the component and the ground, i.e. supporting slabs, the most classical of which are elastomeric rubber bearings.

The general objectives of base isolation systems are to:

- filter the dynamic excitation on the structure and modify the structure response to the excitation,
- decrease the response amplitude by addition of damping,
- cut off the acceleration amplitude transmitted to the structure by allowing free displacement above a certain threshold.

The effect of base isolation on the dynamic response of the component in relation to the free field excitation spectra is presented in Figure 1.

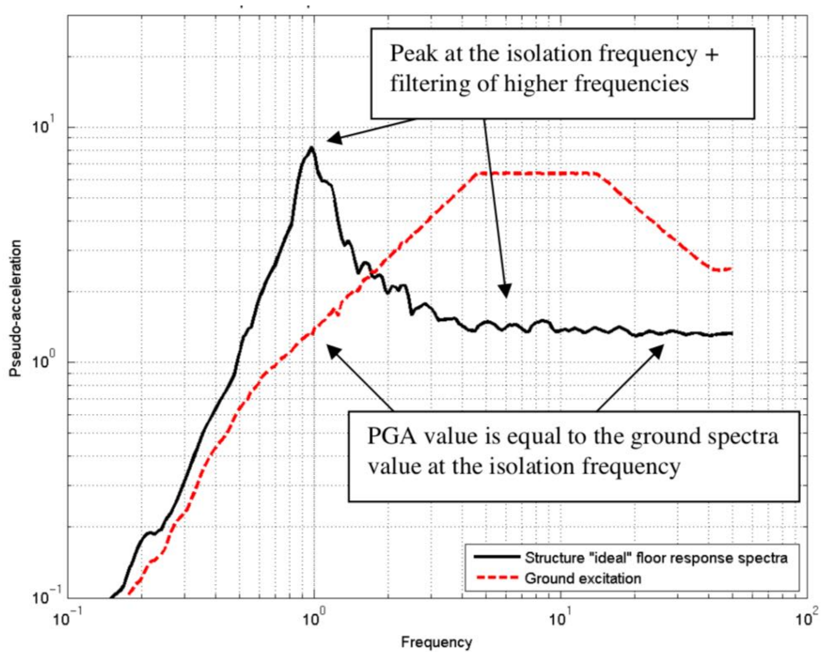

Figure 1: Effect of Base Isolation on the Dynamic Response in Relation to the Excitation

The comparison of the dynamic response in terms of response spectra of a base isolated and non-isolated component, given in Figure 2, shows the benefitial effects of base isolation.

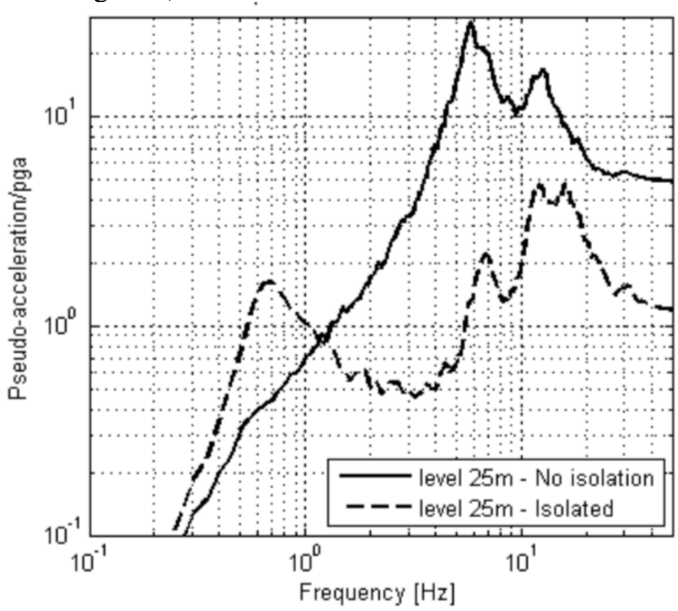

Figure 2: Comparison of Dynamic Response of Base Isolated Structure to Non-Isolated Structure

Although complex interaction effects between vertical and horizontal modes of a large, base-isolated structure - such as for example a fully base-isolated nuclear power plant - can occur, in most cases the base isolated structure is well approximated by an uncoupled, single-degree-of-freedom system. In other words, the motions in each direction mobilize a majority of the modal mass. For such cases, the principles of base isolation are evident from the fundamental equation of motion (1) for a damped free vibration of a single-degree-of-freedom system (Clough et al. (1993)):

$$\ddot{x}(t) + 2\lambda\omega\dot{x}(t) + \omega^2 x(t) = 0 \tag{1}$$

where $x(t)$ is the displacement as a function of time t, λ is the damping ratio and ω the circular frequency. Its closed-form solution is given by (2):

$$x(t) = e^{-\lambda\omega t}\rho\, cos(\omega_d\, t + \theta) \tag{2}$$

where:

$$\rho = \sqrt{x_o^2 + \left(\frac{\dot{x}_o^2 + x_o\lambda\omega}{\omega_d}\right)^2} \qquad \theta = -\left(\frac{\dot{x}_o + x_o\lambda\omega}{\omega_d x_o}\right) \qquad \omega_d = \omega\sqrt{1-\lambda^2} \tag{3}$$

From the closed form solution, illustrated in Figure 3, it can be observed that:

- With reduction of the damped circular frequency ω_d, the relative displacements $x(t)$ increases. If the base isolation is designed with very soft springs, reducing the circular frequency to near 0, the base-isolated structure will not move in the presence of external excitation; the soil, i.e. supporting structure is moving, while the component is uncoupled and thus will not move at all. However, relative displacements between the soil and the base isolated component will occur. This effect has to be taken into account for design of pipes and installations, connecting the interior components to the exterior environment.
- For small damping ratios $\lambda < 0.2$, the damped circular frequency ω_d can be assumed with negligible error to be equal to the undamped circular frequency ω.

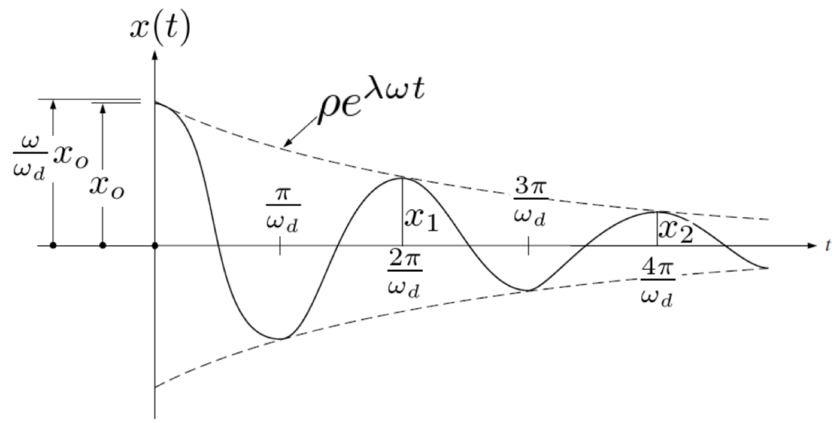

Figure 3: Closed Solution of Damped Single Degree of Freedom Vibration System

DAMPING OF BASE ISOLATED SYSTEMS

In general it is recognized that the increase of damping is favorable for the structural response of a system, exposed to dynamic excitation JNES (2013). For example, in order to prescribe conservative design, national regulatory commissions limit the damping ratio for the evaluation of the structural dynamic response in the case when soil-structure-interaction (SSI) is taken into account:

- US NRC (2007) limits the soil material damping ratio to be taken into account to 15%
- AFCEN (2015) limits the modal damping ratio to be taken into account to 30%
- KTA (2013) restricts the modal damping ratio to be taken into account to 15% in the horizontal and to 30% in the vertical direction

The motivation behind these upper limits in the design is the understanding that the dynamic response is generally more favorable in higher damping conditions in the context of SSI as such, these limits impose conservative conditions due to uncertainties of the soil parameters with the understanding that structures designed under the damping limits will be resistant in higher damping scenarios as well.

Based on the theoretical background of the beneficial influence of damping on the structural response and the limits of damping ratios to be used for SSI, it is often assumed that higher damping is beneficial as a matter of generality, irrespective of the scenario and in particular in the case of the design of base-isolated systems. Furthermore, due to the efforts to provide redundancy in the nuclear industry, base isolated structures are sometimes overdamped with the intention to provide additional safety barriers, if any of the dampers fail. This procedure is not always justified and can potentially lead to detrimental structural behaviour in the case of external dynamic excitations. This issue is examined in current work with the intention to emphasize the importance of the appropriate parameter selection in the design of base isolated systems.

SEISMIC EXCITATION

For the current study, the excitation is defined by the EUR (2017) free field spectrum for medium soil conditions and damping ratio of 5%, presented in Figure 4, scaled to a peak ground acceleration of 1g in the horizontal as well as vertical direction in order to correspond to the expected accelerations at the elevation level of the analyzed component within the building structure.

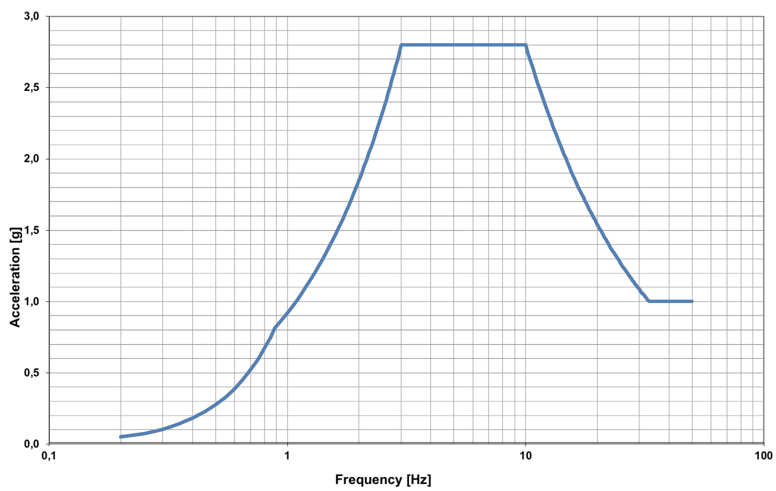

Figure 4: EUR Spectrum D=5 % for Medium Soil, Scaled to a PGA of 1,0 g

Using Code Aster (EDF 2018), spectrum-compatible and statisticallyindependent acceleration time histories with elevation phase of 2 s, strong motion phase of 8 s and total durationof 25 s, shown in Figure 5, are generated.

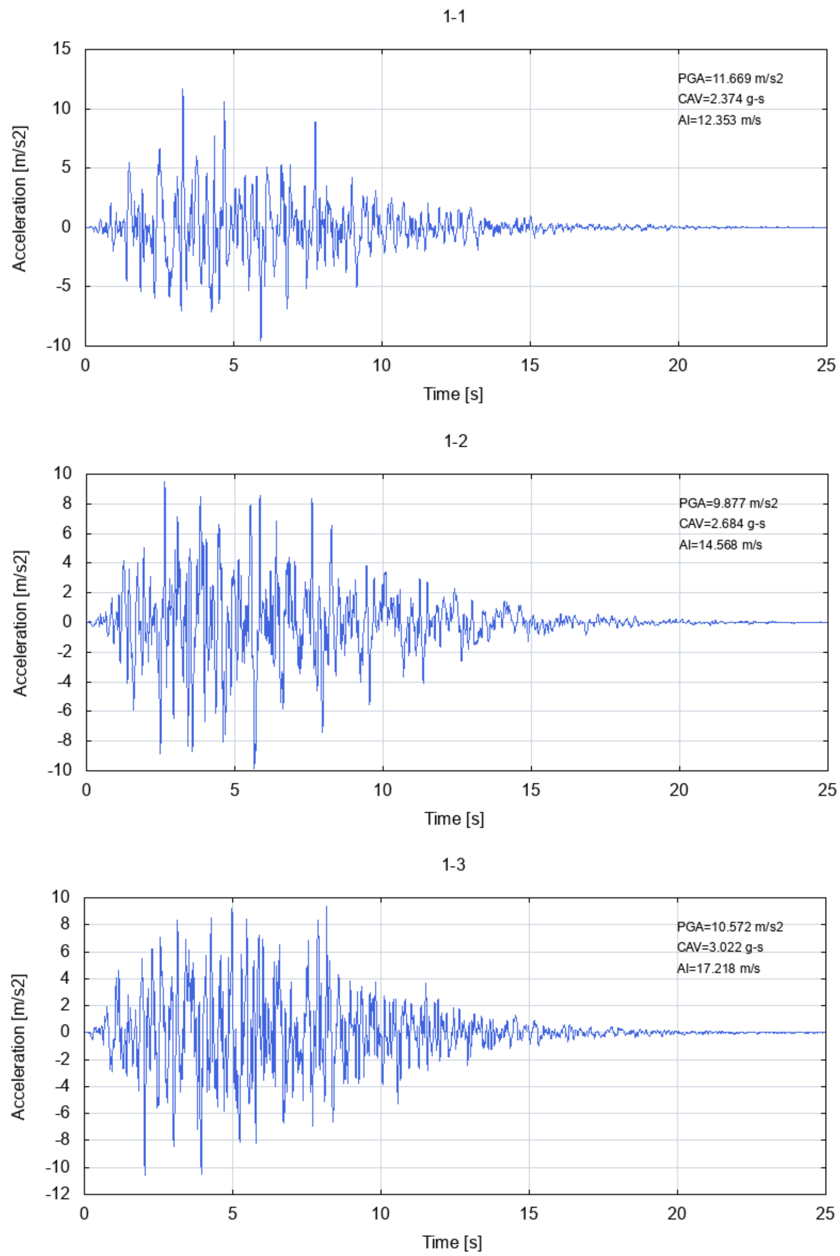

Figure 5: Spectrum-Compatible Excitation Time Histories for Directions X, Y and Z

GENERIC MAIN CONTROL ROOM (MCR)

The Main Control Room (MCR) of a nuclear power plant is considered to be one of the most sensitive components and is in most cases base isolated in order to reduce the induced vibrations due to an earthquake or airplane crash. In general, the reduction of the eigenfrequencies of the MCR leads to reduction of the accelerations within the MCR on one side but increase of the realtive displacements of the MCR in relation to the supporting slab on the other side. Therefor the design of the MCR base isolation should reduce the eigenfrequencies of the system up a a certain limit at which the relative displacements of the MCR to the support do not have negative impact on the installations connecting the MCR to the outer environment. A generic MCR, shown in Figure 6, made of steel profiles with a total mass of 149,8 t is used for the dynamic analyses.

The MCR is connected at 18 support locations to the supporting slab through springs, each with stiffness of 710,0 KN/m in the horizontal and 209,0 KN/m in the vertical direction. In addition to springs, dampers are used at support locations of the MCR. In this paper the number of springs with their stiffness values are kept constant, while the damping values are varied. The finite element model, presented in the current paper is generated using Salome Meca, while all calculations are performed with Code Aster (EDF (2018)).

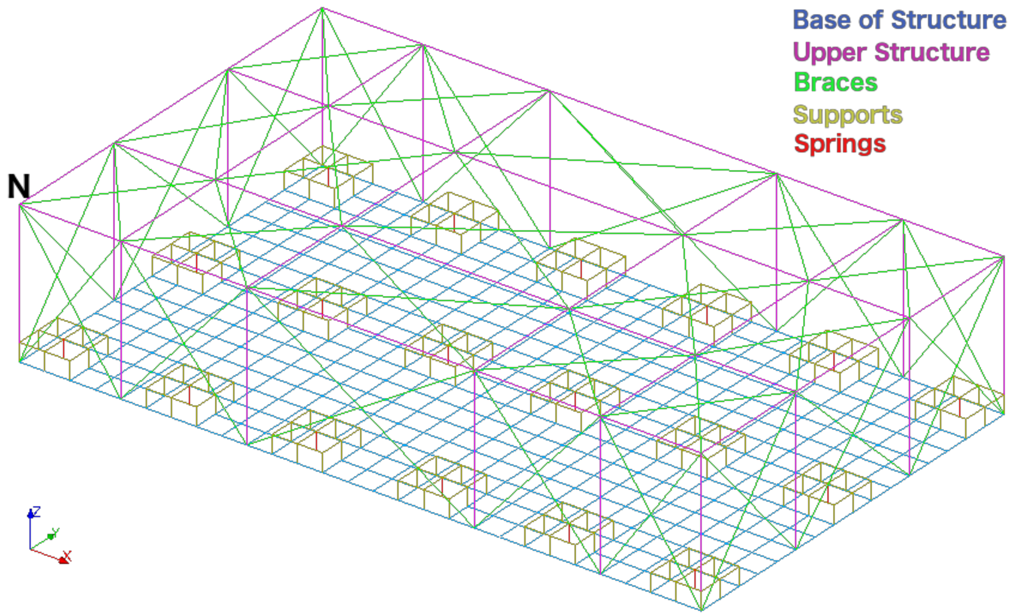

Figure 6: Finite Element Model of the Generic Main Control Room (MCR)

As a first step, a modal analysis is performed, assuming the MCR is not supported by springs and dampers but directly fixed. The results of the modal analysis of the fixed MCR are presented in Table 1. In the case of fixed connections, 260 modes up to 151,0629 Hz would be needed to reach modal mass mobilization of 90 % as required for example by US NRC (2007) and KTA (2013). As evident from the modal analysis of a fixed MCR, there is no global mode, but the modal mass distribution is due to local deformations of the MCR steel structure within a wide range of eigenvalues. Furthermore, the first eigenvalue is at 7,9273 Hz, corresponding to the plateau of the excitation free field spectrum, shown in Figure 4, thus resulting in maximum amplification of the excitation and unfavourble structural response of the MCR.

Table 1: Eigenvalues of Fixed MCR

Frequency [Hz]	Mobilized Modal Mass [%]		
	Dir. X	Dir. Y	Dir. Z
7,9273	0,00	0,00	4,19
13,8088	0,00	0,51	0,00
14,0566	0,00	0,00	0,58
17,0149	0,02	0,00	0,00
...	...	...	...
150,0231	0,23	0,00	0,27
150,6168	0,00	0,02	0,00
150,8704	0,00	0,06	0,00
151,0629	0,00	0,11	0,00

On the other hand, the results of the performed modal analysis with spring supports, presented in Table 2, show that the eigenvalues are completely uncoupled in directions X, Y and Z. The entire dynamic behaviour is influenced by the springs, connecting the MCR to the supporting slab, which leads to global indenpendent movements of the whole MCR like a rigid box in the X, Y and Z directions, i.e. local modes have no significant influence on the dynamic response of the MCR. A very important effect ist the movement of the eigenvaluesinto the lower frequency range, far away from the plateau of the free field excitatition spectrum, shown in Figure 4

Table 2: Eigenvalues of Spring Supported MCR

Frequency [Hz]	Mobilized Modal Mass [%]		
	Dir. X	Dir. Y	Dir. Z
1,4685	0,00	100,00	0,00
1,4692	100,00	0,00	0,00
2,5058	0,00	0,00	99,95

DYNAMIC RESPONSE OF THE MCR, EXPOSED TO SEISMIC EXCITATION

The preferred method for evaluation of the dynamic response of a component exposed to dynamic excitation is the modal superposition time history method due to its simplicity, effectivness and robustness. However, it has to be emphasized that this method assumes that the difference between the damped ω_d and undamped circular frequency ω of the system is negligible. In light of (3), for damping ratios of up to 20 %, the damping ratio has no significant influence on the angular frequency, but for higher damping ratios - as used for base isolation - the error introduced by the mode superposition time history method would not be acceptable.

Therefor the dynamic response of highly damped base isolated systems are evaluated using the direct integration time history method.

The most favorable stiffness and damping parameters have to be evaluated with a parametric study by variation of stiffness and damping parameters in order to estimate the optimal spring and damper values for which the dynamic response leads to minimal response spectra values on one hand and acceptable relative displacements on the other hand.

The number of spring elements to be used for base isolation depends on the number of supports, while the number of dampers can be less, depending on the total damping to be distributed, evaluated out of the parametric study. An example of a distribution of springs (marked with 1) and spring-dampers (marked with 2) is presented in Figure 7.

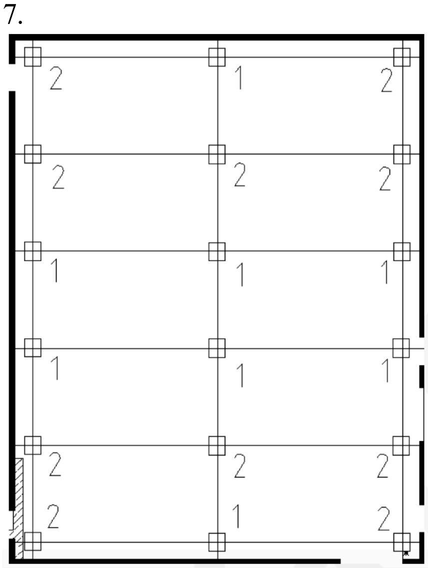

Figure 7: Possible Spring and Damper Distribution (Exemplary Sketch)

The spring values in the current study have been evaluated out of the conditions to shift the eigenfrequencies of the MCR as far as possible to the low frequency range on one side and not to exceed the allowed relative displacements of the MCR in relation to the supporting slab, limited by the deformation capabilities of pipes and installations. Variation of the damper values will be performed in order to estimate the most favorable damper values for optimum dynamic response of the MCR exposed to earthquake excitation.

PARAMETRIC STUDY ON VARIATION OF DAMPING PROPERTIES

In the current study the spring values are kept constant, while the damper values are varried. In total 6 case studies are performed with variation of the damper values in horizontal directions X,Y and vertical direction Z as presented in Table 3.

For each of the 6 case studies, the excitation time histories, shown in Figure 5, are applied as excitation on the supports of the MCR finite element model. Using the direct integration method, the dynamic response at node N (Figure 6) of the MCR is evaluated in terms of acceleration time histories in directions X, Y and Z. Out of these time histories, response spectra for damping ratio of 4 % are calculated. The results of the dynamic analyses are presented for directions X, Y and Z in Figure 8, Figure 9 and Figure 10 respectively. It is evident that for the horizontal direction the increase of damping ratio up to 46,4 % results in reduction of the dynamic response. For the dynamic response in vertical direction, ben efits of increased damping is evident up to a damping ratio of 57,6 %.

Table 3: Damper Values for Paramatric Study

Case	Direction	Damping Constant [KNs/m]	Damping Ratio [%]
1	Horizontal	214,0	7,7
	Vertical	152,0	3,2
2	Horizontal	642,0	23,2
	Vertical	456,0	9,6
3	Horizontal	1284,0	46,6
	Vertical	912,0	19,2
4	Horizontal	1926,0	69,6
	Vertical	1368,0	28,8
5	Horizontal	3852,0	139,2
	Vertical	2736,0	57,6
6	Horizontal	7704,0	278,4
	Vertical	5472,0	115,3

Further increase of the damping ratios above these limits results not in reduction of the response spectra, but in increased response spectra, which are moving towards the spectral shape of the excitation time history. The response spectra in horizontal direction for damping ratio of 69,6 % are exceeding the response spectra for damping ratio of 46,4 % and the response sepctra for damping ratios of 278,4 % are approaching the values of the excitation response spectrum. The same effect is also present for the vertical direction.

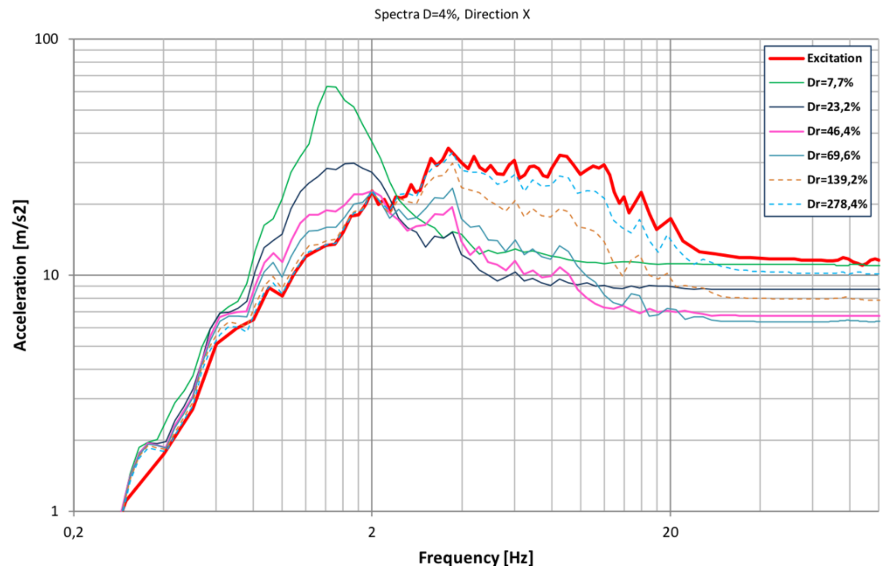

Figure 8: Response Spectra in Direction X for Damping Ratio 4 % and Varied Damper Values

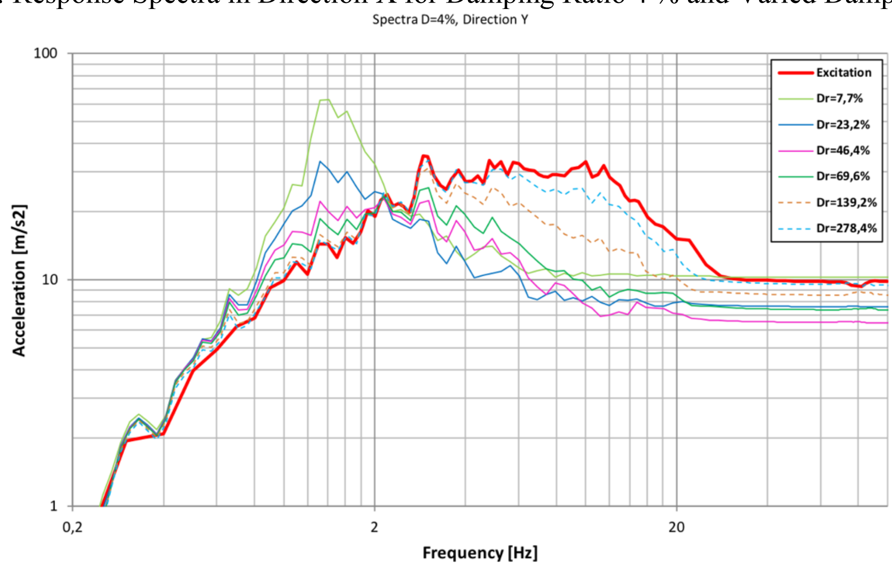

Figure 9: Response Spectra in Direction Y for Damping Ratio 4 % and Varied Damper Values

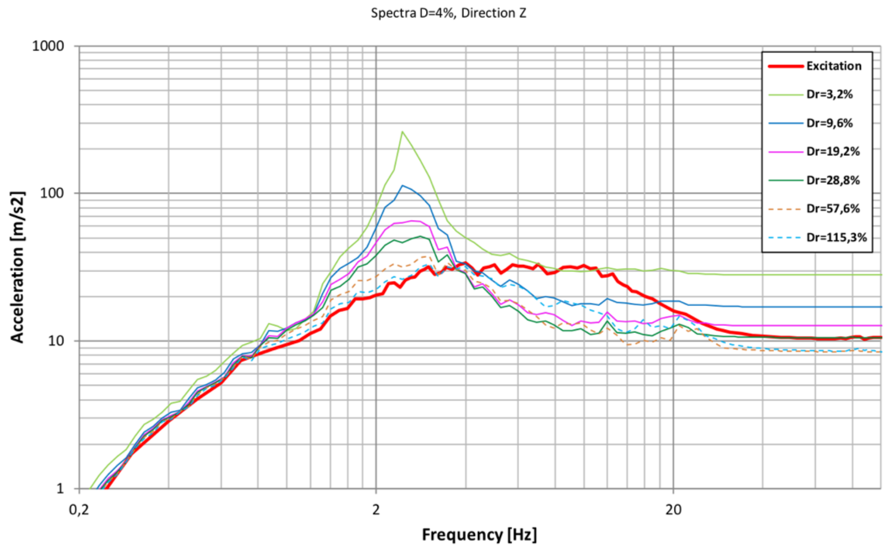

Figure 10: Response Spectra in Direction Z for Damping Ratio 4 % and Varied Damper Values

CONCLUSION

Out of the performed parametric study the following can be concluded:

- The direct integration method is preferrable for the evaluation of dynamic responses in highly damped structures since the approximate $\omega \approx \omega_d$ basis for the modal superposition time history method no longer holds in this scenario.
- The increase of damping reduces the dynamic response of the system up to a certain damping ratio.
- The benefitial effects of damping do not increase linearly. Higher damping does not always result in reduced dynamic response. The case of extreme overdamping leads to a dynamic response similar to the excitation, i.e. in case of extreme overdamping the structure will behave as a fixed system and will loose all benefits of the springs.
- The most favorable damping values have to be evaluated by a parametric study on a case by case basis; higher damping does not yield more favorable response spectra as a matter of generality.

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