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EVALUATION OF FLOOR RESPONSE SPECTRA BASED ON AMBIENT VIBRATION MEASUREMENTS

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ABSTRACT

In this paper, a new practical approach to generation of floor response spectra based on experimental definition of transfer functions of the structures performing ambient vibration measurement is presented. The measurements have been performed in June 2008, on several buildings at NPP Gentilly 2, Quebec, Canada. Some of the test results are presented in this paper. The transfer functions are calculated from the experimentally recorded Fourier amplitude spectra at the ground level and at the floor levels, according to the known relationships. The floor response spectra (FRS) are obtained as a product of considered ground response spectrum and corresponding floor transfer functions. The comparison between analytical and experimental FRS shows good agreement in respect to the dominant frequencies and peak amplitudes of acceleration, which confirm the correctness of the applied methodology. One of the conclusions is that the most important parameter for accurate definition of FRS is consideration of the base level in respect to which the transfer functions are calculated. Based on this study, more realistic FRS have been obtained when the ground surface was considered as a base level, rather then underground basement.

Introduction

The refurbishment of Gentilly 2 Nuclear Power Plant (NPP) required a generation of FRS based on the updated seismic requirements for the site where the power plant is located. The important increase of the site seismicity, prompted Hydro Quebec to verify the numerically generated FRS by using ambient vibration measurements of the existing buildings. The feasibility of this method was evaluated on a small scale test on the vibrating platform by the experts of IEEES in Skopje, Republic of Macedonia. The initial results were encouraging and the procedure was further developed and applied on all buildings of the NPP.

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The evaluation of FRS in common practice is based on time history seismic analysis, considering one or more ground acceleration time history records and calculating the floor acceleration response. Sometimes, synthetic time history of acceleration, representing a typical design ground response spectrum is used (Mahendra and Singh, 1975). This approach assumes direct integration of differential equation of motion or mode superposition of the considered important modes. For that purpose, definition of natural frequencies and mode shapes is required. Typical mathematical model used in this case is the “n” degree of freedom, “stick” model, i.e. lumped mass system linear, classically damped (Chaudhuri, Gupta , 2003).

The approach proposed by Mahendra and Singh (1975, 1991) referring to Biggs (1971), is based on generation of FRS directly from a given Ground Response Spectrum(GRS) having the Transfer Functions of the structures obtained from random excitation. This approach is based on assumption that earthquake motion can be modelled as a homogeneous random process.

The aim of this paper is to introduce the new approach for calculation of floor response spectra, based on experimental definition of transfer functions of the structures, performing ambient vibration measurements. The assumption is that micro-tremor vibrations produced by environment (wind, noise) represent a white noise. In that way, the FRS can be obtained as a product of a GRS considered for the site where the building is located and corresponding floor TF. The TF are calculated from the FAS recorded at the ground level and at each floor, according to the known relationships related to Cross Power spectra (CPS) and Auto Power Spectra (APS). The procedure for definition of FRS within the described approach is given below. The advantage of this approach is that dynamic characteristics of the structure (natural frequencies, mode shapes and damping) are not calculated but measured directly on the structure. Consequently, the transfer functions contain the influence not only of the structural characteristics but also of the other effects such as: soil-structure-interaction, damping, mass influence of the installed equipment etc.

Calculation of Transfer Functions and Floor Response Spectra based on ambient vibration measurements

If the signal is stationary steady-state signal (harmonic), the transfer functions for each floor can be obtained by dividing the FAS amplitude measured at the particular floor "j" ($FFASa_{ij}$) by the FAS amplitude measured at the base (ground) ($GFASa_{ig}$) expressed by the following equations:

$$H_{ij}(f_i) = FFASa_{ij}(f_i) / GFASa_{ig}(f_i) \tag{1a}$$

or

$$H_{ij}(T_i) = FFASa_{ij}(T_i) / GFASa_{ig}(T_i) \tag{1b}$$

where f_i is frequency (Hz) and T_i is period (sec).

If the signal is a random noise, the transfer function can be obtained by dividing the cross power spectrum (CPS) by auto-power spectrum(APS):

$$H_{ij}(f_i) = CPSa_{ij}a_{ig}(f_i) / APSa_{ig}a_{ig}(f_i) \tag{2}$$

where

$$CPSa_{ij}a_{ig}(f_i) = FFASa_{ij}(f_i)xGFAS^*a_{ig}(f_i)/n^2 \quad (3)$$

and

$$APSa_{ig}a_{ig}(f_i)=GFASa_{ig}(f_i)x\ GFAS^*a_{ig}(f_i)/n^2 \quad (4)$$

where $GFAS^*$ is complex conjugate Fourier Amplitude Spectrum of the ground.

To obtain floor response spectra(FRS), it is necessary to multiply the amplitudes of considered ground response spectra($GRSa_{ig}$) by the transfer functions of the particular floor (j), for the frequency (f_i) or period (T_i), considering the corresponding damping ratios of the floor response spectra (β_j) and of the ground response spectra β_g):

$$FRSa_{ij}(f_i,\beta_g,\beta_j) = GRSa_{ig}(f_i,\beta_g)^*H_{ij}(f_i,\beta_g,\beta_j) \quad (5)$$

Practical application of the above expressions is shown on the processed data in the next chapters.

The expressions given above are considered for numerical calculation of the FRS based on time history records of ambient noise. The software named SPECTRA, developed in IZIIS, is a GUI (graphical user interface) program based on MATLAB, for calculating and graphing, aimed at testing of ambient vibrations of different kind of structures. The program computes and plots Fourier Amplitude Spectra, Transfer Functions and Coherent Functions as well as Floor Response Spectra of recorded signals. The computations are based on input parameters specified by the user. All inputs are located in corresponding frames of a GUI window, and outputs are displayed as graphs and can be saved automatically in a word document file. The FAS amplitudes, TF, CF and FRS, are plotted in linear scales by default, but user may select plotting in logarithmic units, too.

The Transfer/Coherent function estimation in SPECTRA is based on periodogram - a classic non-parametric technique for spectral density estimation, so that estimation is done from the signal itself, and no assumptions on the signal are made. SPECTRA uses a modified version of the periodogram proposed by Welch (1967). Welch's method is an improvement on the standard periodogram method and Barlett's method in the sense of reducing the noise in the estimated power spectra. One can manipulate the input parameters in SPECTRA to obtain improved estimates relative to the Transfer function, especially when the SNR is low. The Transfer function estimates have been computed and compared with obtained Transfer Functions from Spectrum Analyzer 3582A. The best resemblance was achieved by the method proposed by Welch, without overlapping. Floor Response Spectra are obtained by multiplying the obtained Transfer Functions by the corresponding Base Response Spectrum. An interpolation on the Base Response Spectrum has been provided, so that the Base Response Spectrum is evaluated at the same frequencies as those obtained by the Transfer functions.

Example: Floor response spectra obtained from ambient vibration test on reactor building-Internal structure

The floor response spectra have been defined as a product between transfer functions and base response spectrum for corresponding frequency within the frequency range of 1-100 Hz. As a base response spectrum, the Gentilly 2 UHS 2008 Median was used (Fig.1). The plots are made in logarithmic scale for the frequency (x-axe) and linear scale of acceleration (y-axe).

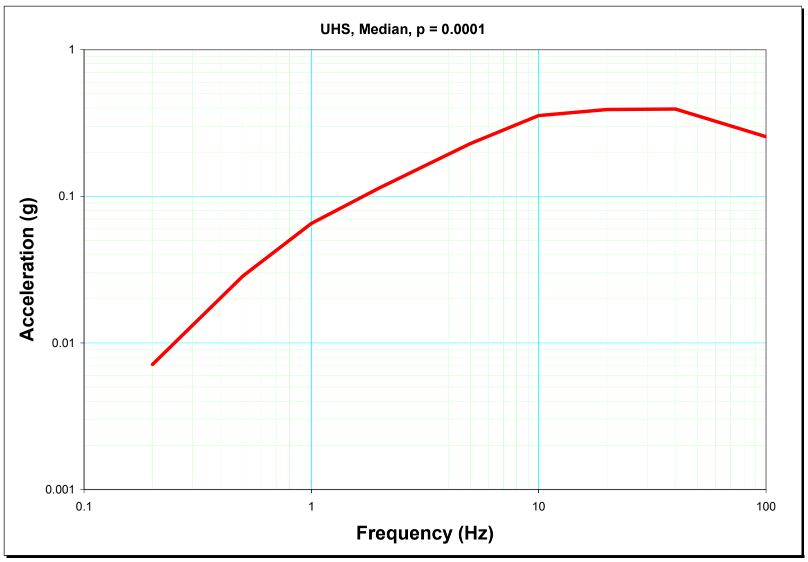
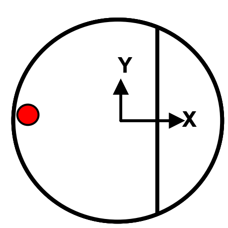


Figure 1. Uniform Hazard Spectra for NPP Gentilly 2.

For this building, 7 points have been measured. Two reference points have been selected: one at the base (level 3’6”) and one at the top (level 80’). The ambient vibration record at reference point at the base was used as a ground input, while the records at other measuring points as the floor responses. Dynamic calibration of the sensors was performed on level 54’. The measurements have been performed also at levels 23’6”, 49’6”, 41’3” and 64’. The location of measuring points (vertical line) is shown in Table 1 and Fig. 2.

Table 1. Position of measuring points.

Level	Point	Position in plan
Level 80'	TR	
Level 64'0"	T4	
Level 49'6"	T3	
Level 41'3"	T2	
Level 23'6"	T1	
Level 3'6"	TB	

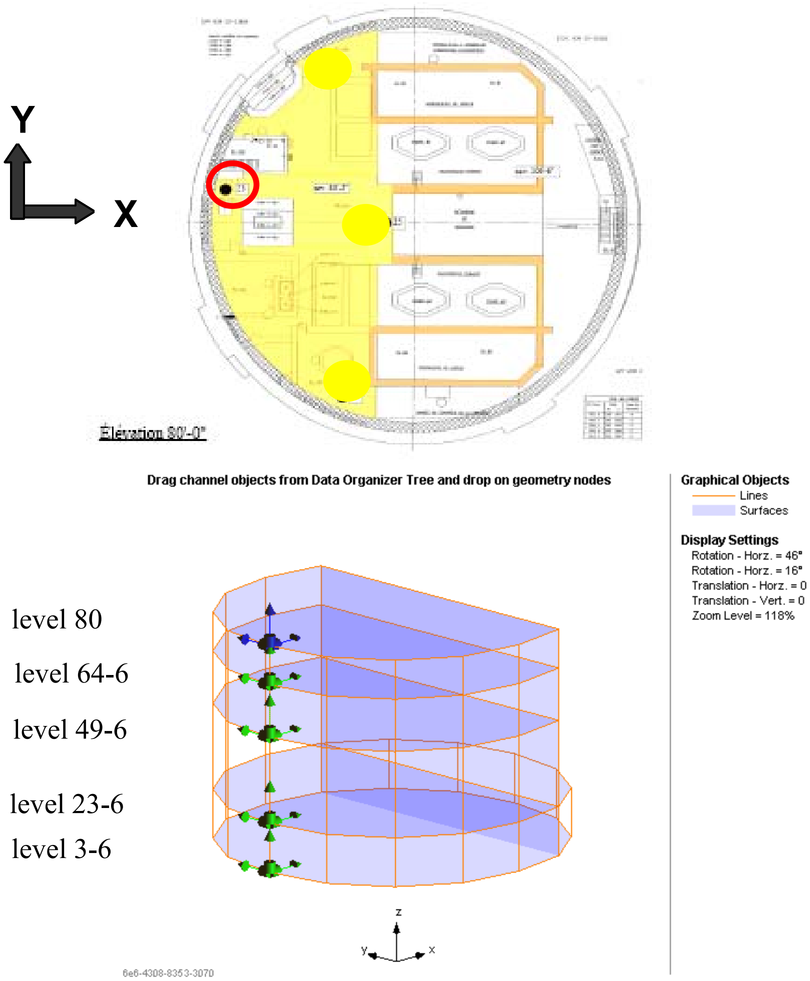


Figure 2. Reactor building-internal structure-location of the measuring points.

The ambient vibration measurements have been performed by Kinemetrics equipment, consisting of three three-axial force-balance accelerometers (epi-sensors ES-T) for the acceleration range of 0.25g, 12 channels digital recorder Model Granite and Compaq PC laptop computer. The data processing has been performed in several stages:

- Definition of natural frequencies, mode shapes and damping by graphical program ARTEMIS
- Plotting of the FAS, calculation and plotting of transfer functions for each floor level and each point at the floor, for three orthogonal components by SPECTRA software
- Calculation and plotting of floor response spectra for each floor level by the SPECTRA program for the given earthquake ground response spectrum.

Seismic analyses of the Gentilly 2 reactor building

The reactor building is analysed using the multi-physics software Abaqus. Hence, a detailed tridimensional finite element model is prepared for performing linear seismic analysis.

As shown by figure 3, this model includes both the internal structure and the containment. First, the finite element model is calibrated with the ambient vibration measurements, and the FRS are calculated from a modal transient dynamic procedure using time histories compatible with the median UHS for the Gentilly 2 site (Hydro-Québec, 2009) illustrated by Fig. 1. Details of the finite element model and model calibration are available in (Hydro-Québec, 2008).

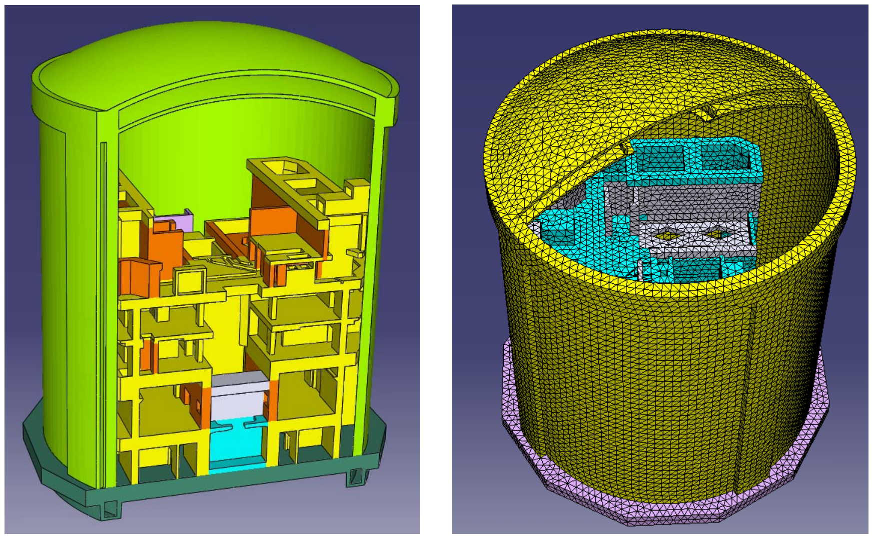


Figure 3. Finite element model for the reactor building.

Figs. 4-7 show the comparative Floor Response Spectra for the level 23-6, obtained for three orthogonal directions: E-W, N-S and V. The experimentally obtained FRS are presented by blue colour, while the numerically obtained FRS for different damping coefficients (1-10%) with different colours, as shown on the left top corner of the plots. The same manner of presentation is used for the other levels: 49-6, 64-6 and 80-9 (fig. 5-Fig. 7). The base level considered in the calculation was the level 3-6, which is 20' bellow the ground surface i.e. at the level of foundation plate of the reactor building. The comparison between analytical and experimental FRS shows good agreement for the damping coefficient 1-3 %. These damping coefficients are also defined from ambient vibration tests.

It should be pointed out that several factors can affect the correct evaluation of the FRS. From analytical point of view, the following factors are most important ones: correctness of the analytical model, consideration of soil-structure interaction effects, damping characteristics, natural frequencies and mode shapes, while from the experimental point of view, the factors such us: measuring conditions, noise disturbances produced by working vibrations of the machinery, averaging of the recording signal, duration of the recording signal, filtering procedure, smoothing of the spectra, elimination of the harmonics from the ambient vibration records etc.

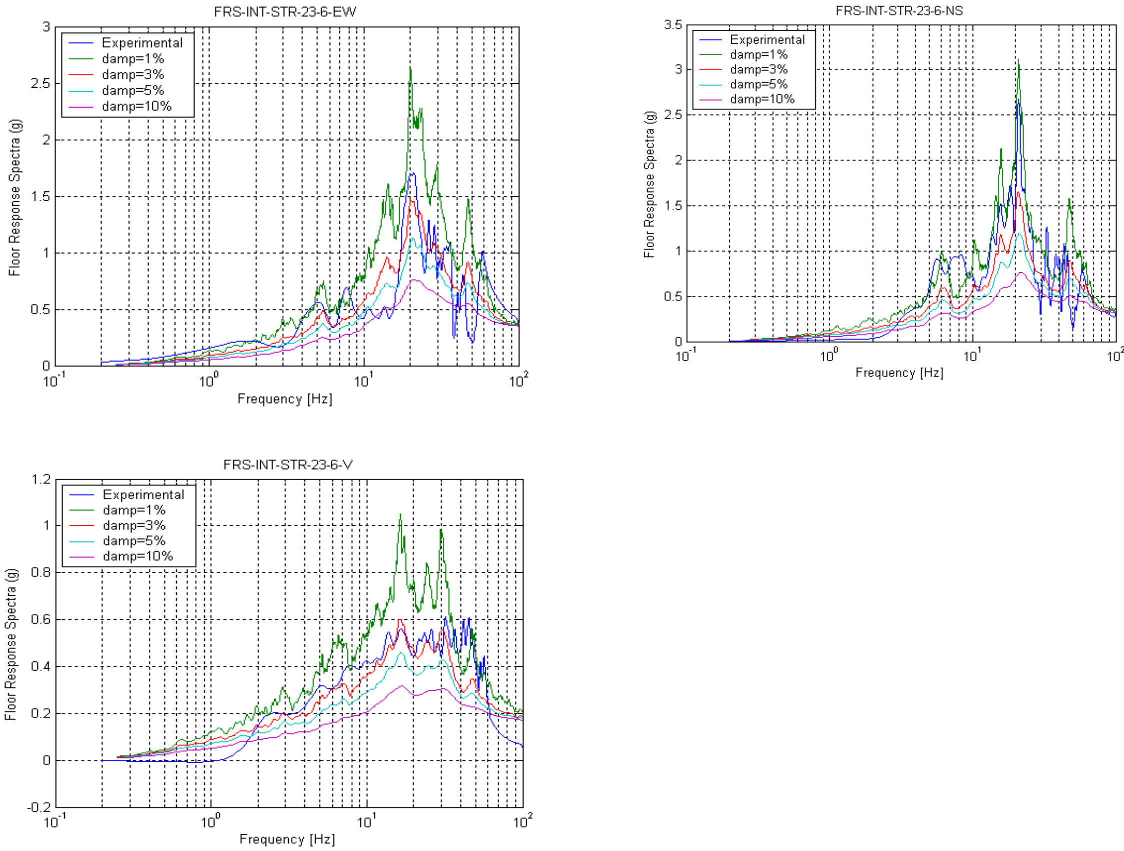


Figure 4. Comparative presentation of FRS for level 23-6, E-W, N-S and V direction.

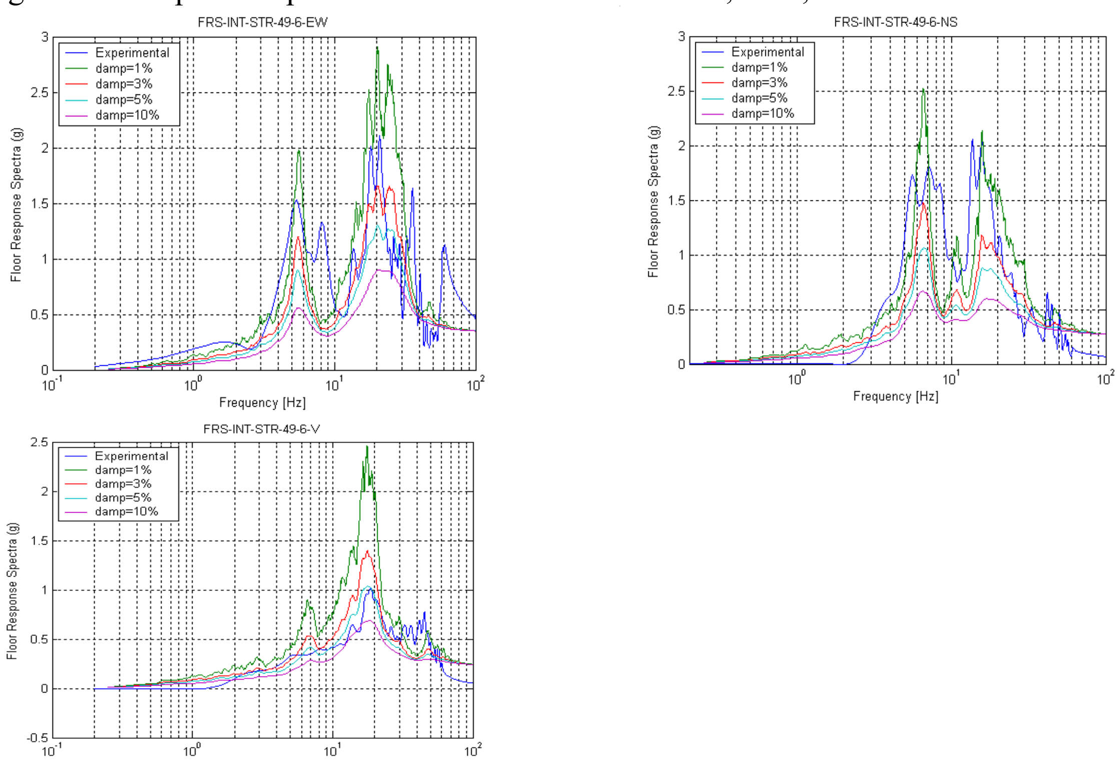


Figure 5. Comparative presentation of FRS for level 49-6, E-W,N-S and V direction.

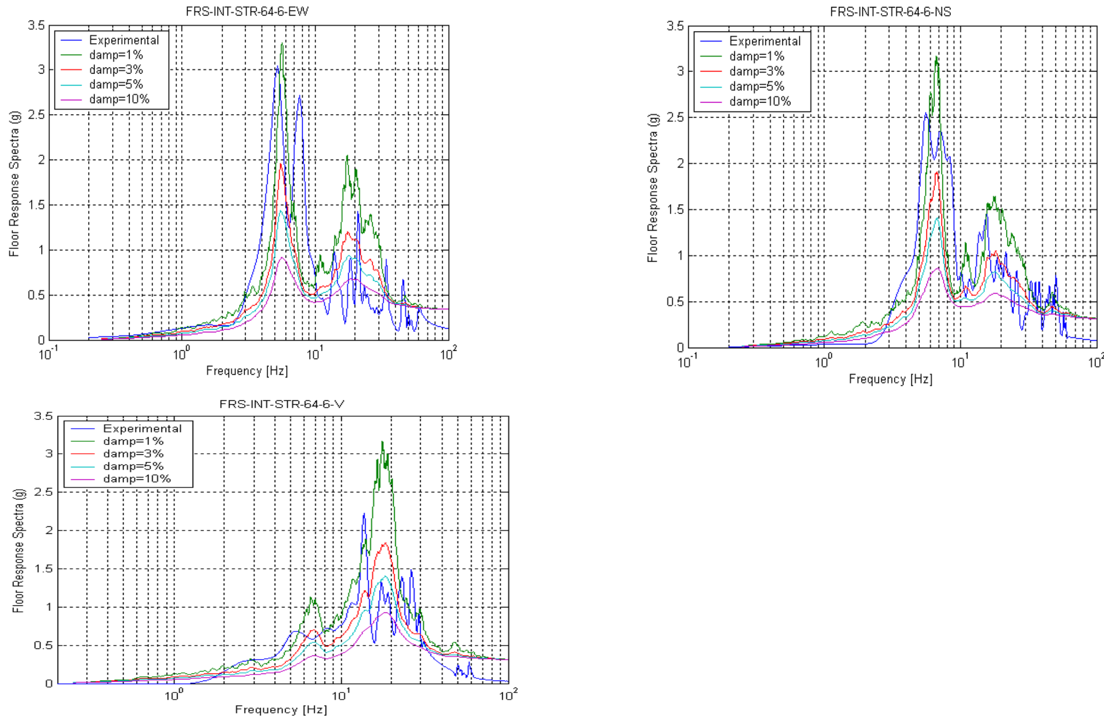


Figure 6. Comparative presentation of FRS for level 64-6, E-W, N-S and V direction.

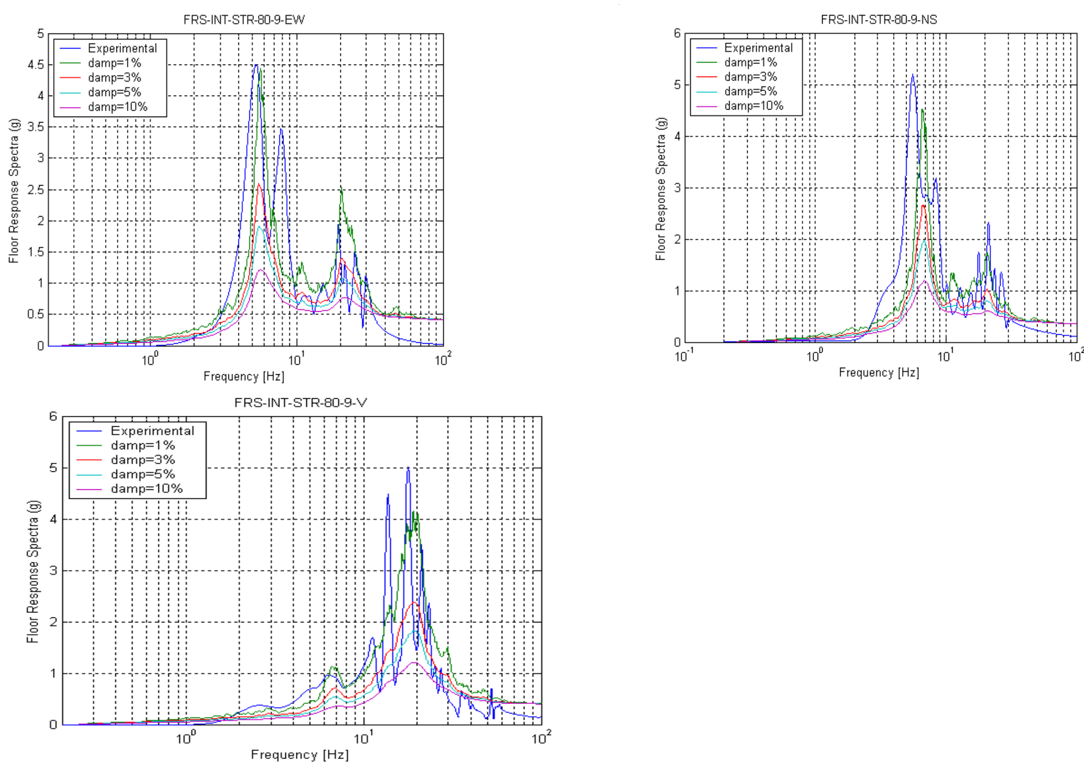


Figure 7. Comparative presentation of FRS for level 80-9, E-W, N-S and V direction.

Conclusions

The comparison between analytical and experimental response spectra shows good agreement in respect to the dominant frequencies and peak amplitudes of acceleration for the damping coefficient 1-3 %, which confirms the correctness of the applied methodology for definition of floor response spectra from ambient vibration tests. In order to upgrade the compatibility of the analytical and experimental FRS, some estimation of damping factors should be performed, as well as filtering of harmonic disturbances in the experimental FRS produced by the working of the machines during ambient vibration measurements. Upgrading of the numerical models should be performed too, regarding the compatibility of calculated natural frequencies with experimentally defined, as well as number of modes considered in the analysis. One of the most important parameter for accurate definition of FRS is consideration of the base level in respect to which the TF and FRS are calculated. Based on this study, more realistic FRS have been obtained when the ground surface was considered as a base level, rather then underground basement. This original and very new experimental approach should be established in the future practice in order to calibrate the numerical approach and to upgrade the experimental one.

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