Analysis of seismic response on the excitation of support structures

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ABSTRACT

Improving the safety of nuclear power plants requires seismic testing of key components. Ever increasing demands on components, devices, and machinery within nuclear power plants, necessitates testing with more extreme loading conditions at low frequencies of vibration. Frequency and modal analyses are very powerful tools for determining excessive or harmful vibration. The goal of the paper is, by means of frequency and modal analyses, to compare the operational frequency spectrum with the Eigen frequencies of an existing support structure. After a suitable measurement point is selected, a frequency analysis is performed and the main sources of vibration are detected. Modal analysis is performed by simulation and measurement. The excitation was generated by a low frequency shake table (up to 100 Hz) capable of generating random and deterministic signals. The Eigen values of the tested structure were compared with the Eigen values obtained by Finite Element Analysis (FEA) of the support structure as well as the response (displacement). For the detection of low frequency waves resulting from vibrating sources, the Fast Fourier Transform (FFT) and modal analysis, in the frequency domain, was used.

Keywords: Seismic waves, Nuclear power, Devices, Safety I-INCE Classification of Subjects Number(s): 42; 49.2; 75.6

1. INTRODUCTION

The response of industrial structures greatly depends on the excitation, whether from earth quake, dynamic shocks, and/or low frequency vibration (technological seismicity) as well as operating conditions of surrounding structures, which effect the conditions of the measured data. Sources from earth quakes are large in magnitude (seismic energy) compared to those generated from human activity. They can cause damage over large distances due to their characteristically low frequency and high energy secondary waves (6). In other words, for the same parameter (i.e. oscillation speed of the measured element), the effects on the system vary. Therefore, seismic measurements are affected by the source of dynamic excitation (frequency), duration and amplitude. The source of the low frequency vibration may be from earth quakes or human activity – technological seismicity (4) which is deterministic in nature i.e. rotational machine systems installed on industrial support structures or within their vicinity (1). This is especially true for nuclear power plants and its many sensitive components where any significant shock (5, 6, 8), vibration from operating conditions (7, 10, 11), transport, or construction activity, can act as a source of unwanted excitation which can have a negative effect on mechanical, electrical, and structural elements.

2. GOALS, INSTRUMENTATION AND METHODOLOGY

2.1 Goal and Object of the Study

The goals of the study were to investigate the response of deterministic and random excitation on a support structure typically implemented in nuclear power stations. A model of the structure was then constructed and simulated under similar conditions to the measurement and the simulated frequency analysis was compared to the measured frequency spectrum and Eigen modes of the support structure.

Figure 1a shows the support structure model, points of measurement, and excitation direction (1).

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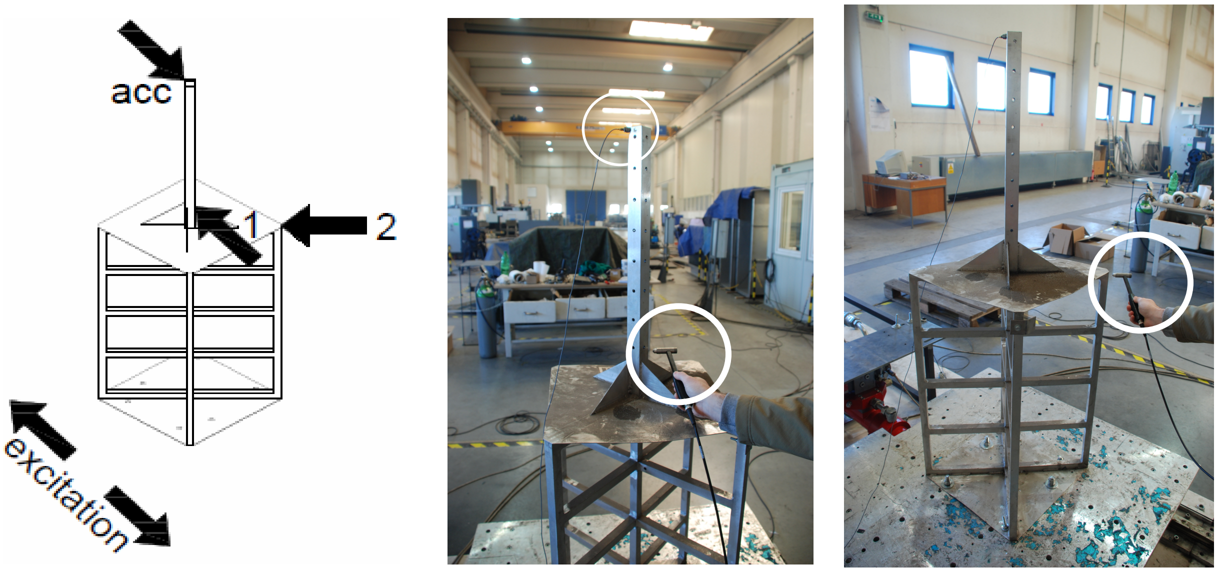
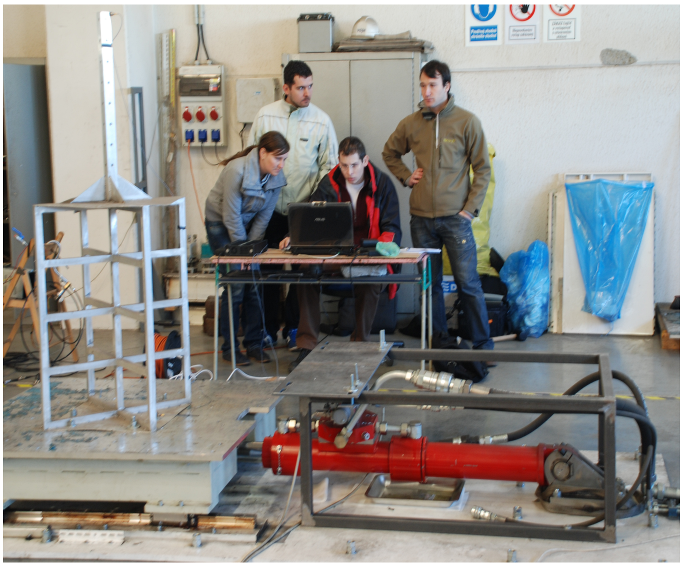
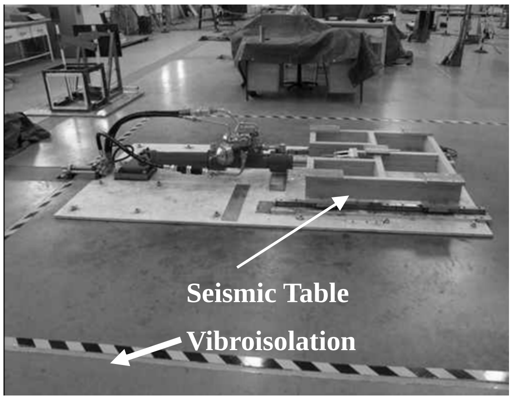
The structure response is first measured using a impact (modal) hammer applied at two different points on the support structure (Fig. 1b). The structure was also subject to horizontal excitation by means of a seismic shake table which generated a deterministic and random low frequency signal (Fig. 2). The base of the support structure was mounted to the seismic table and a second accelerometer was fixed at this base.



a) b)

Figure 1 – a) Isometric representation of the support structure, sensor placement and direction of excitation: 1 first excitation point for modal analysis; 2 second excitation point; b) Actual points of excitation and response measurements





Single axis horizontal seismic shake table with hydraulic cylinder:
± 200 mm – piston stroke;
500 kg – max. mass;
± 25g – acceleration.

Figure 2 – Support structure mounted on a single axis seismic table generating deterministic and natural seismic signals

2.2 Instrumentation and Methodology

Measurement of the deterministic and random seismic signals on the shake table and resulting response on the support structure were performed using the frequency analyzer PULSE, Dyn-X, FFT, M1 3560-B-X10 BRUEL and KJAER platform. This portable analyzer represents a system, which guarantees a reliable measurement process, analysis, and signal evaluation. Parts of this system are an impact hammer PCB 086C03, piezoelectric accelerometer with frequency range from 1 Hz to 10 kHz (at amplitude ± 10 %), display and memory module. To identify the energy dominant natural frequencies more precisely, the fast Fourier transform (FFT) was carried out using the PULSE frequency analyser. The methodology presented in the article can be applied also for other sources of very low frequency vibration. The vibration of the seismic signals and the corresponding support structure response to this signal was measurement in the excitation direction.

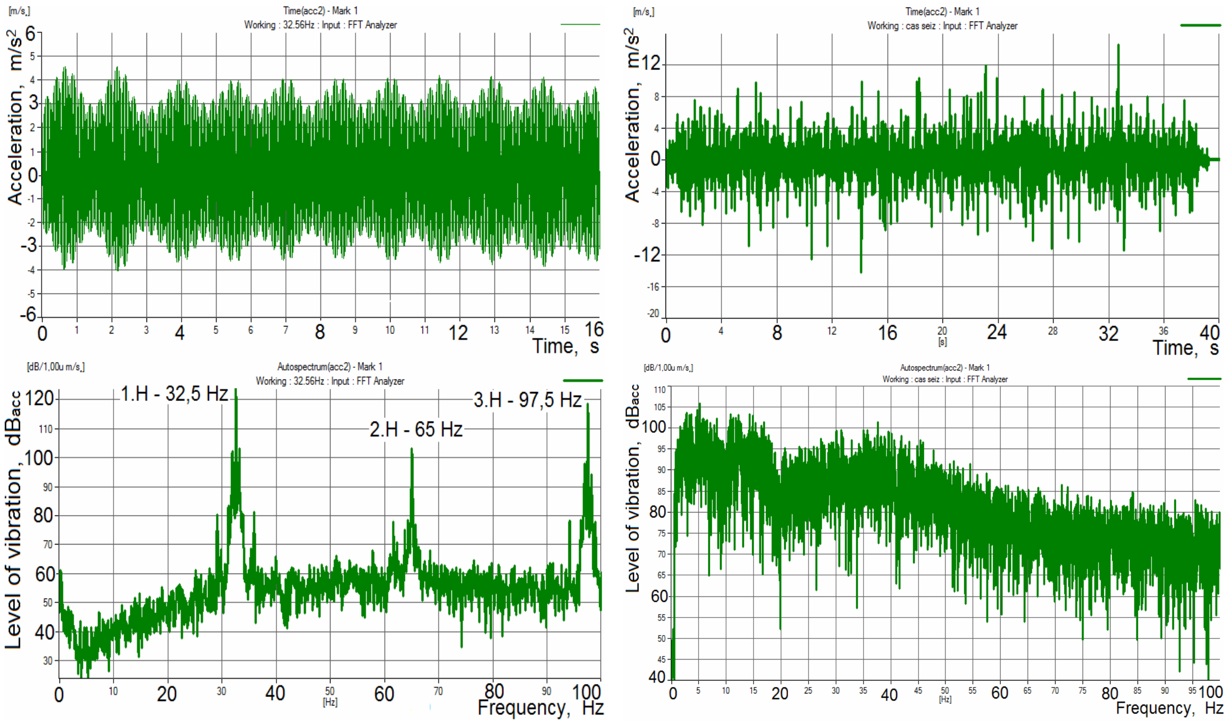
The sensor was mounted on the support structure according to ISO 5348 standard for accelerometers as well as past experience (2). The goal is to ensure that the sensor correctly reproduces the motion of the support structure element or base without interfering with the response of the structure. The upper most point of the support structure was selected as a suitable response element (see Fig. 1b).

The measurement device and its technical parameters were calibrated before measurements (3). Other than the frequency range, for the type of signal, it is also very important to select the appropriate averaging method as well as the number of averages per unit time. Furthermore, a suitable time window must also be selected (12). Modal analysis used the following time windows: averaging for six peak values of the frequency spectrum, exponential for accelerometer signal, and transient for impact hammer. The frequency analysis of the deterministic and random seismic signals used the Hanning time window. The time interval of the seismic signal is the basis for determining the strength of the vibration, since this energy parameter is used to evaluate the effect of the seismic event on the support structure. The measurements devices were isolated against any external disturbances (see Fig. 2).

Throughout the measurements, other essential variables were recorded that assisted in the frequency analysis, identification of measurement points and their corresponding frequency spectra, such as possible unique effects during the response measurements (random impacts and shocks and low frequency vibration caused by human activities in the surrounding areas). Such unique events, which can impact the correctness of the results, are an essential part of seismic measurements. FFT analysis was used to identify the amplitude of high energy frequency components in the measurements.

2.3 Applying Signals

For the force excitation of the support structure two types of signals were used. Deterministic signal from 0 to 100 Hz, and a random signal from 0 to approximately 40 Hz (normative IEC 60068-2-6). The random signal represents a real seismic event. Signal measurements and the corresponding frequency spectrum can be seen in Figure 3. These signals were taken from the base of the support structure (bottom sensor in Fig. 2).



a) b)

Figure 3 – a) Deterministic excitation signal, first Eigen frequency and harmonics; b) Real seismic excitation signal and its frequency spectrum

The second a third harmonic of the first Eigen frequency most likely represents loose clearances or sliding constraints of the seismic shake table while the first and third correspond to the Eigen frequencies of the Eigen modes (first are identical and third harmonic is approximately identical with fourth Eigen frequency). The frequency spectrum of the seismic signal represents the distribution of seismic energy along the frequency axis, which is very strong (approximately up to 40 Hz).

3. ANALYSIS AND RESULTS OF THE MEASUREMENTS

3.1 Experimental Modal Analysis

The experimental modal analysis represents the procedure for obtaining the Eigen (natural) frequencies, mode shapes and modal damping of linear, time invariant systems. The procedure is used to verify the results of analytical and numeric simulations (12).

The goal of the experiment was to determine the Eigen frequencies of the support structure within the range specified by SO 806/1,2, resulting in 4 measured Eigen frequencies (Fig. 4). The first Eigen (natural) frequency occurs in the direction of least stiffness (direction 2 in Fig. 1a) measured at 32,5 Hz. The second Eigen frequency is obtained perpendicular to this direction at 41 Hz. The third Eigen frequency represents torsion vibration at 44,5 Hz around the vertical axis of the structure. The fourth Eigen frequency was measured at 95,5 Hz in the direction of excitation.

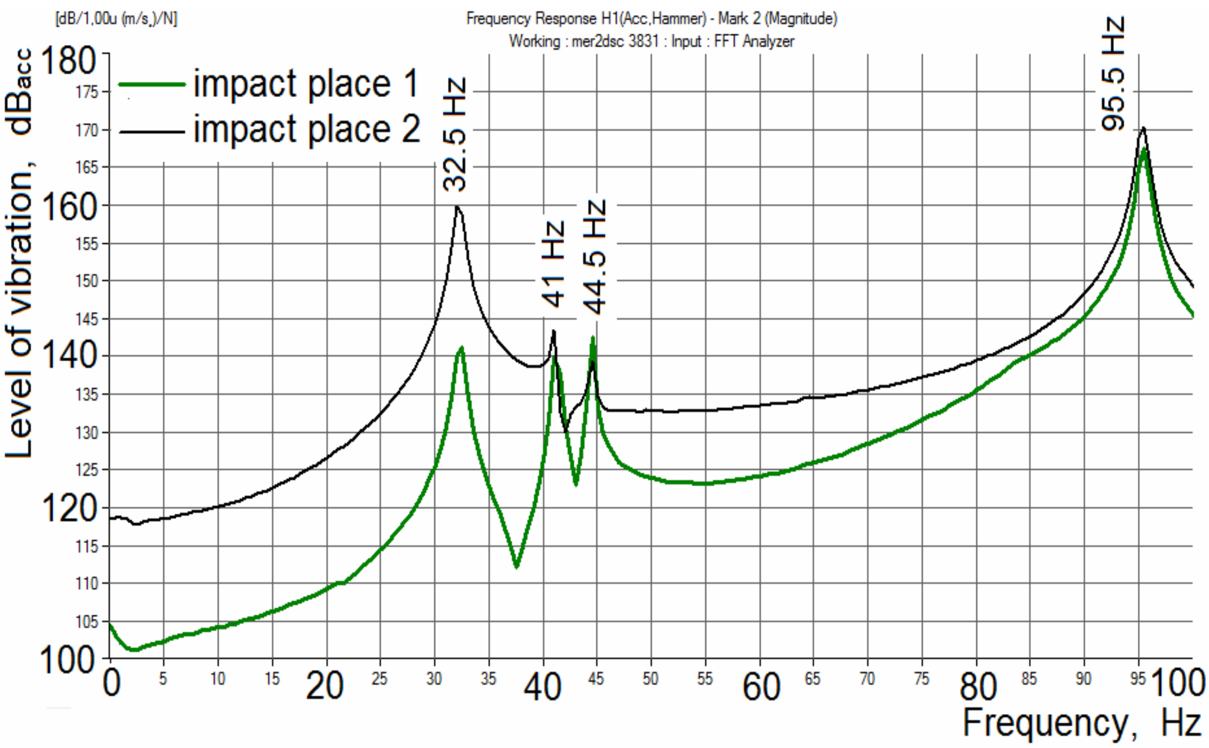


Figure 4 – Eigen frequencies from the modal analysis of the support structure excited at two different points

3.2 Frequency Analysis

As was mentioned in section 2.3 for frequency analysis, the deterministic and random excitation were used as a condition introduced in sections 2.1 and 2.2. Identical Eigen (natural) frequencies were measured when the support structure was excited by the shake table (at continuous, variable, and constant frequencies), confirming the results of the modal analysis (see Fig. 5, 6 and 7).

The results of the frequency analysis, for the deterministic excitation (Fig. 5) and random excitation (Fig. 6) at gradually changing frequencies and constant excitation at 96 Hz (Fig. 7), returned identical results with the modal analysis. This confirms that the measurement methodology was correct in determining the frequency response of the structure. From this analysis, undesirable low frequency vibrations occur even at higher excitation frequencies.

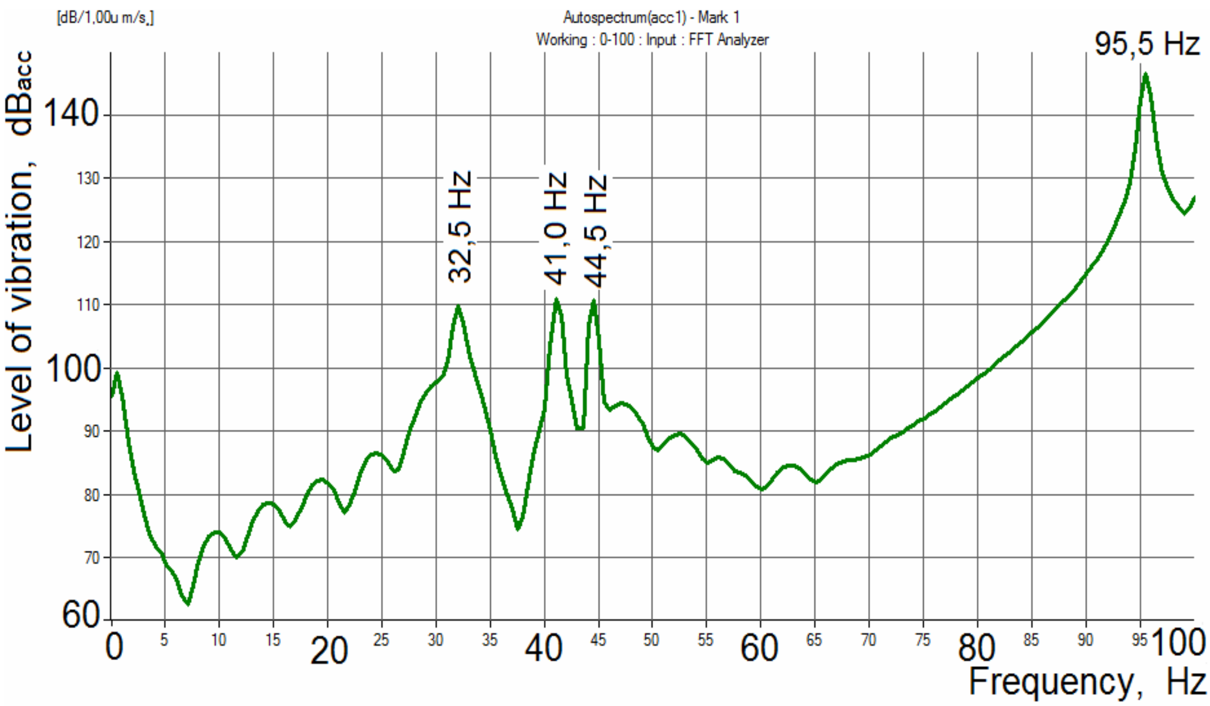


Figure 5 – Eigen frequencies from the frequency analysis of the investigated structure subject to variable, deterministic excitation

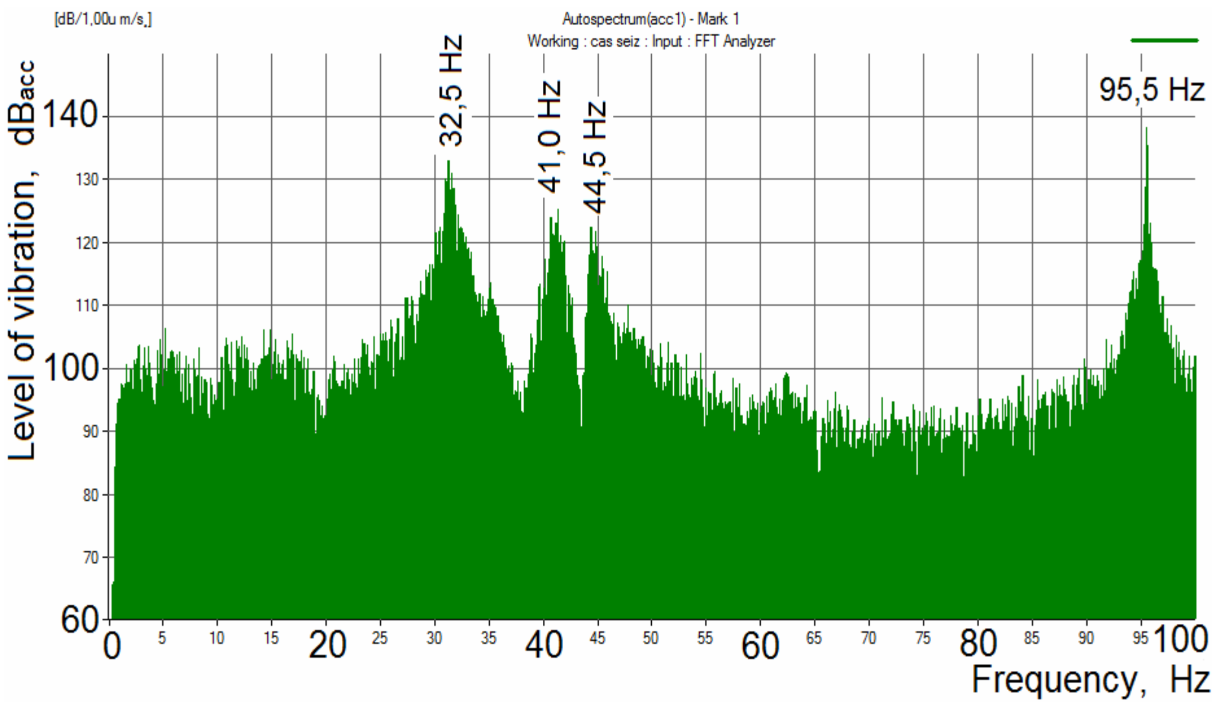


Figure 6 – Eigen frequencies from the frequency analysis of the investigated structure subject to random excitation – real seismic signal from 0 to 40 Hz

In the frequency analysis, for deterministic signals generated by human activity, such as machines and/or machineries, can not be neglected when investigating nuclear power plant safety (see Fig. 5 and 6). The amplitudes of the Eigen modes from the deterministic signals are usually less than the natural seismic signal, but to obtain the resonance state of a support structure and its surrounding devices requires very little seismic energy. If the natural seismic, large energy, acts for a relatively short period of time, lower energy of the low frequency vibration essentially acts for a longer period of time and can damage sensitive technical and electro technical devices, which are essential for nuclear power plant safety.

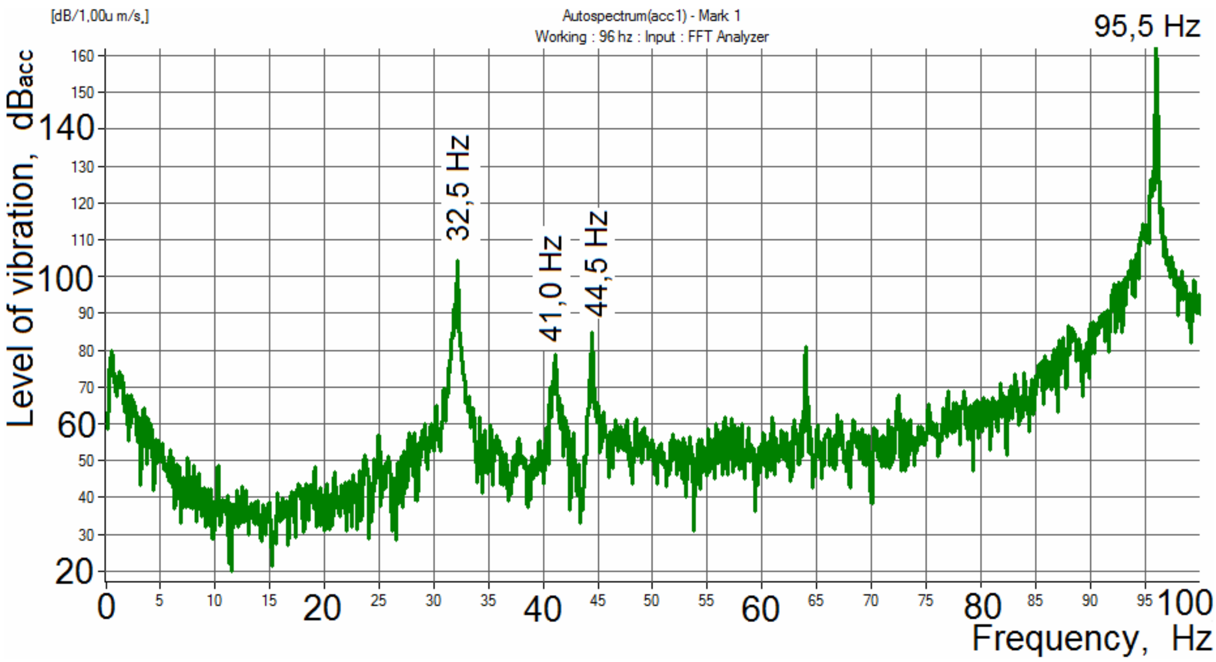


Figure 7 – Eigen frequencies from the frequency analysis of the investigated structure subject to deterministic excitation – Real seismic signal at 96 Hz

4. NUMERICAL ANALYSIS OF THE STRUCTURE

4.1 Modeling the Support Structure

Using precise analytical measurements of the support structure (see Fig. 1 and 2), a virtual model was built using 3D CAD software (Fig. 8-left). This model was then imported into FEA (Finite Element Analysis) software where it was assigned a material model that approximately represented the actual support structures material (6060 Aluminum alloy), meshed and defined according to the measurement conditions. These definitions were performed to reflect, as closely as possible, the actual material properties, bounding, and excitation conditions in the performed measurements.

4.2 Modal Analysis

After importing, assigning material properties, and defining initial condition, a modal analysis was performed for the first 6 modes of the support structure. The initial conditions include a precise definition of support structure mounting. Modal results can be seen in Table 1 while the corresponding mode shapes can be seen on the right in Figure 8 for each natural frequency given in Table 1.

4.3 Transient Analysis

A linked transient analysis is performed using known displacement of the shake table (real seismic signal). The mesh is optimized to give maximum resolution at key points of interest without compromising computational efficiency. The shake table displacement signal represented the base excitation of the support structure. Therefore a time dependent displacement driven motion is defined at the fixation points of the model. To improve computational efficiency, nonlinearities are removed from the analysis since FFT of both excitation signals, and measured response signals do not display any resonant frequencies throughout the whole spectrum (this assumption should not be made if experimental data is unavailable). The analysis is divided into two steps, were stabilization effects are active for the final (second) step of the simulation to account for model stabilization once excitation is finished. A deformation probe is inserted at the approximate area and direction that the actual measurement accelerometer was sensing. The simulation results coincide with the excitation signal (acceleration) in Figure 3b above. The overlaid displacement signals can be seen in Figure 9.

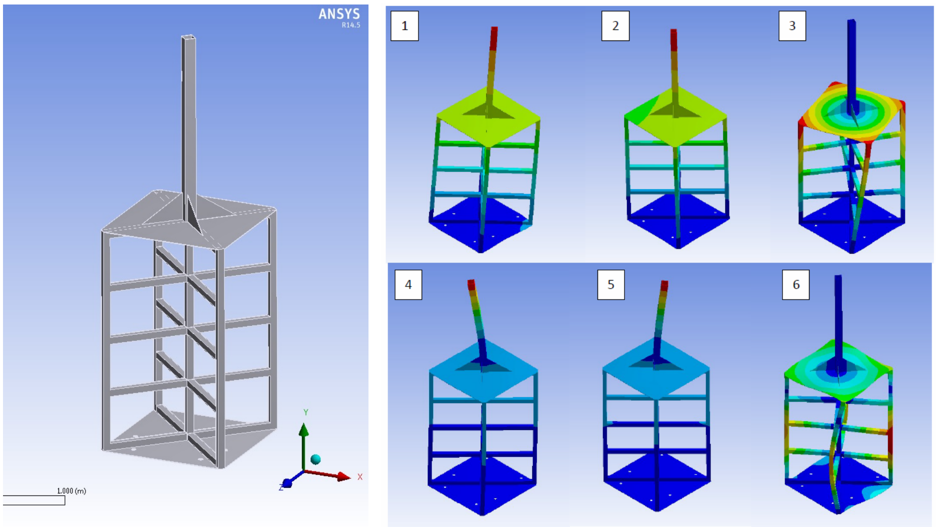


Figure 8 – Virtual model (left). Mode shapes for each Eigen frequency according to Table 1 (right)

Table 1 – Eigen frequencies obtained from measurements compared to numerical results

Mode	Experiment Frequency, Hz	Numeric model Frequency, Hz
1	32.5	32.99
2	41.0	41.18
3	44.5	50.27
4	99.5	102.98
5	*	103.60
6	194.0	198.84

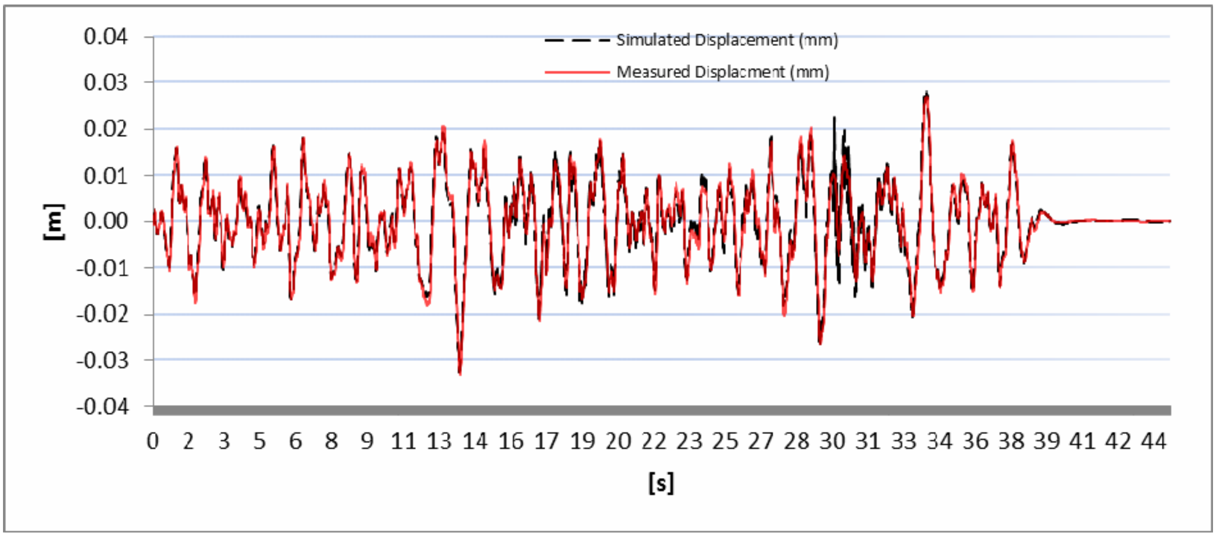


Figure 9 – Comparison of response signal (displacement) obtained by PULSE measuring apparatus and FEA simulation as a result of a seismic excitation signal

5. CONCLUSIONS

From the experimental results (Fig. 4 to 7) and the results obtained using FEA (Fig. 8), it is possible to model the frequency response of a structure with relative accuracy provided that care is taken to create a virtual model that best represents the measurements (geometry, material properties, loading conditions, etc…) (5, 8, 9). This is especially true when analysing existing structural systems in sensitive industrial sectors such as nuclear power plants, where incorrect boundary conditions, poorly defined model, or incorrect analysis settings can result in a poor representation of actual structural behaviour during a critical event. However, provided that care is taken to ensure a true representation of the support structure's analytical model, material model, boundary and loading conditions, and considering any surrounding structures, accurate numeric results can be obtained through simulation. Regardless, each numerical model should be accompanied by a corresponding experimental measurement, not only to verify the simulated results and vice versa, but also to provide a more detailed description of the analyzed system. Furthermore, as shown in the frequency analysis, structures and surrounding devices within nuclear power plants must be investigated not only in terms of their natural seismic events, but also in terms of the deterministic signals dynamic influence which are generated by machines within the nuclear plant and/or its surroundings.

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