ANALELE UNIVERSITĂȚII
“EFTIMIE MURGU” REȘIȚA
ANUL XX, NR. 3, 2013, ISSN 1453 - 7397

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Determination and Verification of the main Dynamic Characteristics of a Spatially Large Structure Using the Basic Records Combination Method

The aim of the paper is to present some methodological aspects regarding the determination of the vibration eigenmodes of a spatially large, symmetric structure and afterwards to show the obtained results for a spectral analysis of the ground motion in the horizontal plane, corresponding to steady state micro-tremors. The recorded velocigrams concern the rigid body motion of the main ring of the structure (translation along different horizontal directions and rotation with respect to the vertical symmetry axis) as well as ovalization oscillations (mainly second order ovalization). The necessary data for the analysis was obtained through an efficient technique of combining basic records gathered with the help of data acquisition systems, on site, using three different schemes for the placement of the recording sensors.

Keywords*: velocigrams, spectral analysis, oscillation ovalizations*

1. Introduction

The use of modern, digital, data acquisition systems (DAS) in all fields of engineering, especially structural engineering, has become almost a necessity in present days. With developments in technology, richer and more accurate information can be obtained with minimum effort and time consumption. These can be conclusive for structural verification, for rehabilitation or for a better seismic control of the constructed system. The obtained measurements for the determination of the dynamic characteristics of structures may lead to important conclusions for the structural analysis (rigidity comparisons at different erection/rehabilitation stages, comparisons of the structural damage in time, immediate identification of the damaged zones after seismic events). A great advantage of using DAS is that, once obtained, the records may form a database extremely useful for future use as well as for probabilistic hazard analyses.

Information about spatial displacements of the structure along different degrees of freedom, at any point, or in the case of circular structures about their ovalization can be obtained directly through the technique of combining basic records. Practically, for large span structures the deformed shapes and spatial ovalizations represent evidence for the non-synchronous character of the ground motion due to seismic actions, fact proven even in the case of micro-tremors [6].

The aim of this paper is to present the results of the spectral analysis and dynamic characteristics of an axial-symmetric structure, based on ground motion micro-tremors, applying the basic records combination method. For this purpose is the Central Pavilion ROMEXPO was chosen due to its isolated location (compared to other structures in Bucharest) and special, circular, symmetrical shape, leading to more accurate results and simplified computations.

2. The Pavilion Structure

The Central Pavilion of the ROMEXPO Complex was built during the years 1960-1963 according to the plans of the architects prof. Ascanio Damian, Mircea Enescu, Vera Hariton and prof. eng. Mircea Soare. The Pavilion having a height of 42 m and a built surface of 10000 m^2 has a circular plan with a diameter of approximately 113 m and a steel dome of 95 m diameter [1].

In 30.01.1963, the dome, which was a replica of the one in Brno, collapsed. The roof was remade based on the plans provided by the Politechnique Institute in Timisoara (acad.prof.ing. Dan Mateescu) and, during the years, the entire structure was checked and strengthened several times. The earthquakes of 1977, 1986 and 1990 led to overall stiffness decreases, while the subsequent interventions led to stiffness increases [8].

On the interior, the Pavilion is formed of three galleries situated at different elevations (3.20 m, 7.70 m and 17.30 m) united through radial stairs allowing visitors' access. The edifice is a combination of glass, concrete and steel, having a modern style for the 60's. The dome is made of radial steel arched trusses resting on a circular reinforced concrete resistant system G+3F. The spatial system is made of 32 one span radial frames (2x32 principal columns). The circular platform at the elevation 4.50 m, resting on 2x30 secondary columns, was added more recently and has a small contribution to the overall stiffness of the structure.

In Figure 1. and Figure 2. the structure of the Central Pavilion ROMEXPO is presented: vertical section and general view.

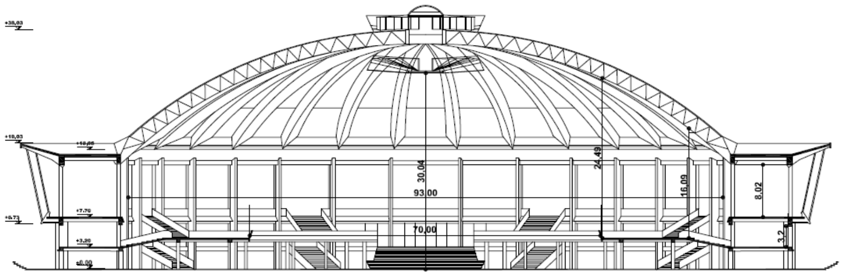


Figure 1. Vertical Section

Figure 2. General view of the building

3. Method and Objectives

Three layouts for placing the sensors of the DAS were created to simultaneously record the displacements of the structure at ambient vibrations on two orthogonal, horizontal directions. The DAS records velocities which are afterwards transformed into displacement recordings and then processed into Fourier spectra.

Taking the first layout (Figure 3.) as a starting point, due to its increased number of sensors compared to the other layouts (8 sensors), the method of basic records combination was used considering that the symmetric and antisymmetric subspaces of motion are orthogonal [2], [3], [4]. Fourier subspaces were considered with respect to an angle at centre for different order ovalizations and the distinct subspace of rotation of the structure. Practically, the eigenmodes separate the space of motion into orthogonal subspaces of one dimension and due to this property the position of the sensors could be established. The motion recorded by the sensors represents the result of subspaces superposition of the eigenmodes [10].

In conclusion, the idea that stands at the base of basic records combination on two orthogonal directions is the decomposition of the motion space into one dimension subspaces and afterwards reuniting them along the directions of interest.

The monitoring of ambient vibrations and the processing of the recordings have as main objective the experimental determination of the dynamic characteristics of the structure and it's motion tendencies.

The possibilities of motion considered important from engineering point of view are:

- Translation on the E-W direction;
- Translation on the N-S direction;
- Rotation around the vertical symmetry axis;
- Second order ovalization.

The vectors of recorded velocities and displacements, $u_g(t)$ and $w_g(t)$, along the two horizontal, normal axes, OX and OY and having 2x32 components, are transformed into $u_e(t)$ and $w_e(t)$, vectors corresponding to the vibration eigenmodes of translation, rotation and ovalization of the structure.

For the first scheme, which offers the richest information, presented in Figure 3, simultaneous digital recordings were done on the directions W-E and S-N at 4 equidistant points on the superior ring of the structure (elevation +17.30 m). The recorded results are noted, for each direction, with: E- u_4 (towards E), u_3 (towards N), N- u_2, u_1, W- u_8, u_7, S- u_5, u_6.

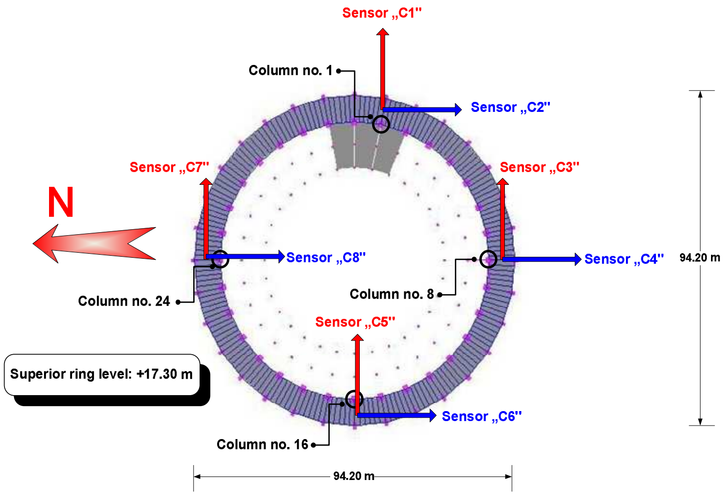


Figure 3. First Sensor Layout

The expected motions for this layout are for the symmetrical axis: dilatation of the ring, rigid translations, ring rotations, 2nd and 4th order ovalizations [2], [5].

a. Symmetrical axis dilatation of the ring

Because there are only four points at which the seismoteres are placed the information is limited and the dilatation oscillations overlap with those of higher order ovalization (4, 8, etc.) The identification of the modes should be done based on the spectral analysis.

$$u_{Dil} = (u_1 + u_4 - u_5 - u_8) / 4 \tag{1}$$

b. Rigid translations of the ring along the two directions E-W and N-S, equivalent to 1st order ovalization:

$$u_{NS} = (u_2 + u_4 + u_6 + u_8) / 4 \tag{2}$$

$$u_{EW} = (u_1 + u_3 + u_5 + u_7) / 4 \tag{3}$$

$$u_{\alpha} = u_{WE}\cos\alpha + u_{SN}\sin\alpha \text{ (at angle } \alpha\text{).} \tag{4}$$

c. Ring rotations:

$$u_{rot} = (u_3 - u_2 - u_7 + u_6) / 4 \tag{5}$$

d. 2nd order ovalization:

$$u_{ov2} = (u_4 - u_1 - u_8 + u_5) / 4 \tag{6}$$

$$u_{ov2\alpha} = u_{ov2}\cos\alpha + u_{ov2'}\sin\alpha \text{ (at angle } \alpha\text{)} \tag{7}$$

e. 4th order ovalization:

$$u_{ov4} = (u_4 + u_1 - u_8 - u_5) / 4 \tag{8}$$

4. Results

The recording on site lasted 300s (for each layout) and the illustrative processed signal samples are presented below for translation N-S and 2nd order ovalization (Figures 4-6.).

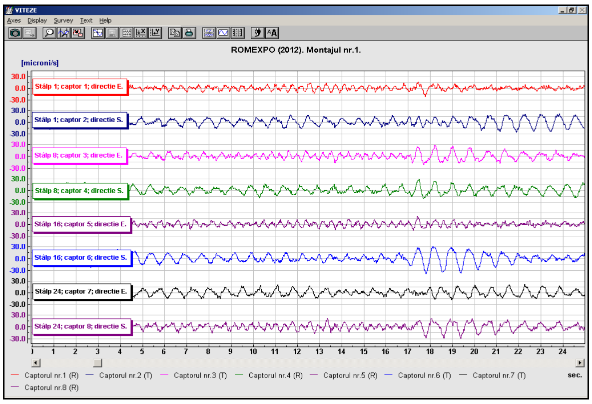
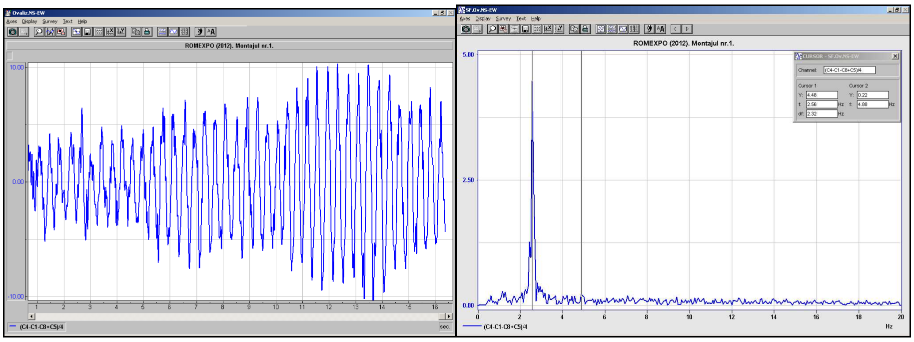


Figure 4. Samples of simultaneous records on 8 channels (velocities)

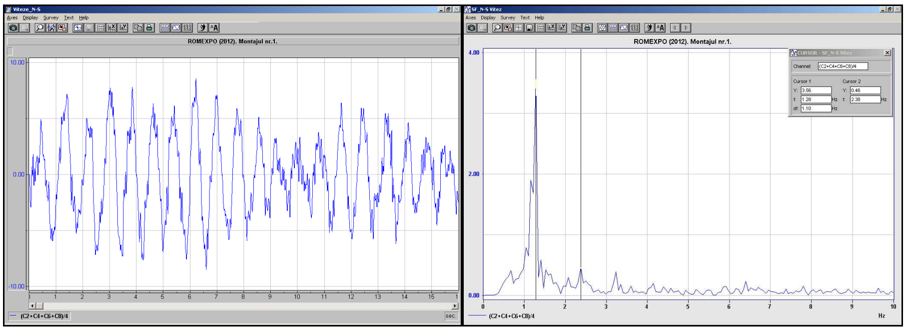


Channel: (C4-C1-C8+C5)/4

Cursor 1
Y: 4.48
f: 2.56 Hz
df: 2.32 Hz

Cursor 2
Y: 0.22
f: 4.88 Hz

Figure 5. 2nd order ovalization in time domain and Fourier spectra, 2.56 Hz, (velocities)



Channel: (C2+C4+C6+C8)/4

Cursor 1
Y: 3.56
f: 1.28 Hz
df: 1.10 Hz

Cursor 2
Y: 0.46
f: 2.38 Hz

Figure 6. Translation N-S in time domain and corresponding Fourier spectra, 1.28 Hz, (velocities)

4. Verification

After the ETABS structural model was realised [5], [6] and the eigen periods thus obtained were almost identical to the ones which resulted from the signal processing considering layout number one (Table 1), the combinations for the second layout were computed. Thus, the validity of the employed formulae and the accuracy of the results were checked. In Figures 7 and 8 the second sensor layout and an image of the structural analysis results from ETABS are presented.

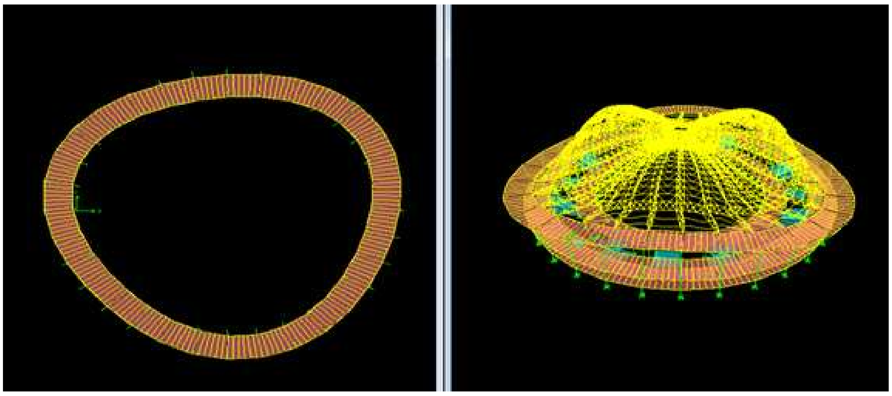


Figure 7. Vibration eigenmode 9 (3^{rd} order ovalization)

For the 2nd layout, simultaneous, digital recordings were performed on the W-E and S-N directions, in 3 equidistant points on the superior ring of the Pavilion.

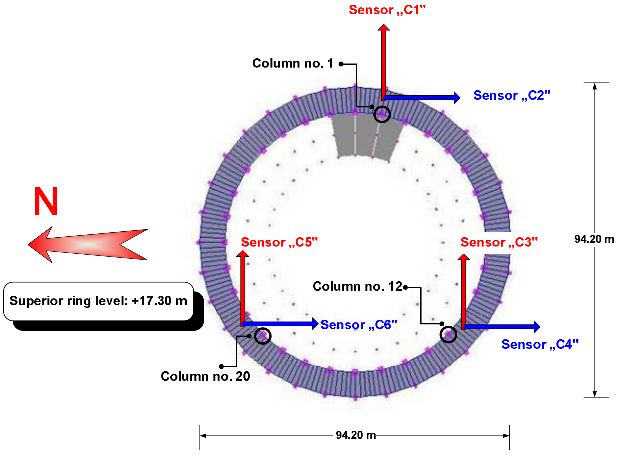


Figure 8. Second Sensor Layout

a. 3rd order ovalization are based on the spectral density analysis:

$$u_{ov3} = (u_1 - u_3 / 2 + u_4 \times 3^{1/2} / 2 - u_5 / 2 - u_6 \times 3^{1/2} / 2) / 3 \qquad (9)$$

b. Rotation in horizontal plane:

$$u_{rot} = (u_2 - u_3 \times 3^{1/2} / 2 - u_4 / 2 + u_5 \times 3^{1/2} / 2 - u_6 / 2) / 3 \qquad (10)$$

c. Translations on two directions:

$$u_{VE} = (u_1 + u_3 + u_5) / 3 \qquad (11)$$

$$u_{NS} = (u_2 + u_4 + u_6) / 3 \qquad (12)$$

Figure 9. shows a sample of the results obtained for the 2nd layout in the case of translations.

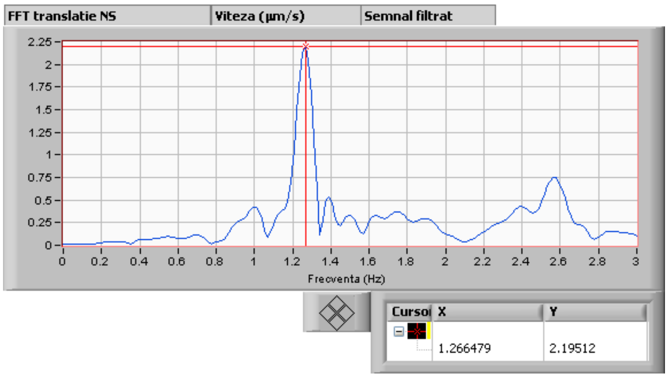


Figure 9. Translation N-S in time domain and corresponding Fourier spectra, 1.27 Hz, (velocities)

Table 1 represents a synthesis of the obtained results from both sensor layouts and from the structural model.

Table 1.

Freq. ETABS (Hz)	**Eigenmode**	**Experimental (Hz)**	**Experimental (s)**	**Spectral Peaks (displ.)**	**Spectral Peaks (vel.)**	**Freq. Check (Hz)**
1.29	Roatation	1.34	0.746	0.52	4.2	1.34
1.44	Translation NS	1.28	0.781	0.35	2.8	1.27
1.44	Translation EW	1.33	0.781	0.32	3.2	1.34

5. Conclusions

The obtained results are clean and with clear spectral peaks leading to the conclusion that the site measurements and processing of the data were performed in a correct manner.

Considering the importance of the building, the structure of the Pavilion has been carefully monitored over the years, many experimental verifications being done [7], [9], ante and post seismic events as well as after successive interventions on the structural system. The present paper completes the information related to ROMEXPO, and it also proposes a direction of research for the higher order modes.

The values of the spectral peaks of the rotation motion in horizontal plane and 2nd order ovalization are visibly larger than those for the horizontal translations, thus proving that the spatial character of the ground motion when prescribing the calculation parameters should be taken into account [2].

By using modern digital equipment, the obtained information is more accurate, richer and can be further processed. The experimental techniques based on in situ records, with highly sensitive dynamic sensors located at well established positions, can capture with great accuracy the main vibration tendencies of the structure. These show great advantages in terms of effectiveness, accuracy and cost [11]. Furthermore, applying the method of basic records combination useful information from engineering point of view can be directly obtained without additional, on site recordings.

It is recommended, for the future, to equip the structure with strong-motion accelerographs which will be able to simultaneously record motions on three directions, placed at four points below the main reinforced concrete ring. Thus an interesting comparison could be made between the behavior of the structure during/after the earthquake and the behavior of the structure under steady state micro-tremors.

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