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Zoran Mišković[1], Marko Popović[2], Nenad Pecić[3], Siniša Savatović[4], Marina Latinović[5]

ANALIZA MODALNIH KARAKTERISTIKA DVE NOMINALNO IDENTIČNE KONSTRUKCIJE TURBO STOLA

Rezime:

U radu je prezentovana identifikacija modalnih parametara konstrukcija dva turbo stola blokova *A1 i A2* u Termoelektrani *Nikola Tesla –A* u Obrenovcu – Republika Srbija, a na bazi merenja ambijentalnih vibracija. Merenje vibracija konstrukcija sprovedeno je u dve kampanje merenja pod ambijentalnom pobudom, oba puta na bloku koji je bio van pogona. Modalne frekvencije i modalni oblici ekstrahovani su koristeći tehniku dekompozicije frekventnog domena (*Frequency Domain Decomposition – FDD*) na osnovu registrovanih ubrzanja. Sprovedenom numeričkom analizom ustanovljene su dinamičke karakteristike analiziranih konstrukcija turbo-stolova adekvatne eksperimentalno utvrđenim.

Ključne reči: Ambijentalna modalna analiza, Ambijentalne vibracije, Modalni parametri, Dekompozicija frekventnog domena, Turbo sto

ANALYSIS OF MODAL PROPERTIES OF TWO NOMINALLY IDENTICAL TURBINE SUPPORTING STRUCTURES

Summary:

The paper presents study of modal parameters identification of two turbine supporting structures of *unit-A1* and *unit-A2* in Power Plant *Nikola Tesla – A* in Obrenovac – Republic of Serbia, based on ambient vibration measurements. Vibration response measurements of structures were carried out in two measurement campaigns under ambient excitation, each time on unit which was out of operation. Modal frequencies and mode shapes were extracted using Frequency Domain Decomposition (FDD) technique according to recorded acceleration data. The performed numerical analysis established the dynamic characteristics of the analysed table-top foundation structure adequate to the experimentally determined ones.

Key words: Ambient Modal Identification, Ambient vibrations, Modal Parameters, Frequency Domain Decomposition, Turbine foundation

[1] *Associate professor, PhD, Faculty of Civil Engineering, University of Belgrade mzoran@imk.grf.bg.ac.rs*
[2] *Associate, MSc, Faculty of Civil Engineering, University of Belgrade, mpopovic@imk.grf.bg.ac.rs*
[3] *Associate professor, PhD, Faculty of Civil Engineering, University of Belgrade, peca@imk.grf.bg.ac.rs*
[4] *Teaching assistant, PhD student, Faculty of Civil Engineering, University of Belgrade, sinisa@imk.grf.bg.ac.rs*
[5] *Teaching assistant, PhD student, Faculty of Architecture, Civil Engineering and Geodesy, University of Banja Luka, marina.latinovic@aggf.unibl.org*

1. INTRODUCTION

The study presents analysis of dynamic properties of two turbine and turbogenerator supporting structures, so-called table-top supporting foundation structures in Thermal Power Plant Nikola Tesla - A in Obrenovac (Republic of Serbia), which includes experimental ambient vibration analysis as well as numerical computation of dynamic properties.

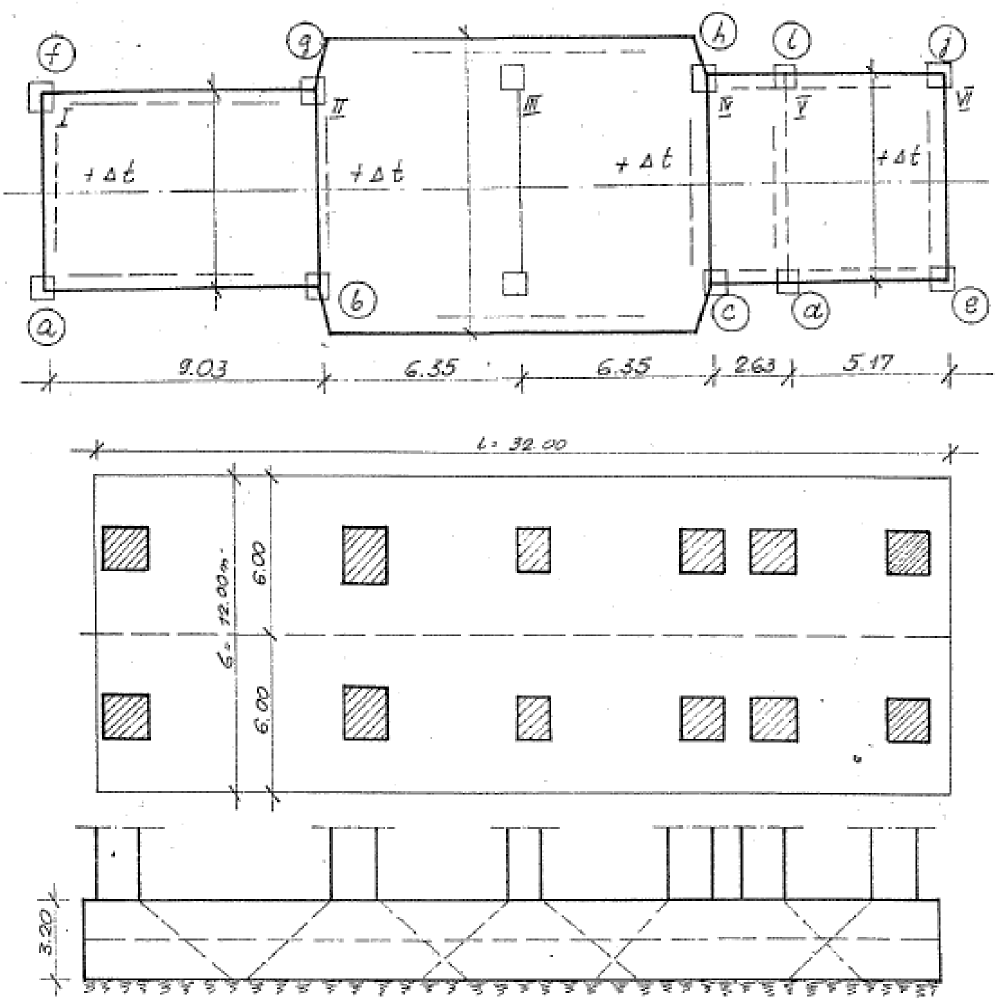

Figure 1 – Plan view and cross section of table-top turbogenerator supporting structure (original design documentation)

Structures were designed by the company *Energoprojekt* – Belgrade in 1967 according to strict requirements for such types of structures. Numerical computation carried out according to actual practice on that time, and computational possibilities before 55 years for quite complicated geometry of turbine supporting structures.

As a part of structural condition assessment of table-top foundation supporting structures of *unit-A1* and *unit-A2*, estimation of modal frequencies and mode shapes was carried out [1]. In order to identify dynamic properties of structure, measurements of structural vibration response under ambient excitation and ambient modal identification were performed.

Table-top foundation supporting structures of *unit-A1* and *unit-A2* are placed in main machine room of Thermal Power Plant *Nikola Tesla – A*. Two, practically identical structures are designed as frame reinforced concrete structures, with the top level at elevation of +9.00m.

Units were out of operation during 2020. Experimental analysis of *unit-A2* was performed with presence of all masses (turbines, turbogenerator, etc.), while during execution of measurements on *unit-A1* a part of machinery (masses) was removed from foundation supporting structures.

2. EXPERIMENTAL IDENTIFICATION OF MODAL PROPERTIES

Measurements of vibration response of structures were carried out under ambient excitation in two measurement campaigns. During each campaign measurement was performed on unit that was out of operation while surrounding machinery (other units and equipment) was operational.

In order to estimate modal parameters based on registered ambient vibrations, ambient modal identification was carried out. As parameters were estimated from measured response without knowing or controlling the input loading force, this method is also known as output-only modal analysis [3].

2.1. MEASUREMENT SETUP

Ambient vibration measurements were conducted with the same arrangement of measuring points given for both structures.

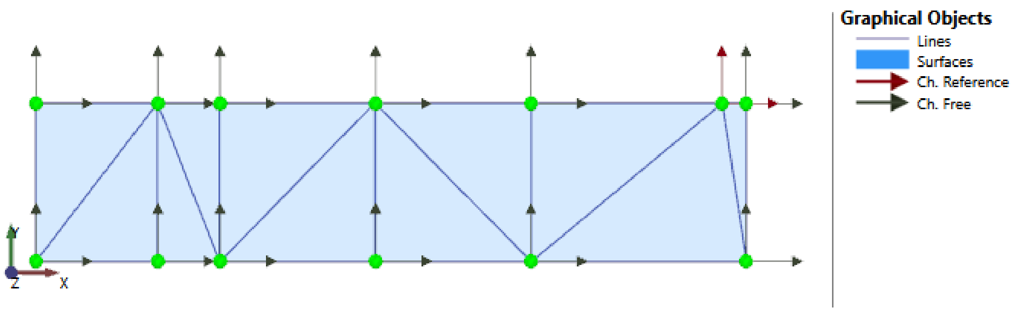

Figure 2 – Layout of measuring points in ambient vibration tests

Measurement was conducted in 7 measuring cross-sections to a total of 13 measuring points on the top face of upper slab. At each measuring point, the measurement was performed in 3 directions - in the direction of the longitudinal (X) and transverse (Y) axes of structure and in a vertical direction (Z).

Vibration response carried out using Multiple Test Setups measurement procedure – sensors were moved from one set of positions to another. There were a total of six measurement test setups, each comprising of tree measurement points – moving sensors were located at two locations, while the reference sensors were kept fixed at point MP-13 in all swaps.

As sensors, high-sensitive accelerometers were used, Silicon Designs model-2240, with measuring range ± 2g. Data acquisition was performed with HBM's multichannel measuring system QuantumX MX840A with 24-bit resolution and simultaneously sampling at 600 Hz during time period of 15 minutes for each setup.

2.2. DATA PROCESSING

After conducted measurement of acceleration under ambient excitation at set of points on the upper slab of the structure, a detailed analysis of the test results using modern techniques was performed. Modal parameter identification based on output-only measurements was carried out.

Preliminary analysis of the structural response showed that the vibration level in the vertical direction is far less than the vibration level in two horizontal orthogonal directions and, due to small levels of signals, it was not possible to distinguish vertical vibration modes. Therefore, further analysis included only the identification of modes with dominant movement in the horizontal plane (XY) – separate and simultaneous analysis of recorded acceleration data in longitudinal and transverse direction. Throughout this stage of analysis, proved sufficient to limit the frequency range of interest up to 15 Hz in order to identify main structural vibration modes.

The extraction of modal frequencies and shapes was performed using Frequency Domain Decomposition (FDD) and Enhanced Frequency Domain Decomposition (EFDD). As a post-processing step, correlation analysis between estimated mode shapes was performed by Modal Assurance Criterion (MAC) procedure [2]. Mode shape similarity is represented by the MAC value – approaching zero indicates no similarity, while approaching one indicates high similarity [3,4].

3. ESTIMATION OF MODAL PROPERTIES

Based on ambient vibration measurement data recorded in two measurement campaigns, modal identification of two table-top foundation supporting structures was performed. Modal frequencies and corresponding shapes were extracted in the frequency range of interest via FDD and EFDD techniques. Based on manual as well as automatic frequency domain peak-picking, in case of both structures, four structural modes were identified. For validation of the obtained results, Modal Assurance Criterion was used. Consistency of estimated mode shapes is presented in form of MAC matrix. As the diagonal elements of the matrix are a comparison of each mode shape with itself, their value is "1". Ideally, each mode should have a different shape than the other modes. The off-diagonal elements have very low values, which implies that modes are uniquely observed.

In total, four modes of vibration were extracted: translational modes in longitudinal and transverse direction, first torsional and first bending mode. Due to the asymmetry of the structures respect to the Y-axis, obtained mode shapes have torsion admixtures.

3.1. EXTRACTED MODAL PROPERTIES OF *unit-A1*

The results obtained in analysis of ambient vibration data of *unit-A1* structure, suggest the existence of structural modes at 4.2 Hz (mainly translational mode in the transverse direction), 4.7 Hz (mainly translational mode in the longitudinal direction), 5.4 Hz (mainly torsional) and 9.7 Hz (mode with significant bending of table top in horizontal plane).

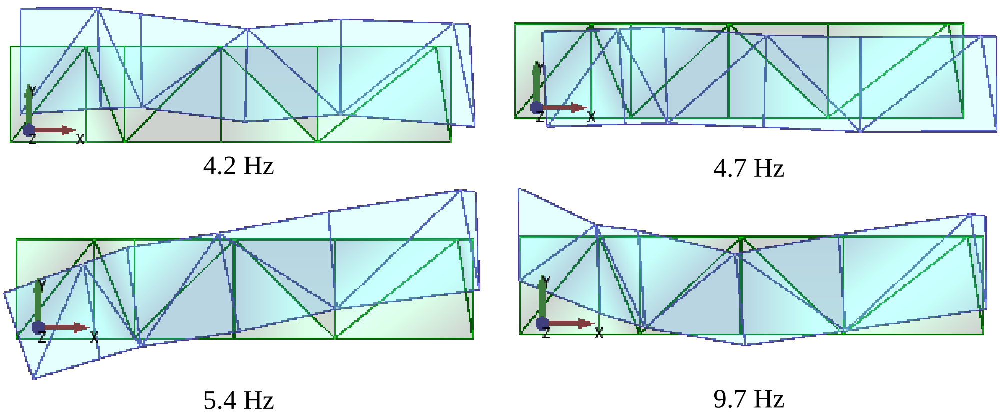

Figure 3 – Estimated mode shape based on ambient vibration measurement and identification by application of FDD-method – unit-A1

Off-diagonal MAC values are quite small (up to value 0.21), which is satisfying taking into the account unfavorable conditions for performing measurements which results in a certain level of complexity of extracted modes.

Table 1 – MAC (Modal Assurance Criterion) matrix of extracted mode shapes of unit-A1

Mode frequency	***4.2 Hz***	***4.7 Hz***	***5.4 Hz***	***9.7 Hz***
4.2 Hz	**1.00**	0.09	0.01	0.21
4.7 Hz	0.09	**1.00**	0.04	0.04
5.4 Hz	0.01	0.04	**1.00**	0.08
9.7 Hz	0.21	0.04	0.08	**1.00**

3.2. EXTRACTED MODAL PROPERTIES OF *unit-A2*

The analysis of recorded ambient vibration data of *unit-A2*, with applied the same measurement setup as in the case of *unit-A1*, showed similar results. It was expected because the structures are practically identical. Four modes were estimated with slightly different frequencies - at 3.9 Hz (translational mode in the transverse direction), 4.4 Hz (translational mode in the longitudinal direction), 5.4 Hz (torsional motion in horizontal plane) and 10.0 Hz (motion with significant bending of table-top slab in horizontal plane).

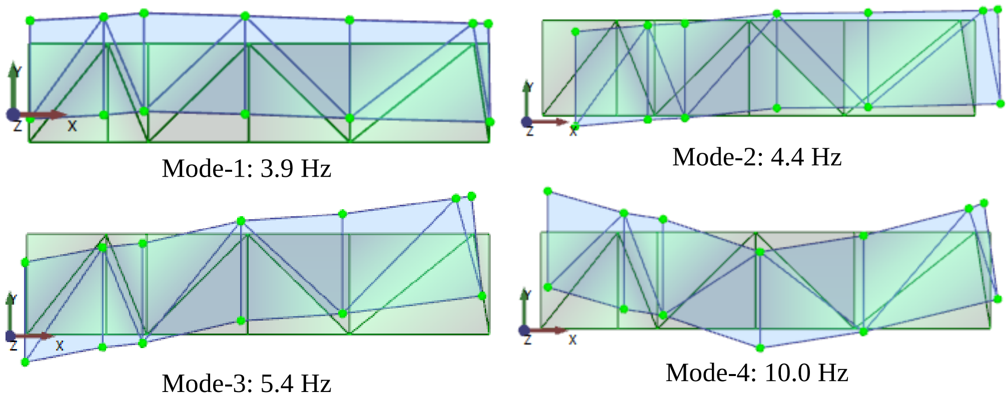

Figure 4 – Estimated mode shape based on ambient vibration measurements and identification by application of FDD-method – unit-A2

Similar level of complexity of extracted modes was established, which is represented by off-diagonal MAC values, with maximal value 0.20. Also, this fact could be considered satisfying taking into the account unfavorable conditions for performing measurements which results in a certain level of complexity of extracted modes.

Table 2 –MAC (Modal Assurance Criterion) matrix of extracted mode shapes of unit-A2

Mode frequency	*3.9 Hz*	*4.4 Hz*	*5.4 Hz*	*10.0 Hz*
3.9 Hz	**1.00**	0.03	0.19	0.20
4.4 Hz	0.03	**1.00**	0.02	0.02
5.4 Hz	0.19	0.02	**1.00**	0.02
10.0 Hz	0.20	0.02	0.02	**1.00**

4. NUMERICAL PREDICTION OF MODAL PROPERTIES

For this purpose, a detailed 3D FEM numerical model was developed in software package *ROBOT - Structural Analysis Professional* software, which included all details of complicated geometry of structure (longitudinal and cross beams, soil stiffness, masses of equipment, etc.), Figure 5.

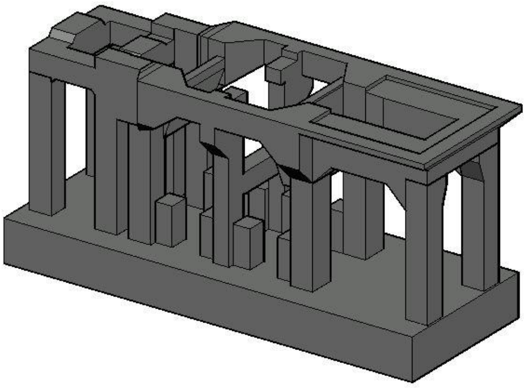

Figure 5 – Developed 3D FEM model of turbine supporting structure for modal analysis

According to conducted computations, modal properties of *unit-A1* and *unit-A2* table-top turbine supporting structures were predicted. In Figure 6 are showed first four mode shapes and corresponding frequencies of predicted modes.

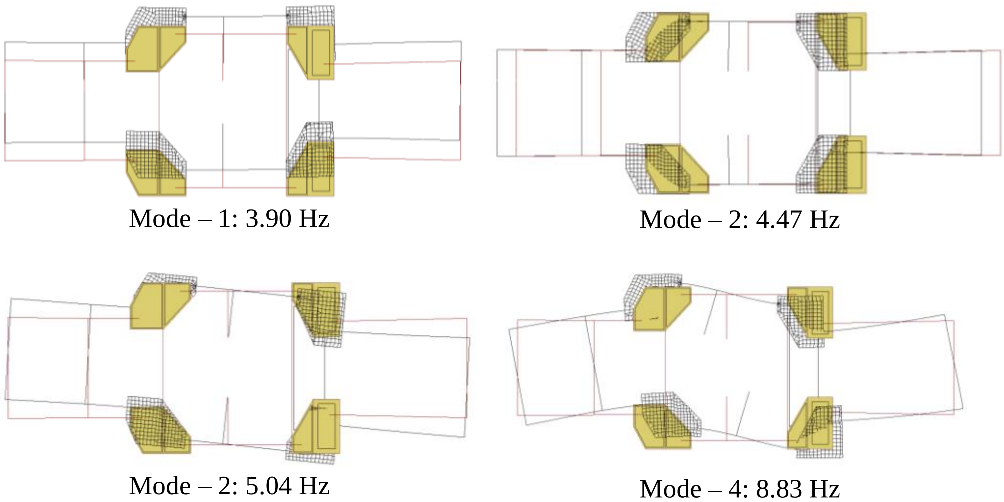

Figure 6 – Numerically predicted mode shapes by developed 3D FEM model of the structure

5. CONCLUSION

An ambient vibration modal identification of two, nominally identical, table-top foundation structures was performed, based on the Frequency Domain Decomposition technique and Multiple Test Setups Measurement Procedure. Experimentally estimated modal properties, for both nominally identical table-top turbine supporting structures, are quite similar in the sense of order of types of motion in consequent modes which represent similar behavior of both tested structures. Also, closed values of modal frequencies and similar mode shapes were estimated in both cases, *unit-A1* and *unit-A2*. A slightly higher modal frequencies were estimated in the case of *unit-A1*, which is consequence of lower mass presence on the turbine supporting structure slab during testing. It should be noted that, beside main RC structural elements, on the lower slab, between concrete beams, exist secondary steel supporting elements for machinery/pipe-lines equipment where were placed accelerometers, which produced some level of complexity of extracted mode shapes.

Conducted FEM numerical prediction of mode shapes showed good agreement with experimentally results in the sense of mode shapes and frequencies, which indicates that the developed model should be used for further assessment of response of turbine supporting structures, for example in operational conditions.

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LITERATURA

[1] Izveštaj o ispitivanju sopstvenih i prinudnih vibracija nosećih konstrukcija turbina i generatora (turbo-stolova) na blokovima *A1* i *A2* sa dinamičkom analizom ponašanja konstrukcije u mašinskoj sali *TENT–A* u Obrenovcu, Građevinski fakultet Univerziteta u Beogradu, 2021.

[2] Rainieri C., Fabbrocino G., Operational Modal Analysis of Civil Engineering Structures, Springer New York, 2014.

[3] Artemis Extractor, http://www.svibs.com/

[4] Allemang R. J., The Modal Assurance Criterion - Twenty Years of Use and Abuse, Sound and Vibration, 37.8, 2003, pp. 14–21

[5] Mišković Z., Popović M., Mišković Lj., Short-term monitoring of turbine supporting structure in ambient and in-operation conditions, Proceedings of the 18th International Symposium of MASE, 2019, pp. 372-381