Proceedings of the 2nd Croatian Conference on Earthquake Engineering - 2CroCEE
Zagreb, Croatia - March 22 to 24, 2023

DOI: https://doi.org/10.5592/CO/2CroCEE.2023.101

AMBIENT VIBRATION MEASUREMENT OF THE INSTITUTE FOR MATERIALS AND STRUCTURES BUILDING IN SARAJEVO

Enver Selimović (1), Hanka Hadžić (2), Goran Simonović (3), Sergey Churilov (4), Mustafa Hrasnica (5), Senad Medić (6)

(1) *Mag.ing.aedif., University of Sarajevo-Faculty of Civil Engineering, enver-selimovic@hotmail.com*
(2) *Univ.bacc.ing.aedif., University of Sarajevo-Faculty of Civil Engineering, hadzichanka94@gmail.com*
(3) *Associate professor, University of Sarajevo-Faculty of Civil Engineering, goransimonovic@yahoo.com*
(4) *Full professor, Ss. Cyril and Methodius University in Skopje-Faculty of Civil Engineering, curilov@gf.ukim.edu.mk*
(5) *Full professor, University of Sarajevo-Faculty of Civil Engineering, hrasnica@bih.net.ba*
(6) *Assistant professor, University of Sarajevo-Faculty of Civil Engineering, senad.medic@gf.unsa.ba*

Abstract

Determination of dynamic properties of structures is the first step in assessing seismic response, and they can be measured in several ways. Controlling or knowing the input excitation usually applied by impact hammer or vibration shaker, typical for experimental modal analysis (EMA) that has been around for the past few decades, is for majority of structures difficult or practically impossible. Ambient vibration testing (AVT) or operational modal analysis (OMA), on the other hand, is the output-only modal analysis. It does not require knowledge of the input excitation, which is practically induced by wind, traffic or similar random source. In this paper, an investigation of ambient vibrations and numerical modelling of the building of the Institute for Materials and Structures (IMK) of the Faculty of Civil Engineering in Sarajevo was carried out. The main goal was to determine the dynamic characteristics of the IMK building using the DIGITEX SENTRY system and Artemis modal software. In addition to testing the IMK building, testing of simpler systems such as a wooden simple beam and a steel cantilever was also conducted. For each experiment, a modal analysis was performed in the Tower 8 software package. The numerical model of the building was more flexible than measured in the experiments, and the results were only comparable after inclusion of partition walls in the analysis.

Keywords: operational modal analysis, ambient vibration testing, DIGITEX Sentry System

1. Introduction

Dynamic characteristics of buildings and other types of structures are essential ingredients in the analysis of the structural response under dynamic loads (e.g., earthquake shaking, strong winds, explosions etc.). Variation of dynamic properties in time (frequencies of vibration, damping ratios and mode shapes), closely related to the change of stiffness, can also be employed for identification of potential structural damage [1] and even assessment of soil-structure interaction [2]. They can be verified by conducting experiments on full-scale structures, usually by ambient and forced vibration [3,4,5]. Testing of small-scale models is conveniently executed in laboratories [6].

The use of experimental tests to gain knowledge about the dynamic response of civil structures is a well-established practice. In particular, the experimental identification of the modal parameters can be dated back to the middle of the twentieth century. Assuming that the dynamic behaviour of the structure can be expressed as a combination of modes, whose values depend on geometry, material properties, and boundary conditions, Experimental Modal Analysis (EMA) identifies those parameters from measurements of the applied force and the vibration response. EMA has been applied in different fields, such as automotive engineering, aerospace engineering, industrial machinery, and civil engineering. The identification of the modal parameters by EMA techniques becomes more challenging in the case of civil engineering structures because of their large size and low frequency range. The application of controlled and measurable excitation is often a complex task that requires expensive and heavy devices. For this reason, the community of civil engineers has more recently focused the attention on the opportunities provided by Operational Modal Analysis (OMA). OMA can be defined as the modal

2CroCEE
22 - 24 March 2023

Proceedings of the 2nd Croatian Conference on Earthquake Engineering - 2CroCEE
Zagreb, Croatia - March 22 to 24, 2023
Copyright © 2023 CroCEE
DOI: https://doi.org/10.5592/CO/2CroCEE.2023.101

testing procedure that allows the experimental estimation of the modal parameters of the structure from measurements of the vibration response only [7,8]. It is a so-called Output Only method, where it is assumed that the wind, traffic, and human activities can adequately excite a structure. Highly sensitive acceleration sensors are used to record, evaluate and interpret the vibration behaviour of a structure without forced excitation in all three directions in space. The main assumption of the Output-Only identification methods is that the ambient excitation input is a Gaussian white noise stochastic process in the frequency range of interest.

The eigenfrequencies are an essential parameter for the description of the vibration behaviour of a structure in the linear elastic field. A mode shape – i.e., a vibration form in which the structure oscillates with the respective eigenfrequency –belongs to every eigenfrequency. The actual oscillation of a real structure is composed of the respective shares of the individual mode shapes. The mathematical modal analysis supplies both the eigenfrequencies and the mode shapes of a structure. Both analyses have to be carried out for system identification. The actual static system is obtained by comparing the measuring results with the calculated values and adaptation of the calculation model to the measurements. To get a correct image of the actual load-bearing system, it is required to consider not only the first eigenfrequency and the respective modal form but also higher frequencies and the respective forms [9].

An important disadvantage of this measuring technique should be stressed. Since the amplitudes of vibrations are small, the ambient vibration tests describe only the linear behaviour of structures. They can be used also to describe the linear behaviour of damaged structures and of their components, and can guide researchers in developing time and amplitude dependent structural models and analysis algorithms, to be used in structural health monitoring and in structural control studies. The measured AVT data might not be representative of stronger earthquakes and should be adopted with care since amplitudes of displacements and accelerations are significantly larger. Cracking is expected for quasi-brittle concrete and masonry structures with low tensile strength and frequencies are generally lower than determined by AVT. Therefore, further development of experimental methods for in situ measurement of full-scale partially damaged structures is of great interest [2].

A process of implementing a damage detection and characterization strategy for engineering structures is often called Structural Health Monitoring (SHM). The SHM process involves the observation of a system over time using periodically sampled response measurements from an array of embedded sensors, extracting damage-sensitive features from these measurements, and performing statistical analysis of these features to determine the current state of system health. Over the long-term data analysis is used to assess the structure’s ability to perform its intended function. After extreme events, such as earthquakes or blast loading, SHM is used for rapid condition screening and aims to provide reliable, real-time information regarding the integrity of the structure. SHM can be applied to fixed infrastructure, such as building and bridges, or mobile infrastructure, such as airplanes and trains [10]. In the case of civil engineering structures, the data provided by the sensors is usually transmitted to a remote data acquisition centre.

DIGITEX Innovative Systems has developed a framework for structural health monitoring using an intelligent and reliable monitoring system termed Sentry System – Digital Solution for Ambient Vibration Measurements [11]. A typical Sentry System architecture was employed for ambient vibration testing (AVT) of the building of the Institute for Materials and Structures (IMK) of the Faculty of Civil Engineering in Sarajevo. It was built more than 50 years ago and it houses laboratories for testing materials and structures, as well as the offices of all teachers from the Structural Department.

2. System Architecture

2.1 Sentry System

The Sentry System digital acquisition system is designed to be an IoT (Internet of Things) solution for structural health monitoring of civil engineering structures. It has a modular and dynamic architecture that allows seamless expansion of the number of channels at any time. The Sentry SHM system has integrated several communication protocols that provide flexibility during the installation phase of the system depending on the complexity of the structure that is being monitored.

One of the main advantages of the Sentry SHM system is that it is a fully digital solution. This means that all AD conversion processes are done next to the sensor itself, thus avoiding to maximum, any inducted noise that is a common problem when using analog sensors and a remote acquisition station. Once the signal is digitized the system use variety of communication protocols (Ethernet, Serial, Wi-Fi) to transfer data to the centralized station for further processing and analysis.

All units of the Sentry System are using GPS timing source. This way multiple units distributed remotely around the world can be synchronized together. Together with the centralized processing part of the Sentry System that can run on any cloud service, the Sentry System can act as one virtual global SHM system with sensing units distributed anywhere.

The Sentry System family of products consist of several units that can be installed as standalone units or as a part of a general SHM system (Fig. 1), and the applied configuration is the following:

- Qty.1 xPlorer, central acquisition unit.
- Qty.5 xWave units - total of 15 channels of acceleration installed on different locations of the structure for monitoring vibration
- Qty.1 xSense units – total of 5 channels for measuring voltage-based sensors.
- Qty.2 xNet unit – total of 2 units for expanding the network coverage on the structure that is being measured.

Total number of channels that this system is acquiring is 15 for acceleration and 5 channels for measuring displacement. For comparison, HBM B12 acceleration sensors were also used for determination of natural frequencies [12].

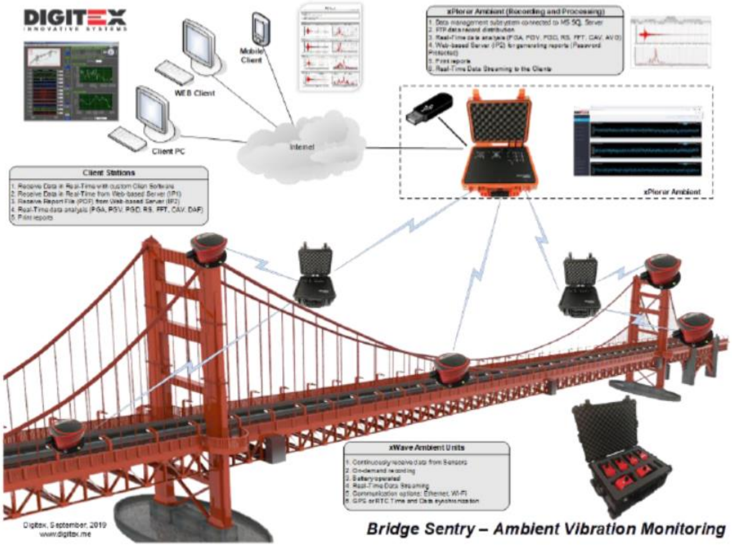


Figure 1. Sentry System Architecture [11].

2.2 Software

Back in 1999, ARTeMIS software [13] was originally developed as a spin-off of research made Aalborg University, Department of Civil Engineering, and even the ARTeMIS name refer to its civil engineering roots as it is the abbreviation of Ambient Response Testing and Modal Identification Software.

ARTeMIS Modal includes up to eight methods for Operational Modal Analysis. From the user-friendly Frequency Domain Decomposition (FDD) methods to the powerful Crystal Clear Stochastic Subspace Identification (CC-SSI) methods. All versions also include Time and Frequency Domain Operating Deflection Shapes analysis (ODS). The modal estimation methods are designed to account for the

Proceedings of the 2nd Croatian Conference on Earthquake Engineering - 2CroCEE
Zagreb, Croatia - March 22 to 24, 2023
Copyright © 2023 CroCEE
DOI: https://doi.org/10.5592/CO/2CroCEE.2023.101

presence of deterministic signals (harmonics) in case of rotating structural parts or another sinusoidal excitation. ARTeMIS Modal Basic includes the Frequency Domain Decomposition (FDD) peak picking method. In this study, FDD was used for the approximate identification of natural frequencies and mode shapes. FDD is a modal analysis technique that estimates the modes of a system from the calculated spectral densities for a lightly damped structure in a condition of white noise input. ARTeMIS Modal Standard includes all features of the Basic version and adds the Enhanced Frequency Domain Decomposition (EFDD) and Curve-fit Frequency Domain Decomposition (CFDD) peak picking methods. ARTeMIS Modal Pro includes all available methods and adds support for Structural Health Monitoring (SHM) plugins used for long term monitoring of structures.

3. Ambient Vibration Tests

3.1 Simple tests

Two preliminary vibration tests were executed on a steel cantilever INP 120 beam and a simple 30/5 wooden beam (plank) to test the equipment and verify the results against analytical/numerical models (Fig. 2). To compare the natural frequencies, two tests were performed: a standard impact test and an ambient vibration test. Difference between the experimentally obtained results is negligible. Numerical analysis was performed using Radimpex Tower Software [14] employing densely discretized beam elements to better approach the analytical solution. Analytical expressions for vibration properties of simple structures with distributed mass for various boundary conditions can be found in literature [15]. A comparison of experimentally and numerically obtained frequencies for the steel beam are provided in Table 1.

a) b)

Figure 2. Simple tests: a) INP 120 cantilever steel beam; b) wooden plank 20/5 cm.

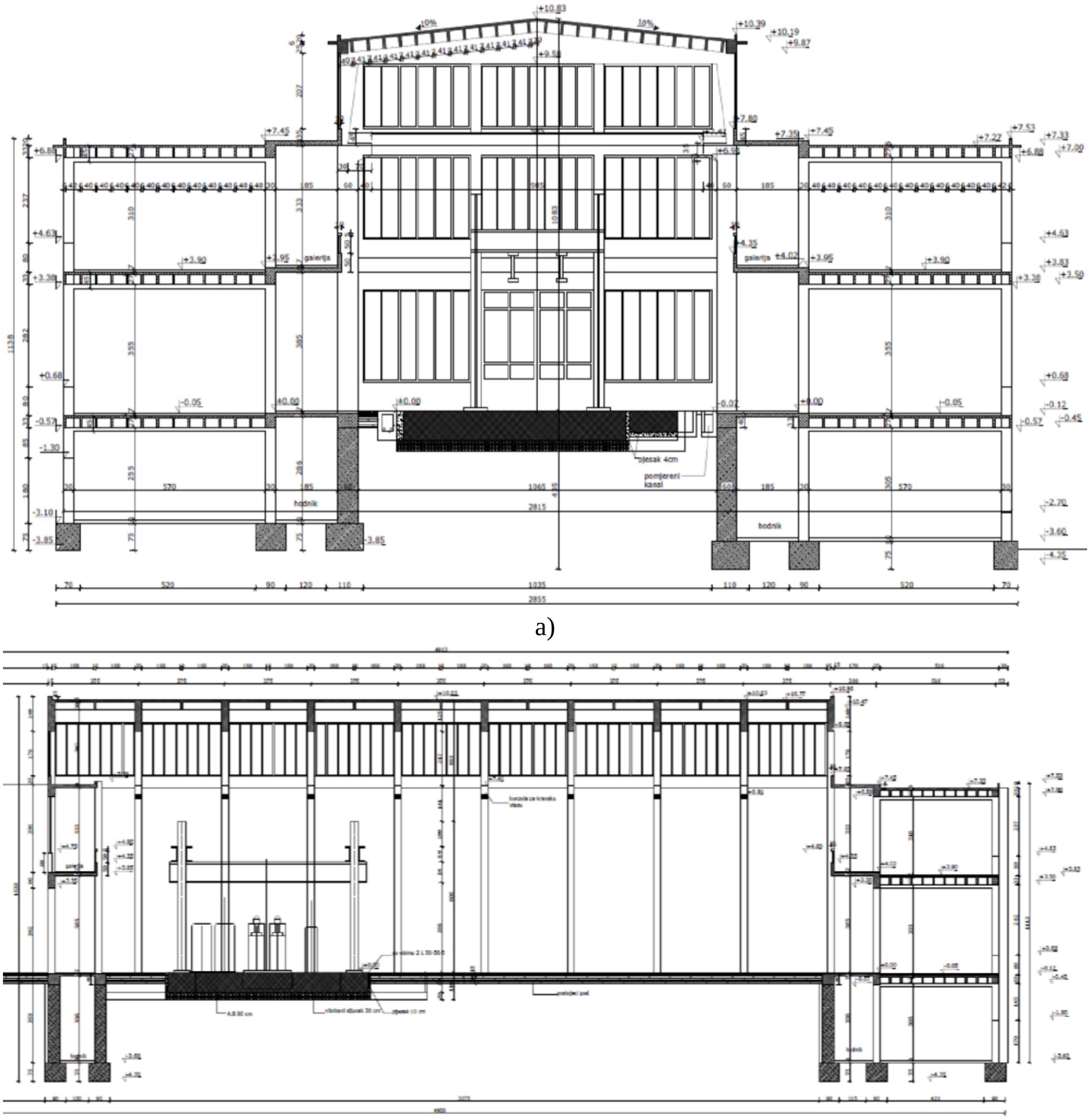
Table 1 – Experimentally and numerically obtained frequencies for the steel beam

Mode	Experimental f [Hz]	Numerical f [Hz]
1	11,03	11,87
2	30,76	36,61
3	67,87	59,35

3.2 IMK building

The building of the Institute for Materials and Structures is located within the Faculty of Civil Engineering in Sarajevo. The structure has three characteristic floors and a two-sided roof above the hall area where a 5t crane is in use. The first characteristic floor is a lower ground floor with a height of 3.50 meters. Other characteristic floors are the upper ground floor, 4.0 meters high, and the first floor, 3.40 meters high. The building has basically an elongated rectangular shape with layout dimensions of 27.8x48.7 m, and a recess on the shorter left side of the building. Typical sections are shown in Fig. 3 and the layout is given in Fig. 4.

Reinforced concrete columns in the office area are 30/30 cm, while in the hall they are 30/60 cm. The floors have a monolithic fine ribbed structure, with narrow ribs at a distance of 33 to 60 cm and a thin topping slab. The foundation of the building is carried out on foundation strips under the walls and on spread footings below the columns. Individual footings are tied with foundation beams.



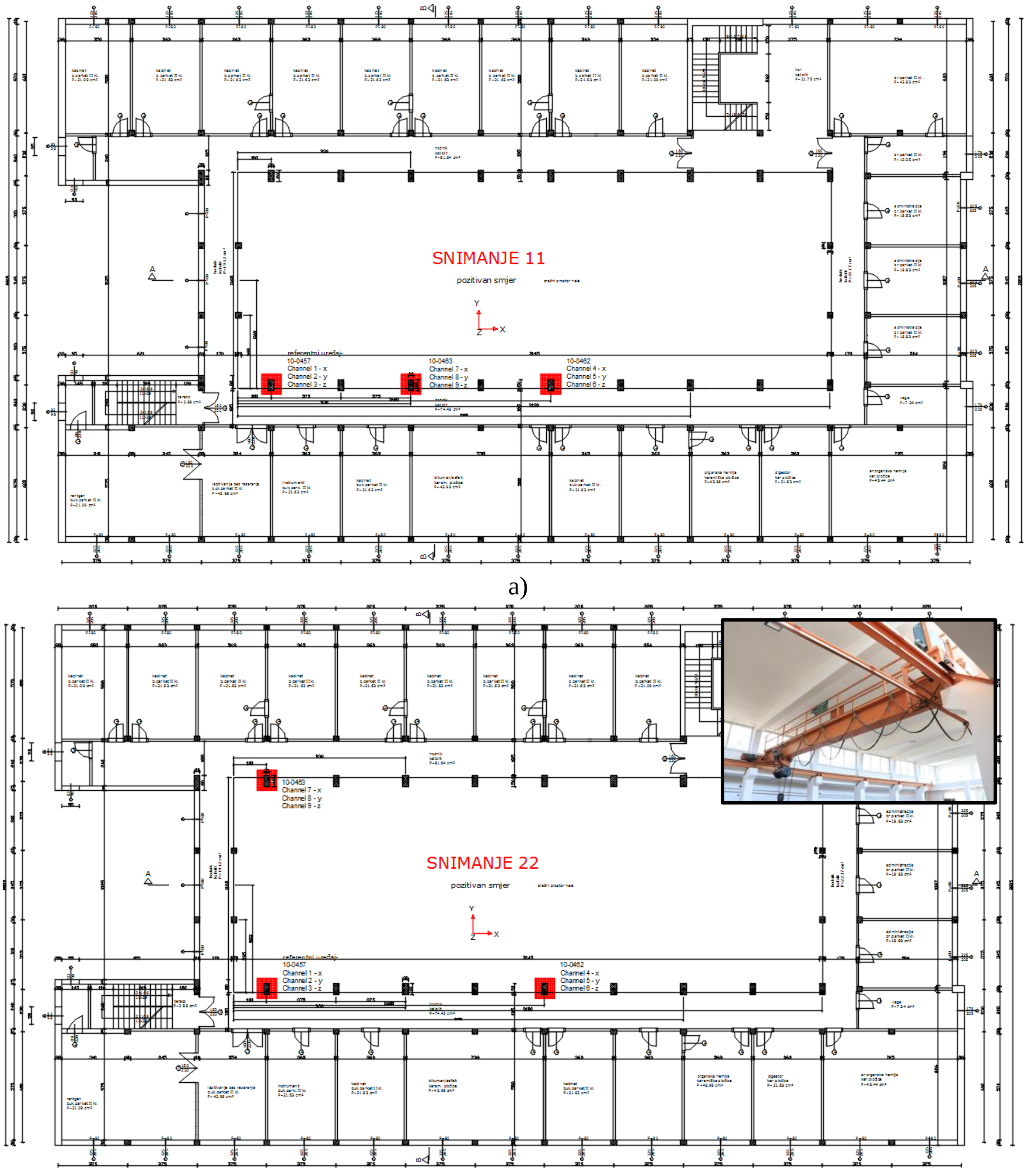
a)

b)

Figure 3. IMK building: a) cross-section; b) longitudinal section.

Digitex Sentry System was used for data acquisition. It consisted of an xPlorer central acquisition unit and 3 xWave triaxial digital accelerometers. The system is capable of providing realtime data acquisition for continuous structural health monitoring for several months. One stationary accelerometer was used as a reference, while the other two were placed in different locations (see Fig. 4). The sampling frequency was 200 Hz. In order to induce vibrations, the 5t crane was used (Fig.4b inset). Typical acceleration record is given in Fig.5 and a power spectrum for longitudinal direction is provided in Fig. 6.

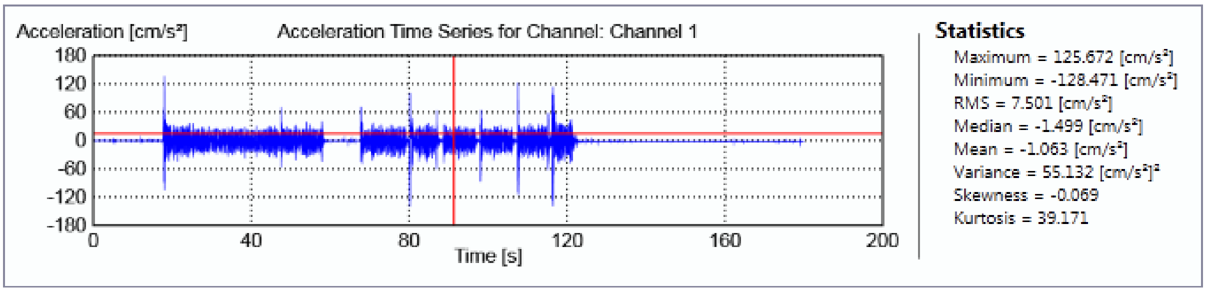
Proceedings of the 2nd Croatian Conference on Earthquake Engineering - 2CroCEE
Zagreb, Croatia - March 22 to 24, 2023
Copyright © 2023 CroCEE
DOI: https://doi.org/10.5592/CO/2CroCEE.2023.101



a)

b)

Figure 4. Different locations of sensors: a) record 11; b) record 22 (inset: IMK crane for vibration generation).



Statistics

Maximum = 125.672 [cm/s²]
Minimum = -128.471 [cm/s²]
RMS = 7.501 [cm/s²]
Median = -1.499 [cm/s²]
Mean = -1.063 [cm/s²]
Variance = 55.132 [cm/s²]²
Skewness = -0.069
Kurtosis = 39.171

Figure 5. Typical acceleration record.

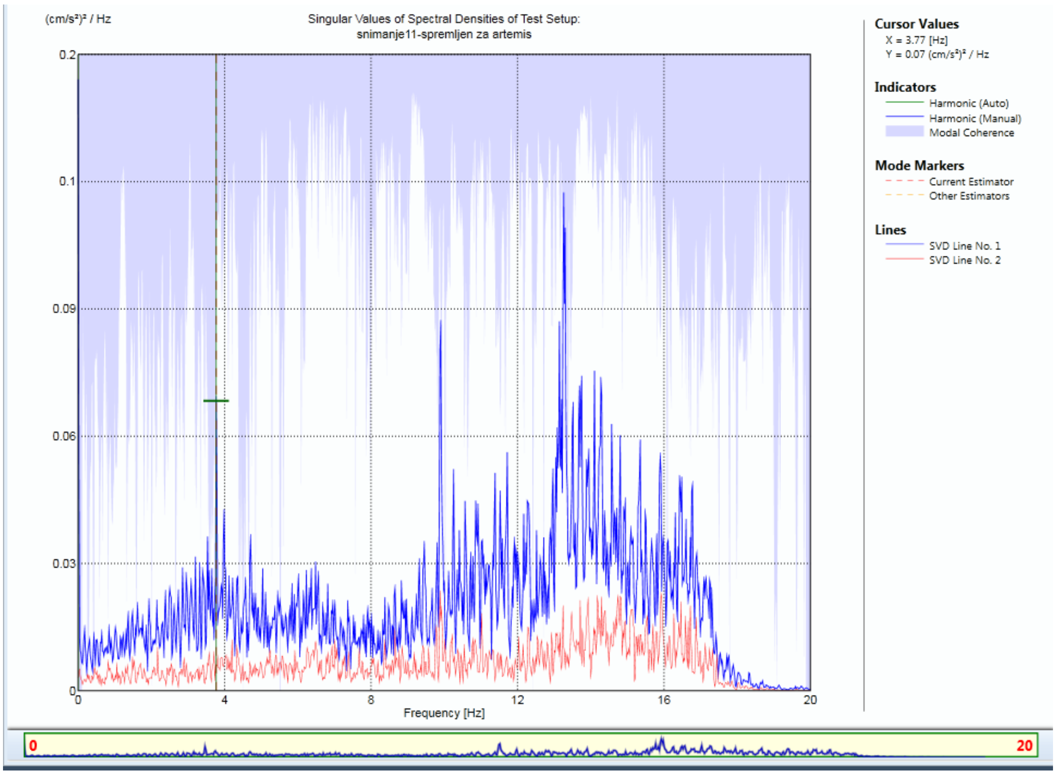
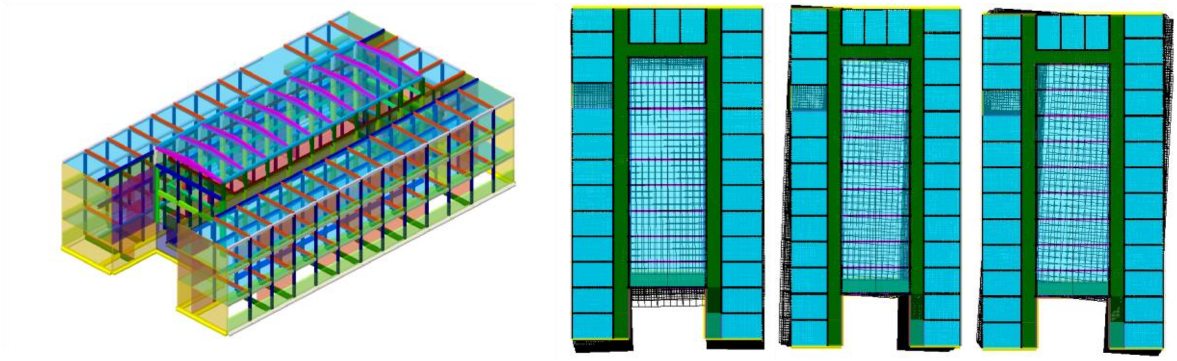


Figure 6. Power spectrum for longitudinal direction.

3D render of a numerical model is shown in Fig. 7a, and vibration modes are provided in Fig. 7b. The model includes all RC elements as well as masonry infill. Not including masonry resulted in large discrepancies between the measured and numerically obtained frequencies. The first mode refers to longitudinal translation (f_1 = 3,78 Hz); the lack of frames in longitudinal direction is obvious. A comparison of experimental and FEA frequencies is given in Table 2.



a) b)

Figure 7. a) 3 D render of the building; b) the first three modes of vibration.

Table 2 – Experimentally and numerically obtained frequencies for the IMK building

Mode	Experimental f [Hz]	Numerical f [Hz]
1	3,77	3,78
2	3,93	3,99
3	4,33	4,55

Proceedings of the 2nd Croatian Conference on Earthquake Engineering - 2CroCEE
Zagreb, Croatia - March 22 to 24, 2023
Copyright © 2023 CroCEE
DOI: https://doi.org/10.5592/CO/2CroCEE.2023.101

4. Conclusion

Dynamic properties of two beams and the IMK building were determined using highly sensitive acceleration sensors and input from the ambient. The first natural frequency of the IMK building amounts to approx. 3.7 Hz and pertains to the longitudinal direction where RC frames do not exist. Frequencies and modal shapes from the finite element model and frequency domain decomposition of the measured signal fit well. Ambient vibration testing does not require knowledge of the input excitation practically induced by wind, traffic, or similar random source. It is practically very useful since the application of an impact hammer or vibration shaker for experimental modal analysis is for the majority of structures difficult or practically impossible.

Acknowledgements

The authors wish to acknowledge the support of this research effort by the Erasmus + Project “Promoting academia-industry alliances for R&D through collaborative and open innovation platform” (Project reference number: 598719-EPP-1-2018-1-MK-EPPKA2-CBHE-JP). Collaboration with Prof. E. Dumova-Jovanoska and Digitexx Data Systems Inc. is much appreciated.

References

[1] Rak, M., Bjelajac, N. (2001): Otkrivanje oštećenja konstrukcija mjerenjem dinamičkih karakteristika. *Građevinar*, *53*(10.), 631-639.

[2] Ivanović, S. S., Trifunac, M. D., Novikova, E. I., Gladkov, A. A., Todorovska, M. I. (2000): Ambient vibration tests of a seven-story reinforced concrete building in Van Nuys, California, damaged by the 1994 Northridge earthquake. *Soil Dynamics and Earthquake Engineering*, *19*(6), 391-411, doi: https://doi.org/10.1016/S0267-7261(00)00025-7

[3] Ivanovic, S. S., Trifunac, M. D., Todorovska, M. I. (2000): Ambient vibration tests of structures-a review. *ISET Journal of earthquake Technology*, *37*(4), 165-197.

[4] Churilov, S., Micevski, S., Dumova-Jovanoska, E. (2018): Ambient vibration testing of public unreinforced masonry buildings from the beginning of the 20th century. In *Proceedings of the 16th European Conference on Earthquake Engineering*, Thessaloniki, Greece.

[5] Baptista, M. A., Mendes, P., Oliveira, S. (2005): Use of ambient vibration tests for structural identification: 3 case studies. In *Proceedings of the 1st International Operational Modal Analysis Conference*.

[6] Franković, T., Paparić, K., Grandić, I. Š. (2019). Laboratorijsko određivanje dinamičkih parametara jednostavne grede OMA metodom. *Zbornik radova (Građevinski fakultet Sveučilišta u Rijeci)*, *22*(1), 43-57, doi: https://doi.org/10.32762/zr.22.1.3

[7] Rainieri, C., Fabbrocino, G. (2014): *Operational modal analysis of civil engineering structures*. Springer, New York.

[8] Brincker, R., Zhang, L., Andersen, P. (2001): Modal identification of output-only systems using frequency domain decomposition. *Smart materials and structures*, *10*(3), 441, doi: 10.1088/0964-1726/10/3/303

[9] Wenzel, H., Pichler, D. (2005): *Ambient vibration monitoring*. John Wiley & Sons.

[10] Sivasuriyan, A., Vijayan, D. S., Górski, W., Wodzyński, Ł., Vaverková, M. D., Koda, E. (2021): Practical implementation of structural health monitoring in multi-story buildings. *Buildings*, *11*(6), 263, doi: https://doi.org/10.3390/buildings11060263

[11] DIGITEX Innovative Systems (2020): General System Description – Sentry System. Digitex Systems. LLC, http://digitexx.website2.me

[12] Hottinger Brüel & Kjær (2023): https://www.hbm.com/de/

[13] Structural Vibration Solution (2023): https://svibs.com/

[14] Radimpex Software for Civil Engineers (2023): https://www.radimpex.rs/en

[15] Chopra, A.K. (2019): *Dynamics of structures*. Pearson Education, 5th edition, USA.