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To cite this article: C Rinaldi *et al* 2024 *J. Phys.: Conf. Ser.* **2647** 142009

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Measured hospital building vibrations induced by air conditioning systems and elevators

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Abstract. A recent large campaign of vibration measurements has been conducted on a hospital building in Italy to perform an operational modal analysis of the structure utilized for model updating. Subsequently, the updated model has been used to carry out a vulnerability analysis of the hospital structural system. The building is composed of 41 structural subsystems separated by technical joints. At the same time, several subsystems are differently interconnected, especially through a roof sustained by large-span wooden beams. Long acceleration time histories have been measured by wireless sensors located at the top level of the building in two days of testing. During the tests conducted in operational conditions, in different locations of the building air conditioning systems and elevators were functioning and they were affecting the measures in the high-frequency content. This work aims to investigate the structural identification of the complex structure, the effectiveness of technical joints, and the influence of the wooden roof connection on the dynamic structural behavior. In pursuing these goals, the main challenge is considering the influence of air conditioning and elevator systems on the natural frequency identification of the structure. Therefore, based on the location of the sensors, the similarities in the geometry, and the vicinity of the sensors to the mechanical equipment, all the sensors have been classified into different groups to observe the dynamic response. Furthermore, an Artificial Neural Network (ANN), trained on numerical model results, is applied to experimental data to establish a relation between increasing prediction error and the influence of the air conditioning system and elevator frequencies.

1. Introduction

In vibration-based structural health monitoring, the identification of modal parameters of structures, starting from the measurement of their dynamic response under ambient excitation, is pursued through Operational Modal Analysis (OMA), which is also referred to as ambient or output-only modal analysis. OMA testing techniques are based on the idea that the excitation has white noise characteristics, whose energy is distributed over a wide frequency range including the modal frequencies expected for the structure [1]. Besides the usual noises in signals generated by monitoring sensors taken into account in the identification process, in some buildings, vibrations induced by mechanical equipment, such as air conditioners or elevators, could make the process of structural identification more challenging. Using the OMA techniques to identify the dynamic behavior of the structure has a long history, OMA results can be exploited for example for model updating [2] and damage detection [3] purposes, but considering the mentioned effects in the identification process was not a subject of many studies.



Recently, with the rapid growth in artificial intelligence and machine learning, the studies to develop algorithms to facilitate the procedures in different fields have been increased and structural dynamic identification is no exception. Xu et al. [4] used a neural network to identify the structural parameters and dynamic response by considering a reference structure as input to train data. Also, Huang et al. [5], proposed a neural network approach for structural identification and diagnosis from seismic response data of the building. Jacobsen et al. [6] proposed a method based on enhanced frequency domain decomposition to eliminate harmonic components in the modal parameter extraction process. Modak [7] presented a method to separate structural modes and harmonic frequencies, by using random decrement of the response to realize different frequencies. In another study, Devriendt et al. [8], suggested an OMA technique based on transmissibility measurements to reduce the risk of wrong identification of the modal parameters due to the presence of harmonics.

This study aims to investigate on the influence of mechanical devices, such as air conditioning and elevators, in the dynamic response of a complex building in operational condition. In the presented case study, which is Massaia Cardinal Hospital in Asti, Italy, the complexity of the structural system, besides several active mechanical devices, can cause some uncertainties in the vibration-based monitoring of the main structure. This study aims to investigate the possibility of identifying structural frequencies and frequencies generated by equipment such as elevators and air conditioners. Considering all the parameters that can cause various dynamic responses in different zones, for the acquisition of sufficient data, 124 measurements in 5 setups have been taken. The modal identification of all this experimental data was done by ARTeMIS. Furthermore, depending on the zone of the installation of the sensors, they are classified into different groups. These groups were based on the similarity of the geometry and their distance from mechanical equipment. Using the PSD of the acceleration signals, a primary observation of the differences and the influence of the machinery have been described. For structural identification, a Finite Element Model (FEM) was implemented and updated according to experimental data. Furthermore, the numerical response under white noise excitation for some of the selected nodes of the FE model was used to train a neural network for further investigation on experimentally measured accelerations affected by the vibrations of air conditioning systems and elevators.

2. Case study description

The “Cardinal Massaia” hospital (Figure 1a) is in Asti, a city in northwestern Italy, which was inaugurated as a part of the national health system in 2003. Having a very innovative architectural design is an important feature of the complex building of the hospital. The total area provided by all the blocks is about 140 000 m² distributed over eight levels. The original structural layout of the project involved the division of the entire building into 41 blocks constructively separated by structural joints with an average thickness of 5 cm. As depicted in Figure 1b, on the roof level, blocks K, L, M, and N are connected to blocks D, E, F, G, and H by wooden beams in the central part. These wooden beams also support a transparent roof system to illuminate the central zone of the hospital. Furthermore, blocks P, Q, R, A, B, and C with the same heights, are connected to the mentioned central zone blocks. These structures are connected by structural joints. The structures of the hospital are supported by deep plinth foundations in reinforced concrete with some piles or with direct foundations on continuous reinforced concrete beams. The vertical structures are mainly made of reinforced concrete. The floors are made up of prefabricated reinforced concrete slabs juxtaposed on-site and connected with a completion. The height of the roof (see level 13 in Figure 2) from the base (the major part of the foundation) where the experimental layout has been installed, is about 24 meters.

3. Experimental dynamic tests and data processing

To perform an OMA which is the most practical technique for such a complex and large building, time history accelerations are needed. The data can be analyzed by a time-domain dynamic identification method directly or transferred to the frequency-domain and dynamic parameters can be determined. Frequency Domain Decomposition (FFD) [9], one of the most common techniques to identify dynamic parameters uses a singular value decomposition of each spectral density matrix.

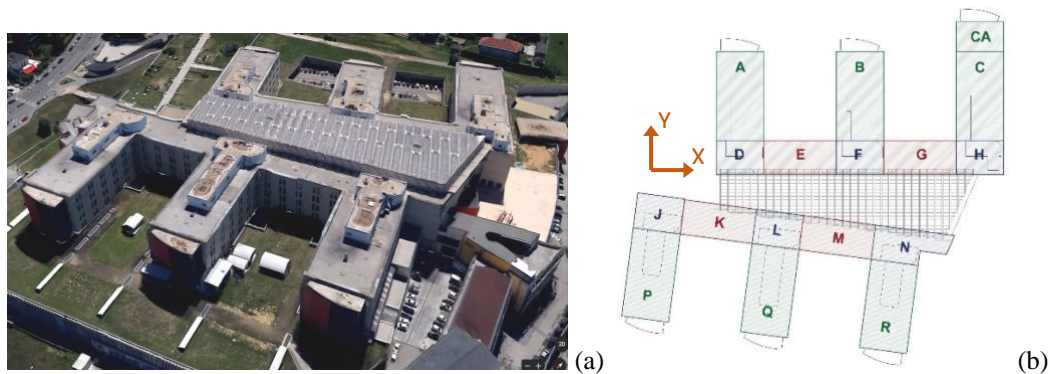


Figure 1. Cardinal Massaia hospital: aerial view of the hospital (a) and plan view of roof level (b).

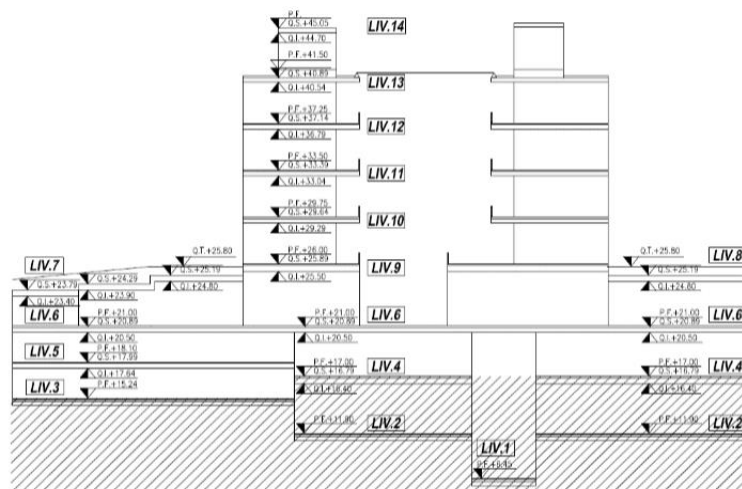


Figure 2. Elevation of the hospital in y-direction.

Considering the large amount of data in all the setups, the use of the FDD technique seems a reasonable choice. Also, some time-domain techniques such as Stochastic Subspace Identification (SSI) can be other options. The power spectral density allows a preliminary evaluation of the identified frequencies.

To investigate the dynamic behavior of the hospital building, an experimental layout including 14 wireless sensors on the roof (level 13) has been implemented. Considering the large dimensions of the building and the complexity of the structural system, to acquire sufficient data that can cover all the blocks, the measuring procedure was done in 5 different setups over two days and it resulted in 124 measurements with a duration of around 1 hour for each. In this sense, a wireless sensor network was an important and necessary feature for implementing the dynamic experimental tests of this case study. Measurements were done by using the accelerations with multi-channel wireless instrumentation (Figure 3 a,b) and a high signal sampling rate. The used wireless instrumentation complies with UNI 9614 and UNI 9916 standards and consists of Lunitek triaxial accelerometers model SentinelM equipped with a low noise MEMS sensor. The device is equipped with 32 GB memory for continuous recording of accelerations and a GNSS receiver for synchronizing recordings between different units. The sensor is equipped with a 20-bit A/D converter that guarantees a dynamic higher than 90 dB in the 0-500 Hz band. The acceleration sampling rate was set at 250 Hz, in order to capture the main expected frequency components, and at the same time ensure an easily manageable amount of data. The other main technical characteristics include, a sensitivity of 1350 mV/g, spectral density noise of 7 $\mu\text{g}/\sqrt{\text{Hz}}$, dynamic measurement of ± 2 g pk, with frequency range (bandwidth) from DC to %50 Hz, and electric connections are 62GB-12E12-10SN. It should be mentioned that some of the sensors functioned in three directions and the others measured in one direction.

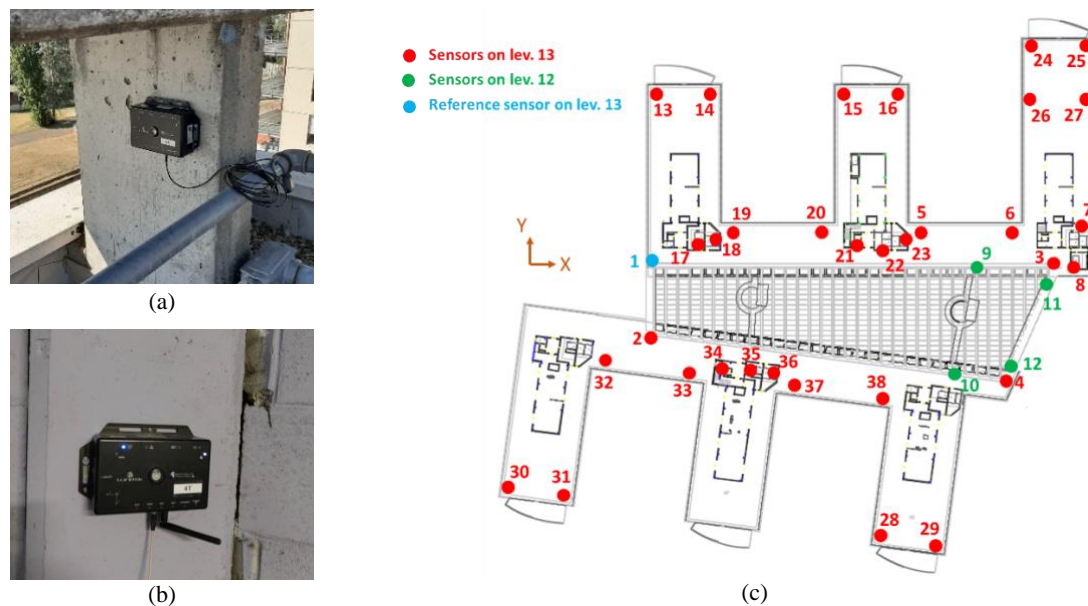


Figure 3. Experimental dynamic tests: installation of sensors on the parapets (a) and on the columns (b); sensors layout including all measurement points considered in the five setups (c).

Considering the large dimensions and the complexity of the building, to cover the major part of the structures and acquiring sufficient data to measure the dynamic response, 5 different measurement setups were implemented. Investigation on the interaction between the two sides of the structure (Side 1 including blocks D, E, F, G, H and Side 2 including blocks K, L, M, N showed in Figure 1b) connected by wooden beams was one of the goals of the study, therefore, in the design of the 5 setups, it is considered as an important parameter. Level 13 or the roof was the main floor for installing the sensors, however, some sensors were used in level 12 to analyze the dynamic behavior of the pedestrian bridges located in the central area which connect Side 1 and Side 2 on levels 10-12.

All measurement points considered in the five setups are depicted in Figure 3c. To normalize all the acquired data, there is a need for some reference sensors. The sensor in position 1 has been considered for this purpose. In each setup, measurement with a sampling frequency of 250 Hz was started after synchronizing all the sensors in the wireless network using the GNSS receiver. To estimate a primary evaluation of the dominant frequencies, the PSD of the time series data has been realized, and using a simple peak picking technique, most observed peak points in these PSDs were in the ranges 2-3 Hz and 8-9 Hz. Using the FDD method by ARTeMIS software, the acquired data were analyzed.

4. Structural identification and model updating

To have an overall understanding of the dynamic behavior of the building, a model of the hospital including the monitored structure has been implemented in ProSap software (Figure 4). The finite element model was obtained by merging 17 models of structural blocks which were implemented separately. The type of structures are concrete frames and only the middle part with the transparent roof has wooden beams. One of the main goals was to assess the effect of beams to cause interaction between the side with blocks D, E, F, G, and H (Side 1) and the across the part with blocks K, L, M, and N (Side 2). With enough vibration data acquired from both sides in one setup, the modal shapes and frequencies can be identified, and the dynamic response of all blocks can be observed. In Figure 5, results of mode shapes from both the finite element model and FDD have been shown. The finite element model was updated using the modal results by measurements. Most significant changes to update the model was related to the connections between the blocks. Also having numerous elements, many local modes were observed, and considering the sensors setups, those modes could not be presented in the measurements, therefore, with some realistic modification on them, these local modes were eliminated from the results to update the model.

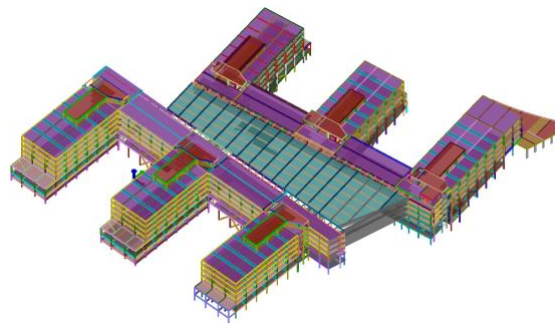


Figure 4. Finite element model of the hospital building implemented in ProSap software.

5. Frequency identification based on acceleration PSD

As mentioned before, the hospital building, besides having some active mechanical equipment, is large and complex, and it is expected to observe different dynamic behavior in various measured zones. Therefore, based on the location of the sensors and the similarities in the geometry and proximity of the sensors to the mechanical equipment, the sensors have been classified into different groups to have a better observation of the dynamic response.

To investigate that, the power spectral density of the measured responses in five setups has been used. By finding the points where peaks happen in PSD, we observe the frequency contents of the structural response under environmental conditions, searching for excitation loads with specific frequencies. The node numbers in the following results are based on the numbering in Figure 3c. In the first observation, four nodes have been chosen to possibly determine structural frequencies and frequencies associated with mechanical equipment. The sensors of nodes 7 and 17 are installed in zones that could be influenced by the harmonic forces of elevators. On the other hand, sensors of points 24 and 31 were distinct from these zones, and detected frequencies most likely would be resulted from structural characteristics. In Figure 6 the PSDs for all these nodes in the x -direction have been presented. Looking at Figure 6, it can be realized that in the two first nodes which are closer to the zones with machinery, there are specific frequencies (represented by lines), that are not present in nodes 24 and 31.

Considering this point that the two last nodes are distant from the zones with mechanical equipment, it can be assumed that their measured frequencies are structural responses not induced by machinery. On the other hand, for the two first points, a significant influence of other vibrations can be observed. Table 1 presents the frequencies identified only in nodes 7 and 17 and not visible in the PSDs of nodes located in other parts of the structure.

Using Table 1, frequencies (almost similar) in both zones with machinery can be observed and these are the points that do not show peaks in PSD in the other zones. For more information about the modal response of the structure, in Table 2, the results for other nodes have been reported. Using these tables, similar peak points that are repeated in every different zone can be realized and they can be an indication of structural vibrations not influenced by the machinery. As can be seen, there are just a few frequencies (colored) that are not repeated in all the zones.

For investigating the similarities in the response of Side 1 and Side 2 connected by wooden beams on the roof level and by pedestrian bridges on lower levels, the best option is to analyze data coming from sensors installed in nodes 1, 2, 3, and 4. In Table 3, the first five observed peaks of the PSD of these sensors have been reported. By referring to Table 3, there is no correspondence between the frequencies of Node 1 and Node 3 in the x -direction. On the other hand, for the y direction, which is aligned with the longitudinal direction of the wooden beams, all the values for Node 1 and Node 3 are very close. The same results were observed for Node 3 and Node 4.

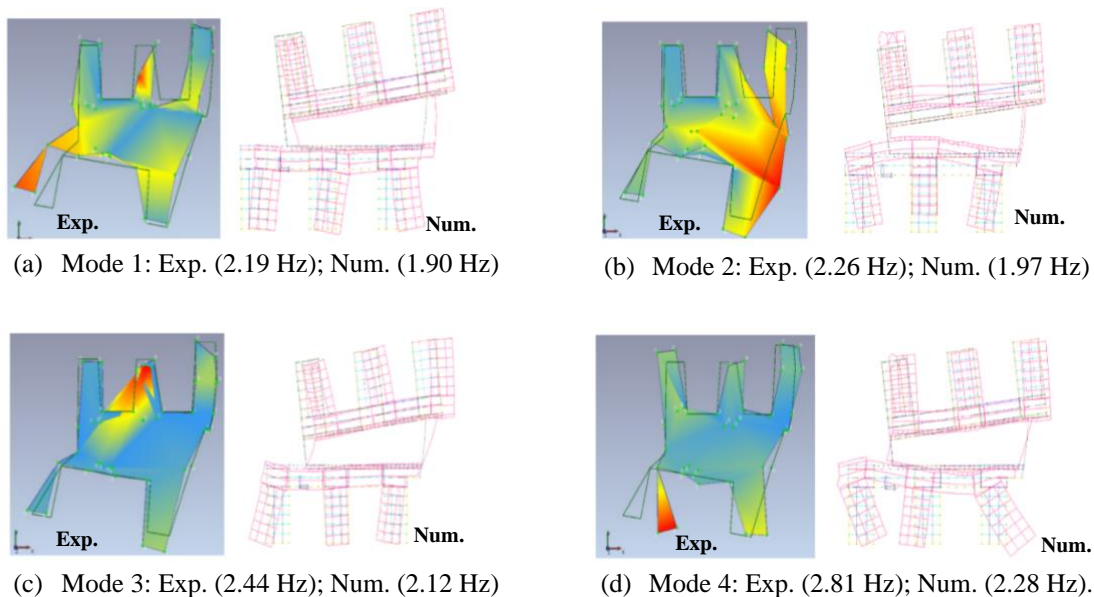


Figure 5. First four mode shapes of the structure by operational modal analysis (Exp.) and numerical modal analysis (Num.).

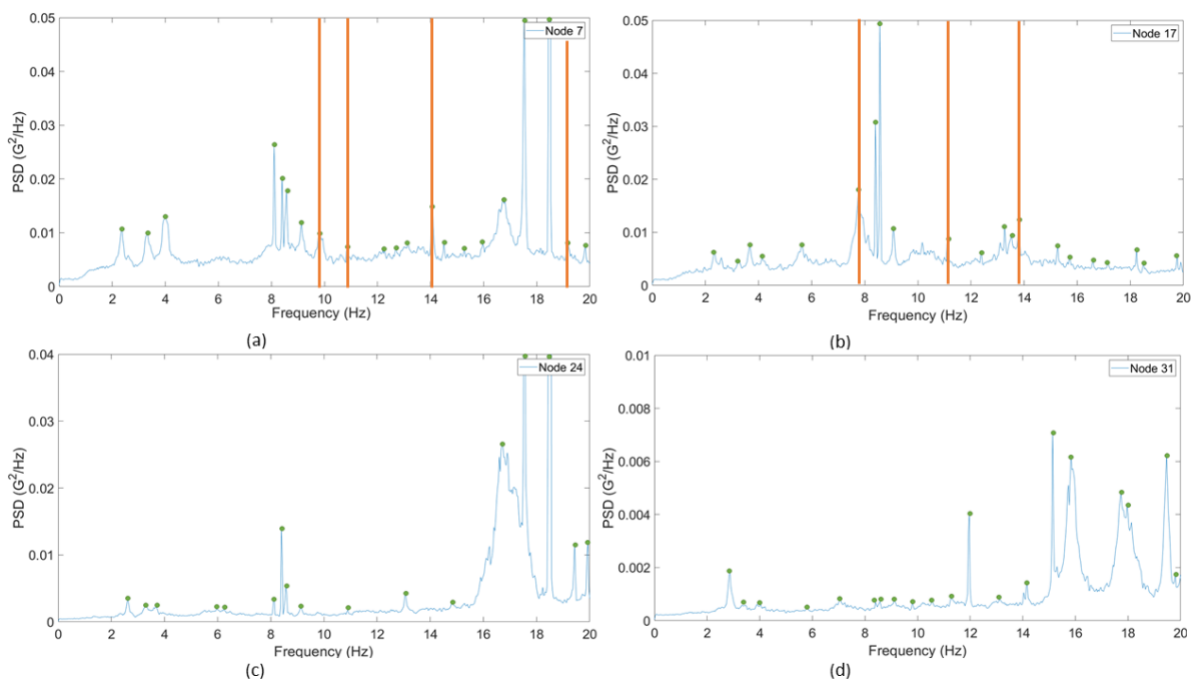


Figure 6. Peak points of PSDs in node 7 (a), node 17 (b), node 24 (c), node 31 (d).

Table 1. Observed peak points in nodes 7 and 17 related to the equipment.

	f_1	f_2	f_3	f_4
Node 7	9.80	10.86	14.03	19.16
Node 17	7.86	11.06	13.80	

Table 2. Frequencies (Hz) of peak points (nodes with long distance from machinery).

	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8	f_8	f_9	f_{10}	f_{11}	f_{12}
Node 1 (reference)	2.33	3.27	3.67	5.63	7.03	8.13	8.57	9.13	10.20	11.13	12.03	13.10	14.03
Nodes 19, 20, 5, 6	2.33	3.23	3.93	5.90	6.70	7.13	8.13	8.40	8.9	9.06	10.16	11.13	12.26
Nodes 32, 33, 37, 38	2.33	3.26	3.93	5.83	7.10	8.23	8.40	9.13	9.76	10.26	10.56	11.26	12.03
Nodes 24, 31	2.60	3.33	4.03	5.76	7.06	8.40	8.56	9.13	9.76	10.53	11.26	13.1	14.06

Table 3. Observable frequencies (Hz) in nodes 1,2,3,4 (group 4).

Node 1	X	2.37	2.60	3.23	3.60	4.03	Node 2	X	2.50	3.13	4.13	7.93	8.40
	Y	2.20	2.97	5.33	7.07	7.67		Y	2.30	2.97	5.27	7.07	7.93
Node 3	X	1.40	4.80	8.10	8.40	8.57	Node4	X	2.80	3.13	3.83	4.20	5.90
	Y	2.30	2.50	3.37	4.00	4.60		Y	2.30	2.50	3.27	4.10	4.60

Despite the differences in peaks in different blocks, those which are connected by the roof show similar responses in the longitudinal direction of the beams of the roof and this can be an indication of the interaction caused by these wooden beams. Observing the sensors at different points, some almost similar frequencies in all PSDs like 2.33, 3.33, 4.00, 5.66, 8.40, 8.56, 9.13, and 11.26 Hz can be picked. But also, some frequencies could be detected only in the blocks with machinery (Table 1) including 9.80 and 19.16 Hz. However, using these observations on PSD, we can have an overall idea of the frequencies that are presented because of machinery and the ones that resulted from the structure itself, but it still cannot completely represent accurate results. Also, it should be mentioned that this observation has been done for a range of frequencies less than 20 Hz and some of them up to 25 Hz, in this part.

6. Dynamic response prediction by neural network

For more investigations on measured accelerations affected by the vibrations of air conditioning systems and elevators, a neural network approach was adopted to compare the experimental accelerations with the ones predicted by a neural network algorithm trained on the numerical results obtained by FEM analysis. A time series dynamic analysis, including 30 modes with a frequency content of up to 36 Hz, was implemented by considering white noise as ambient load. Acceleration responses in the y-direction for nodes 1, 2, 17, and 18 were used as input data for training four different neural networks. Using the structural response under white noise excitation allows to obtain a trained model which can predict the response under ambient vibration and to provide higher prediction error when the tested signals are affected by colored noise. Error increasing can identify which measured structural vibrations are altered by the frequencies of elevators and air conditioning systems. A neural network model has been implemented in MatLab environment by using the available Neural Network toolbox and the Levenberg–Marquardt training algorithm [10] which provided good results for both numerical and experimental bridge data as discussed in [11]. Also, this model proved to be efficient for ambient vibration prediction of a cable-stayed bridge as investigated in [12]. The Nonlinear auto-regressive (NAR) network model was implemented to forecast future values of a time series from past values of the actual time series. The network architecture was designed with 10 hidden layers and 10 input nodes. The number of input nodes is also called *time delay* because it corresponds to the number of past values used to predict the future value of the acceleration time series. The Levenberg–Marquardt optimization was used to train the network and update its weight and bias values. After obtaining the four networks trained for each of the considered nodes, they were tested on their corresponding experimental data by evaluating their prediction error for each time step (see Figure 7 where 2 seconds intervals are reported for each node). As the error amplitude is one order lower than the measured time series, neural network predictions turned out to be effective in forecasting each time step value based on the knowledge of ten past values of the experimental accelerations. Furthermore, the Normalized Root Mean Squared Error (NRMSE) was evaluated for each time series prediction (see Table 4). It can be noted that, in the experimental case, for Node 1 and 2 it resulted to be one order lower than NRMSE evaluated for Node

17 and 18 which belong to Group 5 representing the zones closer to mechanical devices. Furthermore, for Node 17 and 18 experimental RMSE is higher than FEM RMSE. Therefore, the evaluation of the performance of the network prediction through the estimation of NRMSE could be an effective indicator in determining the influence of the air conditioning system and elevator vibrations on acceleration signals acquired. Finally, in Figure 8, the Fast Fourier Transform (FFT) is reported for NAR prediction based on both FEM and experimental signals. These results show that the predicted signal frequency content matches with one of the effective signals (FEM and experimental) and it cannot be exploited for the evaluation of the influence of machinery vibrations.

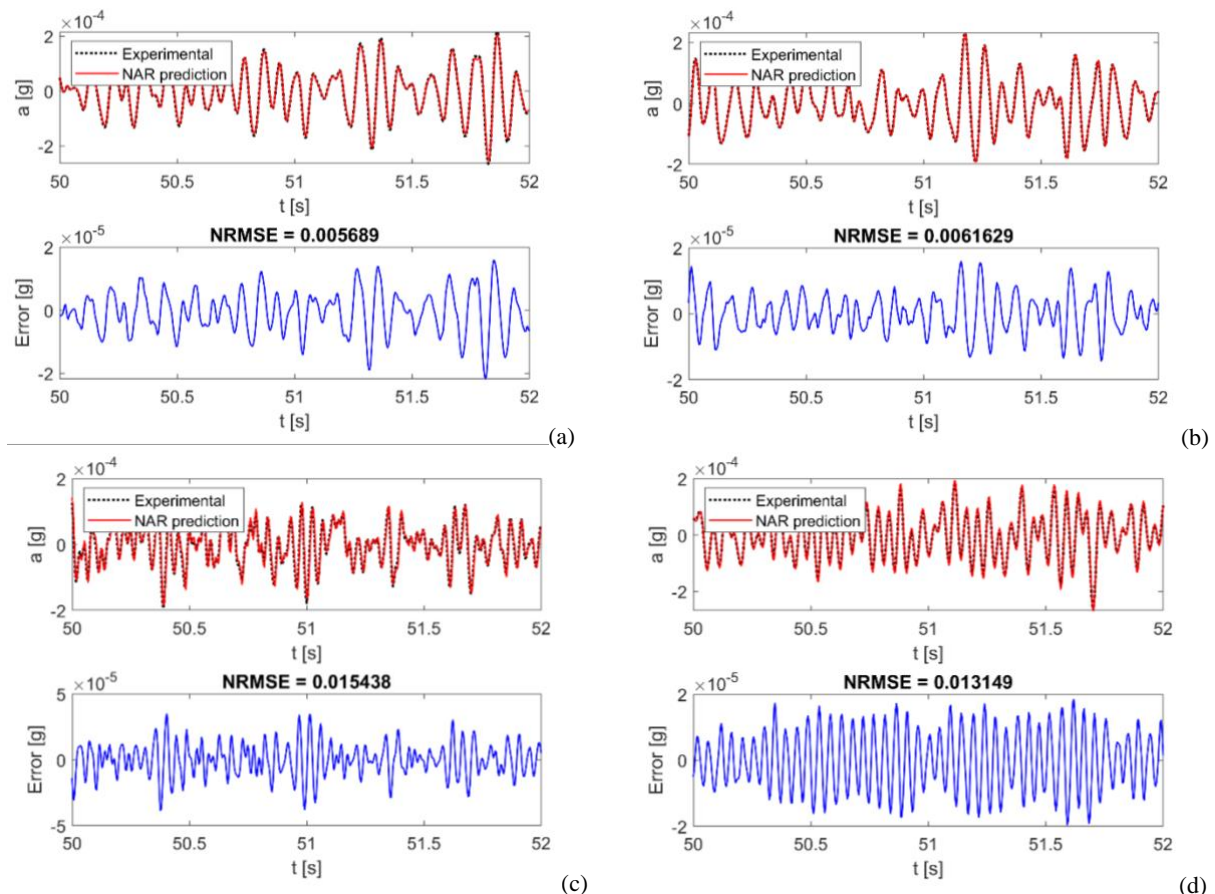


Figure 7. Acceleration time series (y-direction) experimentally measured compared with accelerations predicted by the NAR algorithm and evaluation of error prediction for Node 1 (a), Node 2 (b), Node 17 (c), Node 18 (d).

Table 4. NRMSE of the network prediction referred to experimental data.

	Node 1	Node 2	Node 17	Node 18
NRMSE (FEM – training)	0.018016	0.013475	0.013937	0.007986
NRMSE (Experimental – test)	0.005689	0.0061629	0.015438	0.013149

7. Conclusions

This study aims to investigate the possibility of identifying the natural frequencies of the structure and the frequencies induced by mechanical equipment which is located in different zones of the investigated building. The case study is the “Cardinal Massaia” hospital in Asti in Italy. The complexity and large dimensions of the structural blocks made the implementation of the dynamic tests challenging and five setups were used to provide sufficient data to understand the dynamic behavior of the different parts of the building.

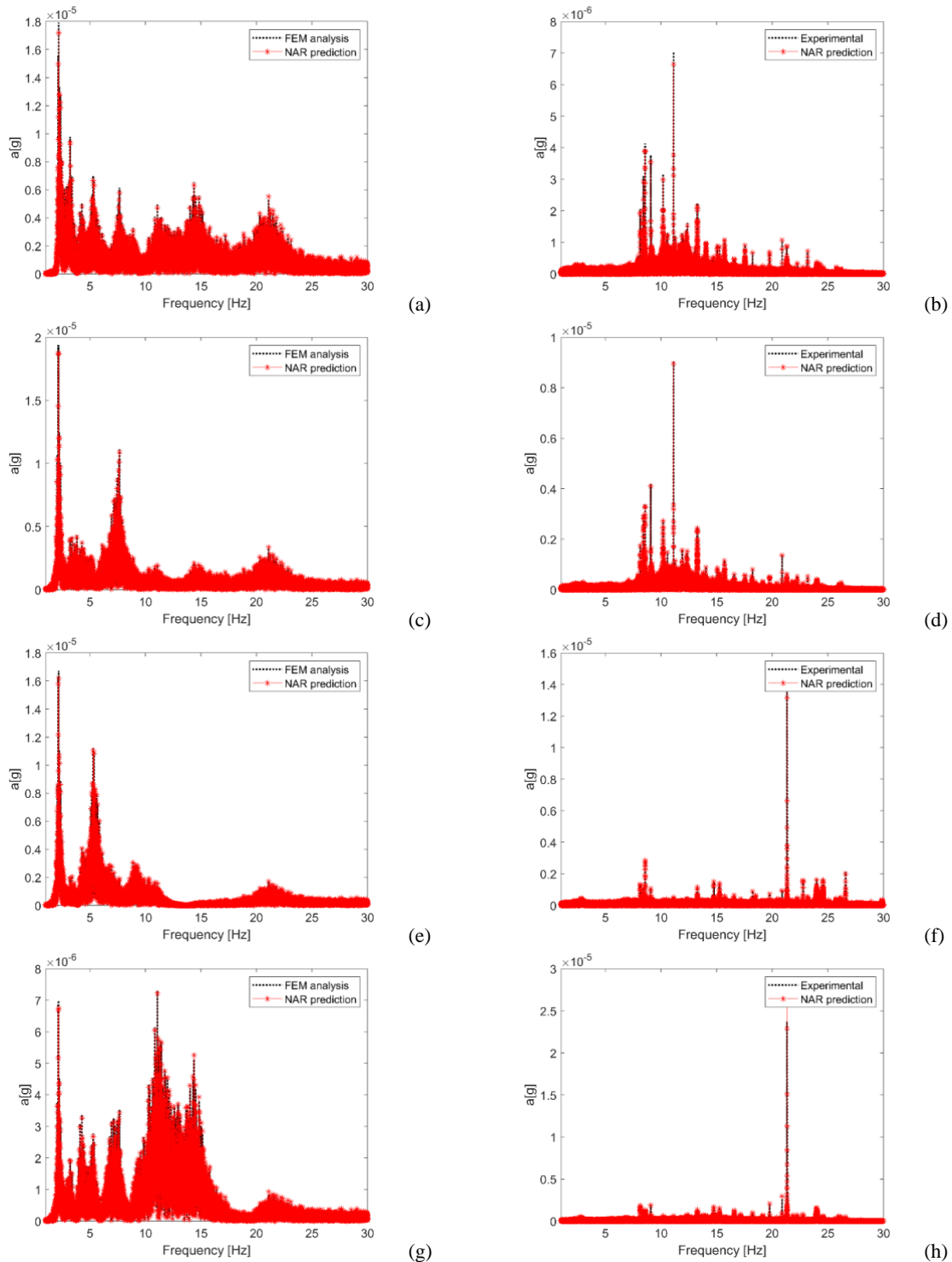


Figure 8. Comparison between FFT overlapping (for accelerations in the y-direction) of FEM/NAR prediction on the left and Experimental/NAR prediction on the right for Node 1 (a,b), Node 2 (c,d), Node 17 (e,f), Node 18 (g,h).

First, an operational modal analysis was conducted to identify frequencies and mode shapes of the structure, and a FEM model was implemented and updated according to experimental data. Then, depending on the zone of their installation, the sensors were classified into several groups, and

using the PSD of the acceleration signals, a primary observation of the differences and the influence of the machinery have been described. Finally, FEM results of acceleration time series response under white noise excitation were used to train a neural network for further investigation on experimentally measured accelerations. The evaluation of the performance of the network prediction through the estimation of NRMSE proved to be a suitable indicator in determining the experimental signals affected by the influence of the air conditioning systems and elevators.

Acknowledgments

This research was in part sponsored by the NATO Science for Peace and Security Programme under grant id. G5924 and by ERIS Project supported by LAZIO INNOVA (n. G09493 - PO FESR LAZIO 2014/2020).

References

- [1] C. Ventura and R. Brincker, *Introduction to Operational Modal Analysis*. Wiley, 2015.
- [2] V. Gattulli, A. Cunha, E. Caetano, F. Potenza, A. Arena, and U. Di Sabatino, "Dynamical models of a suspension bridge driven by vibration data," *Smart Struct. Syst. An Int. J.*, vol. 27, no. 2, pp. 139–156, 2021.
- [3] C. Rinaldi, J. Ciambella, and V. Gattulli, "Image-based operational modal analysis and damage detection validated in an instrumented small-scale steel frame structure," *Mech. Syst. Signal Process.*, vol. 168, p. 108640, 2022.
- [4] B. Xu, Z. Wu, G. Chen, and K. Yokoyama, "Direct identification of structural parameters from dynamic responses with neural networks," *Eng. Appl. Artif. Intell.*, vol. 17, no. 8, pp. 931–943, 2004.
- [5] C. S. Huang, S. L. Hung, C. M. Wen, and T. T. Tu, "A neural network approach for structural identification and diagnosis of a building from seismic response data," *Earthq. Eng. Struct. Dyn.*, vol. 32, no. 2, pp. 187–206, 2003.
- [6] N. Jacobsen, "Aalborg Universitet Eliminating the Influence of Harmonic Components in Operational Modal Analysis Eliminating the Influence of Harmonic Components in Operational Modal Analysis Brüel & Kjær Sound & Vibration Measurement A / S NOVI Science Park , Niels Je," 2007.
- [7] S. V. Modak, "Separation of structural modes and harmonic frequencies in Operational Modal Analysis using random decrement," *Mech. Syst. Signal Process.*, vol. 41, no. 1–2, pp. 366–379, 2013.
- [8] C. Devriendt, G. De Sitter, S. Vanlanduit, and P. Guillaume, "Operational modal analysis in the presence of harmonic excitations by the use of transmissibility measurements," *Mech. Syst. Signal Process.*, vol. 23, no. 3, pp. 621–635, 2009.
- [9] R. Brincker, L. Zhang, and P. Andersen, "Modal identification of output-only systems using frequency domain decomposition," *Smart Mater. Struct.*, vol. 10, no. 3, pp. 441–445, 2001.
- [10] H. Yu and B. M. Wilamowski, "Levenberg--marquardt training," in *Intelligent systems*, CRC Press, 2018, pp. 12–16.
- [11] A. C. Neves, I. González, R. Karoumi, and J. Leander, "The influence of frequency content on the performance of artificial neural network--based damage detection systems tested on numerical and experimental bridge data," *Struct. Heal. Monit.*, vol. 20, no. 3, pp. 1331–1347, 2021.
- [12] M. De Iuliis, C. Rinaldi, F. Potenza, V. Gattulli, T. Toullier, and J. Dumoulin, "Ambient vibration prediction of a cable-stayed bridge by Artificial Neural Network" in *Data Driven Based Methods for Civil Structural Health Monitoring and Resilience: Latest Developments and Applications*, CRC Press, 2023, pp. 242-257.