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Research Article

Experimental and numerical dynamic identification in an RC tower

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Abstract: In this study, the dynamic behavior of one of the prominent structures in Istanbul, Üsküdar Observation Tower (UOT) has been investigated. The structural system of the tower is formed by a reinforced concrete circular tube having 2.8 meters outside diameter with a 40 centimeter thickness. By referring to the ground level, it starts from -18.2 meter due to five basement stories around the tower and its height is 44 meters. Two reinforced concrete floors were partially hanged over at 36 meter and 40 meter in height. The tower has an independent structural system from the ground level but a non-structural cladding assembly connects it to an adjacent building in the complex. With the mentioned structural features, Ambient Vibration Survey (AVS) was utilized to obtain the dynamic characteristics of UOT by Peak Picking (PP) method. The obtained dynamic properties were discussed with the peculiarities of UOT. While the performed analysis revealed the ineffectiveness of the adjacent building and the underground stories in the dynamic behavior of UOT, the torsion action of the floors has been noted. A numerical model has also been constructed to obtain the dynamic characteristics of UOT by Finite Element Analysis (FEA). The model calibration required to increase the code-based modulus of elasticity of the concrete by 23% for pairing the experimental and numerical dynamic properties. The reasons of the increase and the correlation between AVS and FEA were discussed.

Keywords: Ambient vibration survey, operational modal analysis, tower, system identification, mode shape.

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1. Introduction

This study applies experimental and numerical methods to determine the structural behavior of Üsküdar Observation Tower (UOT). In general, high-rise buildings, TV/telecommunication towers, bell towers, minarets, observation towers, cooling chimneys are slender structures which are classified as tower in the construction industry. The analysis of these structures comprises different levels of complexity according to their structural system but special attention is usually paid due to their functional importance, limited number, and historical or moral assess. For this reason, many scientific works have been conducted for the dynamic response of tower type structures. The vast literature has been tightened up by excluding high-rise buildings and cooling chimneys from the concern of this study due to their different structural system from UOT.

Recently, dynamic testing was used by many researchers in similar types of structures due to its practical application and valuable results. Dominant frequencies of Guangzhou TV Tower were identified by Chen et al. (2011). Acceleration records, taken through the height of the tower during ambient conditions, typhoon, and earthquake excitation were used to extract the dominant frequencies and mode shapes. Milad TV Tower in Tehran is another structure studied with an ambient vibration survey (Amiri and Yahyai, 2013). The authors concentrated on the damping ratios of the modes. In another study, Ribeiro et al. (2019) evaluated the dynamic effects induced by the wind on Monte da Virgem telecommunication tower in Porto with a structural health monitoring system.

Bell towers are also studied extensively due to their historical importance. D'Ambrisia et al. (2012) used ambient vibration survey results to tune the numerical model of the medieval civic tower of Soncino to perform nonlinear analysis. San Nicola bell tower in Valencia (Ivorra and Pallares 2006), the Hagia Sofia bell tower in Trabzon (Bayraktar et al. 2009), and the Saint Andrea bell tower in Venice (Russo et al. 2010) are the others studied by vibration surveys for their dynamic characteristics. Gentile and Saisi (2007) applied an ambient vibration-based procedure to assess the damage scenario of the bell-tower of the Monza Cathedral. Instead of vibration-based system identification, Vidiella et al. (2019) used geometric monitoring technique for the leaning tower of Santa María la Blanca church in Agoncillo in Spain.

Minarets can also be categorized as tower types of structures with their slender body. They have been studied especially in Turkey due to their historical importance and past failure phenomenon due to seismic actions. Serhatoğlu et al. (2019) studied the dynamic characteristics of eighteen Ottoman minarets with experimental and numerical methods. Two empirical formulas were suggested to estimate the first natural period of similar minarets. For the seismic analysis of historical minarets, the importance of AVS has been underlined by different studies (Bayraktar et al. 2011; Hökeleki et al. 2020).

UOT became one of the landmark structures in the Anatolian side of Istanbul with its distinguished architecture and the huge number of guests, visiting the science complex. Starting from the foundation level, its height is 58.20 meter, but its 18.20 meter remains underground level and surrounded by the basement floors of the complex. After ground level, its structural system is separated from other structures in the complex. However, its façade cover connects it to a three-story neighboring building in the complex. These suspensive features make AVS preferred to extract and evaluate its dynamic features since the method is an experimental technique used to reveal the dynamic properties of existing structures. Thereby the role of the adjacent building and façade covering into the dynamic behavior of UOT and the participation of the underground part of the tower into its dynamic properties were revealed. A numerical model was also constructed to obtain the dynamic properties of the tower by Finite Element Analysis (FEA). The obtained results were compared to each other. Hence structural behavior of UOT was well-understood and a model calibration was performed. The code-based modulus of elasticity of the concrete used in the numerical model has been increased by 23% for pairing the experimental and numerical dynamic properties. The reasons of the increase in the modulus of elasticity of concrete was evaluated and justified. The correlation between AVS and FEA proved the efficiency of both techniques to search about the dynamic behavior of existing structures. Before presenting the details of AVS, structural features of UOT have been detailed in the next heading.

2. Üsküdar science complex and the studied tower

Üsküdar Science complex was constructed between 2012 and 2016 with a planetarium, exhibition hall, research center, and observation tower (Figure 1). The structural system of the complex was mainly composed of reinforced concrete except for the dome of the planetarium. In total, the project comprises about 31.000 m2. According to the documents obtained from the municipality of Üsküdar, the architectural projects were prepared by Tures Ltd. Sti while the structural design was carried by Timka Ltd. Sti.

The observation tower of the complex has a circular hollow cross-section with a 2.80 meter outside and 2.00 meter inside diameter. The hollow gap is used for an elevator system. A stair system also surrounds the circular cross-section from its outside by a helical geometry. There are two slabs at the top region forming a closed observation room at a height of 36 meter and a terrace at a height of 40 meter measured from the ground level. Figure 2 summarizes the construction scheme of the tower with the mentioned structural system.

Figure 1. Üsküdar Science Complex with Üsküdar Observation Tower, UOT.

The façade of the tower consists of composite cover material carried by a two-layer steel structural system, formed by generally 3 cm by 5 cm hollow steel sections. The first layer surrounds the stair of the tower with vertical orientation, while the second layer forms the external geometry of the tower. These layers are also connected by horizontal elements. The stability of the façade system was formed by three associates; (i) the first layer was connected to the stair system of the tower, (ii) the second layer was hanged on the slabs of the tower, (iii) both layers sit on the slab on the ground level. However, due to the entrance of the tower and the neighboring building, the structural system of the façade does not reach to the ground level. In this region the façade system is directly hanged on the stair system and slabs of the tower. Figure 3 shows the façade system of UOT.

Figure 2. Construction progress of UOT.

Figure 3. Structural system of the façade of UOT.

Figure 4 shows the structural details of two slabs of the tower. They were hanged on the tower's body by a 120 cm thick reinforced concrete plate which partially surrounds the tower body due to the stair system. The ratio of the hanging distance to the whole perimeter of the tower body is 142/360. Reinforced concrete beams with different cross-sections were used to enlarge the area of the slabs. The thickness of the plate on these beams is 10 cm.

The foundation of the UOT was constructed with the foundation of the whole complex. For this reason, the body of the tower starts from -18.20 meter measured from the ground level. Through this portion, the tower is surrounded by five basement floors of the complex. After the ground level, the structural system of the tower is completely separated from the complex. The mentioned characteristics of the tower make its structural behavior worth being the subject of this study and AVS was conducted to determine its dynamic features.

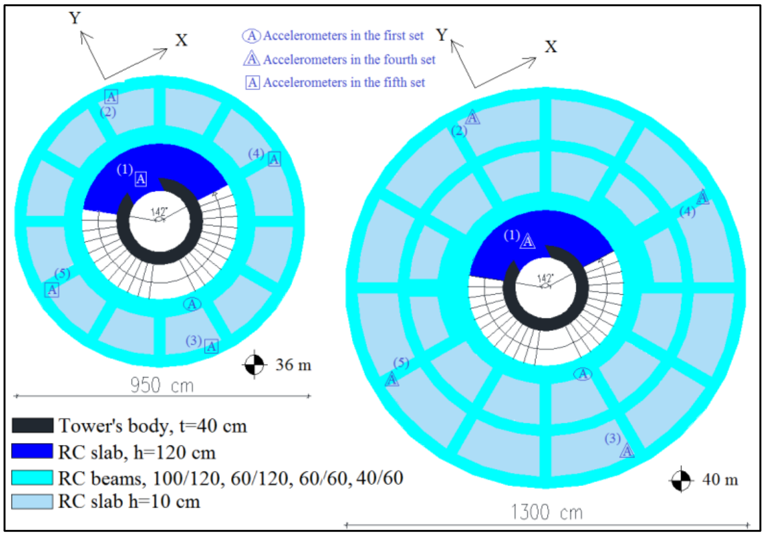

Figure 4. Slab systems of UOT.

3. Ambient vibration survey and extraction of dynamic properties

AVS of the building was performed on a usual day when the exhibition hall of the complex was visited by groups of primary school students but the tower was closed to any human traffic. Five SARA, Acebox, force balance accelerometers, with three sensors, oriented along with two orthogonal horizontal directions and one vertical direction, were used for data collection. Each accelerometer has its own data storage unit and works separately without a particular data acquisition system. The required synchronization for the dynamic identification is provided by a global positioning system antenna. The linear acceleration ranges of each sensor is ±2 g, and its noise floor is less than 20 ng/√Hz. The recording was performed with 200 samples per second.

For the dynamic identification of the tower, five sets of measurements were taken. Three of them were planned to identify the mode shapes of the tower through its height. The connection between the tower and the neighboring building was also evaluated by locating one of the accelerometers on the neighboring building. In these measurements, one of the accelerometers was used as a reference sensor and located on the terrace floor of the tower (+40 m), while the other four were travelled through the height of the tower by locating them on the horizontal platform of its stair system. The horizontal axes of the accelerometers were oriented along with the X and Y axes shown in Figure 4. Figure 5 (a) illustrates the measurement points on three sets of measurements. The fourth and fifth measurement sets are independent of each other and focused on the vertical mode shapes of the slab systems at +40 m and +36 m altitude respectively. One of the five accelerometers was located in front of the elevator door while the others were located on the exterior sides shown in Figure 4.

A brief look, at the vast literature on the modal identification methodologies, demonstrates that the techniques can be divided into two groups as the methods developed in the time domain and the methods used in the frequency domain (Gaylard 2001; Li and Shen 2012; Ibrahim 1986; Brincker et al 2000). The method, known as Peak Picking (PP) can be shown as the easiest and one of the most frequently used method since the representation of the signals in frequency domain exhibits the dominant frequencies of the structure (Consuegra and Santos 2015; Aras 2018; Aras and Karapınar, 2021). Besides, the evaluation of the power of the signals at a specified frequency results in modal displacement forming its mode shapes such that the square root of the power at a specific frequency is proportional to the modal displacement (Inman 2013). As a result, recorded signals from different locations in a structure can be used to extract its mode shapes composed according to measurement points. PP method was used in this study by using Matlab software (2012). No filtering was applied to the data, and modal identification was performed between 0 and 10 Hz, which is adequate for the identification of the studied structure.

As it is seen in Figure 5 (a), acceleration measurement has been performed on thirteen different locations through the height of the tower. The frequency domain representation of six of them, recorded at different levels are shown in Figure 6 for X and Y directions. The horizontal axis of the graphs, which represents the frequency value, is shown on a logarithmic scale to increase the visibility. The lack of frequency peaks for the signals taken from the ground level and the other levels under this demonstrates that the underground part of the tower does not participate in its dynamic behavior within the specified frequency range.

Starting from the ground level, upper measurement locations sense increasing signal power at 0.53 Hz in the Y direction and 0.62 Hz in the X direction. Modal displacements at the specified dominant frequencies are obtained by scaling the square root of the power of each signal to that of a reference accelerometer which exists in all three sets of measurements. Finally, the modal displacement of the top level which again specifies the reference level is set to unity for mode normalization. The obtained mode shapes for the dominant frequencies of 0.53 Hz and 0.62 Hz are shown in Figure 5 (b) and Figure 5 (c), respectively. It is seen that these translation modes have almost identical shapes. The circular main body of the tower makes the modes identified in two orthogonal directions similar to each other, while the heterogeneity in the material, existing elevator door openings, neighboring building, and the façade cover may differ the dominant frequencies in X and Y directions.

The frequency domain representation of the signals recorded from the slab systems at 36 meter and 40 meter showed that the dominant frequency forks out into two. Along with the Y direction, next to the main dominant frequency 0.53 Hz, a weaker dominant frequency appears with 0.62 Hz. Similarly, along with the X direction, 0.62 Hz dominant frequency is accompanied by 0.53 Hz secondary dominant frequency. This reciprocity proves that the slabs' modal displacements are bi-directional. For this reason, in these translation modes, the slabs show torsional behavior. The partial and unsymmetrical connection of the slabs to the main body of the tower is the key reason behind the observed torsion actions.

According to Figure 6, other frequency peaks are seen at 2.46 Hz and 4.27 Hz in the X direction and 3.9 Hz in the Y direction. The peaks at 3.9 Hz and 4.27 Hz are probably representing the double curvature mode since they are more powerful at the mid-height vicinity of the tower. More valid interpretation would be done with the numerical dynamic identification pursued in the next headings.

To evaluate the connectivity between the UOT and neighboring building, the acceleration record taken from the neighboring building is analyzed. As seen in Figure 7, the dominant frequencies of the neighboring building are different from those obtained for UOT. Therefore, it can be concluded that there is no effective connection between UOT and the neighboring building.

For the identification of slab systems' dynamic modes, two separate sets of measurements have been performed. The locations of the accelerometers are shown in Figure 4 for each slab. The recorded vibrations have been analyzed in X, Y, and Z (vertical) directions by using the PP technique. The analyses of the records along with the X and Y directions confirmed the aforementioned dominant frequency values, while the analyses of the records along with the Z direction gave additional dominant frequencies. Figure 8 and 9 shows the frequency domain representation of the vertical signals recorded on the numbered points of each slab located at 36 meter and 40-meter height, respectively. As seen in Figure 4, points (1), (2) and (3) are on the same axis, directed along with Y axis. The first dominant frequency, 0.53 Hz, detected along with Z axis on these points coincide the one determined as the dominant frequency of the tower for the translation mode in Y axis. A similar interpretation is valid for the points (4) and (5). The first dominant frequency determined in Z direction, 0.62 Hz, for the points (4) and (5) coincides the dominant frequency of the mode shape in with X direction, along which the points (4) and (5) lie. These matches simply prove that; the first vertical dominant frequencies are related to the translation modes of the tower.

The second dominant frequency was determined as 3.88 Hz for the points (1), (2) and (3), while it is 4.24 Hz for the points (4) and (5). The frequencies, identified for the signals recorded at 18 m and 30 m elevation are so close to those values, while they diminish at floor levels. Therefore, these frequencies point to double curvature modes of the tower in which the maximum modal displacement is seen around mid-height and top modal displacement is seen with a negative sign. The same interpretation can also be made for the third dominant frequency seen in Figure 8 and Figure 9.

The analyses of the vertical signals recorded on the slabs of the tower showed that each mode shape contains not only the modal displacements on the horizontal directions but also those in vertical directions on the slabs of the tower. The cantilever slab systems of the tower can be shown as the main reason for this result.

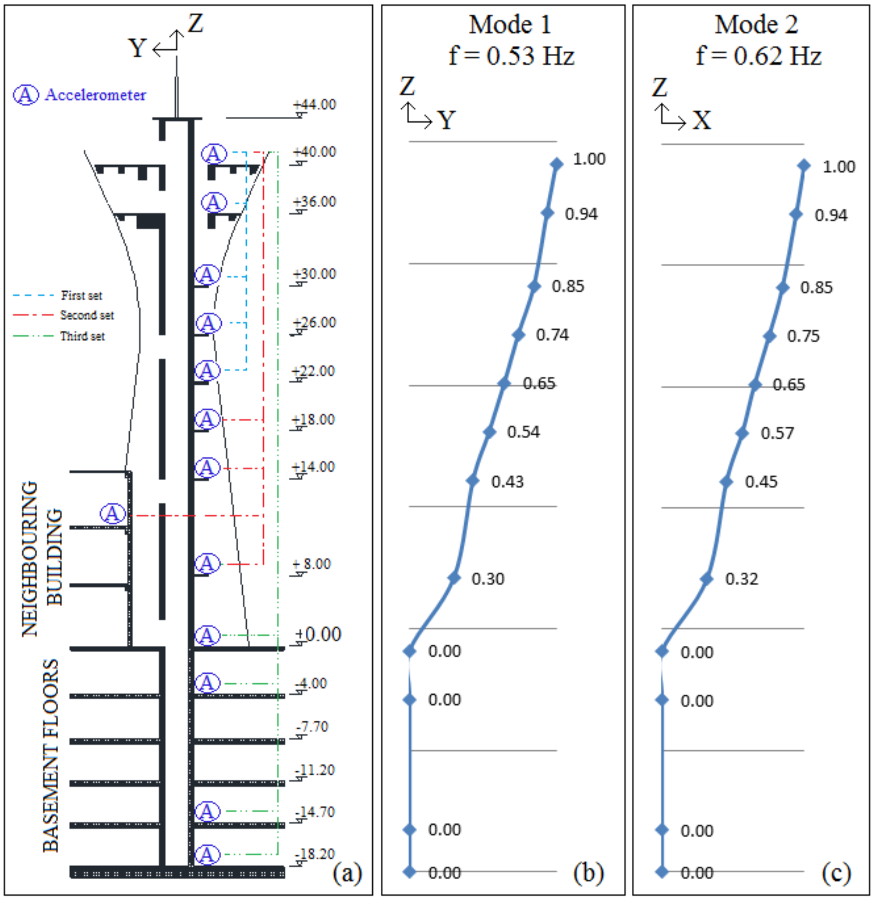

Figure 5. AVS measurement locations and obtained mode shapes for UOT.

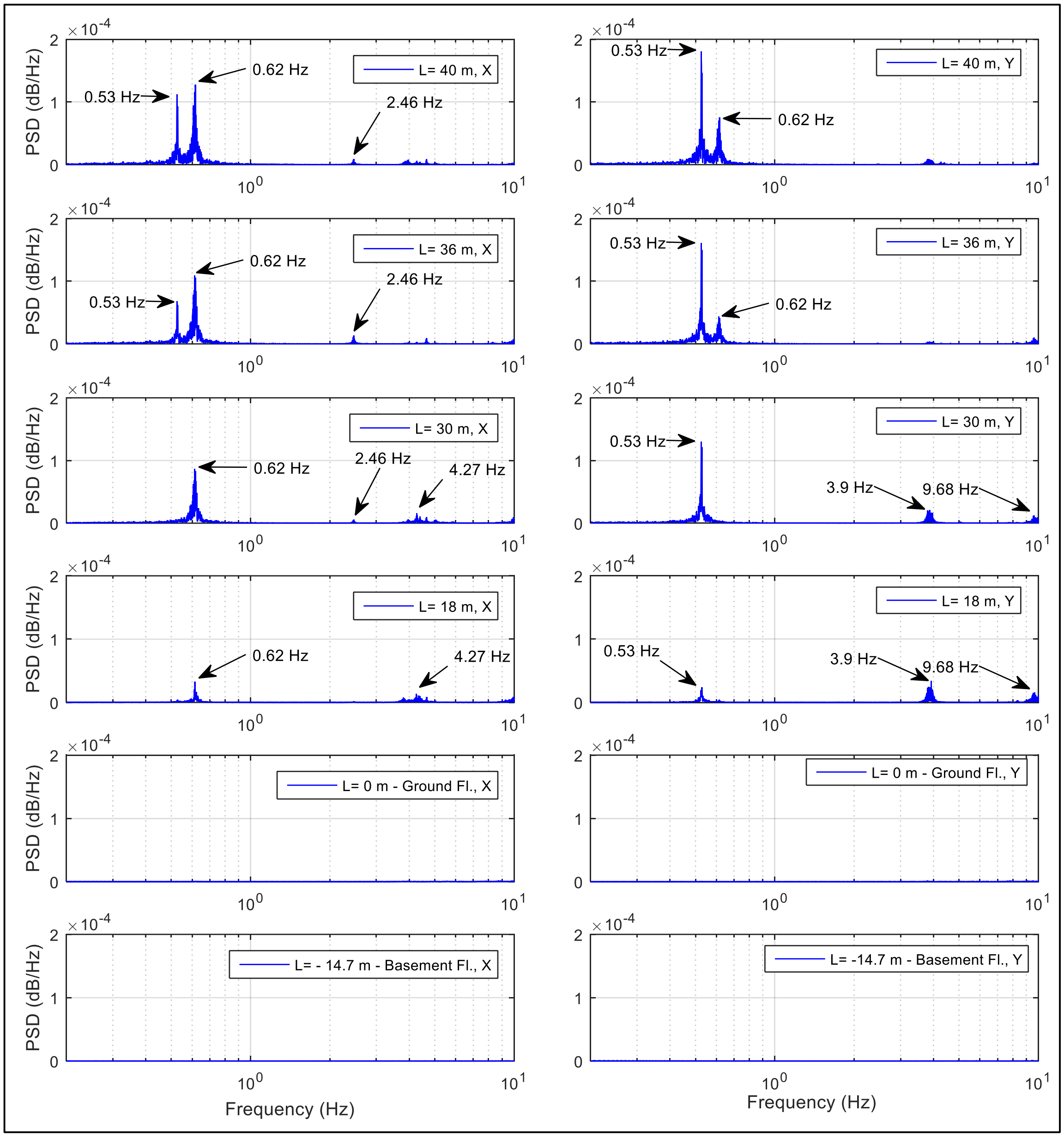

Figure 6. Frequency domain representation of the signals taken through the height of UOT.

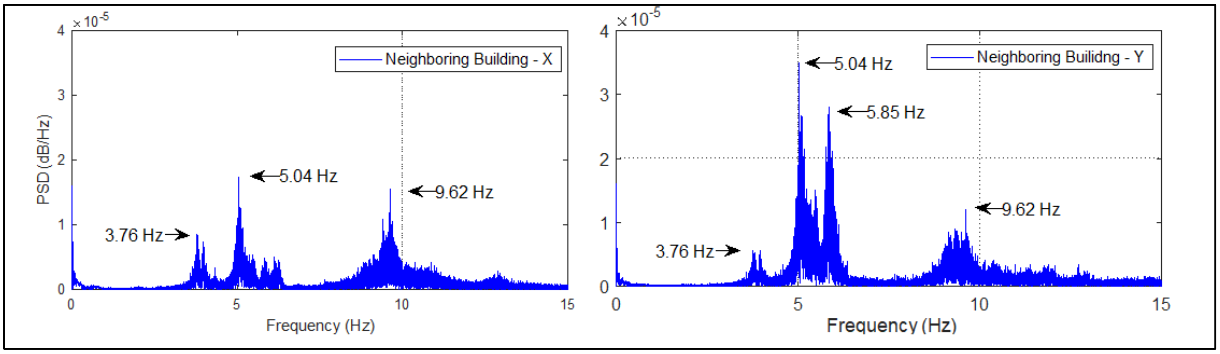

Figure 7. Dominant frequencies determined for the neighboring building

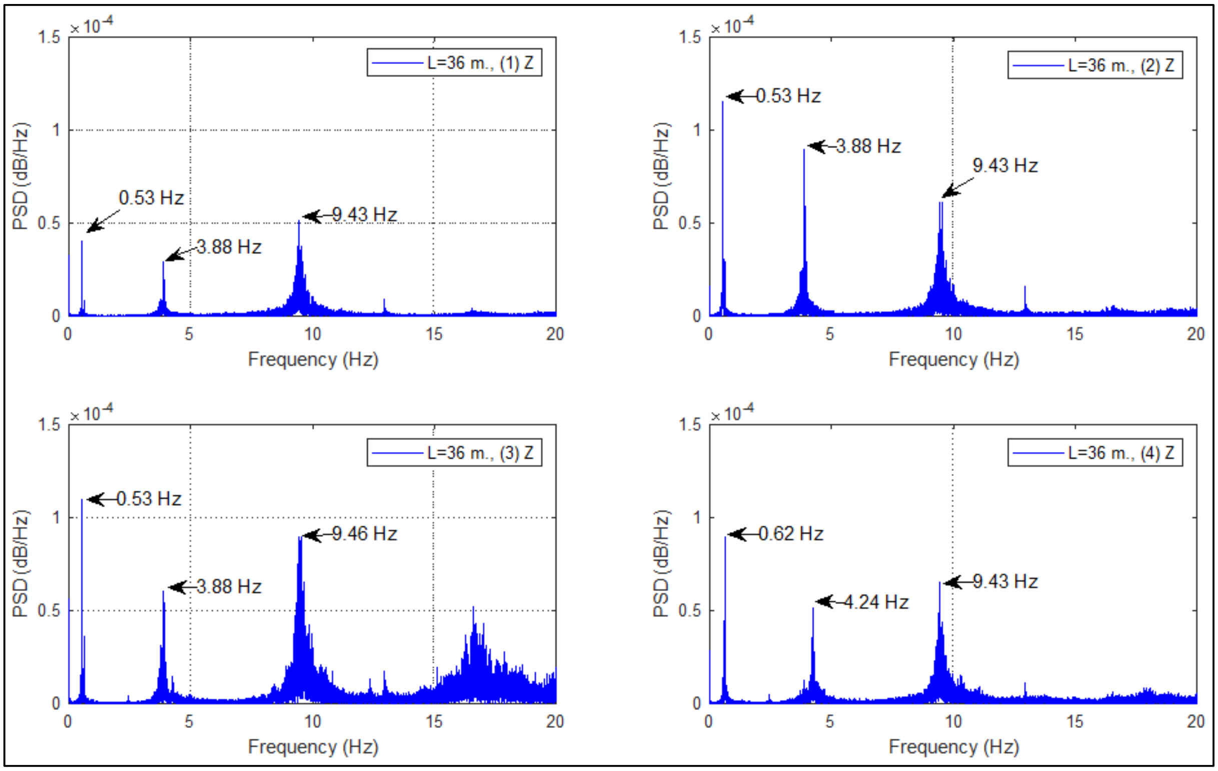

Figure 8. Frequency domain representation of the vertical signals recorded on slab at 36 m height

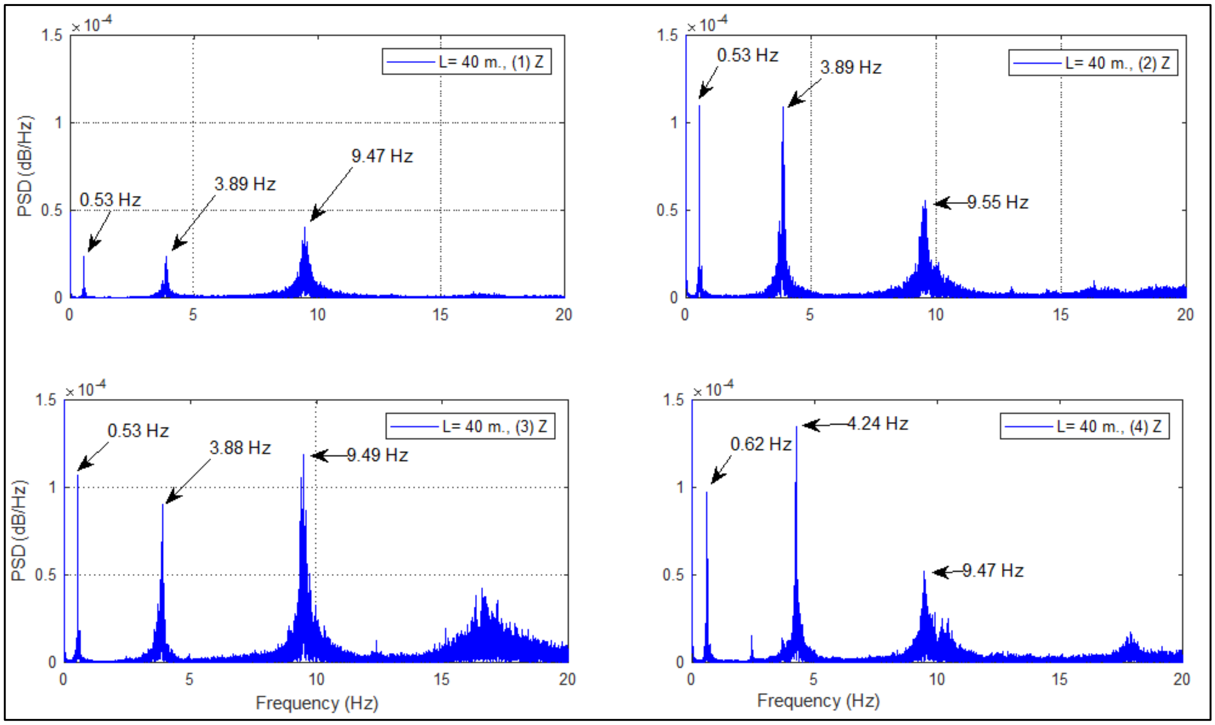

Figure 9. Frequency domain representation of the vertical signals recorded on slab at 40 m

4. Numerical dynamic identification in UOT

Mathematical modelling is a powerful tool for the estimation of the dynamic properties of existing structures although the obtained results may diverge from the real values due to the approximations, ignorance, and assumptions made in modelling stage. Employed modelling techniques, geometrical measurements, mechanical properties of materials and the complexity of the systems play an important role in the dynamic analysis of a civil engineering structure. In this study, dynamic properties of UOT have been searched to understand the details of its structural behavior.

The Finite element modelling technique was employed with complete data for geometrical measurements, structural system, project-based material data and the boundary conditions revealed by AVS. SAP2000 computer package was used for the modelling (2016). Shell elements were used for the tower's body and slabs' plates while frame elements were used for the beams in the slab systems. The structural system, over the ground level, was modelled without the façade since the metallic façade system sits on the slab around the tower. The stair system was accounted as a mass and weight acting on its geometrical location.

As the material property affecting the dynamic properties of the structure modulus of elasticity of the concrete, E_c, was calculated according to the compressive strength of concrete, fc, of the tower's body, which is 35 MPa. The relation between E_c and fc is well-recognized but the codes used in the different regions use different formulas. ACI-318 (2005), Eurocode 8 (2004) and TS500 (2000) specify the relationship by Equation 1, Equation 2, and Equation 3, respectively. Given in MPa unit these formulas result in different numerical values for the modulus of elasticity of concrete. In this study, the formula, giving the greatest numerical value was accounted as Equation 3 and the modulus of elasticity of the concrete is calculated as 33200 MPa.

$$E_c = 4700\sqrt{f_c} \quad (MPa) \tag{1}$$

$$E_c = 22000[(f_c/10)]^{0.3}\ (MPa) \tag{2}$$

$$E_c = 3250\sqrt{f_c} + 14000\ \ (MPa) \tag{3}$$

Eigen Value analysis was conducted to reveal the dynamic characteristics of the tower. The first five modes of the system are shown in Figure 10. The first and the second modes of the tower are the simple movement modes along with Y and X directions with dominant frequencies of 0.477 Hz and 0.490 Hz respectively. The third mode is the pure torsion mode with a frequency of 2.845 Hz, while the fourth and fifth modes are the double curvature modes in Y and X directions with a frequency of 4.105 Hz and 4.26 Hz respectively. These results prove the reciprocity of the AVS and FEA modes such that, 2.46 Hz dominant frequency derived from AVS represent the torsional mode.

Higher modes of the tower generally contain the complex movement of the tower's slab systems and body and they are not interpreted in detail. The numerical values for the first ten modes of the tower are given in Table 1. As a simple structure, behaving like a vertical cantilever, the first two modes of the UOT are important to govern its structural behavior. This fact is also seen in the mass participation ratio columns of Table 1. The first two modes of the tower encompass 76% of its dynamic behavior. The torsion mode has no mass participation and does not govern the structural properties of the tower. The mass participation ratio of the fourth and fifth mode is around 10%. For this reason, more attention should be paid to the first two modes of the tower, rather than the upper modes.

The comparison of the AVS and FEA results prove the compatibility of the obtained dynamic mode shapes. On the other hand, there are slight differences between the obtained dominant frequency values. The differences, ε_i, between the numerically and experimentally obtained frequency values have been computed by Equation 4, where f_i^{FEA} is the modal frequency computed by FEA and fiAVS is the real modal frequency extracted by AVS for each mode. For the first mode, ε_i is computed as - 0.11, while it is - 0.21 for the second mode. Here, more attention should be paid for the dissimilarity between ε_i values computed for the first and second modes. While the same level difference requires the alteration of a most suspicious stiffness or mass terms in the numerical modes, different values may prove some inconsistency of the numerical model.

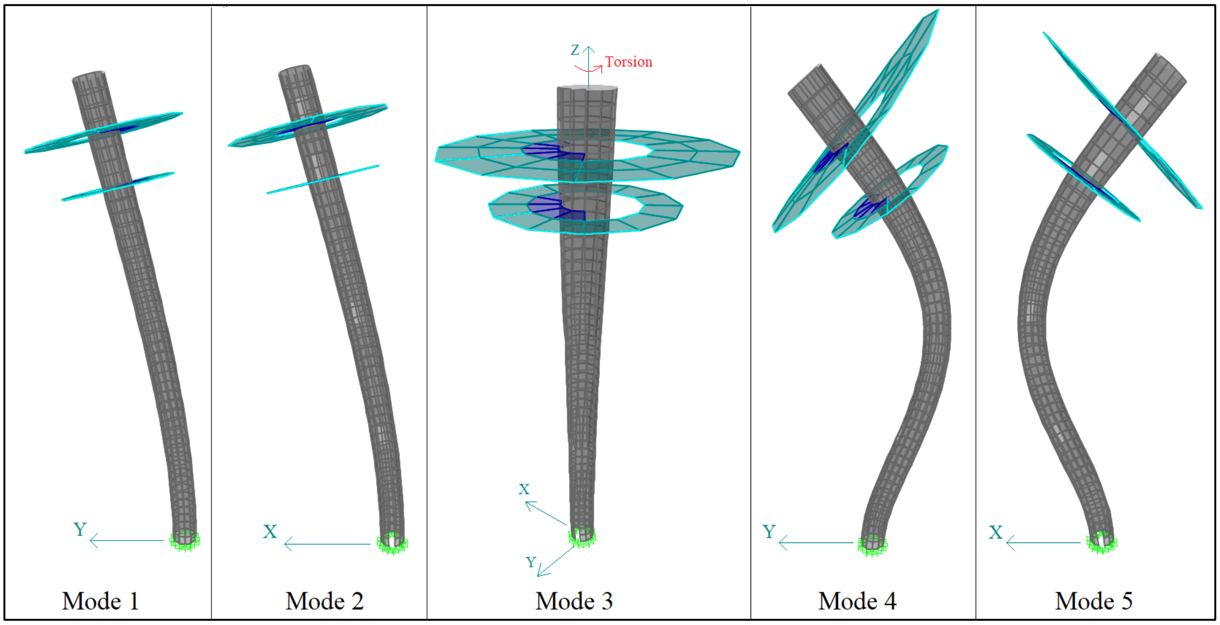

Figure 10. Mode shapes of UOT, determined by FEA.

Table 1. Dynamic properties of UOT determined numerically.

Mode	Period	Frequency	Mass participation ratio			Total mass participation ratio		
	Sec	Hz	UX	UY	RZ	UX	UY	RZ
1	2.096	0.477	0.71	0.05	0.00	0.71	0.05	0.00
2	2.039	0.490	0.05	0.71	0.00	0.76	0.76	0.00
3	0.351	2.845	0.00	0.00	0.97	0.76	0.76	0.97
4	0.244	4.105	0.10	0.01	0.00	0.87	0.77	0.97
5	0.235	4.260	0.01	0.11	0.00	0.87	0.88	0.97
6	0.147	6.806	0.02	0.00	0.00	0.89	0.88	0.97
7	0.116	8.594	0.00	0.02	0.00	0.89	0.90	0.97
8	0.106	9.470	0.01	0.00	0.00	0.90	0.90	0.97
9	0.092	10.843	0.01	0.00	0.00	0.91	0.90	0.97
10	0.086	11.593	0.00	0.00	0.00	0.91	0.91	0.97

Supposedly, the first and second modes' frequencies of a tower with a circular tube cross-section are expected to be the same. For UOT, some parameters are differentiating them, such as four elevator door openings, unsymmetrically hanged slab systems, the neighboring building, unsymmetrical façade system, and naturally expected heterogeneity in concrete. In the numerical model of UOT, four elevator door openings and unsymmetrically hanged slab systems have been accounted for. AVS proved that there is no dependency between the neighboring building and UOT. On the other hand, façade system has not been included in the numerical model of UOT because of its complex and irregular structural system. A careful examination of the façade system showed that, due to the entrance of the UOT on the ground level and the neighboring building, the façade system partially surrounds the main body of the tower. It does not exist on the portion, coinciding with the elevator door of the body. This means that the structural system of the façade contributes to the stiffness of the whole system in the X direction much more than it does in the Y direction. That is why AVS gave greater dominant frequency along with X direction than it gave in the Y direction.

$$\boldsymbol{\varepsilon_i} = \frac{f_i^{FEA} - f_i^{AVS}}{f_i^{AVS}} \tag{4}$$

The modulus of elasticity of concrete is seen as the most suspicious parameter in numerical models of existing structures. Because of the non-linear stress-strain relationship of concrete, its modulus of elasticity is not constant. For this reason, there are different definitions for it, like secant, initial and tangential modulus of elasticity values (MacGregor and Wight, 2005; Ersoy 2000). In this study, the numerical value of modulus of elasticity has been determined by code based empirical formula which refers to the slope of the line between the origin and points of 0.5fc, as secant modulus. In ambient conditions, due to such a small stress value on concrete, the expected modulus of elasticity should be more than that given by the codes.

With the mentioned evaluations, a model tuning procedure is employed to decrease the amount of the difference between the experimental and numerical results by simply adjusting the modulus of elasticity of the concrete. The first mode frequencies are accounted for since the second mode frequency of UOT is affected by the façade structural system. Moreover, the heterogeneity of the concrete is also ignored. The iterations showed that, the numerical model of the tower, giving the first mode frequency as 0.53 Hz is obtained by assigning the modulus of elasticity of the concrete as 41000 MPa. This value is 1.23 times greater than the value, computed by Equation 3. A possible greater compressive strength value for the existing concrete and the pre-explained initial modulus of elasticity concept can justify the determined numerical value for concrete.

Eigen Value analysis performed with the tuned numerical model has resulted in the same mode shapes with the dominant frequency values as 0.53 Hz, 0.55 Hz, 3.16 Hz, 4.56 Hz and 4.73 Hz for the first five modes of the tower. The difference between the frequencies of AVS and FEA of the tuned numerical model was also evaluated with Equation 4. Table 2 shows the dynamic properties obtained by AVS and two numerical models. The compatibility of the numerical results to those of experimental has also been evaluated by □i coefficients computed for each mode. It is seen that the performed model tuning equalizes the dominant frequencies of the first mode. 11% smaller value of numerically obtained dominant frequency for the second mode is due to the ignorance of the stiffness contribution of façade structural system.

Table 2. Modal properties and dominant frequencies obtained by AVS and FEA before and after model tuning.

Mode	Definition of Mode	AVS	FEA, Before Model Tuning		FEA, After Model Tuning	
		f_i. Hz	f_i. Hz	ε_i, %	f_i. Hz	ε_i, %
1	Movement in Y	0.53	0.47	- 11	0.53	0
2	Movement in X	0.62	0.49	- 21	0.55	-11
3	Pure Torsion	2.46	2.84	15	3.16	28
4	Double Curvature Movement in Y	3.90	4.10	5	4.56	17
5	Double Curvature Movement in X	4.27	4.26	0	4.73	11

5. Conclusions

The dynamic behavior of one of the most prominent structures in the Anatolian side of Istanbul, Üsküdar Observation Tower (UOT) was investigated by AVS and FEA techniques in this study. Not only the basic dynamic properties of the tower but also the effects of structure-specific features, such as interaction with the existing neighboring building and basement floors surrounding the tower body through 18.2 meters were investigated. The following findings were revealed.

1. AVS gave the first two modes with almost the same translation modes in Y and X directions with 0.53 Hz and 0.62 Hz respectively. The torsional behavior of the slabs at both 40 m and 36 m in elevation is worth noting. The main reason for this torsional behavior is grasped as the partial hanging of the slabs to the tower's body with a 120 cm thick reinforced concrete block which works as a cantilever.
2. The underground portion of the tower which is surrounded by the basement floors of the complex does not participate in the determined dynamic mode shapes.
3. No mutual dominant frequency is detected for UOT and the neighboring building.
4. The evaluation, performed with the dynamic characteristics obtained by FEA and AVS, proved the efficiency of the structural system of the façade to increase the rigidity of UOT along with X direction.
5. A simple model tuning approach showed that the modulus of elasticity of concrete in UOT is 1.23 times greater than the value predicted by TS500.
6. Last but not least, the efficiency of AVS and FEA to search about the details of the dynamic behavior of existing structures was proved. Detailed and well-organized measurement sets can be used to extract the dynamic behavior of special structures like UOT.

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Conflicts of interest: The authors declare that they have no conflict of interest.

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