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Effects of Ambient Temperature and Magnitude of the Vibration on the Dynamics of Pre-Stressed Precast Isolated Pedestrian Bridges

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ABSTRACT

The dynamic properties of structures are known as inherent properties dependent on the mass and stiffness parameters. However, recent studies showed that the temperature and the magnitude of the vibrations also affect them. This study aims to reveal how the ambient temperature and human-induced vibrations alter the modal characteristics of pre-stressed precast isolated pedestrian bridges. For this aim, operational modal analyses have been applied to the Istanbul Medeniyet University pedestrian bridge. Three-bay pre-stressed precast and isolated bridge has been connecting the two campuses of the university for six years and its dynamic properties were investigated during its construction. In this study, the dominant frequencies of the bridge have been determined to see if they changed or not for its service life. Secondly, the dynamic response of the longest bay of the bridge has been evaluated under different temperatures and human-induced vibrations. Through a year, twelve acceleration measurements have been gathered in a temperature range of 5 - 33 °C and representing the different levels of human-induced vibrations, some jumping actions were applied and its response was recorded. While the performed analyses proved that, the dominant frequencies are dependent on the ambient temperature, no significant correlation was obtained between the amplitude of the vibration and the dominant frequencies of the bridge. High-amplitude vibrations have been used for the vibration serviceability check of the bridge, and it is seen that it satisfies the requirements set by different codes.

Keywords: pedestrian Bridge, dynamic response, field test, temperature effect, human-induced vibrations, vibration serviceability.

1. INTRODUCTION

The dynamic properties are inherent assets that are theoretically dependent on the mass and stiffness parameters of structures, but recent studies also proved their dependency on environmental effects, such as traffic, wind, humidity, solar radiation and, most importantly,

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temperature. The level of change caused by the environmental effects in dynamic properties can mask the changes caused by structural damage. For this reason, considerable efforts were spent investigating the influence of environmental conditions on the dynamic properties of bridges.

The studies have pointed out that temperature is the most important environmental parameter affecting the dynamic parameters of bridges. Ni et al. [1] address the modeling of temperature effects on modal frequencies for a cable-stayed bridge. The authors found that the environmental temperature can change the modal frequencies with a variance range of 0.20% - 1.52% for the first ten modes. For the investigated modes, a decrease in modal frequency is observed with the increase in the temperature of the bridge. Çatbas et al. [2] monitored a long-span truss bridge in the USA for a year. The authors pointed out the importance of ambient temperature on structural reliability. Mosavi et al [3] investigated the effect of temperature variations on the modal characteristics of a two-span steel-concrete composite bridge and concluded that temperature variations can induce modal variability on a daily cycle. Another cable-stayed bridge was investigated by Ni et al. [4]. Both cables and bridge deck have been investigated. The authors reported that for the first mode dominant frequency is not sensitive to temperature change, while for the other modes, an explicit decrease in the modal frequencies has been determined with the increase of the temperature. This dependency arises another problem which is the elimination of temperature effects for structural health monitoring issues. In this direction, Sohn et al. [5] proposed a model to separate the temperature effects in the change of modal frequencies from the effects of structural damage. Peeters and De Roeck [6] used one-year-long monitoring data of a four-span post-tensioned concrete box girder bridge for the same aim. In a more recent study, Ni et al. [7] examined the performance of neural network models to eliminate the temperature-caused modal variability in vibration-based structural damage detection.

Another vital parameter studied in bridges is the magnitude of the vibration induced by human traffic. The importance of the factor mainly stems from the need for checking the serviceability of the bridges. Besides, the variation of the dominant frequencies according to the level of vibration can be another reason. In that respect, many studies can be found in the literature performed in existing bridges. Tubino et al. [8] conducted extensive field tests on two bridges with steel systems to determine their dynamic features and human-induced vibration level. The vibration measurements have been conducted under ambient conditions without human traffic, single pedestrian walking, 10 pedestrian walking, and 15 pedestrian walking conditions. The authors reported maximum acceleration values for each case. Ni et al. [9] applied ambient, forced, and free vibration tests on a pedestrian bridge at the City University of Hong Kong. The modal parameters, i.e., dominant frequencies and damping ratios obtained from the tests were compared. In a more recent study, Moutinho et al. [10] studied the dynamic properties of the historic Dom Luis I truss arch bridge in Portugal with the Peak Picking technique. The authors mainly determined the vibration levels of the bridge at different levels of human activity created in the feast days and athletic races. They also assessed the level of vibrations to human comfort limits. Chen et al. [11] obtained the dynamic properties of an eleven-span post-tensioned concrete bridge under ambient and hybrid excitations in which an artificial force was applied. The authors also used different modal identification methods, such as the autoregressive time series method, the eigensystem realization algorithm with observer/Kalman identification, and stochastic subspace identification methods. The performed analyses showed that the hybrid excitation tests revealed the high-frequency modes that are not recognized in ambient vibration tests.

The literature survey showed that the investigation of the effects of temperature on the dynamic properties of the pre-stressed precast isolated pedestrian bridges has not been studied in detail. Moreover, the relation between the magnitude of the vibration and dominant frequencies was not studied either. To fill this gap in the literature, a field testing plan has been applied to the Istanbul Medeniyet University pedestrian bridge which is a pre-stressed precast isolated reinforced one. The dynamic properties of it were already investigated six years ago when it was taken under service immediately after its construction [12]. In this study, the dynamic properties of the bridge have been determined again and compared to those extracted by Aras [12] to see if they are changed for its six-year service life. A testing plan has been applied within the frame of the Structural Health Monitoring Laboratory course in the Civil Engineering Department of Istanbul Medeniyet University. Throughout the course, eight measurements have been recorded. To answer the specified questions proficiently, additional measurements, i.e., one before the semester on 30 July 2021, and two after the semester in May and June 2022, were conducted. Thereby, a wide temperature range was aimed. Different human-induced vibrations have been applied by the students of the course in different jumping scenarios. The analyses were performed in the vertical direction of the longest span of the bridge to present the results in the most relevant way.

The modal parameter estimation of a structural system based on its vibration response is very important and many signal processing techniques have been developed and validated. These techniques are ranging from frequency domain algorithms based on the Fourier transform, such as peak picking and frequency domain decomposition, to time domain algorithms, such as the Eigensystem realization algorithms and the stochastic system identification [13, 14]. A few studies used both methods to obtain the dynamic properties of structures and stated that they give similar findings [15-16]. The frequency domain methods are the most practical methods to apply in existing civil structures [17]. This study is mainly based on the monitoring of the dominant frequencies of the bridge since no change is expected in the mode shapes. For this reason, the presentation of the signals in the frequency domain enables to reach the intended aim. Hence, the peak-picking technique as a more practical and straightforward modal identification technique is preferred in this study.

The obtained data have been analyzed to see how the ambient temperature and human-induced vibrations affect the dynamic properties of the bridge and if the vibration serviceability requirements are satisfied or not. Before giving the details of the measurements and analysis, the structural details of the studied bridge have been presented in the next section.

2. THE STUDIED BRIDGE

The studied bridge is known as the Istanbul Medeniyet University pedestrian overpass and was constructed within the Istanbul Strait Road Tunnel Crossing Project. It connects two campuses of the university and many people use it to cross the main motorway D100. Figure 1 shows the bridge with its neighborhood. The structural system of the bridge contains two reinforced concrete abutments, two mid piers, elastomeric bearings, precast and pre-stressed reinforced concrete girders, reinforced concrete slab, and steel stairs. Two elevators with steel frame systems also join the bridge abutments from two sides. Caps on the abutments and piers were designed to carry the girders. The abutments also support the steel stair systems. The bridge crosses 69.2 meters via three bays with the span lengths of L1 = 32.3 m., L2 = 22.1 m., and L3 = 12.8 m. The width of the bridge is 5.2 m and two different girder cross-sections are used through the bays. L1 and L2 bays are crossed by four precast pre-stressed girders of 1200 mm height and top flange width is 1275 mm, while L3 is crossed by six precast girders of 900 mm height and top flange width is 800 mm. Figure 2 shows the structural system details of the studied bridge with the locations of the accelerometers and jumping locations used in this study.

Figure 1 - Studied bridge: Istanbul Medeniyet University pedestrian overpass bridge

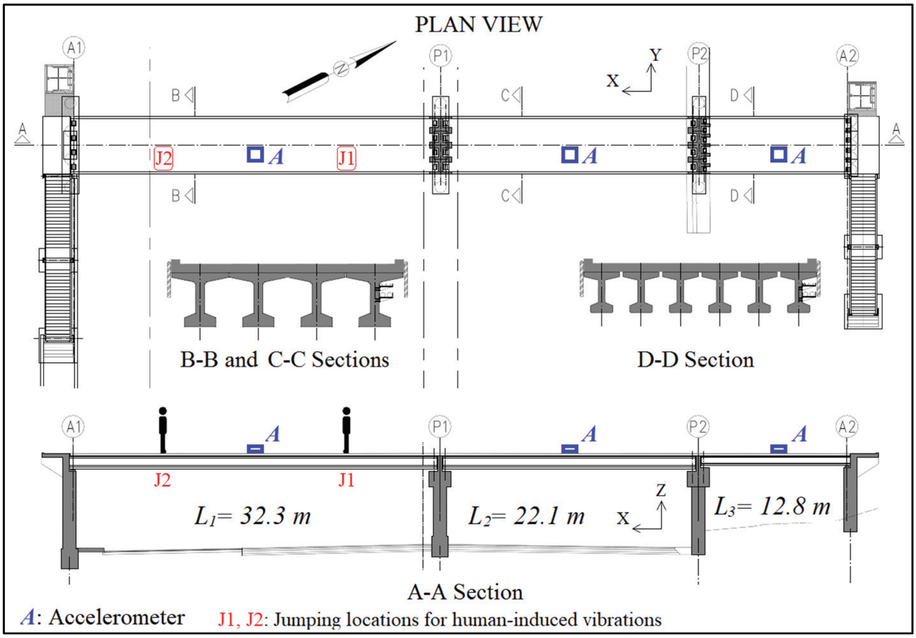

Figure 2 - Structural system of the studied bridge with accelerometer locations

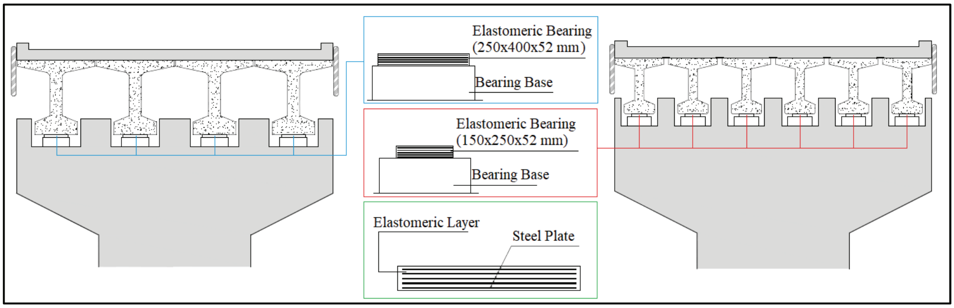

Figure 3 - Details of elastomeric bearings used under the girders

The C35 concrete class is used for all cast-in-place concrete members while C40 is preferred for precast and pre-stressed girders. S420 steel grade is used for all reinforcement. For the pre-stressing strands, 1862 MPa (270 ksi) grade strand is used with a 1.5 cm (0.6 inches) diameter. 21 strands are used for pre-stressing L1 girders, while 8 strands are used for L2 girders. No pre-stressing is applied to L3 girders [18].

Each girder sits on an elastomeric bearing composed of four rubber-type elastomer layers and five steel plates. The thickness of each elastomer layer is 8 mm whereas that of the steel plate is 2 mm. With the 5-mm top and bottom end layers, a total height of each elastomer reached 52 mm. The cross-section of the bearings used in L1 and L2 bays is 250 mm by 400 mm while it is 150 mm by 250 mm in L3 bays. The details of the elastomeric bearing are shown in Figure 3.

3. VARIATION OF THE DYNAMIC PROPERTIES OF THE BRIDGE IN SIX YEARS

Aras [12] determined the dynamic properties of the Istanbul Medeniyet University Pedestrian Bridge by applying operational modal analysis principles by presenting a relatively wide-literature survey on the modal testing of similar structures. The measurements had been recorded on 20 July 2017 at 34 °C ambient temperature and under 2 people/minute of human traffic. Three Kinemetrics, TSA-SMA accelerometers, with three sensors, were used for data collection. The linear acceleration range of each sensor is +-4 g. Each accelerometer has its data storage unit and works separately without a mutual data acquisition system.

Aras [12] has analyzed the recorded vibrations with the Matlab computer program [19] by simply representing each signal in the frequency domain. No filtering was applied to the data due to the high level of uncertainties related to the ambient sources of vibration like wind, vehicle traffic, and pedestrian-induced vibrations. Modal identification was performed between 0 Hz and 10 Hz which is considered adequate for the identification of the studied bridge. The mode shapes of the bridge in the vertical direction have been reported as illustrated in Figure 4 [12]. It is seen that, independent from the adjacent bays, each bay of the bridge formed its mode. The first dominant frequency of L1, L2, and L3 bays were reported as 2.99 Hz, 6.30 Hz, and 12.38 Hz, respectively.

Six years after Aras [12], the dynamic properties of the bridge were studied again with the same measurement equipment, analysis procedure, and under similar environmental conditions. The vibration measurements recorded on 12 July 2023, at 33 °C temperature and approximately 2 people/minute of traffic have been analyzed. Figure 5 shows the vibration recording while Figure 6 illustrates the FFT presentation of the signals recorded on each bay of the bridge. The first dominant frequency of L1, L2, and L3 has been determined as, 3.00 Hz, 6.29 Hz, and 11.63 Hz. A comparison of these values to those obtained by Aras [12] proves that the frequency of L1 bay has increased 0.01 Hz, the frequency of L2 bay has decreased 0.01 Hz, and the frequency of L3 bay has decreased 0.75 Hz. The frequency difference, 0.01 Hz, detected for L1 and L2 bays is such a small value that can stem from uncontrolled and unaccounted effects such as wind or vehicle traffic. For this reason, it can be concluded that the dynamic properties of L1 and L2 bays have not changed over the period of six years. However, a frequency drop, reaching 0.75 Hz is not a usual decrease. Detailed investigation for the frequency decrease and a regular structural health monitoring plan is suggested for the future of the bridge.

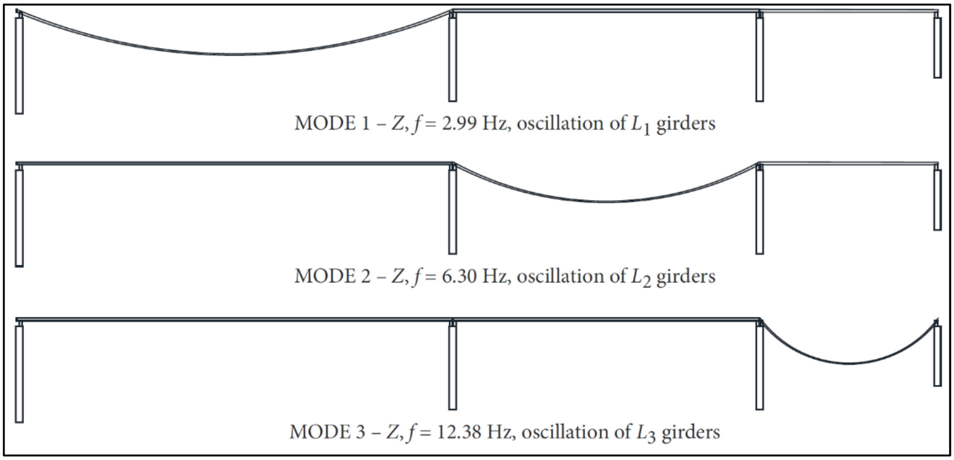

Figure 4 - Determined mode shapes of three-bay bridge on 20.07.2017 at 34 °C [12]

Figure 5 - Vibration recording and accelerometer

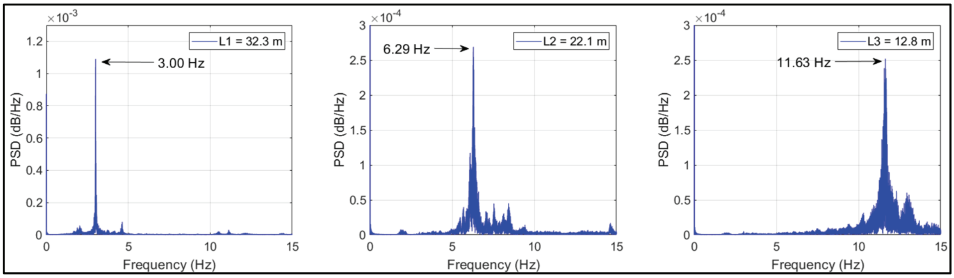

Figure 6 - FFT representations of the vertical accelerations recorded on L1, L2 and L3 bays on 12.07.2023 at 31 °C

4. MODAL TESTING TO REVEAL THE TEMPERATURE EFFECTS IN THE DYNAMIC PROPERTIES

Starting from 30 July 2021 to 30 June 2022, eleven measurements have been recorded from the mid-point of the longest bay of the bridge during the daytime under its normal function. The coldest date was 21 December 2021 at 5 °C and the hottest date is 30 July 2021.

The details of the measurements and analyses are the same as reported in the previous part. Since the amplitude of the vibration affects the dominant frequencies, the data recorded under rare human traffic have been used for the assessment. In this condition, the maximum acceleration reached 0.02 m/s^2 in the longest span. Figure 7 shows the acceleration data recorded at 33 °C. Figure 8 shows the dominant frequencies of the longest bay of the bridge obtained via the measurements recorded at 33 °C, 19 °C, and 5 °C.

Since the measurements were taken from the central location of the span, the out-of-horizontal plane mode could not be determined. For this reason, the vertical mode of the longest span of the bridge can be represented by a single dominant frequency. Figure 9 shows the relationship between the determined dominant frequencies and ambient temperature.

The dominant frequency of the longest span of the bridge varies between 2.98 and 3.11 Hz. The increase in temperature decreases the dominant frequencies. The ratio of the frequencies on the coldest day to the hottest day is 1.044. When the temperature range is widened, the ratio gets higher. The variation of the dominant frequencies has been linked to the decrease in the elastic modulus of the construction materials with an increase in the temperature by Ni et al. [4]. The authors investigated the amount of decrease in the dominant frequencies of the bridge cables made of steel and bridge deck made of concrete. A more evident decrease in the dominant frequencies of cables than that of the bridge deck was shown as one possible proof for their conclusion since steel is more sensitive to temperature variation than concrete. The obtained results also showed that the temperature–frequency relation is close to linear. It is seen that the temperature sensitivity of the dynamic properties of the studied bridge is similar to those of cable-stayed bridges tested by Ni et al. [4].

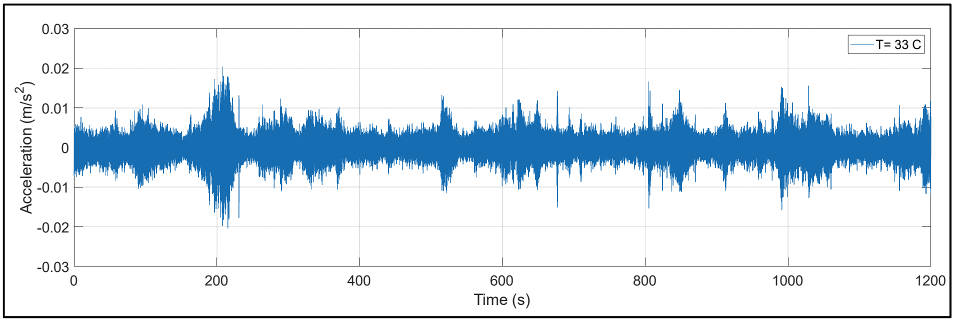

Figure 7 - Acceleration record used to determine the dominant frequency of longest span of the bridge to study temperature effect

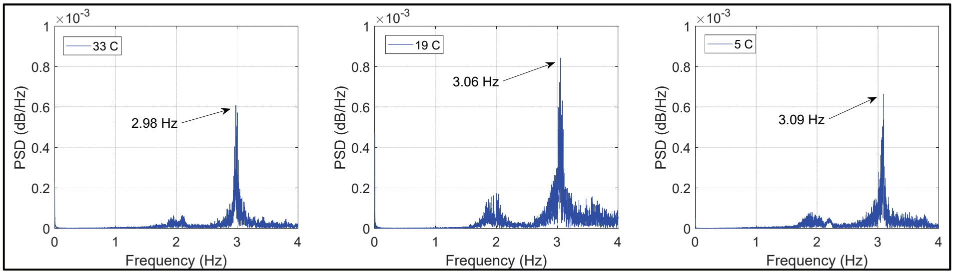

Figure 8 - FFT representations of the accelerations recorded at 33, 19 and 5 °C temperature

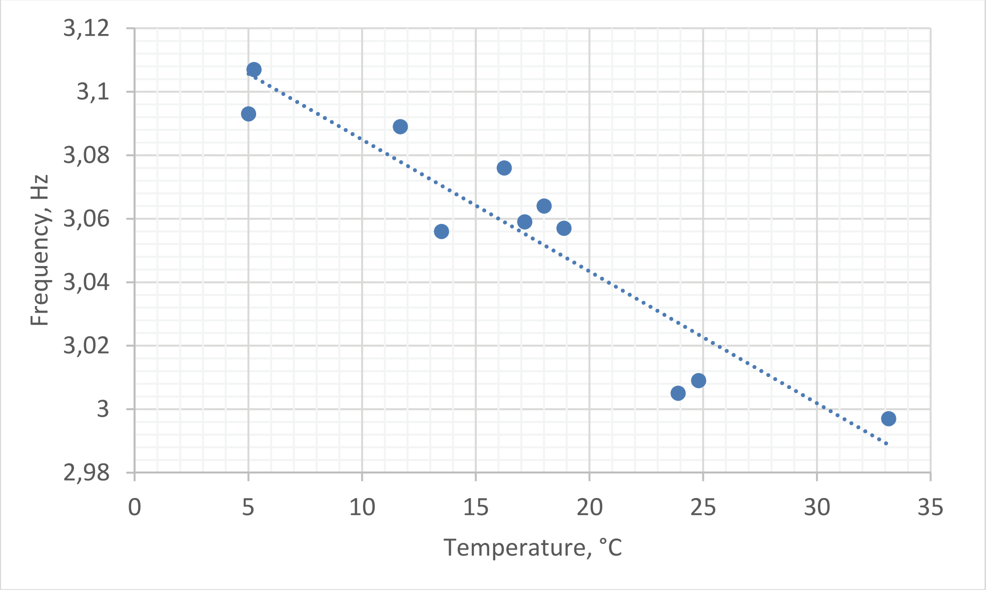

Figure 9 - Determined dominant frequencies and the temperature measured when the signal was recorded

5. INVESTIGATION OF HUMAN-INDUCED VIBRATIONS IN THE DYNAMIC PROPERTIES OF THE BRIDGE

The human-induced vibrations have been applied on the longest bay of the bridge as jumping protocols performed by the students of INS471 Structural Health Monitoring Laboratory course at 16.3 °C. The tests have been performed during normal service conditions. Therefore, the vibrations have been recorded under specifically created human vibrations and those created by pedestrians using the bridge to cross the motorway.

Figure 10 - Application of jumping protocol with five students on point J1

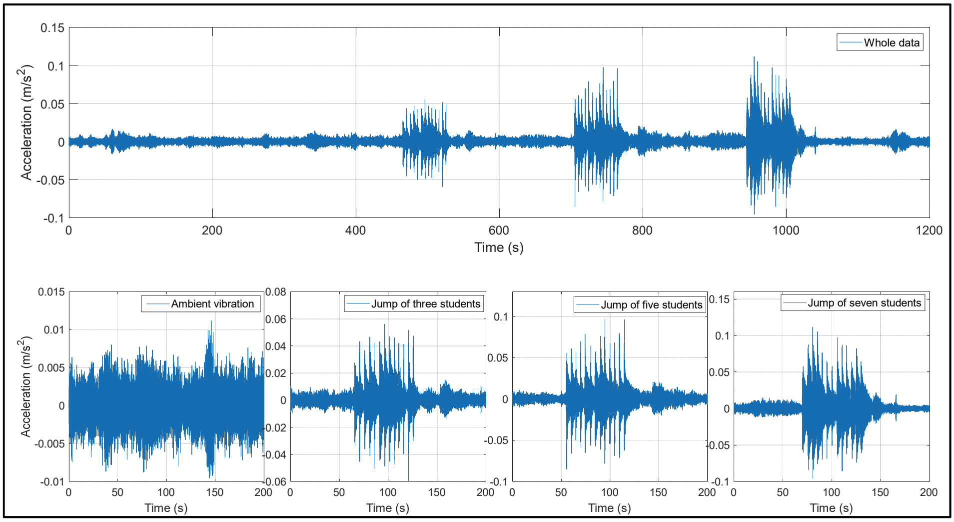

Figure 11 - Recorded vibrations during the jump of three, five and seven students on point J1

Six different jumping protocols have been applied on the bridge as the jumping of three, five, and seven students on point J1 and points J1 and J2 together. As can be seen in Figure 2, points J1 and J2 are located at the quarter-length of L1 measured from P1, pier, and A1, abutment, respectively. At each set, a group of students jumped at a five-second interval for a minute. Figure 10 shows the application of the jumping protocol on J1 while Figure 11 shows the recorded vibrations.

The acceleration record has been taken for 20 minutes which also includes the three jumping protocols. The increase in the magnitude of the acceleration has been seen as the result of the jumping. In ambient conditions, the maximum acceleration is about 0.011 m/s^2. The jump of three, five, and seven students increased it to 0.06 m/s^2, 0.1 m/s^2, and 0.11 m/s^2 respectively.

To see the variation of dominant frequencies, FFT analyses have been performed for the segmented signals with a length of 200 seconds shown in Figure 9. The dominant frequencies of the bridge were obtained as shown in Figure 10 under different levels of human-induced vibrations. It is also noted that the peak at around 2 Hz seen under ambient vibrations has vanished for the analyses under different jumping actions. The disappearance of the peak proves the bridge has no dynamic mode at around 2 Hz frequency and it must be ignored.

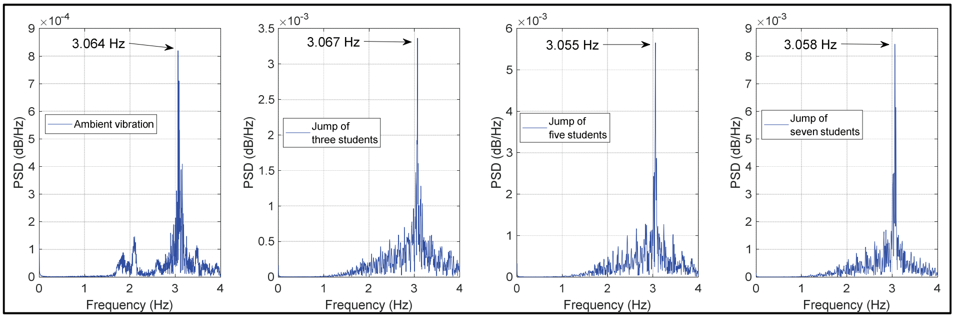

Figure 12 - Obtained dominant frequencies for the portion of the ambient case, the jump of three, five and seven students on Bridgepoint J1

Figure 13 - Application of jumping protocol with five students on points J1 and J2

Figure 13 shows the application of the jumping protocol with two groups of five students on J1 and J2 together while Figure 14 shows the recorded vibrations. As in the previous measurement set, the magnitude of the vibration has increased. In ambient conditions, the maximum acceleration is about 0.015 m/s^2. The jump of three, five, and seven students on J1 and J2 together increased it to 0.09 m/s^2, 0.14 m/s^2, and 0.12 m/s^2 respectively. Unexpectedly, the maximum acceleration measured for the jump of seven students on J1 and J2 points of the bridge is lower than that measured for the jump of five students on J1 and J2 of the bridge. The main reason may be the ordinary human traffic, which uses the bridge for crossing the motorway. Since the measurements have been recorded under normal traffic conditions, the analyses include the effects of ordinary human traffic as well.

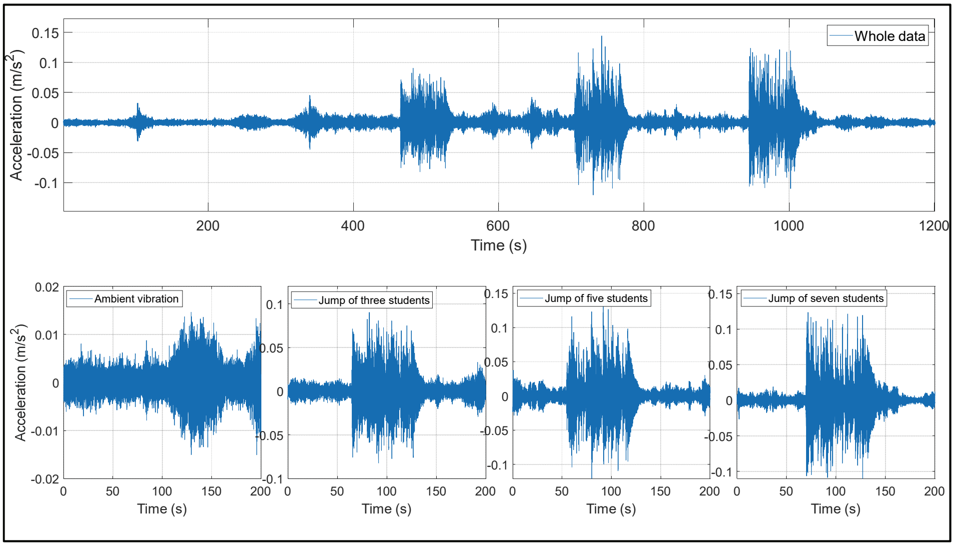

Figure 14 - Recorded vibrations during the jump of three, five and seven students on points J1 and J2

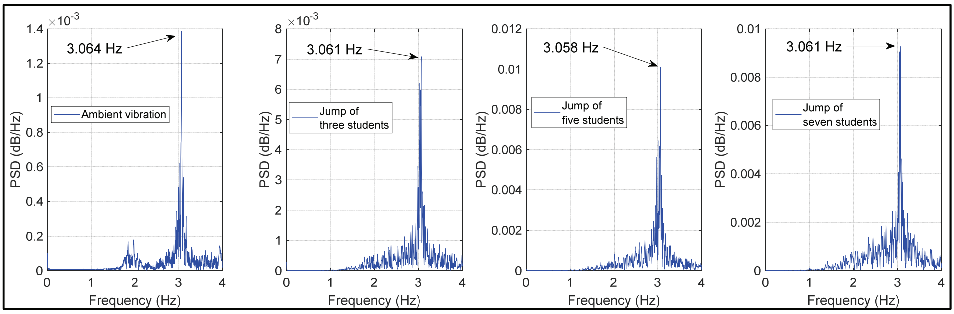

Figure 15 - Obtained dominant frequencies for the portion of the ambient case, the jump of three, five and seven students on points J1 and J2

Figure 15 shows the presentation of the signals shown in the second row of Figure 14 in the frequency domain. For the ambient part of the signal, the dominant frequency of the bridge has been determined as 3.064 Hz while for the jumps of three, five, and seven students on points J1 and J2, they have been extracted as 3.061 Hz, 3.056 Hz, and 3.061 Hz, respectively.

Figure 16 and Figure 17 show the relationship between the extracted dominant frequencies and the maximum magnitude of the acceleration and the Power Spectral Density of the signal at the dominant frequency, respectively. They contain the data in Figure 12 and Figure 15. Besides 100-second signal segments from the ambient parts and human-induced vibrations have been analyzed and their results are included in Figure 16 and Figure 17. The FFT analyses of 100-second signals, containing the 60-second human-induced vibration have resulted in raised signal power at the dominant frequency reaching 0.019 dB/Hz as can be seen in Figure 17. It is seen that the trend lines in Figure 16 and Figure 17 have such a small amount of negative slope that, the amplitude of the vibration does not affect the dominant frequency of the studied bridge.

The performed literature survey showed that the relationship between the magnitude of vibration and the dominant frequencies of the studied type of bridges has not been studied. However, the study performed by Ni et al. [9] can be interpreted to control the validity of the obtained result. Ni et al. [9] conducted field tests on a pedestrian bridge at the City University of Hong Kong (CityU) under (i) ambient conditions, (ii) forced with known pseudorandom excitation, (iii) forced with frequency resonant excitation and (iv) free vibration. Despite the difference in the maximum magnitude of the vibration in the acceleration time history of each test and the obtained dominant frequencies for the modes, no relation was grasped between the magnitude of the vibration and dominant frequencies. Hence, it is seen that the obtained results in this study are compatible with the results obtained by Ni et.al. [9].

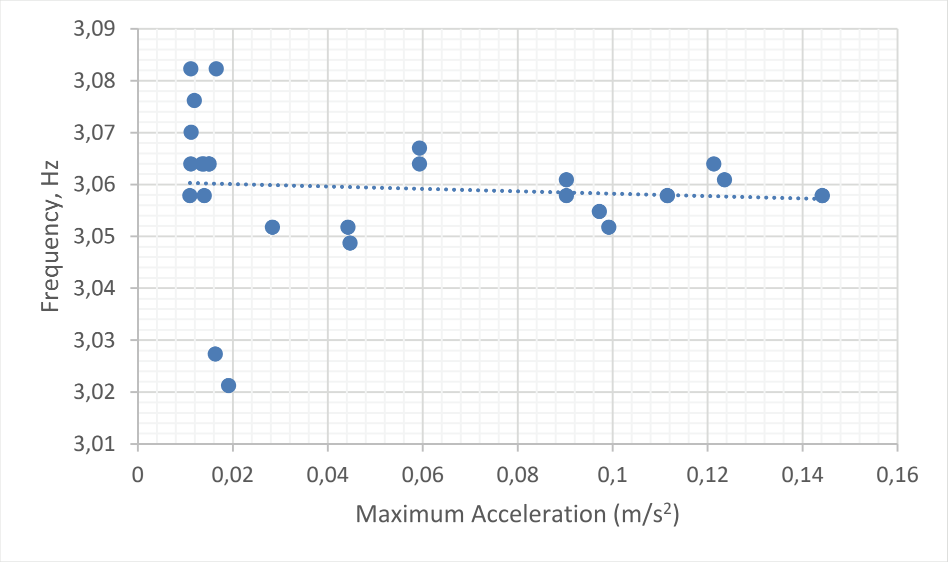

Figure 16 - Variation of dominant frequency with respect to maximum magnitude of the acceleration

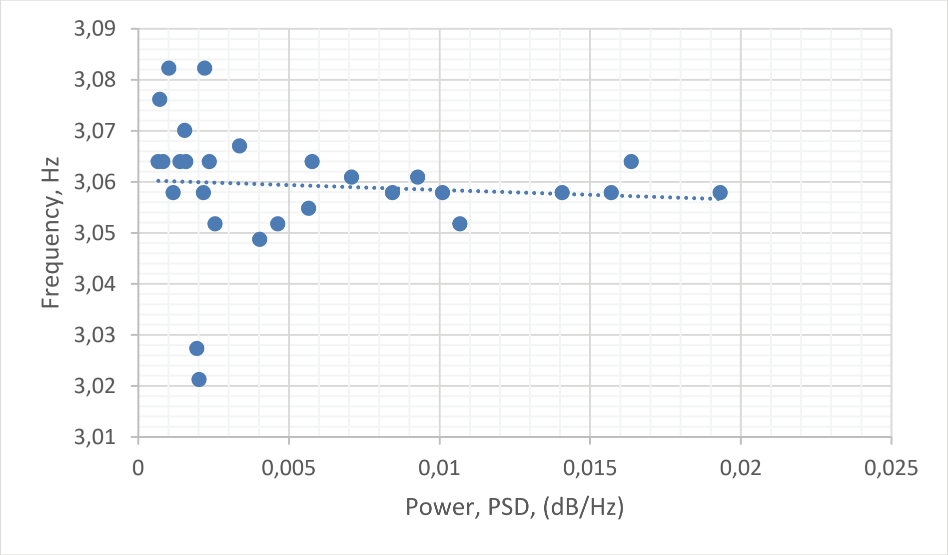

Figure 17 - Variation of dominant frequency with respect to Power Spectral Density (PSD) of the signal at the dominant frequency

6. VIBRATION SERVICEABILITY ASSESSMENT OF THE BRIDGE

Human comfort level is the main parameter setting the serviceability assessment. Živanović et al. [20] pointed out the acceleration response of the bridges as the best parameter to assess their serviceability due to its success in describing people's vibration perception. Indeed, the assessment in the codes is based on the indices derived from the acceleration response of the bridges. In this respect, a serviceability control has been performed in this study.

The vibration serviceability assessment of footbridges in the current codes, i.e., ISO 10137 [21], Eurocode 5 [22], BS 5400 [23], , and Setra [24] have been summarized by Dong et al. [25]. While ISO 10137 employs Root Mean Square (RMS) of the frequency-weighted accelerations, the others use the peak value of the acceleration response. Dong et al. [25] converted the RMS value of ISO 10137 [21] to an equivalent acceleration peak value by multiplying with √2 to present a comparative view. Finally, they illustrated the serviceability control of pedestrian bridges according to the mentioned codes in Figure 18 [25] (courtesy of corresponding author F. N. Çatbaş). As it is seen acceleration limits of BS 5400 and ISO 10137 are frequency dependent while Eurocode 5 sets a constant value, 0.7 m/s^2, for serviceability control. Setra [24] defines three serviceability degrees as extreme, medium, and low serviceability and assigns constant acceleration limits as 0.5 m/s^2, 1 m/s^2, and 2.5 m/s^2, respectively for each. The area under the lines is acceptable for the defined serviceability level and the area above the line is unacceptable.

The measurement presented for the longest span of the bridge indicates its frequency as 3 Hz while the maximum acceleration is determined as 0.145 m/s^2 under the combination of the jumping scenario and normal human traffic. This value proves the serviceability of the bridge according to all mentioned codes and it satisfies the maximum comfort level according to Setra [24]. During the measurement, human vibration perception has also been assessed. A person, standing on the midpoint of the bay and concentrating on feeling the vibration, sensed it while another one walking through the bridge could not.

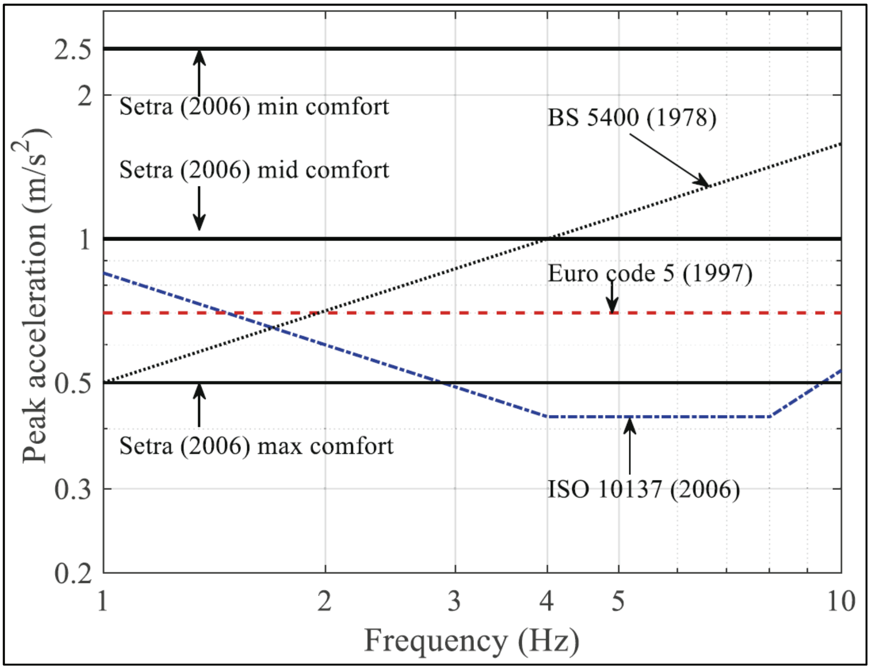

Figure 18 - Acceleration limits for vibration serviceability assessment of pedestrian bridges in different codes [25]

7. CONCLUSION

Operational modal analysis-based dynamic investigations have been applied to a 32.3-meter-long, isolated, precast, and pre-stressed pedestrian bridge in Istanbul. The tests aimed to see if the dominant frequencies of the bridge have changed during the six years of service life after its construction. Besides, the effects of the ambient temperature and human-induced vibrations in its dynamic properties were investigated. Finally, the vibration serviceability of the bridge was checked. The findings showed that;

- For the bridge's six-year service life, the dominant frequency of L1 and L2 bays has not changed while that of L3 has decreased 0.75 Hz. A regular structural health monitoring plan and detailed inspections are suggested for the future of the bridge.
- There is a strong dependency between the ambient temperature and dominant frequencies. The decrease in temperature increases the dominant frequencies. 28 °C temperature decrease (between 33 °C and 5 °C) resulted in a 4.4% dominant frequency increase.

- Human-induced vibrations do not cause a significant change in the dominant frequency of the studied bridge. This shows that the dominant frequencies of the studied bridge are independent from the magnitude of the vibration.
- The vibration serviceability control showed that the bridge satisfies the serviceability requirements of different codes.

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