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AMBIENT VIBRATION ANALYSIS of an INDUSTRIAL BUILDING

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Abstract: Due to the heavy and dynamic equipment, the vibration and resonance effects that are not encountered under static dead loading may amplify over time in industrial buildings. This might cause damage to the structural system and create human comfort problems while the structure is in service. In this study, ambient vibration testing of a building composed of reinforced concrete and steel structural systems and located at a boron processing plant in Turkey was performed. The velocities and accelerations caused by the sieve shaker system attached to the structure with springs, are evaluated under the effect of sample loading.

Keywords: Industrial building, Dynamic behavior, Vibration measurement, Acceleration, Velocity

Bir Sanayi Yapısının Çevresel Titreşim Analizi

Öz: Sanayi yapılarında ağır ve dinamik ekipmanlardan dolayı statik ve ölü yüklemelerde görülmeyecek ölçüde kesit tesirleri zaman içinde oluşabilmektedir. Bu durum yapıların hasar görmelerine ve kullanım sürecinde konfor sıkıntılarına neden olmaktadır. Bu çalışmada Türkiye'de bulunan bir bor işletmesi içindeki bir betonarme ve çelik taşıyıcı sisteme sahip bir binanın çevresel titreşim analizleri gerçekleştirilmiştir. Çalışmada yapının içinde bulunan ve yapıya yaylar ile bağlantılı olan dinamik elek sisteminden dolayı yapının betonarme ve çelik kolonlarında oluşan hız/ivme bileşenleri örnek yüklemeler etkisi altında değerlendirilerek yapının risk durumu incelenmiş ve gerekli önlemelerden bahsedilmiştir.

Anahtar Kelimeler: Sanayi yapısı, Dinamik davranış, Titreşim ölçümü, İvme, Hız

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1. INTRODUCTION

Numerical methods used in the analysis of existing structures include many approaches and assumptions that are incompatible with reality (Ewins, 1995). Therefore, evaluation methods that use only numerical methods cannot determine the actual dynamic behavior of a structure.

In the literature, the dynamic characteristics of structures are generally determined by numerical models constructed by computer programs. Numerical models include approaches regarding structural geometry, building material properties, soil - structure interaction, element cross-sections, structural loads and masses, damping ratios and other parameters. Approximate assumptions for each of these parameters decrease the accuracy and reliability of numerical analysis. Moreover, using numerical methods in the dynamic evaluation of strengthened buildings further increases the effect of approximations on the accuracy.

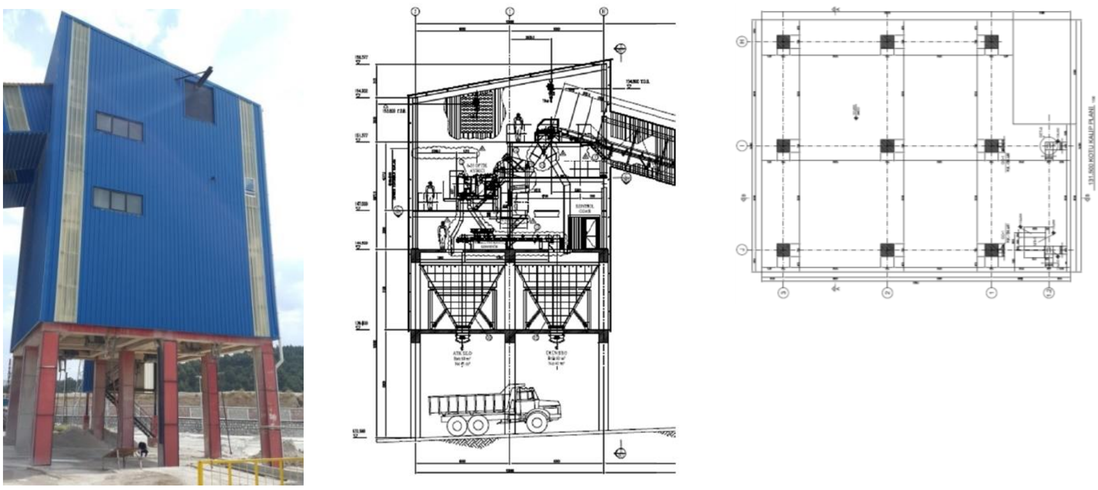
In recent years, the methods described as structural health monitoring and ambient vibration analyses are used to determine the dynamic behavior of existing private structures (Michel et al., 2008; Brincker et al., 2003). These methods can be defined as using vibration records taken from existing structures to determine the dynamic properties of a structure, taking consideration into factors with undetermined amplitude and change, such as wind, vehicle and human movements, machine vibrations and sea waves. In this context, ambient vibration analysis shows the dynamic properties of buildings, functioning as a full-scale experimental study, and fully demonstrating the dynamic behavior of existing structures. Bayraktar et al. (2010) investigated the dynamic parameters of buildings by operational modal analysis. The results of the study indicated that the first frequency value of building obtained by approximate assumptions was %30 smaller than that of real value. It was also concluded that the analytical models created to determine the dynamic behavior of the buildings can be improved by using the measurements obtained from existing buildings. Güneş and Anıl (2017) investigated the dynamic behavior of masonry structure by using operational modal analysis. It was concluded that there are differences between the dynamic characteristics obtained from experimental and numerical procedures, also ambient vibration tests can be used for the improvement of numerical models. Boru and Kutanis (2015) intended to determine the structural dynamic parameters with ambient vibration measurements. It was concluded that it is possible to determine realistic structural dynamic characteristics using ambient vibration measurements. İnel et al. (2013) investigated the determination of dynamic properties of existing structures by microtremor measurements. The results of the study indicated that there are remarkable differences between the microtrotremer records and analysis results for the natural periods of existing structures. Okuyucu (2020) focused on the operational modal analysis application on a single story reinforced concrete building. As a result of the study it was concluded that the theoretical and experimental mode shapes were defined to be similar; whereas the related frequency values were obtained to be different. Moreover, it was not possible to calculate the experimentally obtained modal behavior parameters if the fill walls were omitted in the finite element model. Kusunoki et al. (2018) and Michel et al. (2018) have measured uncertainties in existing masonry buildings behavior with the application of operational (environmental) modal analysis. Martakis et al. (2020) have analysed the vibrational recordings during the demolition of an existing masonry building. In their analyses, the lumped damage during demolition provided a valuable information about the correlation between dynamic response and structural health. Snoj et al. (2013) have conducted a parametric study and investigate the importance of the identified elastic properties of existing structures for the accurate assessment of ductility. Namlı and Aras (2020) examined the dynamic effect of tunnel boring machine on superstructures during tunneling during subway construction, using operational modal analysis over a four-storey reinforced concrete structure in Turkey. Similary, Zou et al. (2015) conducted some field experiments of vibration and noise on the ground, and inside a nearby 3-story building subjected to moving subway trains in a metro depot in China. Altunışık et al. (2011 and 2015) and Aras and Altay

(2015) investigated the vibrational caracteristics of historic buildings and arch bridges by vibrational based operational analyses. Soltys et al. (2020) investigated structural and dynamic caracteristics of an industrial buildings subjected dynamic loading, by using structural health monitoring. Due to the heavy and dynamic equipment in industrial buildings, the cross-sectional effects that are not seen in static and dead loads may occur over time. This causes damage to buildings over time and comfort problems while the building is in use. In this study, the measurements and results obtained within a sample industrial structure with dynamic challenges will be discussed.

2. GENERAL SPECIFICATIONS OF SAMPLE BUILDING

Sample building is located in a Boron Facility in Turkey. During the operation of dynamic sieve system supported by highly rigid springs in the building, considerable vibrations are formed. The authors conducted an ambient vibration analysis for the building and evaluated the vibration amplitudes in the building according to their analyzes.

The building is a steel structure with two floors of reinforced concrete frames as shown in Figure 1. The reinforced concrete part of the main building is symmetrical in the plan. Axle ranges are 6.00 meters. The two-floor reinforced concrete building is designed with high ductility level. There are no irregularities (A1-A2-A3/B1-B2-B3) in the reinforced concrete part of the building, mentioned in the Turkish Building Earthquake Code (TBEC 2018). The anticipated characteristic concrete compressive strength (f_{ck}) of the building is 25 N/mm^2 and characteristic reinforcement strength (f_{yk}) is 420 N/mm^2. The main beams of floors are 600/750 mm and 750/750 mm, and the intermediate beams are 400/600 mm and 500/600 mm. The main columns in the optical separator building are 750/750 mm. Floor thickness is 200 mm. No damage could be detected in the structural system of the building as of the date of the examination by the authors, and no visible corrosion has been observed in the steel elements in particular.



a. *b.* *c.*

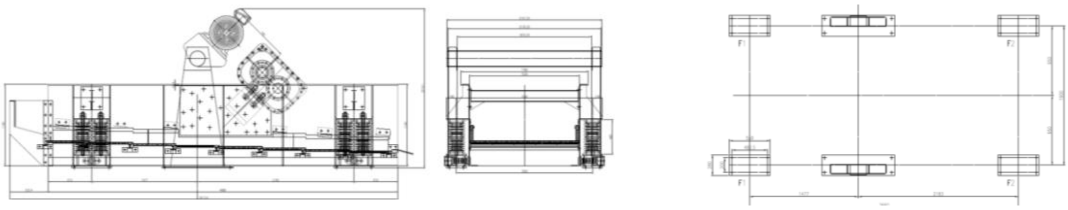
Figure 1:

Optical Separator Building floor plan and cross section

a. *3-D view of building* ***b.*** *Cross section of building* ***c.*** *Floor plan of building*

3. AMBIENT VIBRATION ANALYSIS OF THE BUILDING

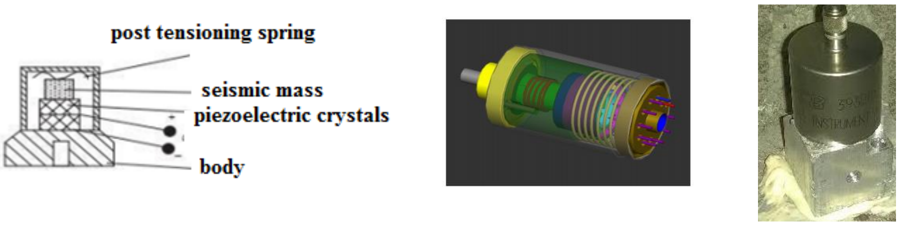
The sieve system in the steel part of the structure, shown in Figure 2 and Figure 3, is 1.90 m x 3.66 m x 2.21 m. The sieve system has been tested for various loading conditions. In the measurements, the vibration values of the upper and lower parts of springs are measured. Nine Piezoelectric type accelerometers (PCB Piezotronics brand, 393B04 model) are used in the measurements (Figure 4-7). The sensitivity, measurement range and frequency range of the accelerometers are 1.0 V/g, ±5 g and (0.06 to 450 Hz), respectively. Accelerometer mounting studs were fixed to the structure using a polyester resin-based adhesive, and then accelerometers were screwed into the studs. Piezoelectric accelerometers are used in various measuring applications, from very low frequency seismic applications to multiplication tests that require a very high frequency linear operating range. These transducers are small sized, may work in high temperatures and have industrial standard enclosures.



a. *b.*

Figure 2:
Sieve system
a. *Cross secitons of sieve system* ***b.*** *Plan of sieve system*
b.

Figure 3:
General view of sieve system



a. *b.* *c.*

Figure 4:
Structure of accelerometer
a. *Section view* ***b.*** *Inside view* ***c.*** *Outside view*

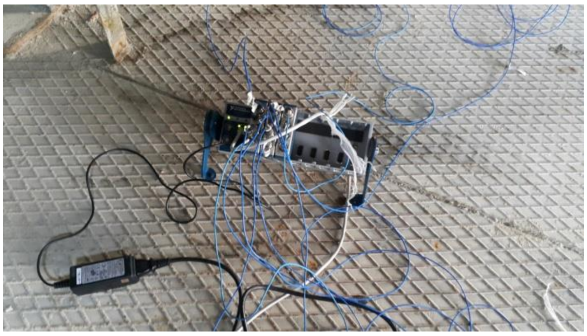


Figure 5:
Data collection system

Figure 6:
Accelerometers placed on the springs under sieve

Figure 7:
Station where data was collected during experiments

The accelerometer data were acquired using National Instruments Compact Data Acquisition system through NI 9234 modules. The acceleration, velocity and displacement histories are analyzed in both time domain and frequency domain by analyzing these acceleration-time values (Figure 3-4 and 5).

During the operation of the sieve system (optical separator), vibrations were measured and studies have been carried out to determine the effects of the vibration on building, as well as to determine the health and safety risks of employees exposed to the vibration, and to determine the acceleration displacement values created by these effects. For critical values, it has been checked whether speed values exceed the limit for relevant standards. Thus, situations that may cause damage are identified.

In order to evaluate the damage caused by vibrations from devices, the damage criteria developed by various researchers have been applied with various degrees of success. Among these developed criteria, two that are similar in terms of the parameters they use and are widely used as reference and comparison sources are US Mining Bureau's damage criterion (USBM 2009) and German DIN 4150 (1999) norm.

In the United States, the damage classification determined by relevant department (USBM RI 8507 Bulletin 1980) is given in Table 1. As can be seen, the damages are divided into three classes: "Threshold Damage”, “Light Damage “and “Basic Damage". The only type of damage that creates permanent deformations and weakens the structure is called "Solid Damage" class. The damage limits in this chart also resemble the Limited Damage (Minimum Damage), Significant Damage and Advanced Damage levels in the Turkish Building Earthquake Code (TBEC-2018).

Also, in Table 2, safe vibration levels which do not cause damage in the structures are given according to types of buildings (USBM RI 8507 Bulletin 1980). The values given here belong to the levels that will not create cracks on carrier elements in buildings.

Table 1. USBM 8507 damage classification (USBM RI 8507 Bulletin 1980)

Damage Class	Damage Description
Threshold Damage (Start of Damage)	Paint cracking and swelling, small plaster cracks on joints of structural elements, growth in old cracks,
Light Damage	Plaster swellings and dropping, splits in stone walls and capillary cracks in windows, cracks up to 3 mm thickness, loose mortar spills.
Solid Damage	Large cracks on walls, cracks on the arches, weakening of bearing elements of structure, stones dropping in in stone walls, for example chimneys and bricks, reduction in load carrying capacity

Table 2. Safe Ground vibration levels (USBM RI 8507 Bulletin 1980)

	Particle speed with maximum vibration	
	Low frequency(<40 Hz)	High frequency (>40 Hz)
Modern building	19.0 mm/s	50.8 mm/s
Old Building	12.7 mm/s	50.8 mm/s

In DIN 4150 German Norm (1999), the particle velocity limit values depending on frequency are given in Table 3 according to the type of structure. This is the speed values to be measured in cases where vibration is not continuous. In Turkey, there is a regulation included in TS ISO 4866:(2006) shown in Table 4, under the name "measurement of vibration in buildings as a result of machine vibration and evaluation of the effects on buildings". In this regulation, the upper limit values which are observed in structure during the operation of machine equipment are given in the frequency range in speed (mm/s). The values given in the relevant regulation are defined for housing and office and include values of 0.3 mm/s and 0.6 mm/s, respectively.

Table 3. DIN 4150 maximum particle speed by structure type (DIN 4150 1999)

STRUCTURE TYPE	Maximum Particle Speed (mm/s)		
	Base level frequencies (Hz)		
	<10 Hz	10-50 Hz	50-100 Hz
Industrial Buildings	20	20-40	40-50
Settlements and similar structures	5	5-15	15-20
Vibration sensitive structures	3	3-8	8-10

Table 4. TS norms on vibration

Test Name	Test Method (National, international standards, business-internal methods)
Personal Vibration Exposure Measurement (Hand-Body-Full Body)	TS 2774:1977 TS 2775:1977 TS ENV 5349-1:2005 TS ENV 5349-2:2004
Measurement of vibration in the entire body of an individual exposed to vibration (1 Hz to 80 Hz) due to continuous impact on buildings	TS ISO 2631-2:2001
Measurement of vibration in buildings as a result of vibration of machine equipment and evaluation of their effects on buildings	TS ISO 4866:2006
Environmental Vibration (Mining - Air Shock and Ground Vibration Measurement)	TS 10354 : 1992

4. AMBIENT VIBRATION ANALYSIS RESULTS

4.1. Results for Sieve System

Accelerometers are used under and above the vertical springs where the sieves are placed. In addition, an accelerometer is placed on the steel profile on which the sieve motor sits (Figure 6 and Figure 8). Vibrations are measured at a total of 9 (a_1 - a_9) points and the direction and positions of the accelerometers are shown in Figure 8. The frequency-acceleration response graphs are obtained for 10 measurements at indicated locations. As a sample, frequency-acceleration response graph for measurement no 1 at location no 5 is shown in Figure 9. Vibration acceleration amplitude was determined as RMS (Root Mean Square) or m/s^2 as the square root of averages. Peak values can be obtained by multiplying the values in the graphs by 1.41. In the experiments, different evaluations were made according to the direction of the springs under the sieves and loading type. These evaluations are shown in Table 5.

Table 5. Measurements and characteristics

Measurement No	Accelerometer Direction	Loading
1	Vertical	Sieve operation
2	Vertical	Operation of sieve and sieve vibrator
3	Vertical	Operation of sieve, under-sieve vibrator and neighbor sieve
4	Horizontal	Sieve operation
5	Horizontal	Operation of sieve and sieve vibrator
6	Horizontal	Operation of sieve, under-sieve vibrator and neighbor sieve
7	Vertical to horizontal springs	Sieve operation
8	Vertical to horizontal springs	Operation of sieve and sieve vibrator
9	Vertical to horizontal springs	Operation of sieve, under-sieve vibrator and neighbor sieve
10	Vertical to horizontal springs	Operation of under sieve vibrator

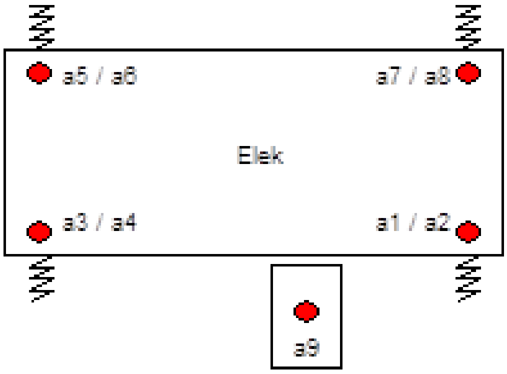


Figure 8:
Direction and position of the accelerometers

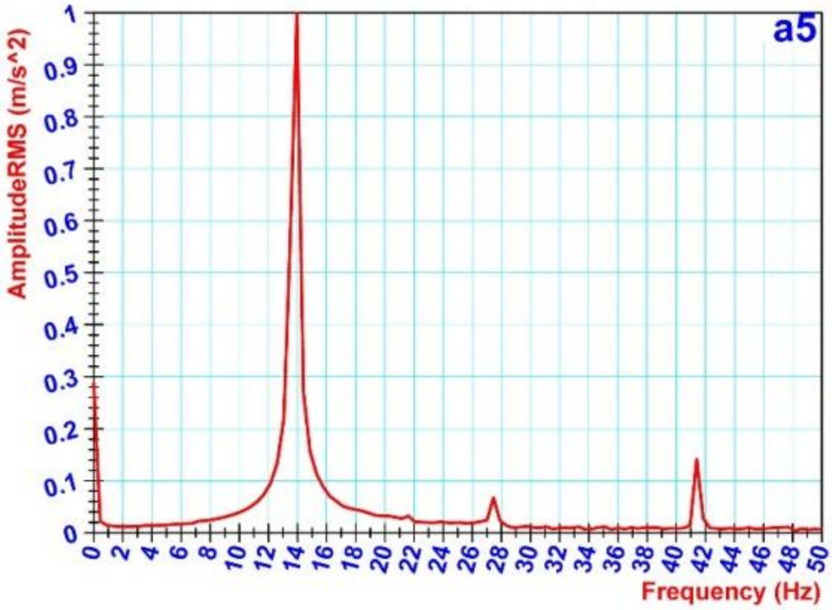
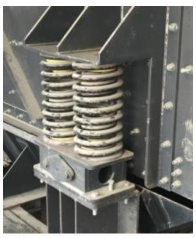


Figure 9:
Change in a5 acceleration values for measurement no: 1

A total of 9 different acceleration measurements (Fig. 8) were made in the motor cell located next to the sieve and in springs on which the sieves are placed. According to the evaluations, the critical values for the condition where sieve and sub-vibrator work together are given in Table 6. In addition, a sample loading and the obtained acceleration value are given in Figure 9. Among these values, it is observed that the speed values, especially between 170 mm/s - 296 mm/s, are decreased by 10 times to 17 mm/s - 30 mm/s. A similar situation exists for amplitude and strength, even at different rates. This also shows the damping properties of the springs. Here, the measurements taken under the springs are related to structure. Because the effects on the structure are related to these values. The high damping capacities of springs are evaluated positively, but the vibration frequencies of springs under load are considered to be a problem because the high amplitude values of the structure overlap with any natural vibration frequency.

Table 6. Lower and upper critical values of sieve springs

		Accelerometer Numbers	**Speed (mm/s)**	**Amplitude (mm)**	**Frequency (Hz)**	**G Force**
		a_2	273.0	4.9	13.78	3.74
Over Spring		a_4	193.0	2.3	13.78	3.14
		a_6	170.0	2.0	13.78	2.68
		a_8	296.0	3.9	13.78	4.35
Under Spring		a_1	17.0	0.17	13.78	0.35
		a_3	30.0	0.29	13.78	0.38
		a_5	27.0	0.30	13.78	0.43
		a_7	17.0	0.17	13.78	0.44

4.2. Results for Building Structural System

Due to the fact that the concrete floors and the upper floors of the building were made of steel, separate measurements were made for reinforced concrete and steel sections. In order to examine the building's response to vibration movement, nine Piezo electric accelerometers were used. For the reinforced concrete part of the structure, the upper part of the floor is measured separately from the upper end of the column. The accelerometers are positioned at four corners of the column beam joints (in areas as close as possible to floor alignment) and the records are linked with the help of reference from accelerometer. Thus, enough measurement to determine the dynamic responses of the structure was completed with nine accelerometers.

By transferring the obtained records on a frequency basis, in other words by transferring the records in time domain to the frequency domain with Fourier Transform, the dominant frequencies of each measurement are obtained. For the post processing of the measured data, National Instruments DIAdem software is utilized. By modifying the power magnitudes of dominant frequencies, the mode shapes of the structure have been defined.

The frequency-amplitude graphs of the vibration displacements and accelerations were drawn from the measurements made in two directions from 8 different points. The graphs given below are for each measurement way and direction, respectively. In addition, the positions and directions of the accelerometers are given in Table 7. The place names in the plan indicate the intersection of the axles and the direction of the acceleration meter. For example, J3X, J and 3 refers to a position in the X direction at the intersection of axes. The results in the frequency domain of the velocity obtained from the measured acceleration are named ‘vf’.

Figure 10 shows the direction and positions of the accelerometers placed in reinforced concrete section. Accelerometers are placed in upper and lower levels of corner columns in the floor plan. The accelerometer at the lower floor is located 500 mm above the natural ground level. The accelerometer at the upper level is located in areas close to the column-beam joint. The vibration velocity and acceleration amplitude given for the respective points are peak values and are determined as mm/s and m/s^2 respectively. Figure 11 shows these values. The harmonic frequency was detected as 15.73 Hz for this case. In the measurements given in the figures, loading is applied for sieve and under-sieve vibrator operation.

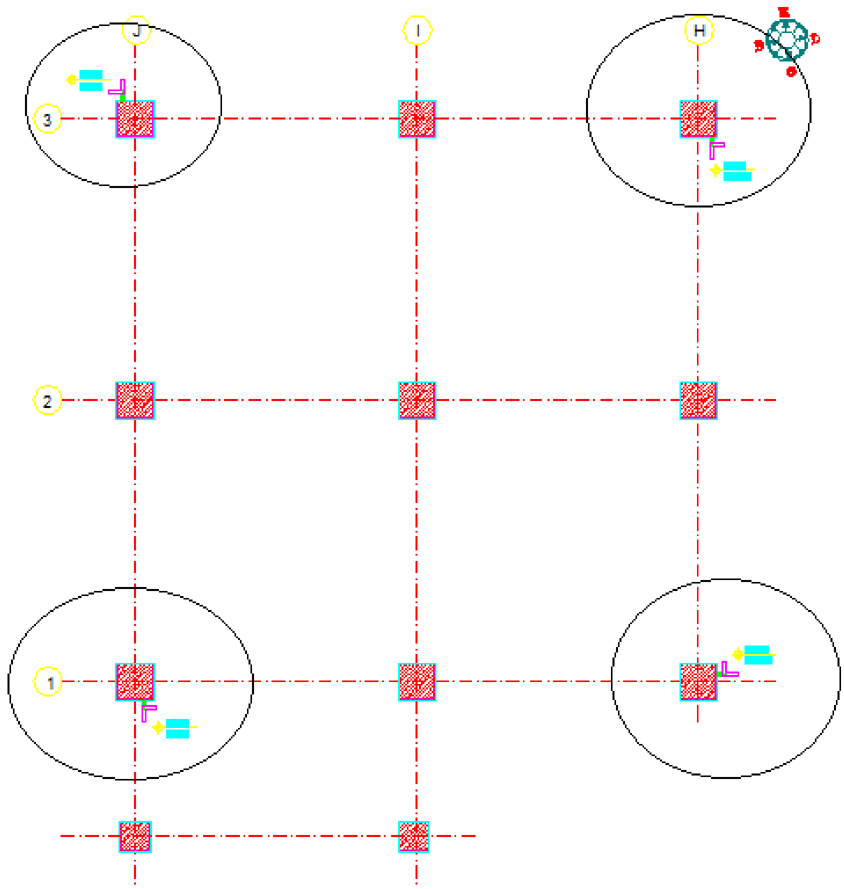


Figure 10:
Direction and position of the accelerometers

Table 7. Position and characteristics of accelerometers

Accelerometer No and Measurement Type	Location and measurement direction in plan	Column location
vf_1	J3X	UPPER
vf_2	J3Y	UPPER
vf_3	H3X	UPPER
vf_4	H3Y	UPPER
vf_5	H1X	UPPER
vf_6	H1Y	UPPER
vf_7	J1X	UPPER
vf_8	J1Y	UPPER
vf_9	H3X	LOWER
vf_{10}	H3Y	LOWER
vf_{11}	J3X	LOWER
vf_{12}	J3Y	LOWER
vf_{13}	J1X	LOWER
vf_{14}	J1Y	LOWER
vf_{15}	H1Y	LOWER
vf_{16}	H1X	LOWER

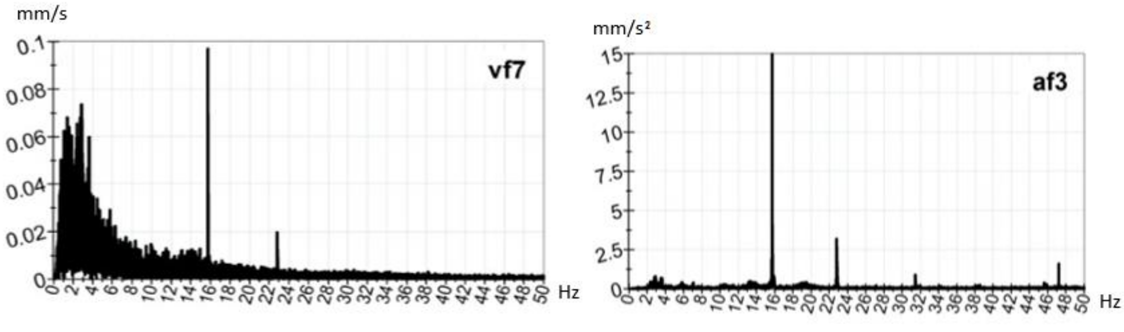


Figure 11:
Critical speed (mm/s) – Frequency and acceleration (mm/s^2)- Frequency speed in reinforced concrete columns at J1 and H3 axes in X direction.
a. *Critical speed (mm/s) – Frequency* ***b.*** *Acceleration (mm/s^2)- Frequency*

For the steel part of the structure, three measurements were made separately and a single acceleration meter was used in the last layer of the building. The other accelerometer is positioned at four corners for each floor in the column beam joints (in areas as close as possible to floor alignments). Thus, the measurement was completed with nine accelerometers to determine the dynamic properties of the structure. By frequency processing of the obtained recordings, in other words, by transferring the time domain records to the frequency domain by Fourier Transform, dominant frequencies of each measurement were obtained. The frequency-amplitude graphs of the vibration displacements and accelerations were drawn from the measurements made in two directions from 8 different points. The graphs given below are for the orientation and direction of each measurement, respectively (Figure 12-14). In addition, the positions and directions of the accelerometers are given in Table 8. Figure 12-14 shows the locations of the accelerometers, and the speed-frequency and acceleration-frequency values obtained are shown in Figure 15-16. The harmonic frequency was detected as 22.48 Hz for this case.

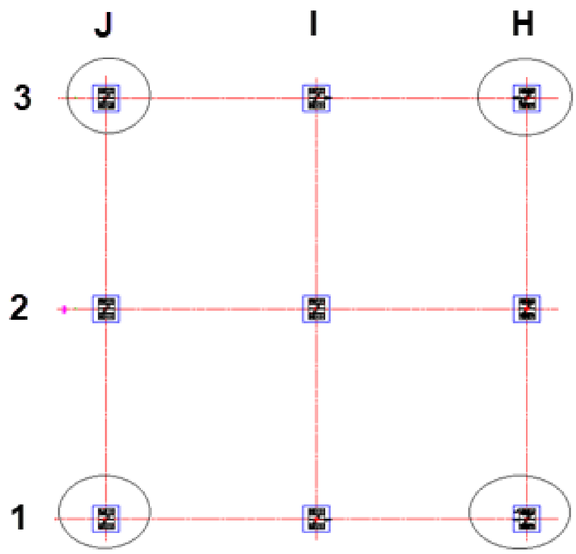


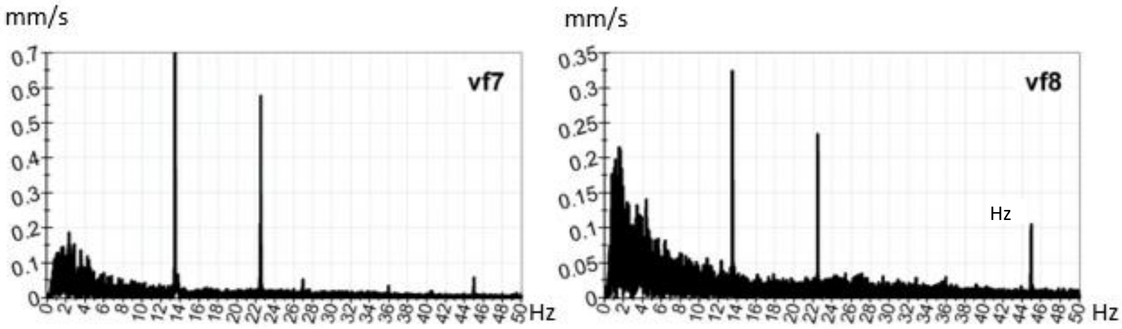
Figure 12:
Direction and position of the accelerometers

Figure 13:
145.33 Code J1 column sensor

Figure 14:
145.33 Code J1 column sensor

Table 8. Position and properties of accelerometers (For steel structure)

Accelerometer No and Measurement Type	Location and measurement direction in plan	Floor Number (Code)
vf_1	H1X	2nd Floor
vf_2	H1Y	2nd Floor
vf_3	J3X	0 Floor (145.33)
vf_4	J3Y	0 Floor (145.33)
vf_5	J1X	0 Floor (145.33)
vf_6	J1Y	0 Floor (145.33)
vf_7	H1X	0 Floor (145.33)
vf_8	H1Y	0 Floor (145.33)
vf_9	H3X	0 Floor (145.33)
vf_{10}	H3Y	0 Floor (145.33)
vf_{11}	J3X	1st Floor (151.187)
vf_{12}	J3Y	1st Floor (151.187)
vf_{13}	J1X	1st Floor (151.187)
vf_{14}	J1Y	1st Floor (151.187)
vf_{15}	H1X	1st Floor (151.187)
vf_{16}	H1Y	1st Floor (151.187)
vf_{17}	H3X	1st Floor (151.187)
vf_{18}	H3Y	1st Floor (151.187)



a. *b.*

Figure 15:

Speed (mm/s) at corresponding points in steel columns - Frequency values at H1 axis in X and Y directions.

a. *Speed (mm/s) - Frequency in X direction* ***b.*** *Speed (mm/s) - Frequency in Y direction*

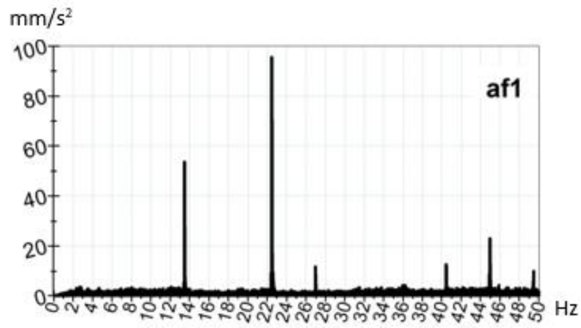


Figure 16:

Acceleration (mm/s^2)- Frequency values in related points of steel columns at H1 axis in X direction.

The velocity and acceleration values obtained from the reinforced concrete columns and the velocity and acceleration values obtained from the steel system (Figure 15 and Figure 16), are quite different from each other. However, velocity amplitudes below the limit of damage are determined according to the values obtained from the columns. This can be interpreted as the fact that the vibration felt on the columns and which become more translucent with local resonances will not have a significant effect on the columns of the structural system.

5. RESULTS AND RECOMMENDATIONS

In this study, ambient vibration analysis of a building, in a boron facility in Turkey, that has reinforced concrete and steel structure was performed. As a result of field work and analysis;

- The maximum particle velocity of the vibrations caused by the operation of the machines in the structural system columns is 0.16 mm/s in the reinforced concrete part according to the measurements; in the steel section, it is 1.1 mm/s. According to the tables given in this study, the frequency-related speed values are not significant enough for the risk of damage.

- The criteria in TS ISO:4866-2006 is not considered valid for this structure type (since it is not a residence nor an office). Therefore, no control has been made under the provisions of this regulation.
- Although there is no damage in the building, there is a risk of damage in the long term considering the time-related corrosion damage due to the ambient conditions affecting reinforced concrete and steel structures.
- Due to the fact that the structure will be used continuously with these measured vibrations, especially in the steel part will suffer from material fatigue over time and the increase in speed and acceleration components of the vibration response is expected. It is also appropriate to check the conveyor system and the machine tool part of such structures at certain intervals. For this, six-month periods can be determined.
- It is very important that the structures exposed to mechanical vibration during the operation of the machines especially for industrial purposes are designed according to these loads and to be considered for dynamic effects.

In the next part of the study, some improvements will be made on the sieve system and comparative analyzes will be made and the effect of the sieve system on the structure will be seen in more detail.

CONFLICT OF INTEREST

Authors approve that to the best of their knowledge, there is not any conflict of interest or common interest with an institution/organization or a person that may affect the review process of the paper.

AUTHOR CONTRIBUTION

Hüseyin Kartal, Yunus Dere and Musa Hakan Arslan determining the concept and/or design process of the research, Hüseyin Kartal and Yunus Dere management of the concept and/or design process of the research, Yunus Dere data collection, Hüseyin Kartal and Yunus Dere data analysis and interpretation of the results, Hüseyin Kartal and Yunus Dere preparation of the manuscript, Musa Hakan Arslan critical analysis of the intellectual content, Hüseyin Kartal, Yunus Dere and Musa Hakan Arslan final approval and full responsibility.

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