Investigating the Movements of Bosporus Bridge by Different Types of Loads

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SUMMARY

Engineering structures like suspended bridges are designed according to responses of the bridge under causes like traffic, earthquake, pedestrian, wind loads and temperature changes. Effects of these loads to bridge may be identical or composite. Besides another loads which did not take into consideration may occur afterwards. A similar situation was occurred during 26th Intercontinental Eurasia Marathon on 10.10.2004 on the Bosporus Bridges which provides the transportation between Europe and Asia continents. Bridge was used for the passing of the runners from Asia to Europe. During this passing, responses of the bridge under the causes like rhythmic race, unsystematic pedestrian load and unsystematic traffic load including temperature changes and wind load were measured by RTK GPS on 4 seconds interval. Measured values have time series characteristics and they had been divided into 12 parts. High frequencies of the structure had been determined by time series analysis in every part. And also It was tried to remove the spectral leakage by multiplying the series with windowing function. And then, frequency values of the temporary bridge vibrations were determined as the result of the high-pass filtering of the series. Also it was understood that, structure are affected by traffic load more than other loads. Because of low sampling frequency, calculated frequency is not compatible with natural bridge frequency. Calculated frequencies are similar to each other and they are very low, so it was seen that, responses of the bridge against to different loads within the marathon are small values.

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1. INTRODUCTION

Predictions during the design and observations during the construction and management of engineering structures explain the safety of the structure. So the movements and shape changes of the structures under temperature changes, wind, pedestrian and traffic load must be measured by appropriate measurement equipments. Determining the deformations dependent on shape and characteristics using measured values and taking necessary precautions on time is very important for engineering works (Heunecke, 2000).

GPS antennas with 10 Hz even 20 Hz sampling rates are usually used for monitoring the structures. Because frequency values of the structure responses under different loads are between 0.1 Hz – 10 Hz (Cheng, John and Zheng, 2002; Lovse, Teskey vd., 1995). Multipath is affected to GPS observations especially on the deck part of the bridge. A detailed investigation of the deteriorating influence of the steel cables is given in Wieser (2002). Even using sophisticated variance models for the GPS processing, like the SIGMA-Δ and SIGMA-F weight models, Brunner et al. (1999) and Wieser (2002) respectively, the result cannot be improved. The main conclusion is that the cables cause multipath and diffraction effects which affect almost all GPS signals recorded. It was expressed by Leach and Hyzak (1994), Lovse, Teskey vd., (1995), Roberts, Meng and Dodson (2001), Wieser (2002) and Wieser and Brunner (2002) that, GPS can be used on structures like bridges because of high sampling frequency, continuous measurement opportunity on every weather condition.

In this study, response of the Bosporus Bridge during the crossing of the runners from Asia to Europe on the 26th Intercontinental Eurasia Marathon on 10.10.2004 was measured by RTK GPS. Observations were divided into 12 parts depending on loads. By analyzing the measured values which have time series characteristics, frequency values of the bridge were determined.

2. TIME SERIES ANALYSIS

By analyzing time series of the responses of engineering structures, characteristics of the series are summarized and series can be clarified. So the linear, periodical etc. behaviors of the monitoring system under different loads can be understood. This process is discussed both time and frequency domain. Both analyses have complementary characteristic and they can give different ideas about the characteristic of time series. Usually $Y(t_i)$ time series on t_i time can be divided into 3 components (i= 1, 2, 3,…., N).

$$Y(t_i)= Y_{Trend} + Y_{Periodical} + Y_{Stochastic} \quad (1)$$

By parsing these components of the series, structure behaviors can be explained. Especially by using the spectral analysis which is used for analyzing the frequency characteristics of series and is defined on frequency domain, information about the structure can be determined as frequency.

During time series analysis, firstly observation forms of time series (trend, periodical component etc.) and unusual observations are tried to explain by drawing the time axis graphics of the series.

Determined periodical component of time series represents long time changes of the series. But also local changes of series can be determined by using the high pass filtering. For determining the local changes (high frequencies) basic filtering process (high pass) based on differencing method is applied. In this method, a new series is formed by d. degree differencing of the series which's observation values are $Y(t_i)$, $Y(t_{i+1})$, …, $Y(t_N)$. First degree differencing is defined with equation 2 and third degree differencing is sufficient for practical purposes.

$$Y(t_{i-1}) = Y(t_i) - Y(t_{i-1})$$
(2)

By differencing the series, noise values of the series can be reduced a little bit and a stable series can be formed by eliminating the trend component (Box ve Jenkins,1970).

By using high pass filtering and eliminating the trend component, a transformation from time domain to frequency domain can be possible with FFT (Fast Fourier Transformation). But because of the periodical characteristic of FFT, when calculating the signal spectrum with FFT, spectral leakage may occur result of the energy leakage to the other frequencies. For reducing the effect of spectral leakage, signal is multiplied by a windowing function which's amplitude closed to zero. For example Hanning Windowing Function is expressed in equation 3. N is measurement count.

$$w(i) = 0.5 - 0.5\cos\left(\frac{2\pi i}{N}\right)$$
(3)

Windowed values are:

$$X(k) = \sum_{t_{ip}=0}^{N-1} Y(t_{ip}).e^{-jk\frac{2\pi}{N}t_{ip}}$$
(4)

N complex multiplying and N-1 complex adding process for each X (k) values, is used for direct calculation of FFT. Meanwhile N number FFT values are calculated and N^2 multiplying and N(N-1) adding process are done. Module square of calculated values as the result of FFT is named as spectrum $P_{xx}(k)$.

$$P_{xx}(k) = \left|X(k)\right|^2$$
(5)

Frequencies of movements on the series are calculated by determining the dense frequencies of signal energy with $P_{xx}(k)$ on equation 5.

3. BRIDGE DESCRIPTION

Crossing the Bosporus easily which separates the Asian and European Continents is attractive idea for centuries. The oldest Bosporus crossing is done in B.C 511. Because of the fast developments in Istanbul and traffic increase between Asia and Europe, it was decided to construct a bridge on Bosporus. Bosporus Bridge construction was started in 1970 and it was finished in 1973.

Bosporus Bridge is a suspended bridge with 1074m main span, and 231m side span on European part, 255m side span on Asian part, hollow box deck, and inclined hangers. Bridge towers are steel box and 165m high from sea. Base area of towers on ground is 7m x 5.2 m and area oh the highest point is 7m x 3m. There are 6 lanes as 3 going and 3 coming each of them 3.5 m wide.

Bridge was projected as to carry the 6 lanes highway traffic. And there are pedestrian roads on both sides. English load standards were accepted by increasing %10 for traffic load and 180 tons special vehicle load was considered. Max wind speed was accepted as 45 m/sec. Also bridge was designed to endure 0.1g basic ground acceleration horizontally and 0.05g vertically.

4. TRIAL DESCRIPTION

During 26th Intercontinental Eurasia Marathon, crossing from Asia to Europe was performed on Bosporus Bridge on 10.10.2004. During this crossing, traffic load, temperature changes, wind load, rhythmic walking of the athletes (Figure 1-a abn Figure 1-c), systematic and random pedestrian walking (Figure 1-b) were affected the bridge. Depending on these effects, structure responses were occurred on different directions and different values. Responses of the Bosporus Bridge to these effects were observed by RTK GPS method as 4 second sampling rate.

Figure 1 Pictures of activities during marathon.

Reference point was chosen on a building 1km far from bridge (point A), and object point was chosen on middle point of deck on south part (point B). Observations were collected between 08:49 and 12:40. Mean temperature change is 20^0 and wind change is 2.2 m/sec on N direction during the observations.

Figure 2 Reference and object points used for measurement of Bosporus Bridge responses under different load.

5. BRIDGE TRIAL RESULTS

The biggest changes on suspended bridges are occurred usually on vertical directions because of the large main span. So vertical movements of Bosporus Bridge were processed and analyzed. For this purpose 4 hours length observations were divided into 12 parts for determining the structure response under different loads like temperature changes, wind, traffic and pedestrian load.

Vertical movements of middle deck point according to mean measured values are shown in Figure 3 as time series. Also different loads are marked on figure.

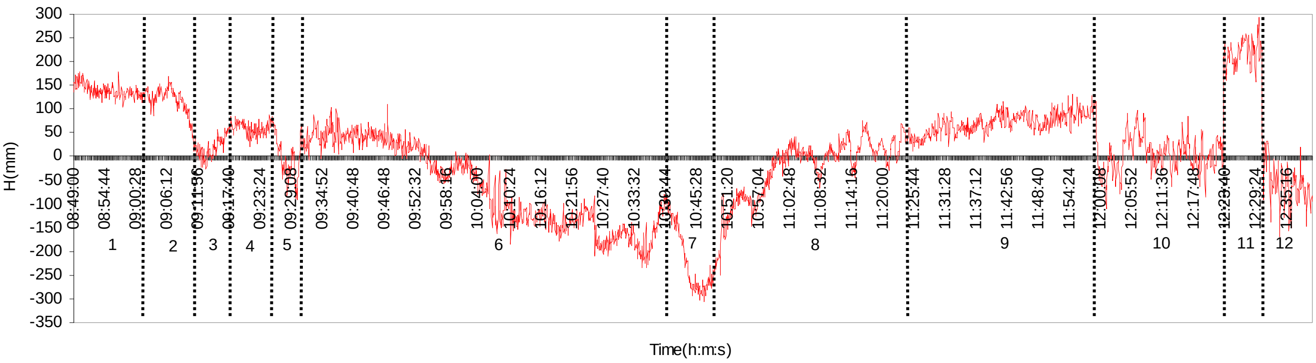

Figure 3 Time series of Bosporus Bridge responses under different loads.

Maximum changes below (-) mean movement and above (+) mean movement are given in Table 1. Also temperature changes and wind load are accepted as the same effect during measurements.

Table 1 ± Maximum changes of Bosporus Bridge for 12 parts according to mean value

Part No	Affected Load	Maximum changes above mean movements (mm)	Maximum changes below mean movements (mm)
1	*Bridge was closed to traffic*	179	----
2	*Marathon (Rhythmic run)*	169	----
3	*Pedestrians entered to bridge*	72	-28
4	*Pedestrians spread out to bridge surface*	85	----
5	*20 buses and pedestrians on bridges*	88	-92
6	*Unsystematic walking on bridge*	110	-236
7	*Pedestrians gathered on south part of bridge*	----	-308
8	*Pedestrians leaved the bridge*	75	-177
9	*Bridge was closed to traffic*	131	----
10	*South part of bridge was opened for traffic.*	99	-109
11	*North part of bridge was opened for traffic.*	293	----
12	*Bridge opened for traffic completely*	34	-171

As it is shown in Figure 3 and Table 1, bridge was closed to traffic on 1st and 9th parts and 179mm, 113mm responses above mean movement were determined. On 2nd part bridges was affected from special load. A rhythmic load is shown and 169mm response above mean movement was determined. This change is increased slowly. When this effect is short, it was seen that the response is short too. As it is shown in 3rd, 4th, 6th and 8th parts, bridge had different responses under different pedestrian loads. Maximum changes on bridge were occurred on 7th part when pedestrians gathered on south part of bridge and -308mm change was calculated. In 5th part both traffic and pedestrians were affected to bridge on same time and changes above and below mean movements were determined. When south part of bridge was opened for traffic, changes about mean movement were determined. But there are a few vehicles on the bridge at this time. When north part of bridge opened for traffic with a lot of vehicle 293mm change above mean movement was determined. In last part bridge was opened for traffic completely (south and north) and changes about mean movement were determined.

Local movements may be occurred on suspended bridges as the result of random and instantaneous load changes (wind direction changes, different vehicle speeds, rhythmic or unsystematic walks). These changes can be discussed as high frequencies which take places on long time changes. 1st degree differencing is applied on time series which represents structure movements by using equation 2 for determining the structure movements. On the other words, high pass filtering is applied to the series and low frequencies of series were determined and noise and trend component of series were eliminated. And then power spectrum of differenced series was calculated as the result of FFT by multiplying the series values with Hanning Windowing function. High frequencies of local response values for 12 parts were shown on Figure 4.

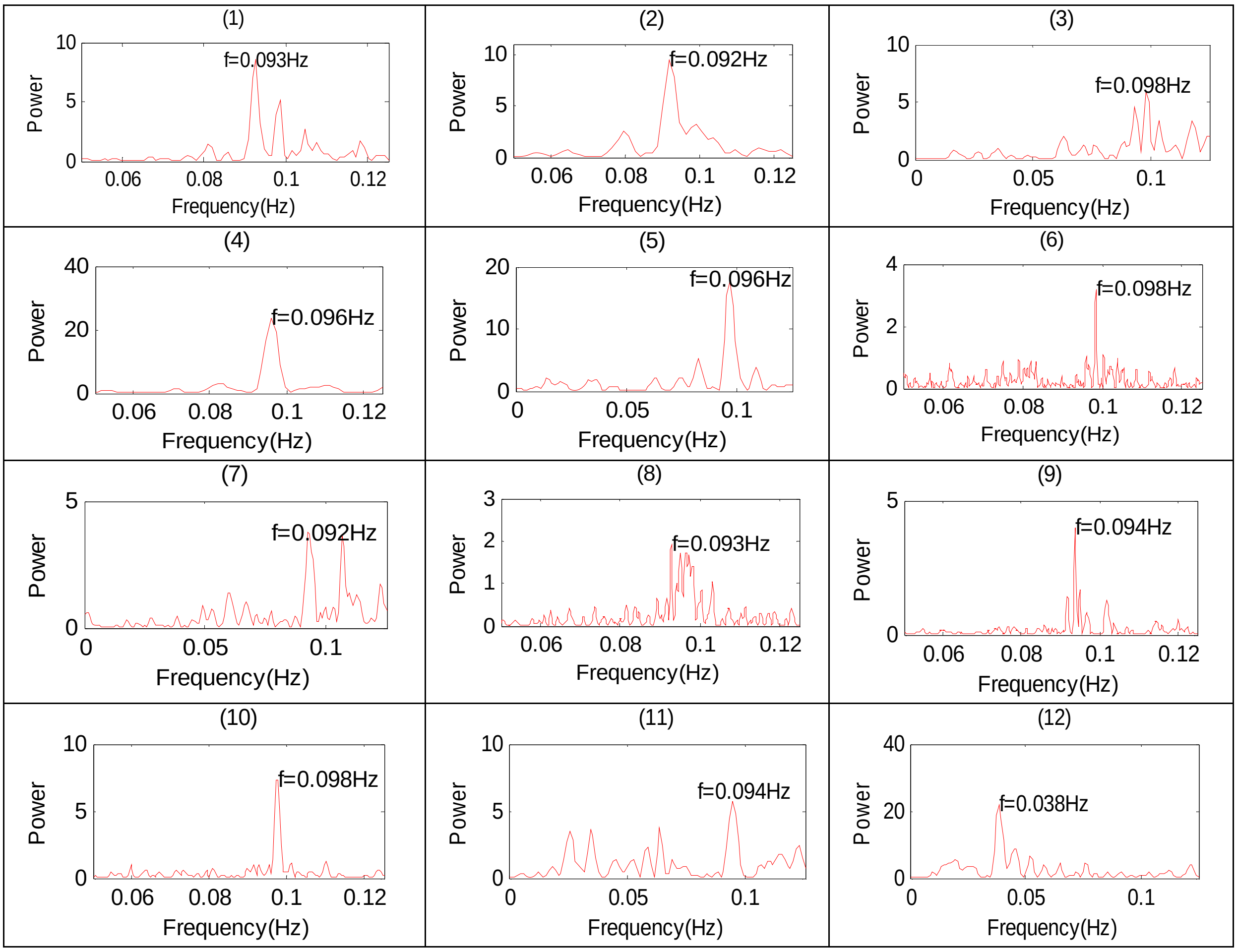

Figure 4 High frequency responses of Bosporus Bridges under different loads.

Horizontal axis of each part's spectrum graphic is Hz unit frequency axis of structure's clear frequencies and vertical axis is power axis that shows the structure responses against to load effects. Frequency values of the structure response values were determined by pairing the determined power of response values to the frequency values. Calculated frequency values of each part are the same except 12^{th} part. As it was expressed before, bridge was opened for traffic completely in 12^{th} part. It is seen that frequency values of bridge responses under different loads are between 0.05 Hz – 0.125 Hz.

On the other hand natural frequencies of Bosporus Bridges for first three modes were calculated in order as 0.127, 0.165, 0.226 Hz by Dumanoglu and Severn (1985) by using Finite Element Method from SAP90 model. Natural frequencies and periods were determined by considering the only mass and rigid matrix of structure and as the result of continuous free vibration. Consequently calculation of structure natural frequencies is independent from affected loads (wind, earthquake, vehicle load etc.). Dumanoglu and Severn (1989) was expressed that, mode types and frequencies of suspended bridges can be determined by measuring the temporary vibrations which occurred as the result of wind and traffic load. They have choose Bosporus and Humber bridges as the sample.

In this study it is seen that, calculated frequency values (Figure 4) of Bosporus Bridges which was affected by different loads don't reflect the natural frequencies of the structure. The main reason of this problem; very low sampling rate (0.125 Hz) was chosen for determining the high frequency movements of the bridge.

4. CONCLUSION

Suspended bridges are affected by different loads like temperature changes, traffic, pedestrian and wind load. Therefore all of the possible loads are considered in design phase. Sometimes responses of the structure against to these effects are tested in laboratories. But the structure must endure usual conditions after the construction had been finished. For example Bosporus Bridge was used for crossing from Asia to Europe during Eurasia Marathon. Suspended bridges are affected by different loads like rhythmic run, systematic and random pedestrian walk. For determining the shape and functions of bridge responses against to these instantaneous and high frequency effects, measurement instruments with appropriate sampling frequency and accuracy must be used.

Sampling frequency which was chosen for determining the responses of structure must be equal to double maximum structure frequency or greater than maximum structure frequency. Otherwise accurate information can not be obtained about structure behavior. But long time period changes (because of temperature effect) on structures can be determined by low frequencies. In this situation measurement period must be long.

Also as the result of time series analysis structure behaviors can be determined on time and frequency domain by measuring the only responses of the structure under different loads. For detailed identification effected values must be measured and mathematical model of the structure must be obtained.

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BIOGRAPHICAL NOTES

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