Experimental and Analytical Studies on Dynamic Characteristics of the Bosporus Suspension Bridges

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Key words: Bosporus Suspension Bridge, ambient vibration measurements, Fast Fourier Transform, finite element

SUMMARY

In this study, traffic and wind excitations have been used to obtain the dynamic characteristics of the Bosporus Suspension Bridge in Istanbul, Turkey. The field ambient vibration measurements on the bridge deck were conducted in 2003 and 2005. The frequencies can be effectively calculated from ambient vibration measurements by the power spectrum (PS) in the frequency domain. For the bridge deck, 7 (in 2003) and 13 (in 2005) vertical frequencies and 7 (2003) and 9 (2005) lateral frequencies were calculated in the range 0-1.5Hz. Furthermore, 13 vertical and 9 lateral frequencies were predicted by use of two-dimensional finite element (FE) model. Predicted frequencies lie in the range 0–1.5Hz. A good correlation is achieved between the FE and ambient vibration test results. Comparison with a more limited study made in 1973, 2003 and 2005 shows that the bridge continues to behave as it was designed to behave.

SUMMARY

Bu çalışmada, Boğaziçi Köprüsü'nün (İstanbul, Türkiye) trafik ve rüzgar yüklerinin etkisi altındaki dinamik davranışları araştırılmıştır. Köprü tabliyesinin dış yükler (trafik ve rüzgar) altındaki titreşimleri 2003 ve 2005 ölçülmüştür. Ölçülen titreşimlerle, köprünün frekansları frekans bölgesinde yapılan güç spectrum analizi ile belirlenmiştir. Tabliye için, 0-1.5 Hz aralığında, 2003'de 7 düşey ve 7 yanal frekanslar, 2005'de 13 düşey ve 9 yanal frekanslar tespit edilmiştir. Ayrıca, köprünün iki boyutlu Sonlu Eleman modelinden 13 düşey ve 9 yanal frekansları tahmin edilmiştir. Ölçülen ve modelden tahmin edilen frekansların uyuşumlu olduğu görülmüştür. Ayrıca, bu frekanslar 1973'de (köprünün trafiğe açıldığı tarih) belirlenen frekanslarla da uyumlu olduğu ve köprünün tasarlandığı gibi davrandığı görülmüştür.

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1. INTRODUCTION

Operational safety and operational condition of engineering structures depend on the acceptances given during the design stage of the structure and on the observations obtained during the construction and operation stages and on the implementation of emergency situation plans in case irregular movements are determined. Particularly, with the fast development of large span bridges, a significant amount of research on the structural health and safety of important bridges has been conducted in the past two decades. It is the most important issue to ensure an adequate level of safety of large span bridges under dynamic loadings such as traffic and wind. This can be achieved if the dynamic characteristics of the bridge are accurately determined.

Dynamic field testing of a bridge provides an accurate and reliable description of its current dynamic characteristics. There are two types of dynamic test on civil structures, forced and ambient vibration tests (Hudson, 1970; Ren et al., 2004; Galambos and Mayes, 1979). Ambient excitations include traffic, wind, people and earthquake loads and combinations of such loads. Ambient excitation cannot be measured. In this case only responses of ambient vibrations are measurable while actual loading conditions are unknown. Ambient excitation therefore needs to base itself on output-only measurements. Therefore, ambient vibration tests have been successfully applied to large span bridges, such as the Humber Bridge (Roberts et al., 1999; Roberts et al., 2000), the Tsing-Ma Bridge, the Kap Shui Mun and Ting Kua Bridges (Wong, 2000), the Human Bridge (Roberts et al., 2001), the Nesenbachtal Bridge (Kuhlman, 2001), the Golden Gate Bridge (Abdel-Ghaffer and Scanlan, 1985), the Bosporous Bridge (Brownjohn et al., 1989; Erdoğan, 2006; Erdoğan and Gülal, 2009), the Deer Isle Bridge (Kumarasena, 1989), the Quincy Bayview Bridge (Wilson and Gravelle, 1991), the Maysville Bridge (Chang, 2001) and the Roebling Bridge(Ren and Harik, 2002; Wei-Xin, 2005; Ren and Obata, 1999).

In this paper, the dynamic characteristics of the Bosporus Suspension Bridge were obtained by traffic and wind excitations. Measurements on the bridge deck were made by Total Station (in 2003) and Global Positioning System (GPS) (in 2005). The frequencies can be calculated from ambient vibration measurements (AVMs) using the Peak Peaking (PP) method in the frequency domain. All these frequencies lie in the range 0-1.5 Hz. A detailed comparison is given between these frequencies and corresponding predicted frequencies, obtained by use of two and three-dimensional finite element (FE) models. A good correlation is achieved between the FE and AVM results.

2. METHOD

Traditionally, a rather basic PP method chosen to identify the natural frequencies of the structures uses AVMs. The PP method is essentially a frequency domain based technique. The frequencies at which extreme amplitudes occur are good estimates for the structural eigenfrequencies. In this way the natural frequencies are directly determined from observation of the peaks on the graphs of the average normalized power spectral densities (ANPSDs), which are obtained by converting the measuremants to the frequency domain by a Fast Fourier Transform (FFT) (Ren, 2004). FFT is an efficient algorithm for computing the Discrete Fourier Transform (DFT) of a sequence; it is not a separate transform. The FFT is extremely important in the area of frequency analysis because it takes a discrete signal in the time domain and transforms that signal into its discrete frequency domain representation. This is an efficient and robust algorithm. This fact also helps to decide which frequencies can be considered as natural.

3. BRIDGE DESCRIPTION

The Bosporus Bridge links the two parts of Turkey and also links the European and Asian parts of the city of Istanbul. Plans for the bridge were made in 1969, construction, started in 1970 and it opened on 29 October 1973. The bridge is 1074 meters long and 33.4 meters wide with six vehicle lanes and a pedestrian footpath on each side. The deck is of hollow box construction and is supported from the main cables by hangers. The towers that support the main cables are 165 meters high and are made of high yield steel with each tower consisting of two legs joined by three horizontal portal members. The approach viaducts between the anchorage and tower are of composite steel and reinforced concrete construction. On the European side, the viaduct is 231 meters long and on the Asian side, it is 255 meters long. The maximum wind force has been determined as $45ms^{-1}$.

4. AMBIENT VIBRATION MEASUREMENTS (AVMs)

Dynamic parameter characteristics of the Bosporus Suspension Bridge were acquired through lateral and vertical AVMs. Traffic and wind excitations have been used to obtain the dynamic characteristics of the bridge. AVMs were made in the two phase. In the first phase, terrestrial measurements had been executed in partnership with Universität der Bundeswehr München Institut für Geodäsie using ATR system Total Station (Leica TCA2003) between 22.09.2003-26.09.2003 with a sampling frequency of 1Hz (Erdoğan, 2006; Erdoğan and Gülal, 2009). In the second phase, Thales Z-Max GPS receivers were used for measuremenst on 04.10.2005. Thales Z–Max GPS receiver has a nominal accuracy of ±5mm+0.5ppm for horizontal displacements and ±1cm+0.5ppm for vertical displacements with a sampling rate of 10Hz.The instrumentations setup are shown in Figs. 1a and 1b for Total Station and GPS, respectively.

Terrestrial measurements at 21, 22 and 24 stations were made at the successive time. Sampling frequency is 1 Hz for terrestrial measurements. Because, the maximum sampling frequency of Total Station (Leica TCA2003) is 1Hz. For each station, the measurements were recorded for 16.15 minutes at intervals of 1 second, which resulted in a total of 975 measurement points.

GPS measurements at 22 and 23 stations were made at the same time and sampling frequency is 5 Hz. For each station, the measurements were recorded for 60.9 minutes at intervals of 0.2 second (5Hz), which resulted in a total of 18045 measurement points (Fig. 1b). During all measurements, normal traffic was allowed to flow over the bridge at normal speeds. Measurements were shown in Fig.2.

(a) (b)

Fig.1 The Bosporus Bridge, stations, instrumentations setup for Total Station (a) and GPS (b) measurements

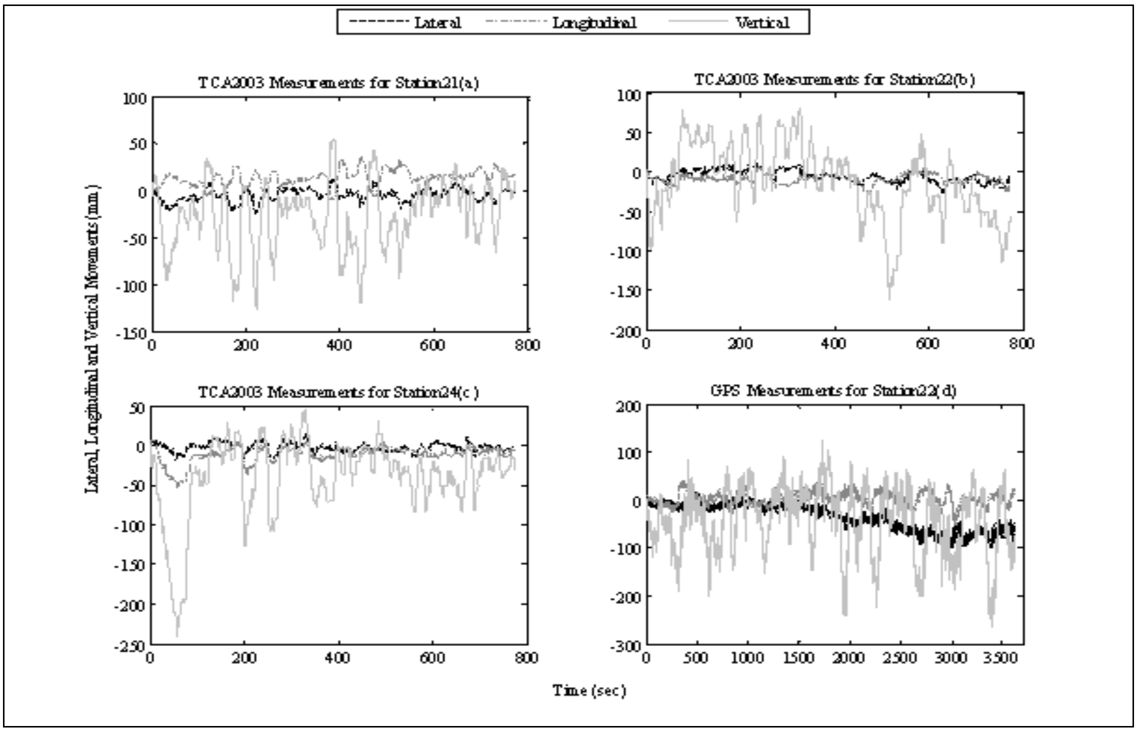

Figure 2. Lateral, longitudinal and vertical Total Station measurements (raw data) for stations 21 (a), 22 (b) and 24 (c) and GPS measurements for station 22 (d)

4.1 Processing and results of measurements

In the pre-processes, firstly, trend in the series were investigated. Because, long-term periodical movements of the bridge are observed as a trend in short-term measurements. Therefore, trend has to be removed from measurements. Otherwise, frequency values that will be used in description of the structure will be different from expected values. Later, Butterworth low-pass filtering was applied to measurements. Cutoff frequencies are 0-1.5 Hz for GPS masurements and 0-0.5 Hz for Total Station measurements. For Bosporus Bridge, the frequency range of interest lies between 0 and 1.2 Hz, which contains at least the first 15 frequencies. In this respect, GPS measurements can reflect the bridge frequencies. Total Station measurements can reflect the bridge frequencies between 0-0.5 Hz. Because, sampling frequency of total station is 1 Hz.

After filtering, the power spectral densities (PSDs) are not acceptable because the PSDs are directly computed as the FFT of all available AVMs (975 and 18045 points for Total Station and GPS). A much smoother spectrum can be obtained by adjusting the PSD parameters. A window length of 256 measurement points was then selected. Subsequently, the PSDs were taken for all succeeding blocks of 256 measurement points, after which the 4 (≈975/256) and 71 (≈18045/256) different PSDs were averaged. Averaging minimized the spurious, noisy components of the results. After this process for all measurements, the measurements are ready to extract the frequencies and mode shapes of Bosporus Bridge.

The vertical average normalized power spectral densities (ANPSDs) are shown in Fig. 4 for station 22. Peak points are clearly shown from which the frequencies were chosen. It should be noted that the figures have been magnified to focus on the frequency range of interest. The calculated lateral and vertical frequencies are summarized in Tables 1 and 2 for Total Station (in 2003) and GPS (in 2005). Note that the calculated frequencies from two separate AVMs are quite stable. The first vertical vibration frequencies of the Bosporus Suspension Bridge are about 0.117 and 0.101 Hz, while the first lateral vibration frequencies are about 0.074 and 0.078 Hz for 2003 and 2005, respectively. Furthermore, in Table 1, the vertical frequency values are given obtained by Tezcan et al. (1975) and Petrowski et al. (1974) in 1973

4.2 Finite-Element (FE) model

The two and three dimensional FE model used to predict the dynamic response of the Bosporus bridge is described in Dumanoğlu and Severn (1985) and Brownjohn et al. (1988, 1989). The two dimonsional mesh comprised 202 nodes, 317 beam elements and had 469 degrees of freedom. It was used to represent either the lateral or the vertical movements of the Bridge, and for vertical movement, models with two types of bearing boundary conditions were used. The three-dimensional mesh comprised 412 nodes, 85 plate/shell elemants, 398 beam elemants and had 1892 degrees of freedom. The two models were used to generate natural modes. Vertical and lateral frequencies of the Bridge derived from FE model are presented in Tables 1 and 2.

4.3 Comparison of calculated and predicted frequencies

The natural frequencies are predicted from the two and three-dimensional FE model, which the representation of the deck by equivalent plate elements was a subject of particular interest. The frequencies were determined before measurements by Dumanoğlu and Severn (1985) and Brownjohn et al. (1988, 1989). Thus, Predicted frequencies assisted in planning the positioning of the Total Station and GPS. Furthermore, Table 1 compares the vertical frequencies; column 3 gives the values obtained by Tezcan et al. (1975) and Petrowski et al. (1974) in 1973.

Table 1 Compares vertical (v) frequencies predicted from FE model and calculated from the AVMs.

Mode No.	Predicted frequencies from the FE model (Hz)	Calculated frequencies from the AVMs (Hz)		
		1973	2003	2005
v1	0.126	-	0.117	0.101
v2	0.165	-	0.156	0.156
v3	0.180	-	0.172	0.195
v4	0.225	0.233	0.211	0.293
v5	0.284	0.282	0.296	0.332
v6	0.372	0.357	0.360	0.391
v7	0.454	0.444	0.445	0.469
v8	0.556	-	-	0.546
v9	0.658	-	-	0.589
v10	0.765	-	-	0.762
v11	0.883	-	-	0.879
v12	0.883	-	-	0.938
v13	1.011	-	-	1.035

Table 2 Compares lateral (ℓ) frequencies predicted from FE model and calculated from the AVMs.

Mode No.	Predicted frequencies from the FE model (Hz)	Calculated frequencies from the AVMs (Hz)	
		2003	2005
ℓ1	0.073	0.074	0.078
ℓ2	0.218	0.211	0.178
ℓ3	0.294	0.297	0.234
ℓ4	0.301	0.309	0.312
ℓ5	0.408	0.414	0.371
ℓ6	0.437	0.441	0.449
ℓ7	0.471	0.480	0.507
ℓ8	0.539	-	0.566
ℓ9	0.753	-	0.781

In the 1973 measurements of Tezcan et al. (1975) and Petrowski et al. (1974) only four vertical frequencies were calculated using, and since the lowest sy AVMs simmetic and antisymmetric frequencies were not among these, it can be inferred that no appreciable response was measured in these modes.

Table 2 compares lateral frequencies from the two-three dimensional FE model and the AVMs. The 1973 measurements used force generators to excite three frequencies above 1 Hz, beyond the range of this study. The lower frequencies would not have been excited due to the force characteristics of the machines used.

Vertical and lateral frequencies of the deck which were calculated by 2003 measurements are between 0-0.5 Hz. Because the sampling frequency of TCA2003 is 1 Hz. According to Nyquist method, movements of the bridge with 0.5 Hz. can be determined by 1 Hz. Sampling frequency. Bridge movement much more than this frequency can not be determined. As the results of the analysis, it was determined that power of the vertical frequencies of the deck was bigger than the lateral frequencies. 7 vertical frequencies (0.117-0.445 Hz.) and 7 lateral frequencies (0.074-0.480 Hz.) were calculated for the deck. Calculated frequencies were given in Table 1 and Table 2. It can be said that these frequencies which were calculated by 2003 frequencies are harmonious with the frequencies which were calculated by 1973 and 2005 frequenices and the FEM predicted frequencies.

Vertical and lateral frequencies of the deck calculated by 2005 measurements were given in Table 1 and Table 2. 13 vertical frequencies (0.101-1.035 Hz.) and 9 lateral frequencies (0.078-0.781 Hz.) were calculated for the deck in Table 1 and Table 2. The most important characteristic of the 2005 frequencies is; 2005 frequencies were calculated by GPS measurements. Also it was seen that frequencies which were calculated by GPS measurements are effective while determining the natural frequencies of the bridge. And also it was seen that vertical and lateral frequencies calculated by GPS measurements were harmonious with the frequencies which were calculated by other measurements.

This would indicate that the bridge behaved in the same way in 1973, 2003 and 2005. The 1973 ambient vibration measurements were made before the bridge was opened and subjected to normal traffic loads, so the vehicular loading does not appear to be a factor in the behaviour of the bearings.There have been no major structural alterations among 1973, 2003 and 2005. If its consired that the traffic loads is increasing day by day, it can be said that traffic load had an effect on the vibrations of the bridge on 2003 and 2005.

5. CONCLUSIONS

AVMs were done in Bosporus Bridge in 2003 and 2005 under wind and traffic loads. The results of these measurements were listed below.

- A rather simple PP method is applicable in the identification of the Bosporus suspension bridge through AVMs. The ambient vibration based test is a convenient, faster and cheaper way to perform the bridge dynamic test. The frequencies can be effectively extracted from AVMs by the ANPSD in the frequency domain.

- For the main span, 13 vertical and 9 lateral frequencies were predicted from the FE model. All these frequencies lie in the range 0–1Hz. For the main span, 7 vertical and 7 lateral frequencies were calculated from the Total Station measurements in 2003 and these frequencies lay in the range 0–0.5Hz. 1 Hz maximum sampling frequency of TCA2003 is the reason of this situation. For the main span, 13 vertical and 9 lateral frequencies were calculated from the GPS measurements in 2005 and these frequencies lay in the range 0–1.5Hz.

- A good correlation is achieved between the predicted frequencies from two and three dimensional FE analysis and identified from field AVMs. Comparison with a more limited study made in 1973, 2003 and 2005 shows that the bridge continues to behave as it was designed to behave.
- Any extraordinary load was not detected on the bridge according to these results. However rigid plate which was not suitable for the lateral oscilation of the bridge broken off on 22 January 2005 because of the 110 km wind speed. Taking measurements on the bridge when these kind of extraordinary situations were occurred may be more important. Also these kinds of studies will be effective for the design and project works of these structures.

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BIOGRAPHICAL NOTES

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