Vibration Measurement of Tsing Ma Bridge Deck Units during Erection

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Summary

The Tsing Ma Suspension Bridge in Hong Kong has a main span of 1377m and an overall length of 2160m. During its construction, ambient vibration measurements were carried out to study the dynamic behaviour of the bridge at various construction stages. This paper reports the random vibration measurements of the first few suspeneded deck units. Two measurements were conducted with the first measurement on the first twin-deck-unit module suspended on the main cables and the second on the three partially connected twin-deck-units suspended on the main cables. The identified lowest 15 natural frequencies of the two systems are within the frequency range 0~0.3 Hz and are very closely distributed. The modal frequencies identified and the corresponding analytical results for both systems are in close agreement with the maximum relative difference being less than 10%.

1. Introduction

The Tsing Ma Bridge, a long suspension bridge with a main span of 1377m and a total length of 2160m, spans the Ma Wan Channel between the islands of Tsing Yi and Ma Wan. It carrys both road and rail transportation on two decks under a harsh marine environment and typhoon conditions. Construction of the Tsing Ma Bridge commenced in May 1992. The towers were completed in November 1993. Anchorages were erected for cable construction in July 1994. Spinning of the main cables commenced in July 1994 and completed in April 1995. The first twin-deck-unit module was lifted into position at the center of the main span of the bridge on 9 August 1995. The construction of the whole bridge was completed and opened to traffic in April 1997. During its construction, ambient vibration measurements were carried out to study the dynamic behaviour of the bridge at various construction stages. Previous studies which included measurements of the two bridge-towers (Law et al 1995) and bridge-towers with the erected cables (Xu et al 1997) had been carried out. This paper presents the third study of the series, in which the global dynamic characteristics of the suspended deck units were investigated by in-situ vibration measurement. The suspended deck structure was composed of 95 units plus two special end modules and were erected from the centre of main span towards the bridge-towers. Most (97%) of the units were of 18m in length and 500t in weight. Each lifting module consisted of two deck units welded together. The first measurement was made from 16-17 August 1995 to measure the ambient vibration response of the single twin-deck-unit module. Then the second measurement was made from 29-30 August 1995 after the other two twin-deck-units had been installed.

2. The Main Cable and the Deck Units

The main cables, which are 36m apart, were built up wire by wire by the in-situ aerial spinning technique. Each of the cables is of cross-sectional area $0.759m^2$ for the main span. The mass density per unit of cable length is 5.832 t/m. The cables are approximately 1.1m in diameter after compaction. The cables are accommodated with saddles located at the top of the tower legs and at the main anchorages and adjacent piers, and transfer the loadings into the towers and anchorages. The suspenders are at 18m centers and are attached to the deck by cast steel sockets.

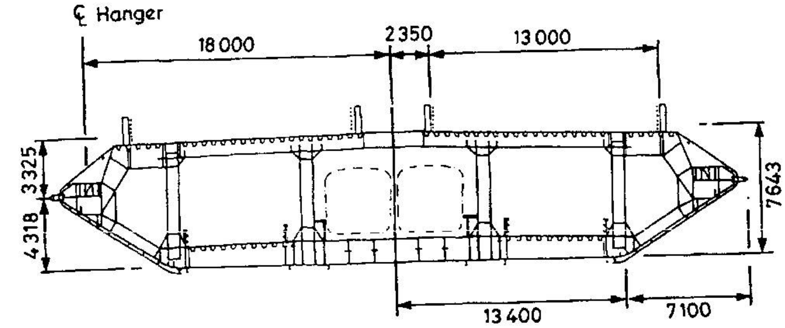


Figure 1 Typical Cross-section of Deck Unit (Beard 1993)

Each deck unit consists of two 6.3m deep longitudinal trusses, spaced at 27 m centers. These act compositely with the orthotropic deck plates supporting the carriageways to provide bending stiffness. Plan diagonal bracing spans the upper and lower vents and acts with the orthotropic plates to provide lateral stiffness. Vierendeel cross frames are located at 4.5m centers. Figure 1 (Beard 1993) shows a typical cross frame of a deck unit. Each basic deck unit, weighing approximately 500 t, is 18 m long with an overall depth of 7.7 m.

Each lifting deck module consists of two 18m deck units welded together to form a 36m module (twin-deck-unit). Figure 2 shows the numbering system of the deck units. The deck units measured in the present study are described as follows.

I) *Single Twin-Deck-Unit* : The twin-deck-unit Nos. {58, 59} with a total length of 36m was the first lifting module being installed to the main cables. They are the center-most suspended deck units.

II) *Three Temporarily Connected Twin-Deck-Units* : The testing section consisted of three twin-deck-units (lifting modules), i.e. Nos. {60 , 61}, Nos. {58, 59} and Nos. {56, 57}. The three modules were temporarily bolted together to form a single section with a total length of 108m.

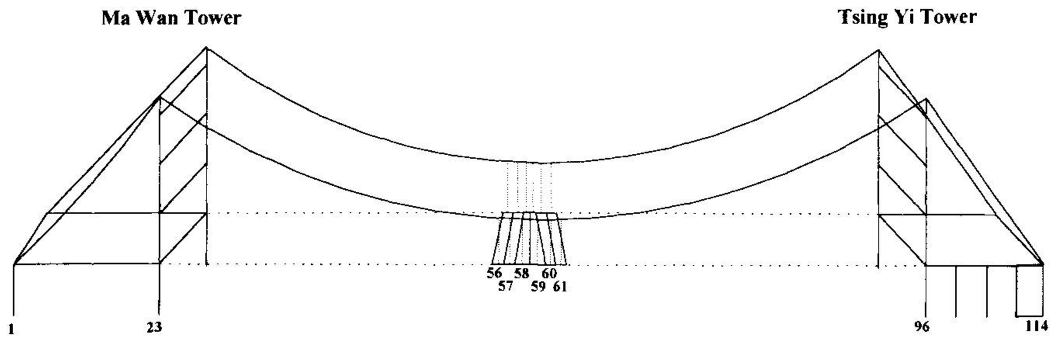
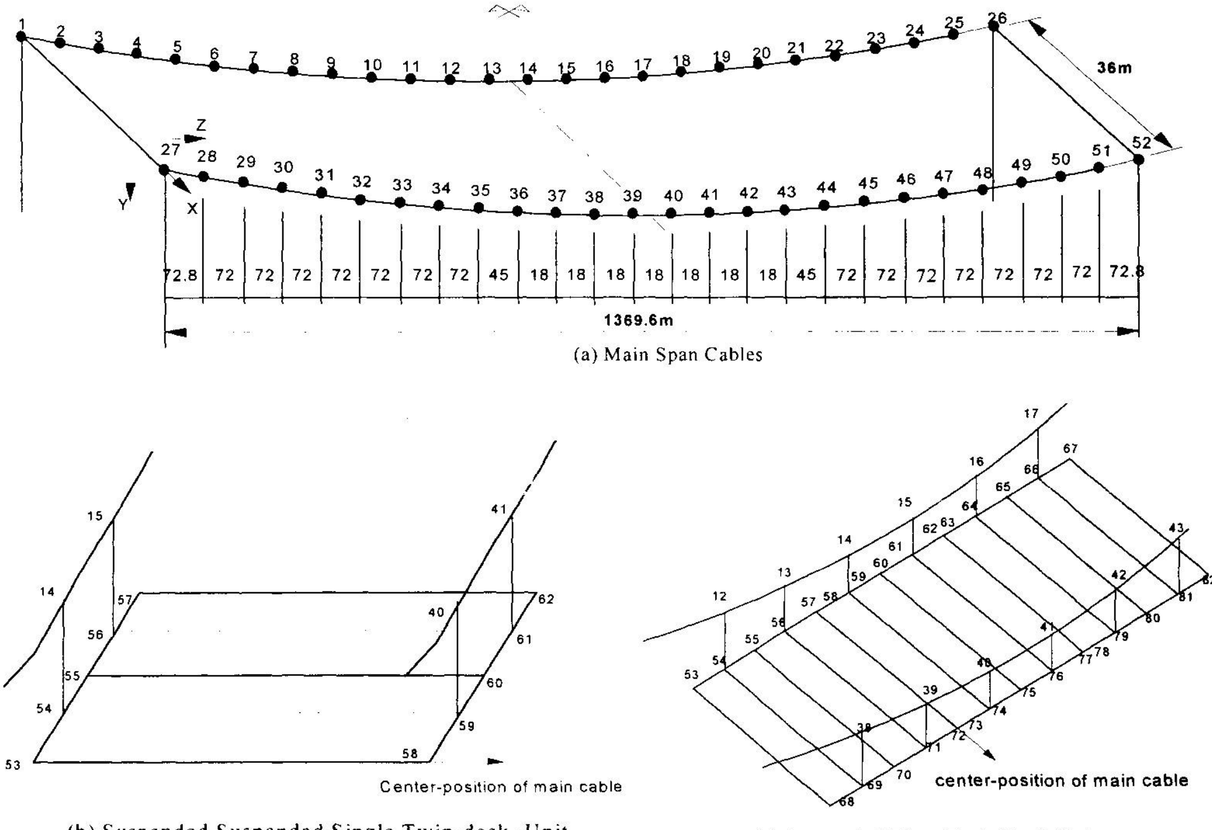


Figure 2 Number System of Deck Units

3. Finite Element Modelling

Based on previous studies (Xu et al 1997), it is valid to assume that the main span cables are suspended on two fixed end-supports at the same level by neglecting the influence of the bridge towers. Cable is a flexible structural element which has hardly any bending resistance. Cable structures are generally elastic in nature but are nonlinear in the geometric sense. In the present study, each cable is modelled by a number of two-node cable elements with six-degree-of-freedoms, i.e. three translational movements in horizontal, vertical and transverse directions for each node. This kind of elements takes account of the cable tension and the geometric deflection. The 6x6 stiffness matrix, which includes linear elastic stiffness, geometric stiffness and large deflection stiffness, and the consistent mass matrix are established by considering the static equilibrium state as initial state. The bridge deck units are freely suspended on the main cables through suspenders. The suspenders are also modelled as cable elements. As the motion of the bridge deck units normally follows the motion of the cables and the objective of the analysis is to find out the global modal characteristics of the suspended bridge-deck units, each twin-deck-unit module is modelled as a rigid body. The temporary site joints between each twin-deck-unit module are treated as such connection that the two adjacent twin-deck-units can rotate freely in vertical direction, but move together in the in-plane direction. In the present analysis, each main span cable is represented by 25 finite elements with different lengths and the bridge deck units are represented by rigid deck units. The finite element models are shown in Figure 3.



(a) Main Span Cables

(b) Suspended Suspended Single Twin-deck -Unit

(c) Suspended Three Twin-Deck-Units

Figure 3 Finite Element Models with Node Numbering

4. The Field Measurement and Signal Processing

It was originally planned to conduct the two measurements in 2 two-day programmes. However, because of the tight schedule of construction and the multitude of construction activities on site, only one full day was allowed for each measurement.

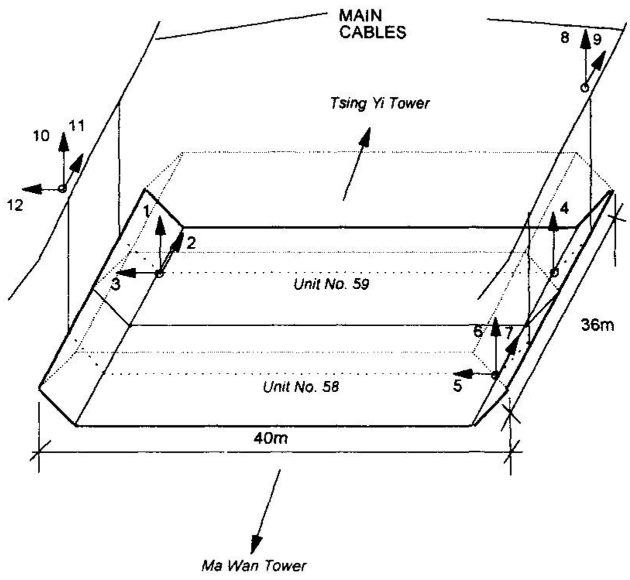


Figure 4 Layout of Sensors for the Measurement of the Single Twin-Deck-Unit System

The location of sensors is a very important aspect in modal testing. In general, the more the sensors the more the information can be got and the more complete the modal parameters can be obtained. However, the number of sensors are always limited. The philosophy of locating sensors is to simulate the test, and to choose locations that give maximum responses. Since the global natural frequencies and mode shapes are essential for the updating of the system parameters, the sensors will be so located such that the bending, torsional and side-sway modes of the suspended deck units and the cables will be measured separately. With the help of the theoretical mode shapes (Ko et al 1996), the locations of 12 sensors in each recording were arranged in such a way so that the measured results could be effectively used to describe each mode. The arrangements of the sensors for the measurement of the single twin-deck-unit system are shown in Figure 4. Similar arrangements were made for the measurements of the three twin-deck-units system.

There were totally five recordings made. The first measurement, in which one recording was made, was for the dynamic response of the single twin-deck-unit system (Nos. {58, 59}). The other four recordings were made for the second measurement. They were carried out after the other two twin-deck-units modules (Nos. {60, 61} and Nos. {56, 57}) had been suspended and the three modules were temporarily bolted together. In general, the sensors in the deck units, which were mounted on magnetic stands fixed on the floor of the deck, were oriented in three directions to measure the vertical, lateral, longitudinal and torsional motions. On the other hand, the sensors on the main cables, which were mounted on magnetic stands fixed to the cable bands of the cables, were to identify the interaction between bridge deck units and the cables.

Theoretical analysis indicated that the natural frequencies of the suspended bridge deck units with main cables were closely spaced in the low frequency range (Ko et al 1996). Therefore the signal processing was performed in the frequency range of 0~1.56 Hz. In order to identify the very closely spaced natural frequencies, a fine frequency resolution of 0.00195Hz, which is the finest frequency resolution set in the B&K 3550 Multichannel Analysis System, was adopted in the spectral analysis. It was found that under the above frequency resolution, some vibration modes were still difficult to identify, therefore the recorded signals on the tapes were played back with a speed of 4 times faster than the original recorded tape speed in the same frequency range of 0~1.56 Hz. In this way, a finer frequency resolution could be achieved and the natural frequencies were obtained by dividing the calcuated values by 4.

5. Results

Comparison between the natural frequencies obtained by the ambient vibration measurement and those obtained by the finite element analysis are shown in Table 1. It is seen that the measured and computed natural frequencies are all in close agreement. The relative difference are within

10%. These comparisons indicate that the finite element modelling established in the theoretical analysis is reasonable and acceptable for predicting the modal properties of the suspended deck units. It also implied that there is a good agreement between the measured structural stiffness and that predicted in the finite element modelling.

Mode of Vibration	Single Twin-Deck-Unit			Three Twin-Deck-Units		
	Theoretical (Hz)	Measured (Hz)	Relative Difference (%)	Theoretical (Hz)	Measured (Hz)	Relative Difference (%)
1st lateral sway mode	0.0510	0.051	0.0	0.0495	0.049	1.0
2nd lateral sway mode	0.1102	0.112	-1.6	0.1195	0.117	2.1
3rd lateral sway mode	0.1478	0.152	-2.8	0.1493	0.150	-0.5
4th lateral sway mode	0.2162	0.209	3.4	0.2369	0.223	6.2
5th lateral sway mode	0.2259	0.234	-3.5	0.2443	0.256	-4.6
1st lift mode	0.1073	0.107	0.3	0.1161	0.113	2.7
2nd lift mode	0.1438	0.139	3.5	0.1474	0.141	4.5
3rd lift mode	0.2165	0.219	-1.1	0.2286	0.230	-0.6
4th lift mode	0.2454	0.258	-4.9	0.2568	0.269	-4.5
1st torsional mode[1]	0.1088	0.110	-1.1	0.1264	---	---
2nd torsional mode[2]	0.1439	0.150	-4.1	0.1486	0.164	-9.4
3rd torsional mode[1]	0.2192	0.223	-1.7	0.2494	0.248	0.6
4th torsional mode[2]	0.2456	0.269	-8.7	0.2615	0.285	-8.2
deck rot. sway mode	0.2105	0.203	3.7	0.1971	0.207	-4.9
deck long. sway mode	0.2229	0.226	-1.4	0.2177	0.225	-3.2

1 - antisymetric mode; 2 - symetric mode

Table1: Theoretical and Measured Natural Frequencies of the two systems

It has to be pointed out that although a fine frequency resolution was taken in the spectral analysis, the first antisymmetric torsional mode of the suspended three twin-deck-units system was still not able to be identified.

From the measured modal vectors of suspended three twin-deck-units system, it can be observed that, in the in-plane direction of the bridge deck (lateral and longitudinal direction), the three twin-deck-units are basically vibrating as a rigid plate, i.e. no large relative motions occurred at the temporary bolted joints between two adjacent twin-deck-units. Therefore the three twin-deck-units can be regarded as one rigid deck section in the in-plane direction. However, in the vertical direction, some relative rotations are observed between two adjacent twin-deck-units, such as that in the fourth lift mode. The above results are consistent with the finite element modelling established in the theoretical analysis.

It is noticed that most of the measured natural modes of the suspended bridge deck units always vibrate together with the main cables. For each system, only one deck rotational sway mode and one deck longitudinal sway mode, which are dominated by deck vibration, are identified at the frequency range of 0~0.3 Hz. This is agreeable to the theoretical predictions.

By comparing the measured modal vectors with the theoretical mode shapes, it can be concluded that the measured modal motions are basically in accord with the theoretically predicted mode shapes. However, it is also noticed that some inconsistency still exists between the measured and the computed modal vectors, such as the fourth and the fifth lateral sway modes of the suspended three twin-deck-units system as well as the second lateral sway mode and the deck rotational sway mode of the suspended single twin-deck-unit system.

6. Conclusions

1. The measurement of the structural response to ambient vibration from wind load and ground micro-tremor has proved to be an effective means for identification of the dynamic properties of a full-scale flexible structure with low natural frequencies. The dynamic properties identified include natural frequencies and mode shapes.
2. Careful planning and execution of the field work is a key factor in the collection of high quality data. Preliminary finite element dynamic analysis is useful in the design and planning of the ambient vibration test programme to achieve appropriate deployment and orientation of the motion-sensing instruments, to determine the reference point and to select appropriate filter setting and the sampling frequency.
3. For both the single twin-deck-unit system and the three twin-deck-unit system, many closely-spaced natural frequencies were found in the low frequency range of 0~0.3 Hz.
4. The modal frequencies identified and the corresponding analytical results for both systems are in close agreement with the maximum relative difference being less than 10 %. These comparisons indicate that the finite element modelling established in the theoretical analysis is reasonable and acceptable for predicting the modal properties of the suspended deck units.
5. It is found that, in the in-plane direction of the three twin-deck-units, no large relative motions occurred at the temporary bolted joints between two adjacent twin-deck-units. Therefore the three twin-deck-units can be regarded as one rigid deck section in the in-plane direction. However, in the vertical direction, some relative rotations are observed between two adjacent twin-deck-units for the suspended three twin-deck-units system.
6. The measured modal vectors are basically agreeable to the theoretically predicted mode shapes, but some inconsistency still exists between the measured and the computed modal vectors for some modes. This is due to the difficulty in representing the actual site conditions in the finite element modelling and the possible coupling of the closely distributed modes.

7. Acknowlegements

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