Evaluation of the Dynamic Characteristics of an Extradosed Bridge Using Microwave Interferometer

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ABSTRACT
The microwave interferometer was used for monitoring the dynamic characteristics of the bridge decking system and cables in present study. Newly introduced to Taiwan, the instrument has a 1-D imaging capability for remotely measuring the displacements of multiple positions simultaneously. In this paper, a general review of the principle and capacity of the instrument would be given. The displacements corresponding to ambient vibration due to traffic loads are used for modal analysis. The operating deflection shape of the main span and the vibrational signals of the cables are monitored to explore the relationship between the through traffics and the dynamic responses.

Keywords: extradosed bridge, microwave Interferometer, health monitoring

1. INTRODUCTION
The Ai-Lan bridge which is located at Ai-Lan, Nan-Tau County, is the first extradosed bridge in Taiwan. The extradosed bridge has spans longer than those of the conventional prestressed box girder bridge and is partly supported by the stay cables extended from the pylons with height much less than the conventional cable-stayed bridge. For Ai-Lan bridge, there are two pylons and 72 stay cables supporting the 300 m long box girder bridge with three spans (80 m-140 m-80 m). The dynamic performance of this unconventional structural system subjected to traffic loadings is worth of exploring. As the cables anchored to the deck with a smaller angle, the cable forces contribute more on prestressing the decking system rather than supporting the live load. (Ruiz-Teran and Aparicio, 2007) As a result, the fluctuation of cable stress due to live load is insignificant and the fatigue problem of the cables is minimized.

A microwave sensor, named IBIS-S shown in Fig. 2(a) was used for monitoring the dynamic characteristics of the super-structure of the Ai-Lan bridge. The equipment can simultaneously measure the deflection of several points of a structure without making contacts with the bridge with an accuracy up to 0.02 mm. The maximum scanning rate and the operating distance are 200 Hz, and 500 m, respectively. Details on the working principle of the equipment can be found in the following section.

In present study, the vertical deflections of the deck due to the ambient vibration triggered by traffic loads were measured by IBIS-S. Several modal frequencies, mode shapes and damping ratio were identified and compared to the ones obtained from the finite-element model. The fundamental modal frequencies of 9 cables at one side of the P1001 pylon were measured simultaneously using the microwave interferometer. The measurements were performed on two side of the pylon P1001. The cable prestressing forces were calculated based on the measured modal frequencies. The fluctuation of cable stresses due to live load is also discussed.

2. INTRODUCTION OF THE IBIS-S MEASUREMENT SYSTEM
The IBIS-S (Image by Interferometric Survey) system is a ground based microwave
Interferometer with 1-D imaging capabilities for remote measurements of displacements. Based on a continuous-wave step-frequency radar (Pieraccini M, Fratini M, etc., 2004) the sensor transmits continuous waves at stepwise discrete frequencies and composes a synthetic bandwidth B at a constant frequency interval Δf. The echo signals provide images with a resolution of ΔR, which can be decided by Eq. (1) with c as the speed of light.

\[ ΔR = \frac{c}{2B} \]  

(1)

Targets in the illuminated scenario can be resolved with a constant range resolution ΔR independent to the target distance.

The resolution of displacement is decided by the phase of the echo signals. Every sample of every range bin, which is defined as range resolution area, has an information in amplitude |I(n)| and phase \( φ_n \). Two images acquired at different times exhibit phase differences (Δφ) depending on the motion of the targets along the radar line of sight. The range displacement \( Δr \) can be calculated from Eq. (2) with \( f_c \) as the band center frequency.

\[ Δr = \frac{c}{4πf_c} Δφ \]  

(2)

To avoid the phase ambiguity, the maximum displacement measurable between two consecutive acquisition is \( ± \lambda / 4 = 4.38 \text{ mm} \).

For bridge measurement, as shown in Fig. 2 the instrument is usually placed under the bridge deck to avoid the severe phase ambiguity of the radar echoes produced by vehicles movement on the upper deck. Because the displacement is measured in the direction of the line of sight of the system, the vertical movement of bridge is obtained by Eq. (3) with known vertical distance between the instrument and the bottom of the bridge deck (h). In Eq. (3) the distance R is directly measured by IBIS-S.

\[ d = d_p \frac{R}{h} \]  

(3)

3. BOX GIRDER MEASUREMENT

During the test, the microwave sensor was placed on the ground directly beneath the edge of the bridge deck with the transmitting cone tilting up. (Fig. 2(a)). Without distinct measuring targets on the bottom surface of the box girder, 17 triangular-corner reflectors, generally 4 m apart, were fastened to the top of bridge curb as shown in Fig. 2(b) and (c). The dynamic vertical displacements of the reflectors generated by the through traffic were then measured by the sensor. The first and the last reflectors are located 20 m from the Pylon P1001 on span 1, and 42 m from the Pylon on span 2, respectively. The vertical and horizontal distances from the sensor to the first reflector are 10.56 and 14.6 m, respectively. The sampling frequency is 121.07 Hz and the total recording length is 20 minutes.
The test was performed under the regular operational condition. An output-only modal identification technique, called Frequency Domain Decomposition (FDD) (Brincker, Zhang and Andersen, 2000), is used to extract the modal parameters of the decking system from the 18 signals of vertical displacement of the reflectors. In the FDD method, singular value decomposition (SVD) is performed on the spectral matrix obtained from the auto and cross spectral densities of the displacement signals. In the spectrum composed by the largest singular values, the dominant peaks usually correspond to the vibrational modes of the structure. The modal frequencies and the shapes can be obtained from the peak frequencies and the corresponding singular vectors.

In present study, the test data was analyzed by the software ARTeMIS in which the FDD algorithm is implemented. The modal frequencies and damping ratios are calculated using the Single-Degree-Of-Freedom (SDOF) Spectral Bell functions (Brincker, Ventura, and Andersen, 2001). The identified modal frequencies and damping ratios are summarized in Table 1. The differences between FEM and FDD identified modal frequencies for the first, third and fourth modes are less than 0.11 Hz, but for the second mode is about 0.28 Hz. The damping ratios are ranging from 3% to 1%.

### Table 1 Identified modal frequency and damping ratio for the decking system

<table>
<thead>
<tr>
<th>No.</th>
<th>FEM modal freq. (Hz)</th>
<th>FDD modal freq. (Hz)</th>
<th>damping ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.749</td>
<td>0.857</td>
<td>2.93</td>
</tr>
<tr>
<td>2</td>
<td>1.919</td>
<td>1.642</td>
<td>2.04</td>
</tr>
<tr>
<td>3</td>
<td>2.669</td>
<td>2.558</td>
<td>1.79</td>
</tr>
<tr>
<td>4</td>
<td>3.58</td>
<td>3.592</td>
<td>1.06</td>
</tr>
</tbody>
</table>

3. CABLE MEASUREMENTS

Two measurements were performed on each side of the Pylon P1001. Using the instrumental setup shown in Fig. 5(a), 9 cables can be identified from one measurement. Fig. 5(b) shows the sight from the IBIS-S system to the cable targets. The measurement labeled by C1 monitored the cables supporting the 80 m first span and the measurement labeled by C2 monitored the cables supporting half of the 140 m mid-span. The sampling frequency is 165.04 Hz and the total recording length is 20 minutes. All the displacement spectra with range bins corresponding to the cable vibrations for C1 and C2 tests are shown in Fig. 6(a) and (b), respectively. The spectra were obtained from the displacement waveforms of 20 min. with a window size of 50 sec. and window overlapping of 66%. Because the IBIS sensor is almost directly under the cables, there are only 6 and 7 records being identified for C1 and C2 measurements, respectively. However, the fundamental vibrational mode for the nine cables, as the peaks indicated by frequencies can all be identified in each record. The phenomena can be explained as follows. The antenna transmits radar signals with certain beamwidths. With scanning angles 17° for the
horizontal plane and 15° for the vertical plane, it is possible the antenna receives signals reflected from neighboring cables in the same range bin as illustrated in Fig. 7.

Fig. 3 The SVD spectra composed by the first four largest singular values for box girder measurement
Comparing the spectra between C2 and C1, the major peaks are all similar but the former has more little peaks than the latter. Some of them may correspond to the vibrational modes of the deck. For instance, the peak at 0.86 Hz, which is not seen in C1 spectrum, may correspond to the first flexural mode of the box girder shown in Fig 3. The spectrum of Rbin 25 for C2 measurement corresponding to the response of the longest cable is more complicated than the response for other range bins. For this cable, the end fixed on the deck is the nearest to the middle of the main span. The significant motion of the deck due to traffic loads may couple the deck response into the cable vibration.

The prestressing force (F) of a cable can be calculated by Eq. (4), where \( f_1 \), L and \( \rho \) represent the fundamental modal frequency, length and the weight of unit length of the cable, respectively.

\[
F = 4f_1^2L^2\rho
\]
designed one. However, the cable forces are similar for the ones with the same length, which means the pylon generally withstands balanced forces at the cable anchoring region, except for cable 9. For these two cables with the longest length, the force level is 30500 kgf higher for the cable supporting the mid of the main span comparing to the one supporting near the beginning of the first span. The variation of cable force due to traffic is not distinct. Table 2 shows the statistics of the cable forces variation with time calculated from the spectra with window length 50 sec. and 25 sec. time interval for C2 measurement. The coefficients of variation (C.O.V.) corresponding to all cables are no more than 1.5% except that the C.O.V. for cable 9 is slightly higher as 2.53%. It might imply the traffic load has more influence on this cable.

Table 2 The statistics of the prestressing force variation with time calculated from the spectra with 50 sec. window length and 25 sec. time interval for C2 measurement

<table>
<thead>
<tr>
<th>Cable no.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ave. force (kgf)</td>
<td>324608</td>
<td>293116</td>
<td>279487</td>
<td>286452</td>
<td>296825</td>
<td>333958</td>
<td>331770</td>
<td>316642</td>
<td>311969</td>
</tr>
<tr>
<td>S.D. (kgf)</td>
<td>2115</td>
<td>2328</td>
<td>3842</td>
<td>3255</td>
<td>2515</td>
<td>3330</td>
<td>3471</td>
<td>2749</td>
<td>7889</td>
</tr>
<tr>
<td>C.O.V. (%)</td>
<td>0.65</td>
<td>0.79</td>
<td>1.37</td>
<td>1.14</td>
<td>0.85</td>
<td>1.00</td>
<td>1.05</td>
<td>0.87</td>
<td>2.53</td>
</tr>
</tbody>
</table>

4. CONCLUSIONS
The paper provides a newly developed non-contacting technique to access the dynamic characteristics of extradosed bridge. The main components of the extradosed bridge, stay cables and prestressed box girder, are measured by microwave interferometer. It is proved the equipment has the ability to obtain the fundamental modal frequencies of several cables in one measurement and the test setup is speedy - within half an hour. The prestressed concrete box-girder was measured with the corner reflectors placing along the side curb of the bridge deck. Several mode shapes and the corresponding modal frequencies and damping ratio were identified. The microwave interferometer provides a way to quickly access the condition of the bridge periodically or after nature catastrophe.

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REFERENCES