Modal Analysis and Identification of a Low Frame Steel Bridge Type System in an Automatic Container Terminal

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ABSTRACT: A low frame steel bridge system was proposed by ZPMC to transfer containers between the seaside cranes and the stack field cranes. Since each bridge of the system has to serve as a support for the crane carriages and a track for the running carrier vehicles, the dynamic characteristics of the system must be investigated. In this paper, the modal parameters of the system were analyzed by finite element method at first, then the piezoelectric sensors were set up on the real system, and the modal parameters were identified from the ambient acceleration responses of the system.

1 INTRODUCTION

1.1 Low frame bridge system

To improve the loading and unloading efficiency of the automatic container terminals, and to reduce the relevant cost, ZPMC, i.e. Shanghai Zhenhua Port Machinery Corporation (www.zpmc.com), proposed a new transfer system, as shown in Fig. 1, to transfer containers between the seaside cranes and the stack field cranes. The new transfer system is composed of the low frame steel bridges, crane carriages and carrier vehicles, shown in Fig. 2. The crane carriages deliver containers to the carrier vehicles, and the carrier vehicles then transfer containers to the required positions. Since each low frame bridge of the system has to serve as a support for the crane carriages and a track for the running carrier vehicles, its dynamic characteristics must be taken into consideration. Meanwhile, the effects of the crane carriages and carrier vehicles to the bridges should not be neglected. Therefore, it is reasonable to take the bridges, the crane carriages and the carrier vehicles as a whole system, and investigate their dynamic characteristics simultaneously.

The number of rows and spans of the low frame bridges, as well as the number of crane carriages and carrier vehicles on each bridge, could be assigned according to the requirement of the automatic container terminal. In this paper, an example system, as shown in Fig. 3, composed of three-row two-span bridges and two carrier vehicles, was investigated. No crane carriages were set up. The natural properties of the system were analyzed by Finite Element Analysis (FEA) at first, then Test Modal Analysis (TMA) was conducted and the natural properties were identified by the Covariance-driven Stochastic Subspace Identification (CSSI) method.

1.2 Ambient excitation

To conduct TMA, the dynamic responses of the system to certain excitation must be recorded. The excitation, if the traditional deterministic identification is applied, should be reasonably distributed on the system to ensure all the modes of interest could be sufficiently excited, which might be difficult for some tests. For the system under consideration, the excitation could come
from the natural wind field, a kind of ambient excitation. In this paper, the wind-induced acceleration responses of the low frame bridge system will be utilized to identify the natural properties.

1.3 Covariance-driven Stochastic Subspace Identification (CSSI)

Covariance-driven Stochastic Subspace Identification (Overschee P.V. and Moor B.D. 1991; Peeters B. and Roeck G. 1999) is a kind of operational identification algorithms and has been successfully utilized to extract aerodynamic parameters of bridge decks from wind-induced responses (Gu, M. and Qin, X.R. 2004; Qin, X.R. and Gu, M. 2004). CSSI identifies modal parameters by solving the eigen value problem of system state matrix $A$:

$$A = o^* T_{2i} s_i^*$$  \hspace{1cm} (1)

in which: $o_i, s_i$ can be determined by the SVD of the following block Toeplitz matrix:

$$T_{2i} = \begin{bmatrix}
\Lambda_1 & \Lambda_{i-1} & \cdots & \Lambda_1 \\
\Lambda_{i+1} & \Lambda_i & \cdots & \Lambda_2 \\
\vdots & \vdots & \ddots & \vdots \\
\Lambda_{2i-1} & \Lambda_{2i-2} & \cdots & \Lambda_i \\
\end{bmatrix}$$  \hspace{1cm} (2)

where: $\Lambda_i = E\left[\{y_{k}\} \{y_{l}\}^T\right]$: the covariance of the output/response $\{y\}$.

According to the definition of covariance, the Toeplitz matrix could be expressed as the
product of the future and the past responses:

\[ T_{fp} = Y_f Y_p^T \]  

(3)

where:

\[
Y_f = \frac{1}{\sqrt{j}} \begin{bmatrix}
  y_0 & y_1 & \cdots & y_{i,j-1} \\
y_{i+1} & y_{i+2} & \cdots & y_{i,j} \\
  \vdots & \vdots & \ddots & \vdots \\
y_{2i-1} & y_{2i} & \cdots & y_{2i,j-1}
\end{bmatrix} \text{: response of the future}
\]

\[
Y_p = \frac{1}{\sqrt{j}} \begin{bmatrix}
  y_0 & y_1 & \cdots & y_{j-1} \\
y_1 & y_2 & \cdots & y_j \\
  \vdots & \vdots & \ddots & \vdots \\
y_{i-1} & y_i & \cdots & y_{i,j-2}
\end{bmatrix} \text{: response of the past}
\]

Therefore, if Eq. (3) is applied to constructed the block Toeplitz matrix, two big matrices, \( Y_f \) and \( Y_p \), should be constructed at first. Since the dimension of the two matrices will be dramatically enlarged with the increase of the number of output, and the number of row and column shift of the Toeplitz matrix, large memory will be required to save the two matrices.

2 FINITE ELEMENT ANALYSIS OF THE SYSTEM

2.1 Finite element model

The low frame bridge system was analyzed by ANSYS 10.0. The bridges, support beams and link rods, as shown in Fig. 3, were all modelled by beam elements (BEAM188). The two carrier vehicles were modelled by beam elements (BEAM188) and mass elements (MASS21). All the six DOFs of the nodes on the wheels of the vehicles were coupled to the corresponding nodes on the bridges.

2.2 Results of finite element analysis

Table 1 summaries the analyzed modal parameters of the first 20 modes for the low frame bridge system. The results suggest that the lateral stiffness of the bridges is much weaker than the vertical stiffness, since the first lateral bending comes much earlier (2.32 Hz) than the vertical bending (6.34 Hz).

Fig. 4 is the first four lateral bending modes of the bridges. Evidently, the carrier vehicles improve the lateral stiffness of the bridges in the specific positions.

Figure 4: Typical mode shape for lateral bending modes of the low frame bridge system
Table 1: Modal parameters of the low frame bridge system analyzed by Finite Element Analysis (the first 20 modes)

<table>
<thead>
<tr>
<th>Mode No.</th>
<th>Frequency (Hz)</th>
<th>Mode shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.12</td>
<td>Bending mode of the support beams</td>
</tr>
<tr>
<td>2</td>
<td>2.14</td>
<td>Bending mode of the support beams</td>
</tr>
<tr>
<td>3</td>
<td>2.32</td>
<td>Lateral bending mode of Bridge 1 and Bridge 3</td>
</tr>
<tr>
<td>4</td>
<td>2.49</td>
<td>Lateral bending mode of Bridge 1 and Bridge 3</td>
</tr>
<tr>
<td>5</td>
<td>3.01</td>
<td>Lateral bending mode of Bridge 2 and Bridge 3</td>
</tr>
<tr>
<td>6</td>
<td>3.12</td>
<td>Bending mode of the support beams</td>
</tr>
<tr>
<td>7</td>
<td>4.13</td>
<td>Lateral bending mode of Bridge 1 and Bridge 3</td>
</tr>
<tr>
<td>8</td>
<td>4.53</td>
<td>Lateral bending mode of Bridge 1 and Bridge 3</td>
</tr>
<tr>
<td>9</td>
<td>4.79</td>
<td>Lateral bending mode of Bridge 1</td>
</tr>
<tr>
<td>10</td>
<td>5.25</td>
<td>Lateral bending mode of Bridge 2 and Bridge 3</td>
</tr>
<tr>
<td>11</td>
<td>5.91</td>
<td>Lateral bending mode of Bridge 1</td>
</tr>
<tr>
<td>12</td>
<td>6.34</td>
<td>Vertical bending mode of the bridges</td>
</tr>
<tr>
<td>13</td>
<td>6.48</td>
<td>Vertical bending mode of the bridges</td>
</tr>
<tr>
<td>14</td>
<td>6.87</td>
<td>Vertical bending mode of the bridges</td>
</tr>
<tr>
<td>15</td>
<td>7.14</td>
<td>Lateral bending mode of Bridge 2 and Bridge 3</td>
</tr>
<tr>
<td>16</td>
<td>7.37</td>
<td>Vertical bending mode of the bridges</td>
</tr>
<tr>
<td>17</td>
<td>7.58</td>
<td>Coupled vertical bending and lateral bending of the bridges</td>
</tr>
<tr>
<td>18</td>
<td>8.11</td>
<td>Torsion of the bridges</td>
</tr>
<tr>
<td>19</td>
<td>8.19</td>
<td>Torsion of Bridge 3</td>
</tr>
<tr>
<td>20</td>
<td>8.38</td>
<td>Bending mode of the support beams</td>
</tr>
</tbody>
</table>

3 TEST MODAL ANALYSIS (TMA)

3.1 The test object

The test was conducted on the real low frame bridge system. The length and height of each bridge are 65.6 m and 8.6, respectively, with a 2.8 m x 2.8 m cross section. The space between two bridges is 7.7 m.

3.2 The test scene

The test object was constructed in the shipside of Changxin Island, a small island in the East China Sea. Therefore, the turbulence intensity of the test scene is quite small.

3.3 The sensors and sampling parameters

12 piezoelectric acceleration sensors were approximately uniformly distributed on Bridge 1 to measure the wind-induced accelerations of the system. The responses were sampled at a rate of 128 Hz, and recorded for around 6 minutes. Fig. 5 shows a segment of the response.

3.4 Identified modal parameters

CSSI was utilized to identify the modal parameters of the system from its wind-induced responses. Since CSSI requires very big memory to save the variables during identification, the row and column shifts of the Toeplitz matrix, as defined in Eq. (2), are limited by the memory. Consequently, the recorded time histories of the responses could not be sufficiently utilized, or in other words, only a small segment of the record was applied for identification.

To construct the frequency stabilization diagram of the identification, the number of modes to be identified was assigned to 1 to 60. Fig. 6 is the corresponding frequency stabilization diagram, where the vertical straight lines denote the structural modes.
Figure 5: Segment of the acceleration response

Figure 6: Frequency stabilization diagram of TMA by CSSI

Table 2: Identified vertical mode modal parameters of the low frame bridge

<table>
<thead>
<tr>
<th>Mode No.</th>
<th>Frequency by TMA (Hz)</th>
<th>Frequency by FEA (Hz)</th>
<th>Damping ratio by TMA (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.42</td>
<td>2.32</td>
<td>0.69</td>
</tr>
<tr>
<td>2</td>
<td>2.88</td>
<td>2.49</td>
<td>0.86</td>
</tr>
<tr>
<td>3</td>
<td>4.37</td>
<td>4.53</td>
<td>1.09</td>
</tr>
<tr>
<td>4</td>
<td>5.01</td>
<td>5.25</td>
<td>0.29</td>
</tr>
<tr>
<td>5</td>
<td>5.76</td>
<td>5.91</td>
<td>0.41</td>
</tr>
</tbody>
</table>

Fig. 6 gives people a false impression that modal parameters of all the modes lower than 30 Hz have been successfully identified by the 12 sensors. Actually, the identified modal
frequency and damping ratio should be correct, but the mode shape could not be reasonably described, since the number of sensors is not enough to model higher modes. Therefore, the identified two modes might have different frequencies and damping ratios, but the mode shapes are quite similar. As a result, it is difficult to compare the modal parameters of higher modes. Table 2 gives the comparison between the modal parameters by TMA and FEA. The results of the first five lateral modes are in reasonable agreement.

4 CONCLUDING REMARKS

(1). According to FEA, the lateral stiffness of the bridges of the low frame bridge system must be improved;
(2). CSSI could determine the modal parameters of the low frame bridge system from the wind-induced responses, but requires a large memory;
(3). The number of sensors of the present study should be increased to get more reasonable descriptions for the higher modes.

REFERENCE

James G.H., Game T.G., 1995, The natural excitation technique(NeXT) for modal parameter extraction from operating structures, International Journal of Analytical and Experimental Modal Analysis, 10(4), p: 260-277