Estimation of Dynamic Characteristics for Steel Frame Membrane Structure

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Changes in dynamic characteristics of a steel frame membrane structure were estimated during construction. Effects of membrane on the dynamic characteristics, especially on damping coefficients, were clarified from ambient response and free vibration by human excitation. It was quantified that membrane raised damping coefficients by an average of 2%. Increase of damping coefficients after membrane installation, however, depended on the natural frequency. Lower modes tended to gain more additional damping coefficients than higher modes.

1. INTRODUCTION

Dynamic characteristics of membrane roof structures are less known compared to those of ordinary building structures\(^1\). The number of field observation data is still short. Membrane is considered to add the damping of the structure as well as to add the stiffness through the friction at the joint between the membrane and the structure, the internal friction due to deformation of membrane, and the aerodynamic damping.

In this paper, we report the result of the field observations at the Shimokita Kokusetsu Dome, a steel frame membrane structure constructed in Aomori Prefecture, Japan. The effect of membrane on the dynamic characteristics, especially on the damping coefficient, is estimated. The field observations were conducted three times during the construction. The dynamic characteristics were estimated from the ambient response, the free vibration by the human excitation and the eigenvalue analysis. In this study, the frequency domain decomposition (hereafter FDD) technique\(^2,3\) is applied to estimate the dynamic characteristics from the ambient response. FDD technique is suitable for the dome structures, which often have closely spaced modes in the frequency domain. Meanwhile, with a conventional technique applied to the ambient response, e.g. Random Decrement technique\(^4,5\), the characteristics of only limited number of modes can be estimated due to technical limitation.

2. OUTLINE OF ROOF STRUCTURE, FIELD OBSERVATION AND ANALYSIS

The span of the roof of the Shimokita Kokusetsu Dome is 108.3 meter, while its rise height is 45 meter. The outer and the inner membranes cover the upper and lower side of the roof truss. The surface pressure of the outer membrane (20N/m\(^2\)) is four times higher than that of the inner membrane (5 N/m\(^2\)). It is because the outer membrane should resist the snow load in winter, while the inner membrane need not.
The field observations were conducted three times during the construction. The first time was at before the membrane installation as shown in Fig. 1. The second time was after outer membrane installation. The final was at completion, i.e. after outer and inner membrane installation.

The eight servo type velocity meters (VSE-15, Tokyo Sokushin) were installed on the roof truss as shown in Fig. 2, with which the ambient response and the free vibration after the human excitation (by stamping or pushing the truss by one or two people) were measured. SPC-51 (Tokyo Sokushin) is used to record time series data. The sampling frequency is 50 Hz and the duration of the ambient response measurement was about 30 minutes.

Fig. 1 The Shimokita Kokusetsu Dome at before membrane installation

Fig. 2 The roof truss structure and vibration measurement point
The FDD technique was applied to analyze the ambient response. Though the FDD technique was proposed in Ref 2, the general picture of the technique used in this study is summarized below with some numerical conditions. In the analysis, firstly, the cross spectral density matrix is estimated. The enough frequency resolution of the cross spectral density is required for the preciseness of the damping estimation\(^3\), which is 0.00305 Hz in this case, i.e. 16384 points data, and 50 percent overlap for the Fourier transform in this study. The singular value spectra \( \mathbf{S} \) and the corresponding normalized mode shapes \( \mathbf{U} \) are estimated from the singular value decomposition of the real part of the cross spectral density matrix \( \mathbf{G}_{\mathbf{yy}} \) as Eq. (1).

\[
\text{Re}[\mathbf{G}_{\mathbf{yy}}(f)] = \mathbf{U}(f) \mathbf{S}(f) \mathbf{U}(f)^T
\]

(1)

The auto correlation coefficient of a particular mode is estimated from the inverse Fourier transform of the band-passed singular value spectra, thick lines in Fig. 4. The natural frequency and the damping coefficient are estimated using Eq. (2) by the least square method.

\[
C(t) = \exp(-h \omega t) \cdot \cos \sqrt{1 - h^2 \omega^2}
\]

(2)

The dynamic characteristics of the roof structure were also estimated from the free vibration by the human excitation for comparison purpose. From the responses at the eight measurement points, the response where the maximum amplitude was observed was used for the estimation from the free vibration. The time history of the response was band-passed in the frequency domain to estimate the dynamic characteristics, so as to remove the effects of the other modes. Additionally, the excitation position and the measurement position should be carefully determined from the mode shape estimated from eigenvalue analysis.

The eigenvalue analysis using the structure model was also conducted at each construction stage for comparison in natural frequency. Commercial software, TDAP (ARK Information Systems), was used for the analysis. In the analysis, the mass of the membrane was considered, while its stiffness was not considered.

3. ANALYSIS RESULT

Firstly, the field observation was conducted at before membrane installation. To schematically illustrate the existence of the closely spaced modes, the power spectral density at \( x, y, z \) components of point A (\( AX, AY, AZ \)) and \( y \) component of point D (\( DY \)) are shown diagonally and coherence between each component are shown in the upper right side in Fig. 3, which were estimated from the ambient responses. In the lower left side, phase differences between each component are also presented. The peaks in the power spectra were clearly observed in all four components at around 2.2 Hz. However, not all coherence between four components was high at around 2.2 Hz. It implied the existence of two closely spaced modes here. Fig. 4 shows the 1st to the 4th singular value spectra estimated from the ambient responses of all eight components obtained from the FDD technique as in Eq. (1). Each thick line indicates the existence of the corresponding vibration mode. From the result, we can confirm the existence of two modes at around 2.2 Hz. The natural frequency and the damping coefficient of each mode were estimated from the correlation function by the least square as mentioned. The result estimated for the 2nd mode is shown in Fig. 5. Additionally, as shown in Fig. 6, the mode shape estimated from the different techniques agrees well with each other. Table 1 shows the natural frequency and the damping coefficient estimated. The results from the ambient response corresponded to those from the human excitation. The damping coefficients estimated were from 0.5 % to 1.0 %. The ratio of the natural frequency observed to that of the eigenvalue analysis was from 1.3 to 1.4. This disagreement possibly came from the structural model, which was developed for large amplitude responses such as earthquake responses.
Diagonal: power spectrum density
Upper right: coherence
Lower left: phase difference

Fig. 3 Power spectral density and coherence at before membrane installation

Fig. 4 Singular value spectrum at before membrane installation
Fig. 5 Correlation function for 2nd mode at before membrane installation

![Correlation function]

Fig. 6 Vibration mode estimated for 2nd mode at before membrane installation (left: eigenvalue analysis, right: crosssection)

Two more field observations were conducted at after the outer membrane installation and at completion. Table 2 shows the natural frequency and the damping coefficient at completion, for a representative case. The damping coefficients estimated were from 1.4% to 3.7%, which was larger than those at before membrane installation by the average of 2%. The results from the ambient responses agreed well with those from the human excitation in several modes. Blanks in the table indicate that the corresponding mode could not be excited by the human excitation due to higher damping coefficients than before membrane installation. The ratio of the natural frequency estimated to that of the eigenvalue analysis varied from 0.9 to 1.4. The ratio of the estimated values to those of the eigenvalue analysis tended to decrease in case of horizontal modes compared to that before membrane installation, while it was comparable for vertical modes (2.76Hz & 2.86Hz for the eigenvalue analysis). The mode shapes obtained from the eigenvalue analysis are shown in Fig. 7 for reference.

Fig. 8 shows the changes in the damping coefficient before and after membrane installation. After outer membrane installation, the damping coefficient increased by the average of 2%. After inner membrane installation, however, the damping coefficient was comparable to that after outer membrane installation. It was considered due to the smaller surface pressure in the inner membrane compared to that in the outer membrane. In Fig. 8, the damping coefficients of existing membrane structures (three steel structures (span: 145m\(^6\), 132m\(^6\), 206m), one wooden structure (span: 25m)\(^7\)) are also shown. These values were estimated from free vibration, by e.g. human excitation, or from ambient vibration using Random Decrement technique. The damping coefficients of the Shimokita Kokusetsu Dome were smaller about 2 ~ 3% compared to those of the other structures. The difference of the damping coefficients was considered due to the difference in relation between the structural characteristics, i.e. mass density or stiffness, and strength of damping force. To identify the mechanism, the source of damping force need to be quantitatively identified, which needs further study.
Table 1 Natural frequency and damping coefficient at before membrane installation

<table>
<thead>
<tr>
<th>Mode no.</th>
<th>Eigenvalue analysis</th>
<th>Natural Frequency [Hz]</th>
<th>Damping Coeff. [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Ambient response (ratio to eigenvalue)</td>
<td>Human excitation (ratio to eigenvalue)</td>
</tr>
<tr>
<td>(i)</td>
<td>1.54</td>
<td>2.00 (1.30)</td>
<td>- ( - )</td>
</tr>
<tr>
<td>(ii)</td>
<td>1.66</td>
<td>2.21 (1.33)</td>
<td>2.20 (1.33)</td>
</tr>
<tr>
<td>(iii)</td>
<td>1.62</td>
<td>2.23 (1.38)</td>
<td>2.23 (1.38)</td>
</tr>
<tr>
<td>(iv)</td>
<td>2.77</td>
<td>3.53 (1.27)</td>
<td>3.52 (1.27)</td>
</tr>
</tbody>
</table>

Table 2 Natural frequency and damping coefficient at completion at completion (after outer and inner membrane installation)

<table>
<thead>
<tr>
<th>Eigenvalue analysis</th>
<th>Natural Frequency [Hz]</th>
<th>Damping Coeff. [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ambient response (ratio to eigenvalue)</td>
<td>Human excitation (ratio to eigenvalue)</td>
</tr>
<tr>
<td>1.47</td>
<td>1.49 (1.01)</td>
<td>- ( - )</td>
</tr>
<tr>
<td>1.81</td>
<td>1.83 (1.01)</td>
<td>1.97 (1.09)</td>
</tr>
<tr>
<td>1.70</td>
<td>1.89 (1.11)</td>
<td>- ( - )</td>
</tr>
<tr>
<td>2.30</td>
<td>2.17 (0.94)</td>
<td>- ( - )</td>
</tr>
<tr>
<td>2.43</td>
<td>2.60 (1.07)</td>
<td>- ( - )</td>
</tr>
<tr>
<td>2.62</td>
<td>2.69 (1.03)</td>
<td>2.65 (1.01)</td>
</tr>
<tr>
<td>3.19</td>
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<td>- ( - )</td>
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<tr>
<td>2.76</td>
<td>3.98 (1.44)</td>
<td>3.99 (1.45)</td>
</tr>
<tr>
<td>2.81</td>
<td>4.02 (1.43)</td>
<td>- ( - )</td>
</tr>
</tbody>
</table>

Fig. 7 Mode shapes obtained from eigenvalue analysis
(left: Horizontal mode at 1.81 Hz, right: Vertical mode at 2.76 Hz)

Fig. 8 Damping coefficient of membrane structures
4. CONCLUDING REMARKS

The dynamic characteristics of the Shimokita Kokusetsu Dome were estimated from the ambient response, from the free vibration by the human excitation and from the eigenvalue analysis. The effect of the membrane on the dynamic characteristics was estimated. The results were summarized as follows:

The dynamic characteristics from the ambient response were estimated by the frequency domain decomposition (FDD) technique to separately estimate the characteristics of closely spaced modes in the frequency domain.

The dynamic characteristics from the ambient response agreed with those from the free vibration by the human excitation.

The damping coefficients estimated were from 1.4 % to 3.7 % after membrane installation, while they were from 0.5 % to 1.0 % at before membrane installation. Increase of damping coefficients due to membrane installation, however, depended on the natural frequency. Lower modes tended to gain more additional damping coefficients than higher modes.

The damping coefficients didn't increase after inner membrane installation. It was considered due to the smaller surface pressure in the inner membrane compared to that in the outer membrane.

The effect of membrane on the stiffness had a tendency to depend on its mode shape. The membrane tended to increase the stiffness for horizontal modes, while not for vertical modes.

The damping coefficient of the Shimokita Kokusetsu Dome was smaller than those of the existing membrane structures. The reason of the difference was considered due to the relation between the structural characteristics and mechanism of damping force, which was not discussed in this paper and it needs further study.

REFERENCES