Analytical study on wind-induced vibration of power transmission towers

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Abstract

This paper describes a method for analyzing wind-induced vibrations of power transmission towers coupled with power lines and the results of two case studies. It also discusses the influence on response characteristics of differences in transmission support systems and differences between peak factors, computed from a time-series and from power spectrum density. The results of this study show that differences in the way power transmission towers support power lines have an influence on response characteristics, and peak factors computed from a time-series response are greater than those computed from power spectrum density. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Power transmission tower; Transmission support system; Time-series response; Peak factor

1. Introduction

Since taller- and longer-span power transmission towers are recently being constructed in Japan, power transmission towers tend to be sensitive to wind action. A great deal of damage was done to the power transmission system by Typhoon 9119, and this has led to a growing interest in the structural safety and reliability of power transmission towers in Japan. It is therefore very important to accurately estimate their response to strong winds and to take this into account in their design.

Power transmission towers are connected with power lines, which show geometrically nonlinear behavior and have many complex vibration modes whose frequencies

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are normally very close. Furthermore, it has been shown that the characteristics of wind-induced vibration of a power transmission tower are strongly influenced by the behavior of the power lines [1,2].

This study describes a method for analyzing buffeting of power transmission towers coupled with power lines and results of two case studies. It also discusses the influence on response characteristics of differences in transmission support systems and differences between peak factors, computed from a time-series and from power spectrum density.

2. Outline of power transmission towers

Power transmission towers fall into two main groups according to the way they support power lines. One is referred to as a suspension-type tower and the other is referred to as a tension-type tower. In this study, wind-induced vibrations of both types of power transmission support systems are analyzed. To control tower characteristics, the same transmission tower is used in the study of both types of supports.

As shown in Fig. 1, the power transmission system in this study included 3 towers, 4 ground lines and 24 conductors. The tower studied was a steel angle tower 71 m high. The spans to the adjacent towers were both 260 m and the angles of inclination of the line chord were both zero. The upper 12 conductors were 2-bundled and lower ones were single.

3. Analytical method

3.1. Wind force

As shown in Fig. 1, analyses were conducted for a wind direction perpendicular to the transmission line.

Mean wind speed at 10 m height was assumed to be 31.8 m/s [3]. The exponential of the power law of the vertical profile of mean wind speed was assumed to be 1/6. A Karman-type fluctuating wind speed spectrum density was used. The turbulence intensity was assumed to be 0.145 [3], and the turbulence scale was computed according to "Recommendation for Loads on Buildings [4]". Three sets of fluctuating wind speed simulations were conducted [5], each one for 27 min, at time intervals of 0.2 s. Figs. 2 and 3 show a simulated fluctuating wind speed and its power spectrum density at the suspension-type tower tip. The power spectrum density was evaluated by ensemble mean values for 2 trials, in which the last 20 min of the simulated fluctuating wind speed were provided for evaluation.

Air density was assumed to be 0.120 kg s⁻²/m⁴ [3]. The drag coefficients of the tower members and the power lines were based on JEC-127-1979 [3].
Fig. 1. Target transmission system and wind direction.

Fig. 2. Simulated fluctuating wind speed at tower tip.

Fig. 3. Power spectrum density of simulated fluctuating wind speed at tower tip.
3.2. Model of structures

The post members of the central tower were modeled as beam elements and the bracing members were modeled as truss elements or beam elements. Masses were lumped on the tips of the arms and the panel points between post members and bracing members. Adjacent towers were both modeled as beam elements with the same stiffness as the panels of the central tower. Masses were lumped on the ends of elements.

A ground line and a conductor were modeled as 30 truss elements and an insulator was modeled as 4 truss elements. Masses were lumped on the ends of the elements. It was clarified that the above-mentioned number of elements of lines to model was sufficient by some sets of eigenvalue analyses and response analyses.

3.3. Response analysis method

Taking into account their geometrically nonlinear deformation, the equilibrium equation of the power transmission towers coupled with power lines under dead load and mean and fluctuating wind force can be generally expressed by:

\[ M\ddot{X}_{t+\Delta t} + C\dot{X}_{t+\Delta t} + F_{t+\Delta t}^r = F_{t+\Delta t}^d + F_s, \]

where in a global coordinate system, \( M \) is the mass matrix, \( C \) is the damping matrix, \( F_{t+\Delta t}^r \) is the restoring force vector, \( \dot{X}_{t+\Delta t} \) is the response acceleration vector, \( \ddot{X}_{t+\Delta t} \) is the response velocity vector \( F_{t+\Delta t}^d \) is the fluctuating wind force and aerodynamic damping force vector; \( F_s \) is the dead load and mean wind force vector and suffix \( t + \Delta t \) is used to indicate the time.

The nonlinear stiffness of power lines under dead load and mean and fluctuating wind force is assumed to be equivalent to one under dead load and mean wind force, thus yielding

\[ M\ddot{X}_{t+\Delta t} + C\dot{X}_{t+\Delta t} + KX_{t+\Delta t} = F_{t+\Delta t}^d \]

where \( X_{t+\Delta t} \) is the response displacement vector.

Here, \( K \) is the stiffness matrix under dead load and mean wind force, and it is obtained by the following steps. First, initial coordinates and tensile forces of ground lines, conductors and insulators under a static dead load are computed from a catenary curve. Second, a static mean wind force is applied at each node. Then, both deformations and tensile forces of elements are computed, taking into account their geometrical stiffness and the change in relative angles between wind direction and elements. Thus, the equilibrium equation is obtained and a time-series response analysis is carried out according to Eq. (2).

In this study, viscous damping was assumed. The damping ratios of the towers were assumed to be 1% at their primary mode frequencies, and those of the ground lines, conductors and insulators were assumed to be 0.4% at 1 Hz. The aerodynamic damping is based on the following Eqs. (3) and (4). The duration time of each analysis is 17 min, in which the last 10 min is provided for evaluations. The results are
evaluated from ensemble mean values for 6 trials.

\[ F_{T,K,t+\Delta t}^d = \frac{1}{2} \rho C_k A_k (U_k + u_{K,t} + \Delta t - \dot{x}_{u,k,t})^2 - U_k^2 \right) T_T^e, \]  

\[ F_{m,t+\Delta t}^d = \frac{1}{2} \rho A_m ((U_m + u_{m,t} + \Delta t - \dot{x}_{u,m,t})^2 - U_m^2) T_C C_C(z_m), \]  

where \( \rho \) is the air density, \( F_{T,K,t+\Delta t}^d \) and \( F_{m,t+\Delta t}^d \) are the global fluctuating wind force vectors, \( C_k \) is the drag coefficient, \( C_c(z_m) \) is the drag coefficient matrix in local coordinate system, \( A_k \) and \( A_m \) are the projective area, \( U_k \) and \( U_m \) are the mean wind speed; \( u_{K,t} + \Delta t \) and \( u_{m,t} + \Delta t \) are the fluctuating wind speed, \( \dot{x}_{u,k,t} \) and \( \dot{x}_{u,m,t} \) are the response velocities parallel to wind direction; \( T_T \) and \( T_C \) are the local-global transform matrices, \( z_m \) is the angle between the wind direction and the element axis, suffixes \( T \) and \( k \) are used to indicate the mass no. in tower, and suffixes \( C \) and \( m \) are used to indicate ground line, conductors or insulators element.

### 4. Analysis results

#### 4.1. Eigenvalue analysis results

**4.1.1. Towers**

Table 1 shows the primary and secondary mode frequencies of a tower without power lines. The primary mode frequencies of both transverse direction and line direction are near 1.3 Hz.

**4.1.2. Power lines**

Table 2 shows the primary mode frequencies of both suspension- and tension-type power lines under dead load and mean wind force without towers, and also those of suspension-type power lines without mean wind force in parentheses. As shown in Table 2, the primary mode frequencies move to a higher range under mean wind force. This shows that the mean wind force increases power line stiffness, because it increases their tensile force. Primary mode frequencies of tension-type power lines are higher than those of suspension-type ones. This shows that one is supported more firmly than the other.

<table>
<thead>
<tr>
<th></th>
<th>Tranverse direction</th>
<th>Line direction</th>
<th>Torsional direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>1.28</td>
<td>1.29</td>
<td>3.37</td>
</tr>
<tr>
<td>2nd</td>
<td>3.51</td>
<td>3.62</td>
<td>6.96</td>
</tr>
</tbody>
</table>
Table 2
Primary mode frequencies of power lines under dead load and mean wind force without towers: Hz

<table>
<thead>
<tr>
<th>Power line type</th>
<th>Out-of-plane vibration</th>
<th>In-plane vibration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground line</td>
<td>0.31 (0.23)*</td>
<td>0.61 (0.46)*</td>
</tr>
<tr>
<td>C2 Conductor</td>
<td>0.23 (0.20)*</td>
<td>0.26 (0.21)*</td>
</tr>
<tr>
<td>Suspension-type</td>
<td>0.26</td>
<td>0.51</td>
</tr>
<tr>
<td>Tension-type</td>
<td>0.26</td>
<td>0.27 (0.22)*</td>
</tr>
<tr>
<td>C5 Conductor</td>
<td>0.25 (0.21)*</td>
<td>0.26</td>
</tr>
<tr>
<td>Suspension-type</td>
<td>0.26</td>
<td>0.51</td>
</tr>
<tr>
<td>Tension-type</td>
<td>0.26</td>
<td></td>
</tr>
</tbody>
</table>

*Frequencies without mean wind force.

See Fig. 1.

4.1.3. Towers and power lines combined

Figs. 4 and 5 show vibration modes of towers coupled with power lines, which are equivalent to primary mode frequencies of a tower without power lines shown in Table 1. Fig. 6 shows absolute participation functions at the tower tip for both types of towers coupled with power lines. The natural mode frequency, which has a peak near 1 Hz, is equivalent to the above mentioned one. However, the frequencies of towers coupled with lines are lower than the ones without power lines. In comparing the tension-type tower with the suspension-type tower, it can be seen that the former has more peaks than the latter, so it is of more influence to the power line than the other.

4.2. Power spectrum density

Figs. 7 and 8 show the power spectrum densities of transverse response displacements at the tower tip, and the axial forces of the bottom post-members and the bottom bracing members. The peaks in the lower-frequency range are excited by power line vibration modes. The peaks near 1 Hz are excited by the aforesaid tower vibration modes.

The shapes of power spectrum densities of post-member axial forces are similar to those of displacements. However, those of bracing member axial forces are not. Power spectrum densities of the bracing member axial forces are greater than those of the post-member axial forces in high-frequency regions of greater than 1.07 Hz. This shows that higher vibration modes have more influence on the former than the latter.

In comparing the suspension-type tower with the tension-type tower, it can be seen that the former has more excited peaks than the latter in a low range of less than 1 Hz. This shows that the power lines on either sides of suspension-type tower move as a body.

4.3. Frequency distribution

Fig. 9 shows frequency distributions of fluctuating wind speed, displacement at a tower tip and tensile force of a power line. The frequency distributions of fluctuating
wind speed, displacement at tower tip without power lines and tensile force of a power line without towers ignoring nonlinear component of aerodynamic damping are Gaussian. However, those of tensile force of a power line without towers considering
nonlinear component of aerodynamic damping is distorted from the Gaussian distribution. This shows aerodynamic damping has more influence on the power line’s response than on the tower.
Fig. 9. Frequency distributions of wind speed and responses: (a) fluctuating wind speed at tower tip, (b) displacement at tower tip without power lines, (c) tensile forces of a power line without towers ignoring nonlinear component of aerodynamic damping, (d) tensile forces of a power line without towers considering nonlinear component of aerodynamic damping, and (e) displacement at tower tip with power lines.

4.4. Peak factor

Fig. 10 shows peak factors of displacements and axial forces of post-members and bracing members. In this figure, the open circles and triangles are computed from time-series response, and the solid ones from power spectrum densities in Figs. 7 and 8 from the following equations.

\[ g_T = \sqrt{2 \ln vT + \frac{0.5772}{\ln vT}}, \quad v = \sqrt{\int_0^n n^2 S(n)\,dn/\int_0^n S(n)\,dn} \]  

(5)

where \( g_T \) is the peak factor, \( T \) is the evaluation time, \( n \) is the frequency, and \( S(n) \) is the power spectrum density.

4.4.1. Peak factors from time series

The peak factors of displacements and post-member axial forces for both types of towers and the bracing member axial forces for the suspension-type tower are almost constant with respect to tower height. The peak factors of displacements of the
suspension-type tower are greater than those of the tension-type tower. However, the peak factors of the member axial forces for the former are less than those for the latter. This shows that the power lines on either sides of suspension-type tower move as a body. The peak factors of the member axial forces are greater than those of the displacement, because higher vibration modes have more influence on the axial force than the displacement.

4.4.2. Peak factors from power spectrum density

They range from 3.2 to 3.4, and are less than those derived from the time-series response. One reason for this is that Eq. (5) should be used only when one vibration mode is excited and the frequency distribution of response is Gaussian. However, in this study, there were many excited peaks of power spectrum densities and the frequency distribution of response is distorted from the Gaussian distribution. An alternative method of calculation is required, in which the peak factor would be evaluated from the power spectrum density.

5. Conclusion

This study described analyses of buffeting for both suspension- and tension-type power transmission tower. The results support the following conclusions:

(1) The difference in the way that power transmission towers support power lines has an influence on response characteristics.
(2) The peak factors of displacements and post-member axial forces for both types of towers and bracing member axial forces for suspension-type tower are almost constant with respect to tower height.
(3) The peak factors of transverse direction displacements of the suspension-type tower are greater than those of the tension-type tower. However, peak factors of
member axial forces for the suspension-type tower are less than those of the tension-type tower. This shows that the power lines on either sides of suspension-type tower move as a body.

(4) The peak factors of member axial forces are greater than those of transverse direction displacement, because higher vibration modes have more influence on the axial force than the displacement.

(5) Peak factors computed from a time-series response are greater than those computed from power spectrum density using Eq. (5).

References