Two-step Detection Method of Compressed Member Instability Damage of Transmission Towers

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Abstract
The transmission tower is prone to the strong wind and catastrophic wind, which may cause the collapse of the tower. The major members of tower body may begin to buckling under compressed force and finally collapse due to the compression induced instability. Therefore, the accurate and timely identification on instability damage of major members is essential for the structural strengthening and the prevention of tower collapse. The relationship among axial compressing force, bending moment, and axial stiffness of the major member is established based on numerical simulation with the aiding of commercial package ANSYS. Thus, a two-step detection method for the instability of major member of transmission tower is proposed: (1) The changing rate of three order wavelet packet energy curvature of nodal floor of the transmission tower is selected as a new index to detect the possible damage region; (2) Modal strain energy and interval estimation is utilized to determine the exact position of damaged major members. Finally, a real transmission tower constructed in China is taken as an example to examine the feasibility and possibility of the proposed approach. The made observations indicate that the detection quality of the two-step approach developed in this study is satisfactory.

Key words: Axial stiffness, damage detection, changing rate of wavelet packet energy curvature, modal strain energy, interval estimation.

1. Introduction

The electrical industry is very important for a country. The safety of transmission tower-line systems during service is essential for the normal electric transmission. The members of a transmission tower can be divided into there categories: major members, web members and auxiliary members. As the major force bearing members of the transmission tower, major members are subjected to axial compression forces and bending moment. This means that the major members are typical compress-bending components. It is reported that the vertical members may occur elastic-plastic instability by considering initial geometric imperfection, geometric nonlinearity and material nonlinearity, which may further induce the degradation of structural force-bearing capacity and even entire collapse. Therefore, the accurate and timely identification on instability damage of major members is essential for the structural strengthening and the prevention of tower collapse.

The damage detection of high rise truss tower has not been substantially investigated up to now. Lazarevic et al (1) investigated the damage detection of transmission tower by using classifying clustering algorithm. The relationship among the member damage and the first lower natural frequencies of the tower are established. Then, a damage detection approach is developed by using the two level artificial neural networks (ANN) based on the variation of natural frequencies. Lou W.J et al (2) identified the damage location of tower by using the spatial domain information of structures based on Wavelet Transform. Structure deformation curve is decomposed in one scale by using the bi-orthogonal wavelet bior 6.8 to identify the damage locations of uniform and non-uniform cantilever beams. The results show that the spatial domain information wavelet transform can reveal structural damage location very efficiently. The proposed method is applied to the damage detection of tall electricity transmission tower. It is shown that the method can identify the damage location of high-rise latticed tower with uniform stiffness or gradual changing stiffness along the height effectively, but fails for the latticed tower with abrupt change in stiffness. Qu W.L. et al (3) examined the relationship between the stiffness change of vertical bars and the horizontal displacement responses of nodes based on the slender and pliant characteristics of mast structure. They proposed a detection index of bars locations with damage based on the transient horizontal displacement responses, and clarified the detection process of vertical bars in the time domain. The numerical examples indicated that the proposed the index can accurately detect the location of damaged bars. Finally, the influence of signal noise on the detection index was analyzed. Liu C.C. and Xu J. proposed a new damage identification method based on neural network for towers to identify the damage location and extent. The method was applied to a 500 kV transmission tower and the results showed that the method could obtain satisfactory identification results even if there were errors existing in the structural parametric finite element models.

The elastic-plastic instability of the transmission tower is investigated through examining the stiffness degradation characteristics of the vertical major members. The instability damage is simulated by using the stiffness reduction of vertical major members. The relationship among axial compressing force, bending moment, and axial stiffness of the major member is established based on numerical simulation with the aiding of finite element method. A two-step detection method for the instability of major member of transmission tower is proposed to find the possible damage region firstly and then determine the exact position of damaged major members. The made observations from numerical simulation indicate that the detection quality of the two-step approach developed in this study is satisfactory.

2 Basic principle and method

2.1 Axial compressing force-bending moment-axial stiffness relationship

As the major force bearing members of the transmission tower, major members are subjected to axial compression forces and bending moment. The major damages are the elastic-plastic instability under initial geometric imperfection (i.e. the small bending of members). In reality, the instability is mainly caused by axial force and bending moments at the ends of members and the buckling members still have the force bearing capacity to some extent (This can be depicted using equivalent axial stiffness). Therefore, it is beneficial to establish the relationship among axial compressing force, bending moment and axial stiffness. This process can be simulated by using commercial package ANSYS. First, the fine finite element model of the major members with initial imperfection under compression force is constructed. Then, set the bending moment at the member end to be a constant value and gradually increase the axial force at the member ends. The elastic-plastic simulation is carried out by using ANSYS until the equivalent axial stiffness is zero. Finally, the he relationship among axial compressing force, bending moment and axial stiffness can be determined.

2.2 Detection on possible region of instability damage of major members

The main body of a transmission tower can be divided into several sub-regions. The dynamic responses of the exact nodal floor with damage members and adjacent nodal floor may change due to the member instability. Therefore, the acceleration responses of the nodal floor with/without damage events can be decomposed and reconstructed to obtain the energy distribution variation in each frequency band by using Wavelet Packet Transform (WPT). Then, the possible region for the damage events can be determined (8),(9). The detection process based on the changing rate of wavelet packet energy curvature can be illustrated as(5):

(1) The acceleration responses of the nodal floor are decomposed by using WPT with j level and 2j frequency bands with equal width are obtained. The signal decomposition coefficients X_j^i $(i=1,2\cdots 2^j)$ are extracted from low to high frequency component. To reconstruct the decomposition coefficient in WPT and obtain the signal in each frequency band $f_j^i(t)$;

(2) To compute the WPT energy in each frequency band. Let the signal energy of node (j,i) at j level to be E_j^i, it has:

$$E_j^i = \int_{-\infty}^{+\infty} \left| f_j^i(t) \right|^2 dt \tag{1}$$

To construct WPT energy vector $\overline{E_j^i}$ and then obtain the WPT energy distribution at each nodal floors of the transmission tower;

(3) The WPT energy curvature of the ith frequency band of the kth nodal floor is defined as

$$EC_{j,k}^i = \frac{2l_{(k-1),k}(E_{j,(k+1)}^i - E_{j,k}^i) - 2l_{k,(k+1)}(E_{j,k}^i - E_{j,(k-1)}^i)}{l_{(k-1),k} \cdot l_{k,(k+1)} \cdot l_{(k-1),(k+1)}} \tag{2}$$

In which, $E_{j,(k-1)}^{i,u}$, $E_{j,k}^{i,u}$ and $E_{j,(k+1)}^{i,u}$ are the WPT energy of the (k-1)th, kth and (k+1)th nodal floors, respectively; $l_{(k-1),k}$, $l_{k,(k+1)}$, and $l_{(k-1),(k+1)}$ are the distance between (k-1)th and kth nodal floor, distance between kth and (k+1)th nodal floor, distance between (k-1)th and (k+1)th nodal floor, respectively.

(4) The changing rate of the WPT energy curvature of the ith frequency band of the kth nodal floor is defined as

$$ECCR_{j,k}^i = \left| \frac{EC_{j,k}^{i,d} - EC_{j,k}^{i,u}}{EC_{j,k}^{i,u}} \right| \tag{3}$$

In which, superscript u denotes the original transmission tower without damage event, d denotes the damaged tower. The possible regions for the instability damage can be determined based on the abrupt information of the changing rate of the WPT energy curvature of the ith frequency band of the structural nodal floors.

2.3 Detection on damage location of major members with instability

The damage can be depicted as the reduction of structural stiffness, which may induce the variation of structural modal parameters (natural frequency and modal shape). Therefore, the change in modal parameters can be taken as a symbol of damage events (6),(7). The modal strain energy of the jth element regarding the ith modal shape is

$$MSE_j^i = \{\phi_i\}^T [K_j] \{\phi_i\} \tag{4}$$

In which, $\{\phi_i\}$ denotes the ith modal shape; $[K_j]$ denotes the element stiffness matrix of the jth element.

The change of modal strain energy of the jth element regarding the ith modal shape is (omit the high terms):

$$MSEC_j^i = MSE_j^{i,d} - MSE_j^i = 2\{\phi_i\}^T [K_j]\{\Delta\phi_i\} \tag{5}$$

Where, superscript'd' denotes the damage event.

Changing rate of modal strain energy of the jth element regarding the ith modal shape is

$$MSECR_j^i = \left| \frac{MSE_{ij}^d - MSE_{ij}}{MSE_{ij}} \right| \tag{6}$$

The modal strain energy of the members adjacent to the damage members may change to some extent. In addition, the noise pollution may affect the quality of the detection index based on changing rate of modal strain energy. Thus, a statistical approach is utilized to construct the damage index.

The ith modal strain energy of an element is assumed to be a random variable following the normal distribution:

$$MSECR_j^i \sim N(\mu, \sigma^2), j = 1, 2, \cdots, ne \tag{7}$$

Where, ne is the total number of members in the possible damage region. If the changing rate of the ith modal strain energy of all the elements in the possible damage region are taken as a sample, the mean and standard deviation are X and S^2, respectively. It has,

$$\frac{\overline{X} - \mu}{S / \sqrt{ne}} \sim t(n-1) \tag{8}$$

The upper limit value regarding to confidence level $1-\alpha$ of the mean value μ of the changing rate of the modal strain energy is

$$\mu = \overline{X} + \frac{S}{\sqrt{ne}} t_{\frac{\alpha}{2}}(n-1) \tag{9}$$

Thus, the damage index for the location of major members with instability is

$$Index_j^i = MSECR_j^i - \mu \tag{10}$$

If $Index_j^i \geq 0$, the jth element may has damage under $(1-\alpha)\%$ statistical level. If $Index_j^i < 0$, the element has no damage event.

3 case study

3.1 Structural information

A real transmission tower constructed in China is taken as an example to investigate the feasibility of the proposed detection approach. The finite element model of the tower is displayed in Fig.1. The physical parameters of the vertical major members are listed in Table 1.

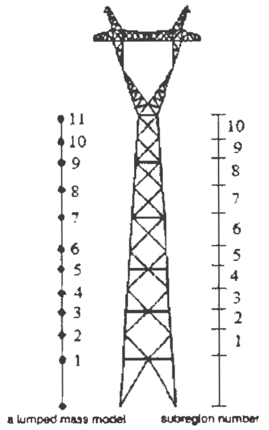

Fig.1 finite element model of the tower

Fig.2 Fine finite element model

Table1 physical parameters of the vertical major members

Member type	R (m)	r (m)	I (m4)	E (pa)	EI (Pa.m4)	EA (Pa.m2)	ρ (kg/m3)
I	0.15	0.11	2.82E-4	2.06E+11	5.81E+7	6.80E+9	7850
--	0.1	0.1	1.73	2.06E	3.56E+	3.71E+	----

Where, R and r are the inner and outer radius of circular major members respectively, I is inertia moment of major member respectively, E and ρ are the Young's modulus and density of the steel respectively. I denotes the major members in the 1st, 2nd and 3rd nodal floors, II denotes the major members in the 4th, 5th, 6th and 7th nodal floors.

3.2 Axial compressing force-bending moment-axial stiffness relationship

The vertical major members may occur instability under compression force subjected to external excitations such as strong wind. It is known that the instability of steel members is substantially controlled by the element stiffness $_{[14]}$. The elastic-plastic instability process can be investigated by study the stiffness reduction of the major members in this study. The fine finite element model of the vertical major a member is constructed by using commercial package ANSYS and displayed in Fig.2. The member is simulated by using Beam 188 element. The Possion's ratio of steel material is 0.3. A constant bending moment is applied on the member end and then axial compression force is applied gradually to analyze the member buckling. Then, the axial compressing force-bending moment-axial stiffness relationship are established as shown in Fig.3

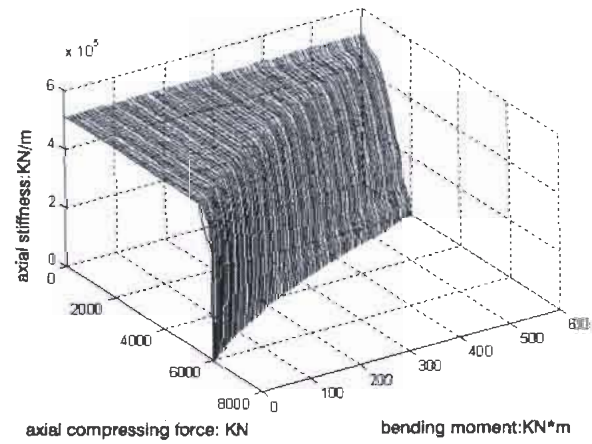

Fig.3 3D curved face of axial compressing force-bending moment-axial stiffness relationship

It is seen from Fig.3 that if the bending moment at member end is zero, the maximum axial compression force the member can bear is 6200 kN. If the bending moment at member end is 620 kN*m, the maximum axial compression force the member can bear is 1650 kN. The data in Fig.3 indicate that if the stress of the vertical major member is under elastic range, the axial stiffness will no reduce. If the strain-stress relationship of the vertical major member is under plastic range, the axial stiffness may gradually reduce with the increasing plastic area.

3.3 Damage detection

The damage efficacy is investigated in this section. The damage cases are listed in Table 2. Case 1 is the instability damage in a single subregion and case 2 is the instability damage is two subregions. Then, the damage detection is carried out based on the proposed approach in this section.

Table 2 Damage cases of the transmission tower

Case	Damaged member	Damaged extent	Subregion of damages
1	33 36	30% 40%	5
2	24 38 44	50% 40% 45%	Member 24 in subregion 3 Members 38 and 44 in subregion 6

3.3.1 Detection on possible subregion of damage event

Only the instability damage of the vertical major members is detected in this study. The tower body is divided into 11 nodal floors and 10 subregions as shown in Fig.1. A rectangular impulse is applied on top of tower in x direction and the first 10 seconds acceleration responses 44 nodes at the 11 nodal floors in x direction with/without damage are computed. The response time histories are decomposed into three levels by using bior6.8 wavelet and WPT energy of the first frequency band are utilized to construct the changing rate of energy curvature (9). The detection results for the case2 1 and 2 are displayed in Figs.4 and 5, respectively.

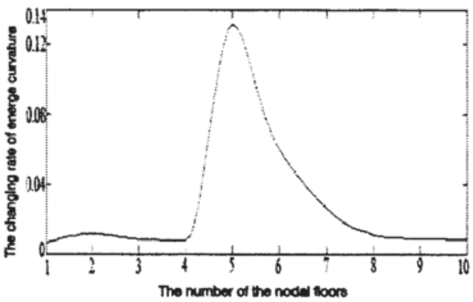

Fig.4 Detection results for case 1

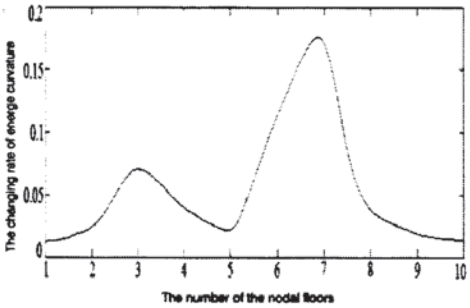

Fig.5 Detection results for case 2

It is seen from Fig.4 that the changing rates of energy curvature at the 5th, 6th and 7th nodal floors are changed remarkably for case 1. Thus, the instability damage events may exist in subregions 4, 5 and 6. The curves in Fig.5 indicate that two spikes can be observed for case 2. The changing rates of energy curvature of the 3rd and 4th nodal floors are changed. Therefore, it is judged that the instability damage events may exist in subregions 2 and 3.

3.3.2 Detection on damage location

The possible regions for the instability damage are determined in the former section. The modal strain energy can be computed by using the first two modal shapes of the transmission tower in the three orthogonal directions. The modal shapes for rotation are not involved. The proposed damage detection approach is adopted to determine the exact location of damage events. The detection results for case 1 are displayed in Fig. 6.

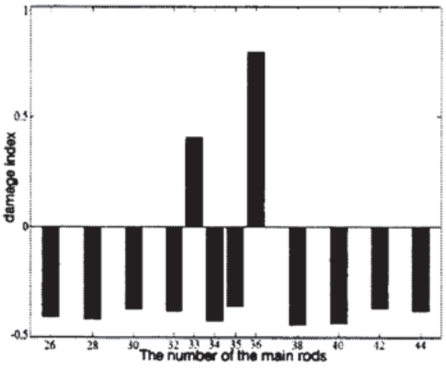

Fig.6 Detection results for case 1

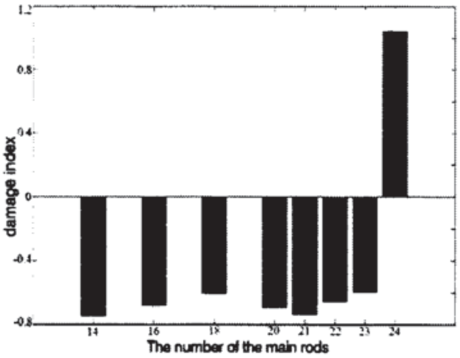

Fig.7 Detection results for case 2

Fig. 6 demonstrates that only the damage index of the members 33 and 36 are large than zero for the possible 12 members. This means that the exact damage members are 33 and 36 which is the same as the fact. The detection results for case 2 are displayed in Figs. 7 and 8 respectively. The data in Fig.7 indicates that the damaged members are located in subregion 2 or 3. Only the damage index of member 24 is large than zero and thus the member 24 is the exact damaged member, which is the same as the fact. The results in Fig.7 indicate that the damaged members are located in subregion 5, 6 or 7. Only the damage indices of members 38 and 44 are large than zero and this means the exact damaged members.

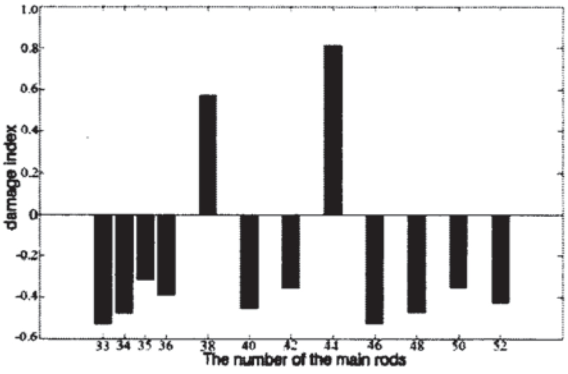

Fig.8 Detection results of subregion 6 for case 2

4 Conclusions

A two-step detection method for the instability of major member of transmission tower is proposed in this study. The relationship among axial compressing force, bending moment, and axial stiffness of the major member is established based on numerical simulation with the aiding of finite element method. The made observations from numerical simulation indicate that the detection quality of the two-step approach developed in this study is satisfactory. Some beneficial conclusions can be drawn:

(1) The vertical major members of a transmission tower still have some force bearing capacity even after an elastic-plastic instability damage. The characteristics of the stiffness reduction of major members are obtained in this study. If the middle section of the vertical major member is in elastic stage, the axial stiffness is not decreased. If the middle section of the vertical major member is in plastic stage and the axial force is larger than the crucial value, the axial stiffness gradually decrease to zero.

(2) The proposed two-step detection approach can detect the instability of the major members and the detection accuracy is 100%.

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