RESEARCH ON DYNAMIC SIMILARITY MODEL TEST OF DAMAGE DETECTION FOR TRANSMISSION TOWER

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ABSTRACT

In order to explore the dynamic similarity model test method different from atmospheric boundary layer wind tunnel and shaking table model test, in accordance with dynamic similar theory, an elastic model of a transmission tower with 1/35 scale and 5.2m height has been designed and manufactured with thin-walled circular pipes of high-density polyethylene. The model has been tested in the laboratory for time and frequency domain responses under suddenly unloading, essential dynamic characteristic of the scale model is also analysed and compared with that of its prototype tower, the dynamic similarity of the two is confirmed. By the mathematical deduction of Wigner-Ville Distribution (WVD) signal terms of structural free vibration response, the new damage detection index with clear physical signification is forwarded for damage detection for transmission tower, the damage detection test of the scale model of transmission tower is then carried out, totally three damage cases, related with chord rod weakening, flank rods failure, different damage degrees and positions, are tested to validate the proposed damage detection index.

KEYWORDS

Dynamic similarity, Model test, Damage detection, Transmission tower

1. INTRODUCTION

Transmission tower is the main structure of the power transmission project, the safety of which is the basis of the large scale regional power system reliability, but the engineering failures of transmission tower at home and abroad occasionally have happened in recent decades. Existing research [1-4] indicates that the vibration of transmission tower with so much members is more complex than general civil engineering, and dynamic characteristics are influenced much by environment condition, incitation factor, tower-line coupling and stiffness changing point, which lead many present proposed damage detection methods and indexes difficult to be applied [5-8]. As the two-dimensional function of time and frequency, the Wigner-Ville Distribution (WVD) has almost all the expected mathematical properties of damage detection, which has been successfully applied in the field of mechanical fault detection [9-10], it is also a very effective method for the damage detection of transmission tower.

Up to now, the researches of transmission tower are mainly focused on the structural dynamic response under wind load and earthquake. The few atmospheric boundary layer wind tunnel and shaking table model test of transmission tower are the application research, which regard the practical project as the research background, mainly measure the structural dynamic characteristics and response, in order to test the rationality of dynamic calculation model and its analysis method, and ensure the safety and construction of the specific project [11-12]. Meanwhile, the researches on damage detection for transmission tower are still at preliminary stage, even the research on model test of damage detection for transmission tower has not been reported yet.

Therefore, to explore the dynamic similarity model test method different from atmospheric boundary layer wind tunnel and shaking table model test, in accordance with dynamic similar theory, an elastic model of a transmission tower with 1/35 scale and 5.2m height has been designed and manufactured with thin-walled circular pipes of high-density polyethylene. The model has been tested in the laboratory for time and frequency domain responses under suddenly unloading, essential dynamic characteristic of the scale model is also analysed and compared with that of its prototype tower, the dynamic similarity of the two is confirmed. The damage detection test of the scale model of transmission tower is then carried out, totally three damage cases, related with chord rod weakening, flank rods failure, different damage degrees and positions, are tested to validate the proposed damage detection index.

2. DYNAMIC SIMILARITY CRITERION

The similarity of physical process or phenomenon is expressed by the similarity of various physical characteristics in physical process or phenomenon. There is a certain relationship between the various physical characteristics in the similar physical phenomena, which is the similarity condition of the two similar physical phenomena, is also the principle of the model test. Four similar conditions should be satisfying for general mechanic's phenomena: the similarity of material, the similarity of geometry, the similarity of kinematic and the similarity of dynamic.

The model test takes the transmission tower as the structure prototype, the dynamic characteristics and the free vibration response of the structural system is mainly simulated, and the free vibration equation of the whole quantity form can be expressed in a general manner:

$$\boldsymbol{Ma} + \boldsymbol{Cv} + \boldsymbol{Ky} = 0 \tag{1}$$

where, $\boldsymbol{M}$, $\boldsymbol{C}$ and $\boldsymbol{K}$ is respectively mass, damping and stiffness matrix, $\boldsymbol{a}$, $\boldsymbol{v}$ and $\boldsymbol{y}$ is respectively acceleration, velocity and displacement vector.

Due to the structural damping theory is still not perfect, the damping mechanism is not fully reflected by the viscous damping and hysteretic damping theory, the structural damping parameter is difficult to be controlled in the design and manufacture of the model. Thus, the free vibration equation of the prototype of the n -degree structural system without quantitative damping is simplified as:

$$\boldsymbol{M}_{\boldsymbol{p}}\boldsymbol{a}_{\boldsymbol{p}} + \boldsymbol{K}_{\boldsymbol{p}}\boldsymbol{y}_{\boldsymbol{p}} = 0 \tag{2}$$

To the model:

$$\boldsymbol{M}_{\boldsymbol{m}}\boldsymbol{a}_{\boldsymbol{m}} + \boldsymbol{K}_{\boldsymbol{m}}\boldsymbol{y}_{\boldsymbol{m}} = 0 \tag{3}$$

Set:

$$C_M = \frac{M_{im}}{M_{ip}},\ C_K = \frac{K_{im}}{K_{ip}},\ C_a = \frac{a_{im}}{a_{ip}},\ C_L = \frac{y_{im}}{y_{ip}},\ \ i = 1,\cdots,n \tag{4}$$

where, subscript i is i th degree, subscript p and m is respectively prototype and model, C_M 、C_K 、C_a and C_L is respectively similar coefficient of mass, stiffness, acceleration and geometry.

By equation (4) and decoupling, the equation (2) is deformed as:

$$\frac{C_K C_L}{C_M C_a}\boldsymbol{M}_{\boldsymbol{m}}\boldsymbol{a}_{\boldsymbol{m}} + \boldsymbol{K}_{\boldsymbol{m}}\boldsymbol{y}_{\boldsymbol{m}} = 0 \tag{5}$$

Only:

$$\frac{C_K C_L}{C_M C_a} = 1 \tag{6}$$

The phenomena of model and prototype are the same physical phenomena, in which the basic equations describing the relationship between physics in model and prototype and are the same.

The essence of similarity index is to maintain the similarity between the elastic restoring force and the inertia force, according to the dimensional analysis method, the equation (6) is deformed as:

$$\frac{C_E C_t^2}{C_\rho C_L^2} = 1 \tag{7}$$

where, C_E、C_ρ and C_t is respectively similar coefficient of elastic modulus, density and time. The similarity conditions of the model are mainly derived from the similarity of geometry, elastic modulus and density, the similarity coefficient of time determines the similarity of velocity, acceleration, frequency and other physical variables. Thus, the selection of geometry and material of model is particularly important and key.

3. DAMAGE DETECTION INDEX

Under initial displacement condition, the acceleration response of free vibration at position k of non-damping structural system with n degrees of freedom is:

$$a_k(t) = \sum_{i=1}^{n} \varphi_{ki} \cdot \boldsymbol{\varphi_i^T M y_0} \cdot \cos(\omega_i t + \theta_i) \tag{8}$$

Where, $\boldsymbol{\varphi_i}$ is i th mode shape, $\boldsymbol{M}$ is mass matrix, $\boldsymbol{y_0}$ is initial displacement condition, ω_i is i th natural frequency, and θ_i is i th initial phase of acceleration response.

After $a_k(t)$ is transformed to analytic signal $z_k(t)$ by Hilbert transform, the Wigner-Ville Distribution (WVD) signal terms of $a_k(t)$ can be deducted as:

$$W_k^{signal}(t, f) = \sum_{i=1}^{n} (\varphi_{ki}\ \boldsymbol{\varphi_i^T M y_0})^2 \cdot \delta(f - \frac{\omega_i}{2\pi}) = \sum_{i=1}^{n} A_k(t) \cdot \delta(f - \frac{\omega_i}{2\pi}) \tag{9}$$

Can be seen from analytic expression, the signalterms in WVD of free vibration response are as follows: n impulse functions located at frequency $f_i = \omega_i / 2\pi$ in time-frequency plane.

If frequency parameter f_i of a signal term is determined, while the i th natural frequency ω_i is easy to be acquired by frequency spectrum or time-frequency analysis, then the time-decaying amplitude $A_k(t) = (\varphi_{ki} \cdot \boldsymbol{\varphi_i^T M y_0})^2$ can be determined, the response function of i th mode shape at test point k also can be acquired, by analogy with $k = 1,2,\cdots n$, the response function of i th mode shape at one time point ($t = t_0$) can be obtained at any test point, finally the i th mode shape can be acquired:

$$\varphi_i = [\sqrt{A_1(t)}, \cdots, \sqrt{A_k(t)}, \cdots, \sqrt{A_n(t)}]^T = (|\varphi_{1i}|, \cdots, |\varphi_{ki}|, \cdots, |\varphi_{ni}|)^T \cdot |\boldsymbol{\varphi_i^T M y_0}| \tag{10}$$

The positive and negative relations between mode shape components can be determined by the phase relationship of cross-power spectrum at test points, with same direction as positive and different direction as negative.

The structural damage generally will bring changes in physical parameters (such as mass, stiffness and so on), and then results in that structural vibration mode also will change, so the damage massage is inevitably contained in the change of mode shape. Meanwhile, the response function relation between WVD signal terms amplitude of free vibration response and mode shape has been revealed. To determine the specific position of structural damage, the key features of damage information can be extracted by WVD signal terms amplitude. Therefore, based on the principle that quadratic index is more sensitive to small change in mode shape and can find the mutation of damage position, the index WAC is proposed for damage detection for transmission tower:

$$WAC(i)=\frac{\left|C^{d}(i)-C^{u}(i)\right|}{\sum_{i=1}^{n}\left|C^{d}(i)-C^{u}(i)\right|} \tag{11}$$

where, $C^{u}(i)$ and $C^{d}(i)$ is respectively amplitude curvature of signalterms in WVD at test point i before and after damage , which can be calculated by central difference method:

$$C(i)=\frac{\sqrt{W_{i-1}^{signal}(t,f)}+\sqrt{W_{i+1}^{signal}(t,f)}-2\sqrt{W_{i}^{signal}(t,f)}}{2l_{i}^{2}} \tag{12}$$

where, l_i is the space between test points.

4. MODEL DESIGN, MANUFACTURE AND TEST

At present, there are two kinds of transmission tower model design and manufacture methods, which are concentrated stiffness method and discrete stiffness method. The concentrated stiffness method is that the stiffness distribution of prototype is simulated by stiffness distribution along height of the mandrel made with appropriate elastomer, although the design and manufacture of model is simplified, this method has some obvious deficiencies, such as structure stress transmitting path distortion and so on. The discrete stiffness method requires all the members of model to be stiffness similar, the main difficulty of this method is the material and manufacture, because thin-wall steel tubes and angles of transmission tower prototype are scaled down, according to the geometric similar coefficient, the wall of members is very small, which cannot be finished in the actual manufacture.

However, according to the mechanic characteristics of transmission tower, the tower structure can be regarded as the spatial truss structure composed of two force bars by ignoring local bending of the bar, so the simulation of stiffness is only required to meet the similarity of tensile stiffness. The model regards a transmission tower with 181.8m height as structural prototype, the members of model are manufactured with thin-wall circular pipes of high-density polyethylene, a small amount of thin-wall steel angles are replaced according to the principle of equal section area, the density and elastic modulus are respectively 0.958g/cm^3 and 0.7GPa. The model similar coefficients are shown in Table 1, Figure 1 is the photo of transmission tower model in laboratory, and Figure 2 is the position of acceleration sensors and simulated damages.

Tab.1 Model similar coefficients

Similar coefficient	Symbol	Value
Dimension	C_L	$1/35$
Mass	C_m	$1/351324$
Tensile stiffness	C_{EA}	$1/351750$
Frequency	C_f	$\sqrt{35}$
Displacement	C_y	$1/35$
Velocity	C_v	$1/\sqrt{35}$
Acceleration	C_a	1

Fig. 1. - Model of transmission tower

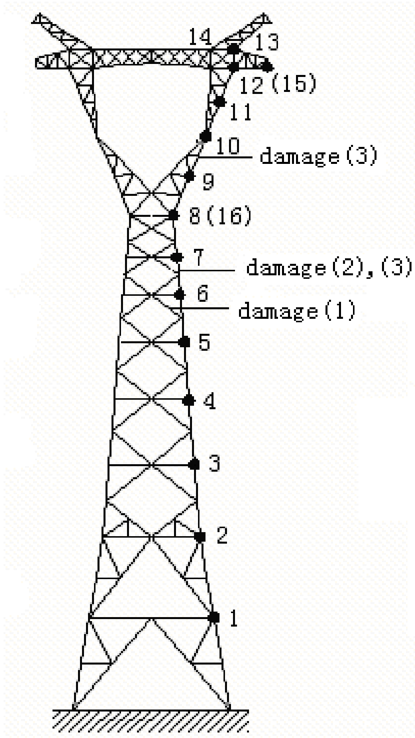
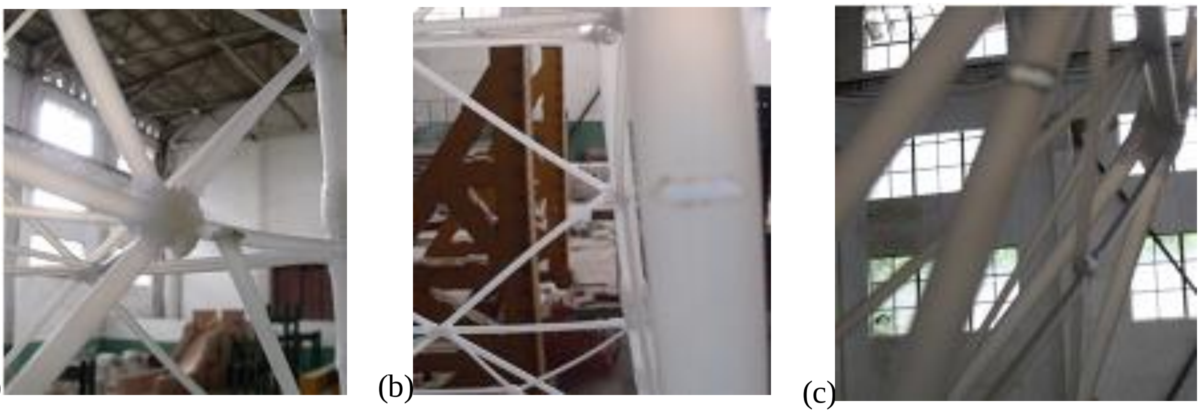


Fig. 2. - Position of sensors and damages

Totally sixteen micro acceleration sensors are used, the test point No.1 to No.14 sensors testing x direction (line direction) acceleration are in turn attached on the surface of chords from tower foot to tower head, the No.15 and No.16 sensors testing y direction (traverse direction) acceleration are respectively attached on the side of chord of tower body and tower head. Considering the test sequence feasibility of different simulated damage states, two types of structural damages of chord rod weakening and flank rod failure are simulated by directly creating damage on the model pipes, as shown in Figure 3. Totally three simulated damage states related with damage type, damage degree and damage position are set up: (1) Single flank rod failure, located at 6th segment of tower body, (2) Single chord rod cross-section weakening 30%, located at 7th segment of tower body, (3) Two chord rod cross-section weakening 30% and 50%, located at 7th segment of tower body and tower head.



(a) (b) (c)

Fig. 3. - Damage simulation: (a) flank rod failure (b) chord rod cross-section weakening of tower body (c) chord rod cross-section weakening of tower head

The suddenly unloading incitation is exerted by cutting the tensile wire (diameter 0.2mm) along the horizontal direction, incentive point is located at the bottom of tower head and middle of crossarm, which is respectively load case (1) and (2), the incentive amplitude is the weight (500g) hanged to the wire through the pulley.

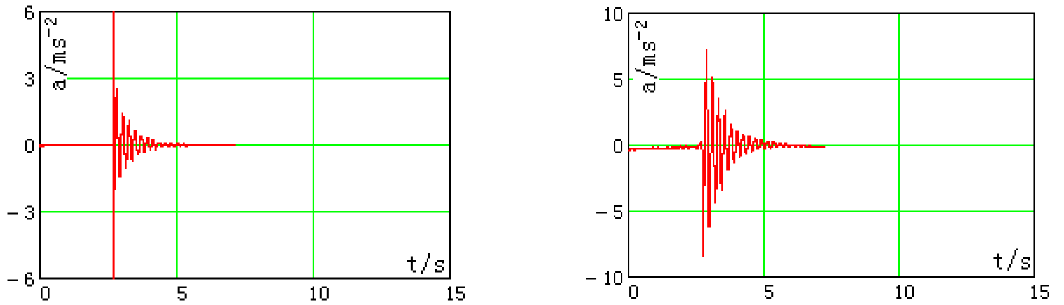
5. RESULTS AND DISCUSSIONS

Figure 4 and Figure 5 are respectively the model typical acceleration response of x and y direction under suddenly unloading incitation, it is shown that the vibration response of the model fade very fast because of the damping effect, the acceleration responses of the model are mainly the low frequency components. Figure 6 and Figure 7 are the model typical acceleration spectrum of x and y direction under suddenly unloading incitation, it is shown that the first order modal response is absolutely dominant in the dynamic response for high rise structures such as transmission tower, and the structural dynamic analysis of the first three order modal components is sufficiently accurate.

Table 2 is the natural frequency of transmission tower model; the model expectation valve comes from prototype theory valve according to the frequency similar coefficient. It can be seen that the model test valve is well identical with the expectation valve, indicating that the design and manufacture of transmission tower model based on dynamic similarity criterion is successful.

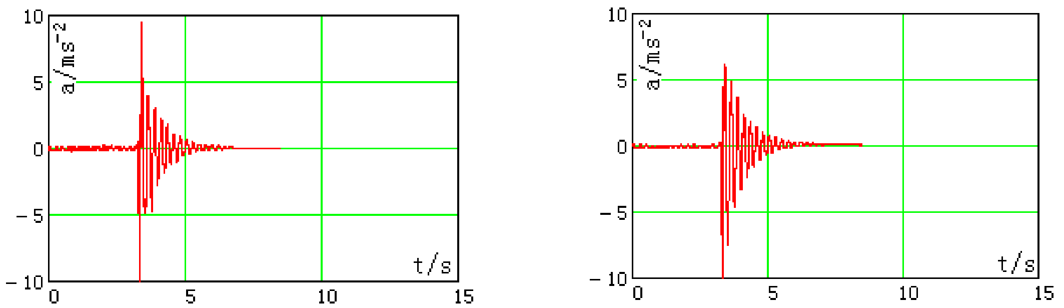
Tab.2. - Natural frequency of transmission tower model Hz

No.	Prototype theory valve		Model expectation valve		Model test valve	
	x direction	y direction	x direction	y direction	x direction	y direction
1	0.7526	0.7134	4.4524	4.2205	4.3950	4.1660
2	2.0071	1.6724	11.8742	9.8941	11.719	9.7660
3	3.2628	3.0118	19.3030	17.8180	19.0430	17.5780



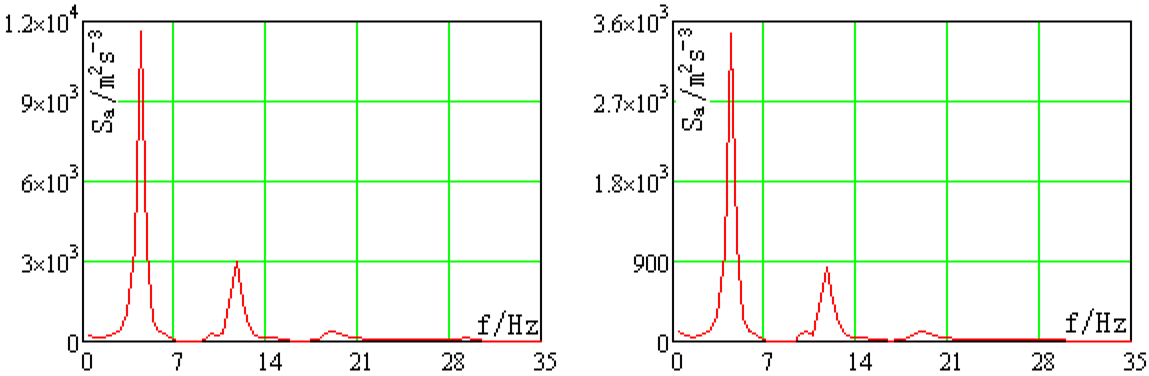
(a) Test No.6 *(b) Test No.8*

Fig.4. - Acceleration response of x direction



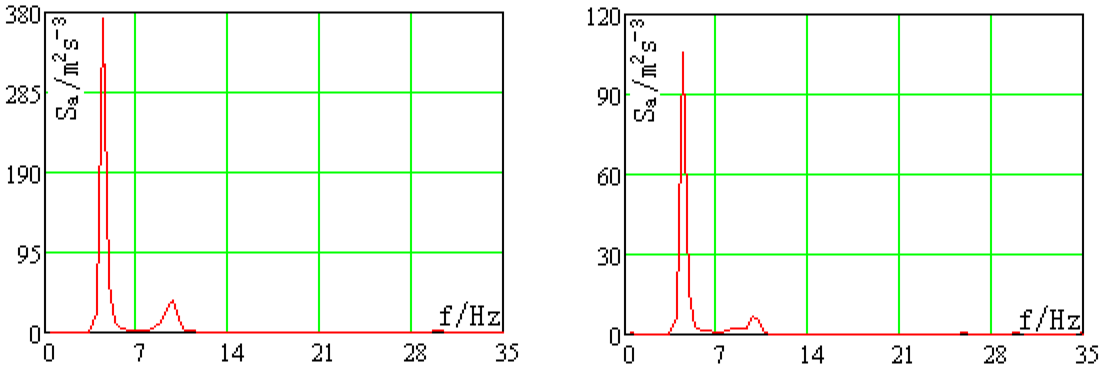
(a) Test No.15 *(b) Test No.16*

Fig.5. - Acceleration response of y direction



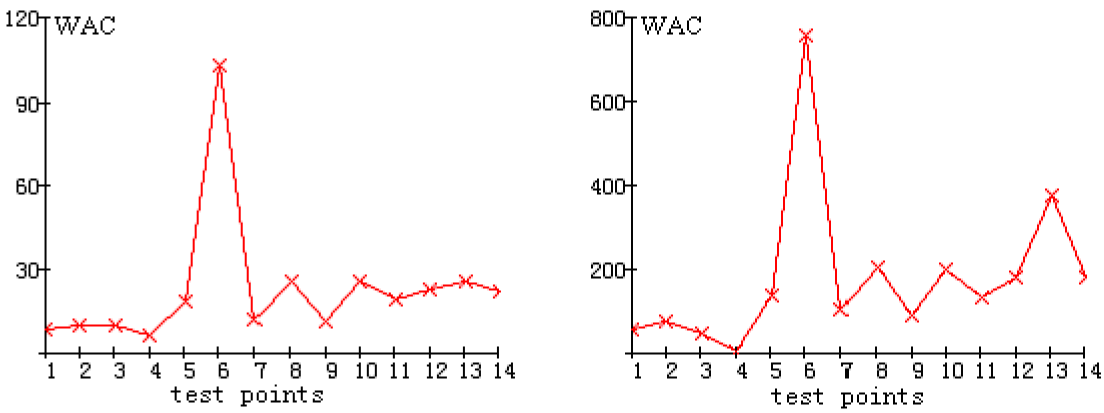
(a) Test No.6 *(b) Test No.8*

Fig.6. - Acceleration spectrum of x direction



(a) Test No.15 *(b) Test No.16*

Fig.7. - Acceleration spectrum of y direction



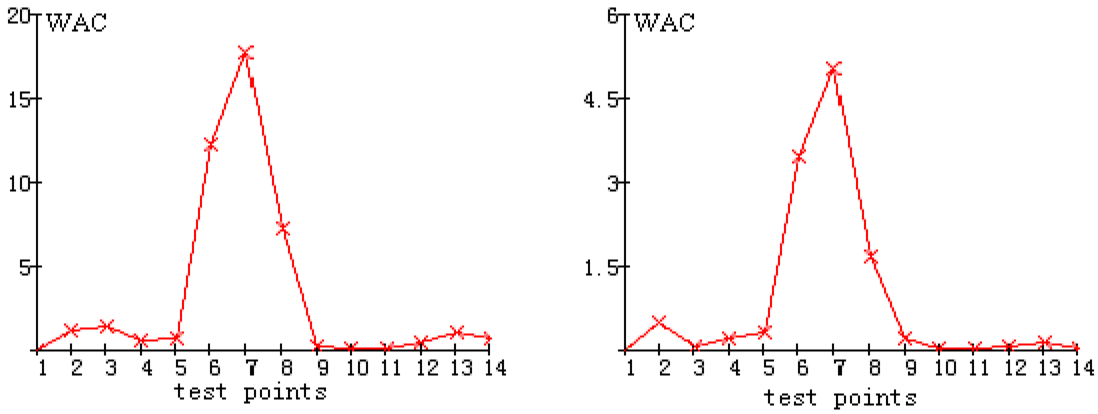
(a) Load case (1) *(b) Load case (2)*

Fig.8. - Detection result of simulated damage (1)

Figure 8 is the detection result of index WAC for simulated damage (1), it is seen that the value of WAC is as a single peak at test point No.6 under two load cases, accurately showing the position of local damage from flank rod failure. The WAC small peak values at junction of tower body and head (test point No.8), middle of tower head (test point No.10) as well as crossarm (test point No.13) are caused by structural itself stiffness mutation.

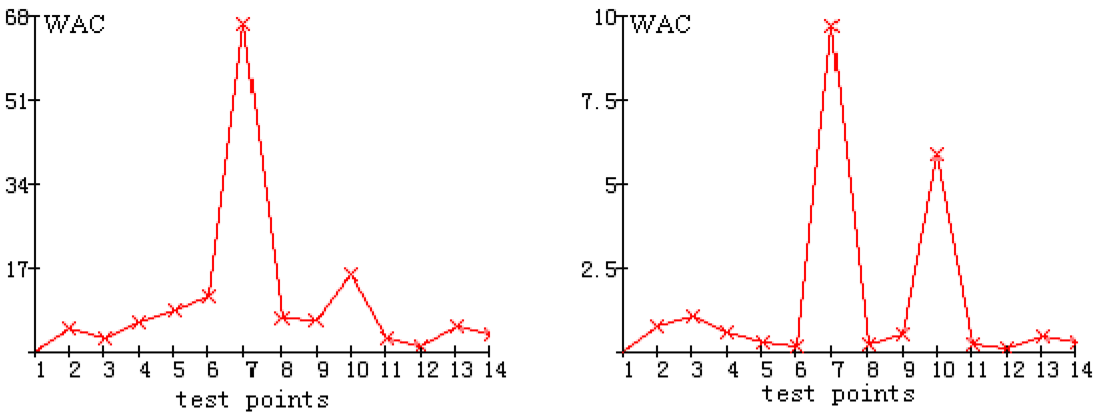
Figure 9 is the detection result of index WAC for simulated damage (2), it is seen that the value of WAC is as an independent single peak at test point No.7 under two load cases, clearly displaying the position of local damage from chord rod cross-section weakening of tower body.

Figure 10 is the detection result of index WAC for simulated damage (3), it is seen that the value of index WAC at test point No.7 and test point No.10 under two load cases are as two single peaks, indicating the damage position of tower body and tower head. But the index fails to quantify the relative relationship of two damage degrees at different position.



(a) Load case (1) *(b) Load case (2)*

Fig.9. - Detection result of simulated damage (2)



(a) Load case (1) *(b) Load case (2)*

Fig.10. - Detection result of simulated damage (3)

6. CONCLUSIONS

To explore the dynamic similarity model test method different from atmospheric boundary layer wind tunnel and shaking table model test, in accordance with dynamic similar theory, an elastic model of a transmission tower with 1/35 scale and 5.2m height has been designed and manufactured with thin-walled circular pipes of high-density polyethylene.

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