STUDY ON TRANSMISSION LINE COUPLING SYSTEM'S DYNAMIC BEHAVIOR

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ABSTRACT:

Studying the dynamic characteristics of the transmission tower-line coupling system is the theoretical basic to analyse its dynamic response accurately. Analyzing some research results comparatively, the line's mass and its tensile stiffness have influence on the tower's dynamic character admittedly, but some conclusions have differences based on their actual projects. So 32 tower-line coupling models are designed under comparable conditions. Contrasting the mode parameters of each coupling model by ANSYS modal analysis, some significative conclusions have be gotten. The in-plan natural frequency of the coupling system is less than that of the single tower, and the line's sag has a main influence on the frequency's increment, contrarily the line's span has an important effect on its decrease. The out-plane natural frequency of the coupling system with the same span is up-and-down markedly when its sag has be different, but few change when its span has be large. The torsional natural frequency of the coupling system is less than the single tower, and its trendline is complicated when the line's sag has be different, but fall to the in-plane natural frequency when its span has be large gradually.

KEYWORDS: tower-line coupling system, dynamic characteristics, model design, modal analysis

1. INTRODUCTION

The tower-line coupling system, as an important composition of the electric system constantly working in the open country, is affected by various natural factors, especially for the most frequent wind-induced. Because of the nonlinear line, the tower-line coupling effect, and also the gas-solid coupling interaction, they form a very complicated dynamic coupling system (Liang Shuoguo et al, 1999; Li Hongnan and Wang Qianxin, 1997).

To assess the dynamic characteristics of the tower-line coupling system is the pre-condition of researching the wind-induced vibration and earthquake-response (Liang Shuoguo et al, 2003). It is thus of very great significance. Usually, for small-span transmission towers, due to the large gap between the mass of the transmission line and that of the tower, the influence by the tranmission line is neglected in the tower's dynamic calculation, and the separate tower-line design has little influence on the whole system. But for large-span transmission system, the mass of the line would have considerable impact on the dynamic characteristics of the transmission tower, and there is no established conclusion how long the span between towers be unneglected the influence of the line (Li Hongnan et al, 2003).

In order to explore the objective law, some existing research results, both forreign and domestic, have been analyzed about their common ideas and disparities firstly, and then two kinds of model towers, transmission line sets XA and XB are designed. The two line sets are hung up separately on each model tower to make modal analysis of tower-line coupling systems.

2. SOME RESEARCH RESULTS

In recent years, some scholars home and abroad have made researches relatively on the calculation model of the transmission tower-line system, its calculation method, its model experiment and its field measure, and some significant results have been achieved as follows.

2.1. Researches in China

Pro. Liang Shuguo et al proposed multiple degree-of-freedom calculation method for dynamic characteristics of large-span transmission tower-line systems. Taking the Beijiang large-span transmission tower-line system as the example, results obtained are presented in Table 1, which shows that when the tower has great mass, there has less influence from tower-line coupling vibration on the tower's first natural frequencies in plane. The larger the mass ratio of lines to towers is, the more the low-order frequencies in plane decrease. But there has little influence from the mass ratio on the system's out-plane frequencies.

Table 1 Comparison Results from Pro. Liang Shuguo et al

Comparing terms	Single tower		Tower-line system	
Mode description	In-plane	Out-plane	In-plane	Out-plane
Circular natural frequencies (rad/s)	1.684	1.663	1.392	1.667

Pro. Deng Hongzhou et al once got results of comparison between natural frequencies and vibration modes of the acroelastic model simulated the 500 kV Jiangyin large-span transmission tower attached the line before and after in calibrating the dynamic characteristics (Deng Hongzhou et al, 2003), which are shown in Table 2. The first natural frequencies in two directions of the tower-line system are both higher than those of the single tower. The in-plane frequency of the single tower or the system was a little higher than the out-plane one. The damping ratio of the tower-line system is higher than that of the single tower, and the in-plane damping influence from the line is greater too.

Table 2 Comparison Results from Pro. Deng Hongzhou et al

Comparing terms	Single tower		Tower-line system	
Mode description	In-plane	Out-plane	In-plane	Out-plane
Natural frequencies (Hz)	3.533	3.511	3.645	3.545
Damping ratio (%)	0.28	0.27	1.90	0.97

Pro. Zhou Fulin et al used the ANSYS software to set up the finite element analysis model of the large-span transmission tower-line system (Zhou Fulin et al, 2005), which combines steel tubes, and the results obtained are shown in Table 3. It was considered that the equivalent restraining action of ground wires and transmission lines' stiffness had not the same effect on the tower's dynamic characteristics in or out of plane as the their increased mass action.

Table 3 Comparison Results from Pro. Zhou Fulin et al

Comparing terms	Single tower		Tower-line system	
Mode description	In-plane	Out-plane	In-plane	Out-plane
Natural frequencies (Hz)	0.973	0.974	1.010	0. 960

Pro. Liu Qun et al made field measurement about the tower-line coupling phenomenon (Liu Qun et al, 1997), some results shown in Table 4, that in wind-resistant design, the coupling effect should be paid special attention to. In some conditions, the dynamic characteristics of the tower may control the line's, that is, the tower's vibration maybe exacerbate the line's, and aggravatingly damage the line, the suspension fittings and even the tower.

Table 4 Comparison Results from Pro. Liu Qun et al

Comparing terms	Single tower		Tower-line system	
Mode description	In-plane	Out-plane	In-plane	Out-plane
Natural frequencies (Hz)	2.26	8.06	2.45	8.33

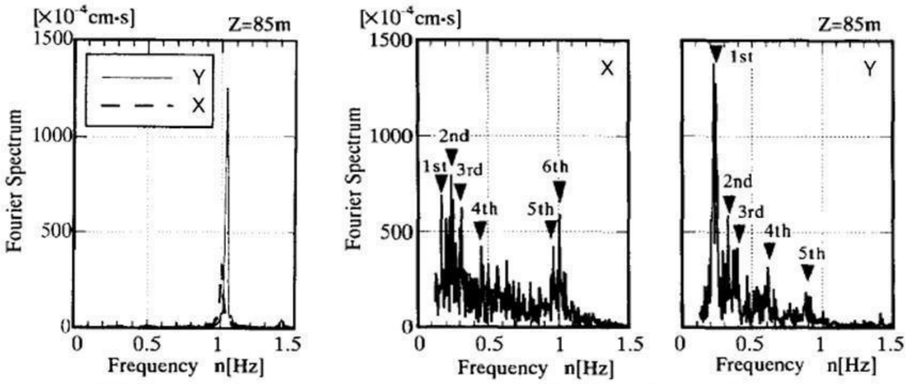
Pro. Qu Weilian et al used multi-mass-point model to analyze the one tower-line system in the 500KV Nanzhen transmission line (Qu Weilian et al, 2003), with results presented in Table 5. They believed that tower-line coupling vibration had little influence on the out-of-plane frequency of the tower, while had some influence on that of the in-plane, and the line had damping action to the tower.

Table 5 Comparison Results from Pro. Qu Qiubai et al

Comparing terms	Single tower		Tower-line system	
Mode description	In-plane	Out-plane	In-plane	Out-plane
Natural frequencies (Hz)	1.348	1.409	1.044	1.444

2.2. Foreign Researches

Y. Momomura et al, when studying actual wind-induced vibration of the transmission tower-line system in the mountainous area (Y. Momomura et al, 1997), used artificial excitation to measure the free vibration of the tower before and after the line-attaching , and used the random decrement technique to identify its dynamic characteristics, with results shown in Figure 1. The peak value of single tower's Y-direction frequency (vertical to cross arms) was slightly larger than that in X direction (in the direction of cross arms), but both were about 1.0 Hz. Meanwhile, the damping ratios in Y and X direction were 0.3% and 0.1%. There appear many peak values in the range of 0.1-1.0 Hz in two directions of the tower-line system, and the highest peak values in both directions at about 0.23 Hz, at which the damping values in both directions are 3.3% and 1.7%.



(a) Single tower (b) Tower-line system

Figure 1 Comparison Results from Y. Momomura et al

H. Yasui et al, when studying coupling wind-induced vibration of the transmission tower-line system (H. Yasui et al, 1999), got dynamic characteristic comparison shown in Table 6, that natural frequencies in both directions of the single tower are both around 1.3Hz, while the tower-line coupling frequency was lower than that of the single tower.

Table 6 Comparison Results from H. Yasui et al

Comparing terms	Single tower		Tower-line system	
Mode description	In-plane	Out-plane	In-plane	Out-plane
Natural frequencies (Hz)	1.29	1.28	0.90	1.07

3. COMPARETIVE ANALYSIS OF REPORTED RESULTS

On the basis of the preceding reported research results home and abroad, a common idea about the dynamic characteristics of the tower-line coupling system is obtained that the dynamic characteristics of the tower-line system differs from those of the single tower, and the existence of the line makes the damping ratio of the system higher than that of the single tower; and meanwhile, some disparities are also revealed as follows.

3.1. Comparing the Natural Frequencies of the Tower Tied Line to or not

As is presented by Pro. Liang Shuguo and Qu Weilian, the in-plane frequency of the tower-line system is less than that of the single tower, while the out-plane frequency of the system is larger. The in-plane frequency of the tower-line system increases while the out-plane frequency decreases, which is shown by Pro. Zhou Fulin et al. The natural frequencies in-plane and out-plane of the system both increase, which is presented by Pro. Deng Hongzhou and Liu Qun. The two-direction natural frequencies of the system both decrease, which is presented by Y. Momomura and H. Yasui et al.

The above presentation shows that probably caused by the mass and stiffness's corresponding relation between the line and the tower, which is shown in results by Pro. Liang Shuguo, when the mass of the line is greater than that of the tower, the influence on the transmission tower at lower order frequencies from the tower-line coupling vibration is decreased. Considering that the mass ratio of lines to towers is matched or not large while the axial tensile stiffness of the line is high, the in-plane frequency of the tower-line system might largen. In the same way, the out-of-plane frequency might also be affected by the mass ratio and stiffness.

3.2. Comparing the First Mode of the Tower Tied Line to or not

The fundamental frequency of the single tower is out of plane, while that of the tower-line system is in plane, which is shown by Pro. Liang Shuguo, Momomura and Yasui et al. The fundamental frequencies of the single tower and the system are both out of plane, which is shown by Pro. Deng Hongzhou et al. The fundamental frequency of the single tower is in plane, while that of the system is out of plane, which is shown by Pro. Zhou Fulin et al. The fundamental frequencies of the single tower and the system are both in plane, as is shown by Pro. Liu Qun and Qu Weilian et al.

Analysing the first three types, one common feature is concluded that the in-plane and out-of-plane fundamental frequencies of the single tower are almost equal, that is, there is no markedly weak axis in the single tower's cross section, and the tower's equivalent flexural stiffness in the two directions are almost equal. So it is hard to determine which direction the fundamental frequency of the single tower was in, and that of the tower-line system depends on the mass and stiffness's corresponding relation between the line and the tower.

Analysing the last type, a clear feature different from that of the first three ones is concluded that the two-direction natural frequencies of the single tower are markedly unequal. Especially for the research object of Pro. Liu Qun et al, the equivalent flexural stiffness of the single tower differ greatly around its strong axis and weak axis. So The vibration modes unchanged are also determined by the mass and stiffness's corresponding relation between the line and the tower.

4. MODEL DESIGNING AND CALCULATION

Analysing reported results comparatively, it is revealed that the mass and axial tensile stiffness of the line influence the dynamic characteristics of the transmission tower, but only qualitative analysis has been made for the actual influence extent, and is only restrained by actual projects. In order to explore the regularity, two simplified transmission tower models are designed as following, one having markedly strong and weak axes about the equivalent flexural stiffness in the single tower's cross section, and the other having no differed strong or weak axes. Then 8 types of line with equal span and unequal sag and other 8 types of line with unequal span and equal sag are designed with the same material. Lastly, the two sets of line are attached one by one to each tower model, and the modal analysis of the tower-line coupling sytem is carried out in each of 32 working conditions. The regularity is concluded as to the influence of the mass and tensile stiffness of the line on the dynamic characteristics of the transmission tower.

The modal analysis of the tower and line is made by Ansys software separately.The cable unit LINK10 in unit library is chosen to simulate the line with great geometric transform, whose prestrain feature can perfectly simulate he initial tension.Considering that the simulated tower is combination of slender member bars, in integrated calculation, usually the influence of rotational inertia and shear deformation would not be taken into consideration, that is, it can be treated as Bernoulli-Euler beam. Therefore, BEAM44 is chosen to do the simulation of the member bar. The structure of the tower-line coupling system is presented in Figure 2.

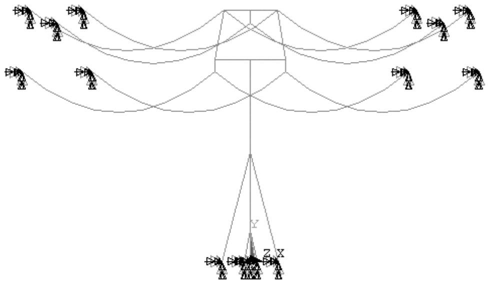


Figure 2 Structure sketch of the tower-line coupling system

4.1. Towers' Models

In order to verisimilarly simulate the mass distribution and outside size of the transmission tower, two types of model towers are designed, whose structures and forms are presented in Figure 2. Trapezoidal tower head is the simulation of multi-layer crossing arms or Cat-Head tower window The external diameter of the head bar's section is 8mm, and that in the tower body is 12mm. The material chosen is the usual Q235 rolled plain steel bars with node welding. By adjusting the height of connecting point between the two symmetrical sets of inclined supporting bars and axia bar, two representative kinds of tower in actual power system are obtained: one with clearly weak axis (T1), and the other without differed weak axis (T2). The two towers have the same outside size and line attachment method. The related parameters of single tower are presented in Table 7, in which z direction is in-plane direction of the system, and x direction is out-of-plane one. For T1, the first frequencies in both directions differ markedly, while for T2, those almost equal.

Table 7 Related parameters of single tower model

Tower's label	Mass (kg)	The first three natural frequencies (Hz)		
		In-plane	Out-plane	Torsional
T1	3.421	4.63	6.70	15.72
T2	2.644	3.437	3.436	13.323

Table 8 Related parameters of the line's set XA with the equal span 8m

line's label	Sag (m)	Line's tension (N)	Single line's mass (g)	The first two natural frequencies (Hz)	
				Out-plane	In-plane
XA1	0.04	51.94	212.0	2.77	3.71
XA2	0.10	20.78	212.1	1.76	3.59
XA3	0.14	14.84	212.3	1.49	3.03
XA4	0.20	10.39	212.5	1.24	2.53
XA5	0.26	7.99	212.7	1.09	2.21
XA6	0.40	5.19	213.5	0.87	1.76
XA7	0.60	3.46	215.2	0.71	1.41
XA8	1.00	2.08	220.5	0.54	1.03

4.2. Lines' Models

Under the condition of small sag-span radio (<1/8), one set of 8 lines with equal span 8m and unequal sag (XA) is designed, and the other of 8 lines with unequal span and equal sag 0.26m (XB) is designed also. The material chosen is konstantan wire, with an outside radium of 2mm. The related parameters of the two sets are presented in Tables 8 and 9.

In set XA, every line's mass is almost the same, its modals (vibration modes and frequencies) are only controlled by its sag, and its tension decreases with the its sag increase, displaying certain inverse function relationship. Therefore, after coupling the set with the tower model, the influence from the line's mass on the modal of the tower-line system can be neglected, and only the influence from the sag or the tension of the line (or the extension rigidity) is taken into consideration. While in set XB, all lines have equal sag, the modal of each line is almost the same, and the line's mass and tension increase with the increase of the span, displaying certain function relationship. Therefore, after coupling, the influence from the line's modal on that of the tower-line system can be neglected , and only the influence from the span is taken into consideration.

Table 9 Related parameters of the line's set XB with the equal sag 0.26m

line's label	Span (m)	Line's tension (N)	Single line's mass (g)	The first two natural frequencies (Hz)	
				Out-plane	In-plane
XB1	3	1.13	81.1	1.07	2.123
XB2	4	2.00	107.2	1.08	2.168
XB3	5	3.13	133.5	1.08	2.189
XB4	6	4.51	159.9	1.08	2.201
XB5	8	8.01	212.7	1.09	2.212
XB6	12	18.02	318.5	1.09	2.222
XB7	16	32.04	424.5	1.09	2.225
XB8	20	50.06	530.4	1.09	2.226

4.3. Comparative Analysis of the Coupling System under Different Condition

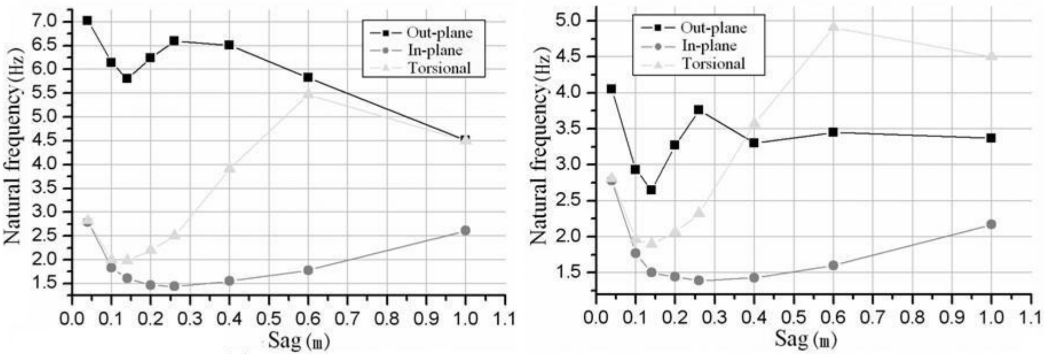
The two line sets are attached to each tower model alternately, and the modal analysis of the tower-line coupling system in each working condition is made to propose the its main vibration mode and natural frequency one by one, out of plane, in plane and twisting direction, which are collected, and their change curves are drawn with the sag and span, which are shown in Figs. 3 and 4.

It can be shown from Fig. 3 that after the combination of each tower modal with line set XA, the changes of the uni-directional natural frequency tend to be consistent. Meanwhile, the same tendency is seen from Fig. 4 when combined the each tower modal and line set XB.

The in-plane natural frequency of the tower-line coupling system is lower than that of the single tower under random condition. Under the condition of equal span and unequal sag, the in-plane natural frequencis, with the increase of the line's sag, decrease initially and then increase gradually. The tower-line coupling frequencies at the line's 0.26m sag are all of the minimal values, approaching the out-of-plane natural frequency of the line. Under the condition of equal sag and unequal span, the in-plane natural frequencies tend to becomes flat with the decrease of span, approaching the in-plane natural frequency of the line.

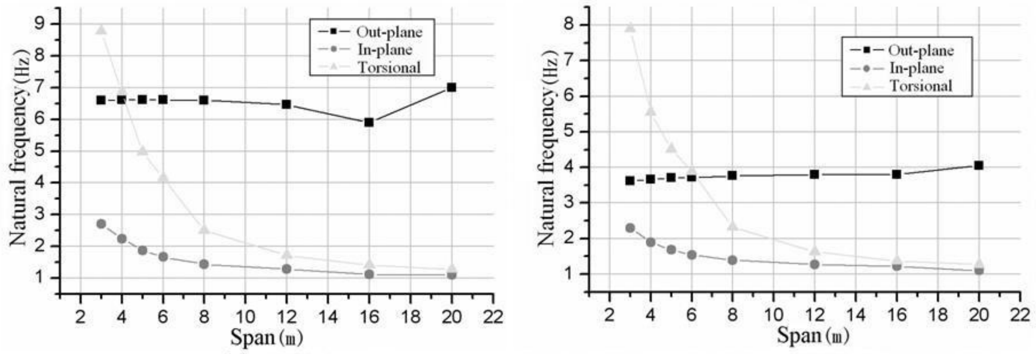
Under all conditions, the out-plane natural frequencies are influenced markedly by the line's unequal sag, and, with the consistently increase of sag, tend to decrease initially, and then increase and decrease finally. At the line's 0.04m sag, the out-plane frequencies of the tower-line system are higher that those of the single tower. At 0.26m sag, the maximal frequencies occur again, one of the system containing tower T1 is almost equal to that of the single T1, but one of the system containing tower T2 is higher than that of the single T2. The system's out-plane frequencies are not so influenced by the line's equal sag and unequal span, but tends to increase a little with the increase of span. The out-plane frequencies of the combination of T1+XB is basically the same as that of the single T1, while that of T2+XB is higher a little than that of the single T2.

Under all conditions, the system's torsional natural frequencies are much lower than those of the single tower. In the combinations of equal span and unequal sag, there is the torsional natural frequencies' tendency, that is, the frequency decreases initially, then increases, and decreases finally with the increase of line's sag. At the sags 0.14 and 0.6m, the torsional frequency of every combination shows minimum and maximum value respectively. And at the sag 0.6m, the frequency of the system containing tower T2 is higher than the system's out-plane natural frequencies, and then it gradually decreases. In the combinations of equal sag and unequal span, the frequencies in the twisting direction of the tower-line combinations tend to decrease with the increase of the line's span, showing a tendency equaling to the in-plane natural frequency under the same condition.



(a) T1+XA (b) T2+XA

Figure 3 Combination of the line set XA and each tower model



(a) T1+XB (b) T2+XB

Figure 4 Combination of the line set XB and each tower model

5. CONCLUSION

By analying the dynamic characteristics of the tower-line coupling system under the specific conditions discussed above, the following regularity can be achieved.

1. After the tower-line coupling, the in-plane natural frequencies are lower than those of the single tower. When span remains unchanged, they decrease initially, and then increase with the increase of the sag. When the sag remains unchanged, with the increase of the span, they tend to decrease and tend to be leveled, that is, the tension (caused by the variational sag) plays a principal role in the increase of the natural frequency in-plane, while the mass increase (caused by the variational span) of the line mainly cause the decrease of the frequency in-plane.

2. The out-plane natural frequency of the tower-line coupling system is greatly influenced by the the line's unequal sag, showing a tendency of first decrease, followed by increase and final decrease. But the line mass causes little variation of its value, but still a little increase

3. The torsional natural frequency of the tower-line system is lower than that of the single tower, tending to

decrease firstly, then increase and finally decrease with the increase of the line's sag, and tending to decrease with the increase of the span, approaching the in-plane frequency under the same condition.

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