IDENTIFICATION OF LARGE AMPLITUDE GUST RESPONSES OF BUNDLE-CONDUCTORS WITH PROPER MODEL

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ABSTRACT

A series of accidents due to large amplitude vibrations (LAV) of transmission line systems in gusty wind, such as loosening of bolts and breaking of insulators' attachments, spacers, porcelain plates, etc., observed in field and reported recently by Tokyo Electric Power Company (TEPCO), forces people to rethink on the cause of LAV as only galloping. This paper presents the results of large amplitude gust response (LAG) identification of bundle-conductors in frequency domain with taking into account of a proper static equilibrium configuration of conductors. Based on these results it can be understood that LAV is not necessarily due to the galloping-type unstable phenomenon but can be gust response especially in turbulent wind. Such LAGs can result in dynamic responses of other components, such as insulator, spacer, jumper, tower, etc., and lead to their damages as observed in field.

Keywords: Transmission line, bundle-conductor, gust response, FE model, field data.

1. INTRODUCTION

Since Den Hartog firstly explained LAV in iced conductor as galloping-type phenomenon, any form of LAV in conductor has been thought to be caused by galloping that is characterized by low frequency, large amplitude, self-excitation in moderately strong and steady wind (Den Hartog 1932). However, the LAV of conductors in gusty wind has been observed and reported by TEPCO. These LAGs that are characterized by low frequency, large amplitude and random fluctuation in gusty wind, can be another cause of LAV of transmission line conductors. It can be understood that the LAGs are definitely different from the galloping response and the way to minimize or control them would be different (Yamaguchi et al. 2003). Therefore, it is indispensable to identify, interpret and distinguish LAGs from other galloping-type phenomena. In a different way to discuss the problem of transmission lines from our preliminary studies (Jawad et al. 2011), the current study emphasizes on the importance of modeling properly the static equilibrium configuration of conductors. Based on the new observations, the LAGs are identified properly and more clearly.

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2. PROPER FINITE ELEMENT MODEL OF TRANSMISSION LINE

In this paper, the transmission line with 4-bundle conductors is studied. Its geometry and the equipments for the field measurement in detail are presented in Figure1. The Finite Element (FE) model of transmission line is created and analyzed in FEMAP with NX Nastran computing software, because one of main objectives of this study is to derive a proper FE model of transmission line. The results of eigenvalue analysis based on the model as well as associated gust response analysis are expected to be used for interpreting properly the field observed vibrations.

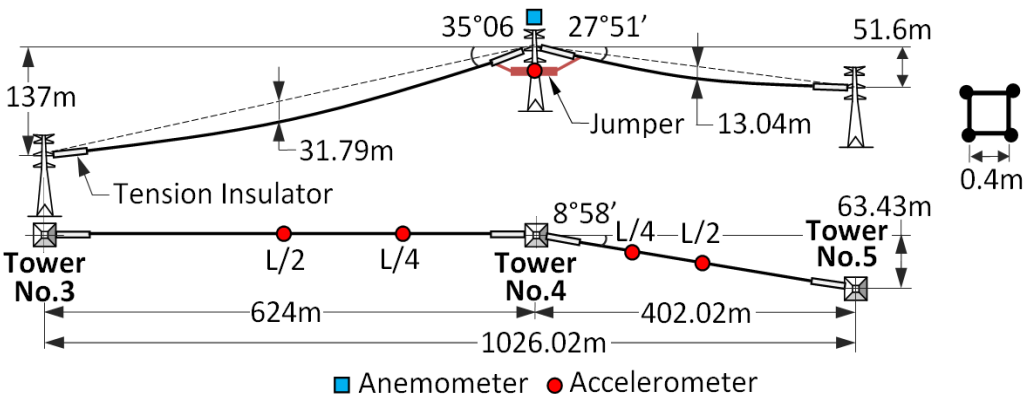


Figure 1: Geometry of studied transmission line.

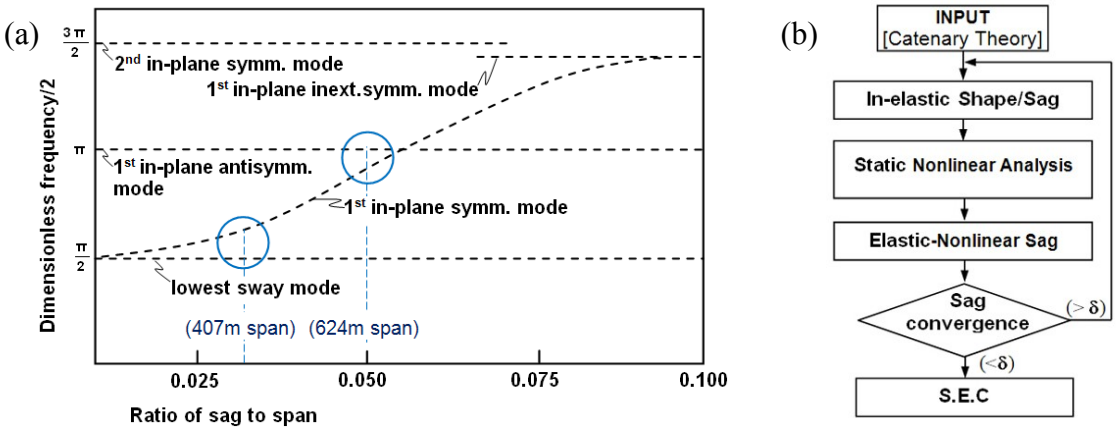


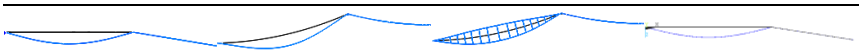
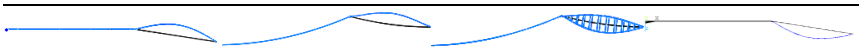
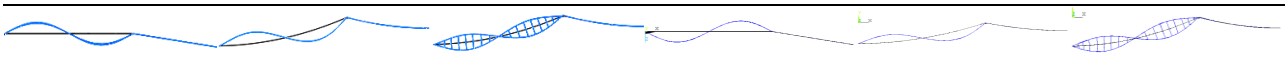
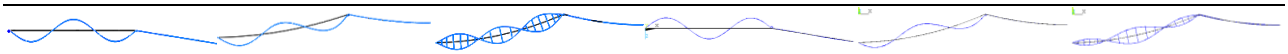
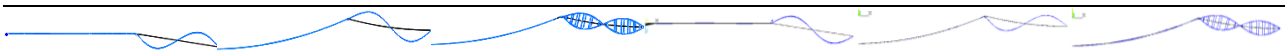
Figure 2: (a) Frequency vs. sag ratio and (b) scheme of iterative algorithm.

In creating the FE model of transmission line, one of important parts is finding out the proper static equilibrium configuration of conductors. Based on the quantitative discussions in the reference (Irvine 1981), depicted in Figure 2(a), the sag-to-span ratio of the studied transmission line is carefully taken into account. That is, the target sag-to-span ratios for the 624 m span and 407 m span are accurately set to 0.05 and 0.032, respectively, slight errors of which cause relatively large changes in their natural frequencies, as shown in figure 2(a).

In our preliminary studies, the target sag of model was based on the catenary theory without careful consideration of the extended deformation due to the static pre-stiffening of conductors, and the sag-to-span ratio could be larger than the target sag-to-span ratio. In the present study, on the other

hand, an iterative algorithm is proposed as shown in Figure 2(b) to create the proper FE model by taking into consideration of cutting the extended part of the sag due to the static pre-stiffening. It is noted that the conductor and insulator are modeled by 3-DOF two node tube elements with zero bending stiffness, while the spacer by 6-DOF two node tube element in this modeling.

Table 1: Mode shapes and natural frequencies

Present results			Previous results		
Horizontal	Vertical	Torsion	Horizontal	Vertical	Torsion
				N/A	N/A
0.099Hz	0.145 Hz	0.131 Hz	0.099 Hz		
				N/A	N/A
0.156 Hz	0.190 Hz	0.183 Hz	0.158 Hz		
					
0.197 Hz	0.195 Hz	0.212 Hz	0.197 Hz	0.195 Hz	0.198 Hz
					
0.296 Hz	0.298 Hz	0.313 Hz	0.294 Hz	0.276 Hz	0.272 Hz
					
0.310 Hz	0.312 Hz	0.337 Hz	0.313 Hz	0.312 Hz	0.319 Hz

The results of present and preliminary eigenvalue analyses are summarized in the left and right hand sides of Table 1, respectively. It can be seen that the lowest frequency modes is one-loop horizontal mode, which is most easily excited by wind forces as a major portion of total responses. In fact, the dominant peaks near 0.099Hz can be seen in all horizontal response spectrums of 624m-span data sets, which will be discussed later with Figure 6(a). Table 1 also shows that the one-loop vertical and torsional modes in the previous model are not available. There may be many reasons leading to this difference but it can be explained mainly by the sag-to-span ratio which is set larger than that of the present study. As previously mentioned, our preliminary model sag could be larger than the target sag because of careless consideration of the extended part of the model sag due to the pre-stiffening.

3. LARGE AMPLITUDE GUST RESPONSE IDENTIFICATION

The results of modal analysis and some basic analyses on the field measured data are used to identify the LAGs observed in the field. Firstly, in order to understand the general characteristics of the field wind velocity and vibration, the wind direction, turbulence intensity, maximum peak-to-peak amplitude (MPPA) and time history of dynamic response are discussed based on the data of field measurements, which were carried out by TEPCO from December 2008 to July 2009 in order to identify the LAGs and the causes of damages.

The variation in the direction and magnitude of mean wind velocity during the measurements and their turbulence intensity are shown in Figure 3(a) and (b). As seen in the figure, the direction of mean wind velocity is not normal to the transmission line, and therefore, the normal component velocity is calculated and used in the following discussions. The turbulence intensity with respect to

the normal wind velocity is relatively high that may indicate the possibility of observed vibrations as gust responses. Figure 4 shows the MPPAs of all data sets the increasing tendency in parabolic fashions with the increase of mean wind velocity, that is the characteristics of gust responses. The time history of typical events in Figure 5 again confirm that, different from galloping response, the LAGs appear with the peak responses increasing suddenly within very short period of time corresponding to the increases of wind velocities.

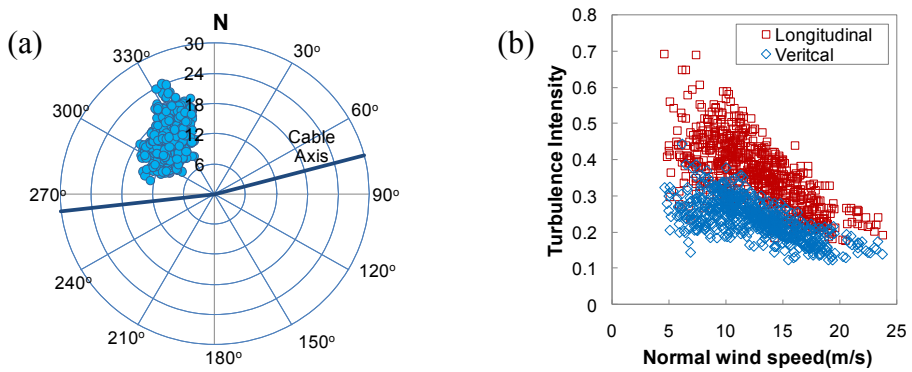


Figure 3: (a) Wind direction and (b) turbulence intensity.

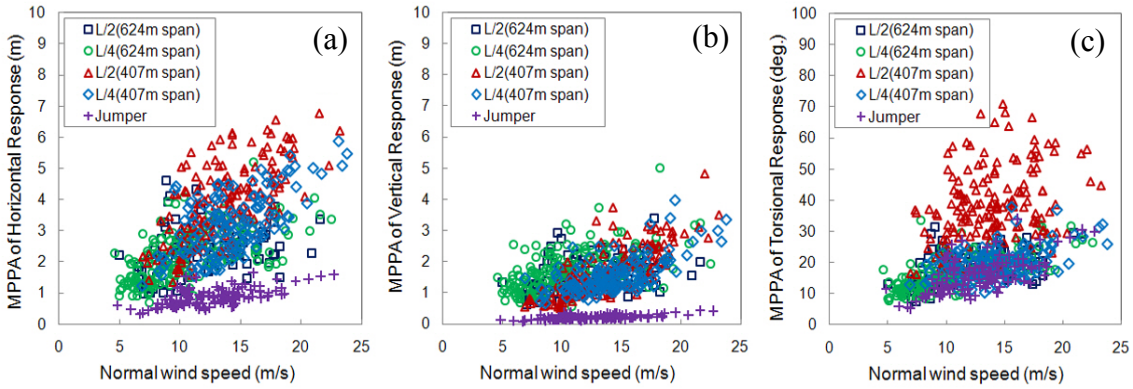


Figure 4: MPPA of (a) horizontal, (b) vertical and (c) torsional vibrations.

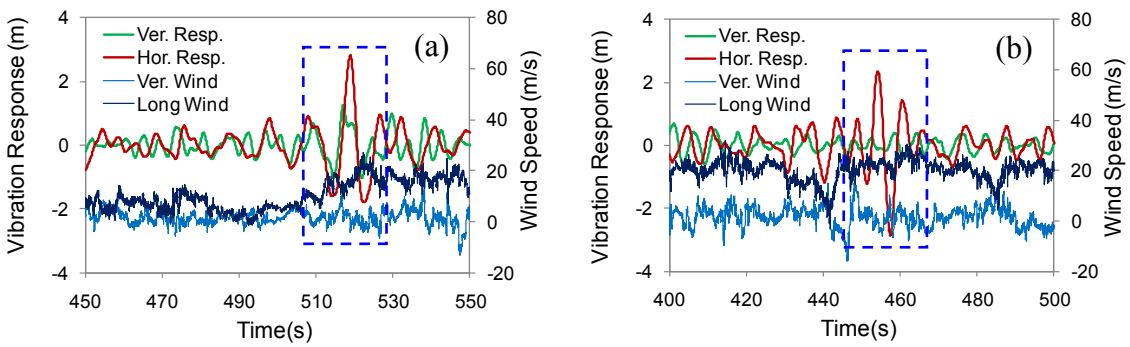


Figure 5: Typical LAGs in time history at (a) L/2 and (b) L/4 of 624 m span.

Secondly, the characteristics of field vibrations of transmission line is interpreted by its analytically evaluated natural frequencies and mode shapes. In power spectral densities (PSD) of the horizontal

responses in the Figure 6(a), for example, the peak frequencies near 0.099 Hz at L/2 of 624 m span and 0.156 Hz at L/2 of 407 m span correspond to the one-loop horizontal mode of 624 m span and the one-loop horizontal mode of 407 m span, respectively. In the PSD of torsional responses in Figure 6(c), on the other hand, the peak frequencies near 0.3 Hz at L/2 of 624 m span and 0.35 Hz at L/4 of 407 m span correspond to the three-loop torsional mode of 624 m span and the two-loop torsional mode of 407 m span, respectively. Furthermore, the vertical response spectra at L/4 of 407 m span shows a dominant peak frequency near 0.32 Hz corresponding to the two-loop vertical mode as shown in Figure 8(b), which will be discussed later.

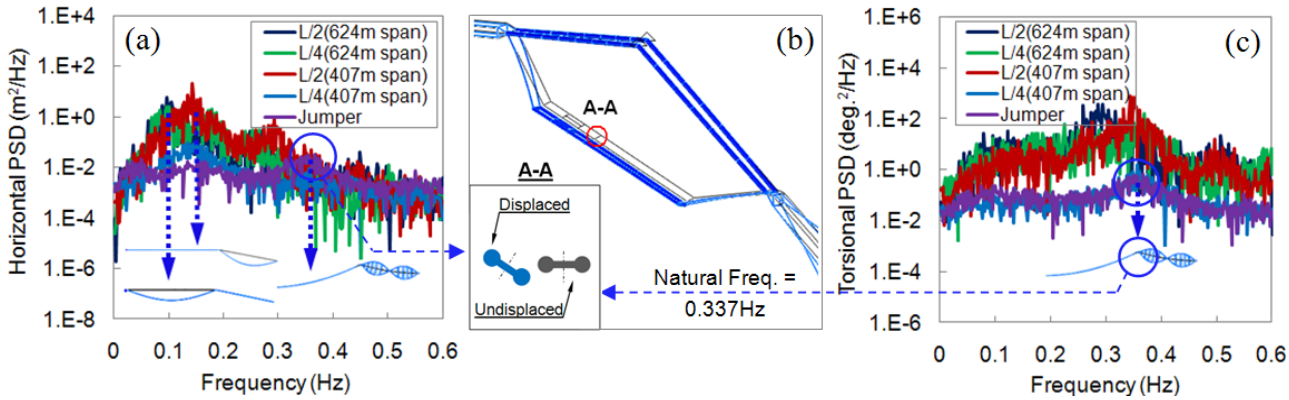


Figure 6: Identification of vibration modes and coupling of jumper-span: (a) PSD of horizontal responses, (b) coupling mode and (c) PSD of torsional responses.

Similar to our preliminary studies, Figure 6(b) shows an interesting phenomenon of coupling between the span mode and the jumper vibration. In fact, in the Figure 6(a) and (c), three dominant peaks in the jumper lateral response spectra, jumper torsional response spectra and span torsional response spectra appear at almost same peak frequency of about 0.35 Hz. The occurrence of these peaks at the same frequency is due to the linear coupling of the two-loop torsional mode of 407 m span and jumper horizontal/torsional mode in Figure 6(b). Such coupling is important as it can induce very large vibration in jumper and result in its damage reported by TEPCO. In summary, the results of present eigenvalue analysis give the good interpretation for the peak response spectra of field-measured large amplitude responses.

Thirdly, the results of eigenvalue analysis are then used in conjunction with the gust response analysis. That is, for further identification of LAGs, the Davenport's approach in the frequency domain (Davenport 1962), summarized in Figure 7, is employed to determine the resonant response in particular modes of vibration as a new investigation of the proper FE model analysis. The formulation and main assumptions in the functions and parameters of the computing procedure are given in the references (Jawad et al. 2011 and Stroman 2006) in detail. The PSD comparison between the field measured data and the gust theory-based prediction at L/4 of 407 m span is shown in Figure 8. The horizontal, vertical and torsional response spectra show the dominant peaks that correspond to the one-loop horizontal mode, two-loop vertical mode and two-loop torsional mode at

the natural frequencies of 0.156 Hz, 0,32 Hz and 0.35 Hz, respectively. The results show excellent agreement between the field data and the gust response analysis, and the field response of event can be predicted well by the gust theory. Therefore, it is concluded that the field observed LAVs by TEPCO could be gust responses.

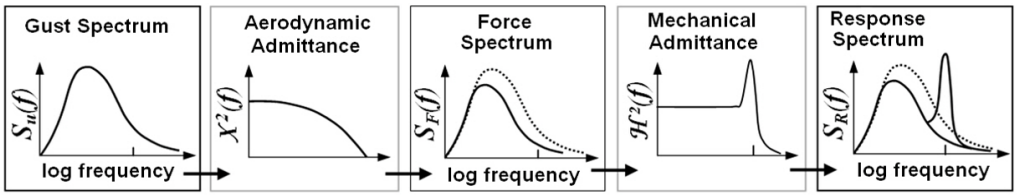


Figure 7: Davenport's approach for wind-induced resonant response due to gusty wind.

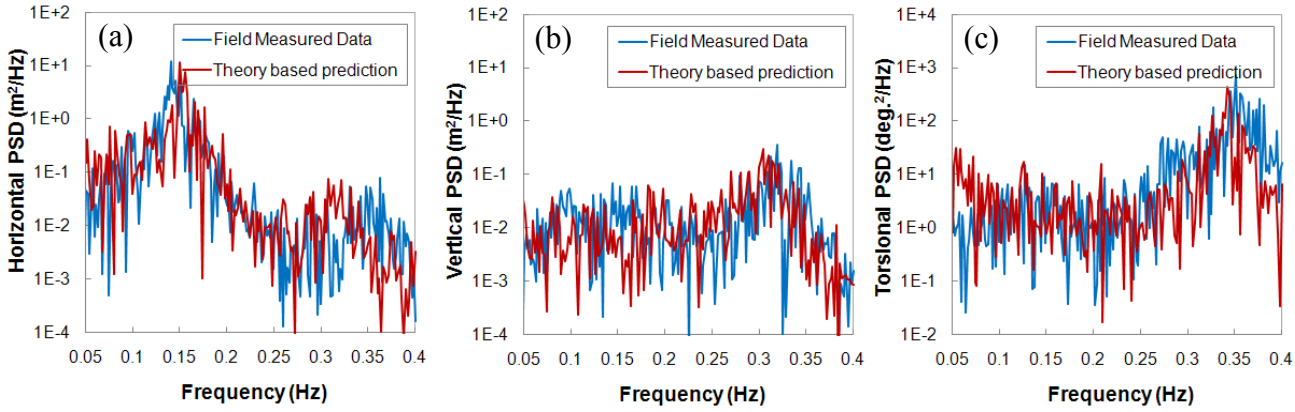


Figure 8: PSD comparison at L/4 of 407m span for (a) horizontal, (b) vertical and (c) torsional responses.

4. CONCLUSIONS

The results of numerical analysis based on the new FE model of transmission line give better interpretation of the field measured events, where the method of deriving the static equilibrium configurations of conductors plays an important role. It is also concluded that the LAVs observed in the field are clearly identified as LAGs with the parabolic pattern of MPPA and the excellent agreement between the gust theory and the field response spectra.

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