

Prediction of Wind Induced Vibration of High Voltage Electrical Bundled Conductors based on Time Domain Analysis

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Abstract — Study is made to predict wind induced vibration of high voltage electrical bundled conductors in time domain. A finite element model of bundled conductors associated model of nodal wind forces is analyzed by using “Direct transient response analysis” solver. The comparison of field-measured data and simulation of wind induced vibration is presented to investigate the response developed in time. The result may be used in designing and controlling damages due to wind induced vibration of bundled conductors. A significant feature of this approach is that the time dependent characteristics of unsteady aerodynamic forces and the nonlinearities of both aerodynamics and structural behavior of bundled conductors can be taken into account.

Keywords—*Electrical conductor; prediction, wind-induced vibration, time domain*

I. INTRODUCTION

High voltage electrical bundled conductors are used to transmit electricity from power plants over many types of terrain. The electrical conductors are long, slender, flexible, and wind sensitive structures. Wind induced vibration of conductors leading to the accidents like the breaking of insulators attachments, spacers and porcelain plates due to the large amplitude vibrations of high voltage electrical bundled conductors in gusty winds is observed in the field (Fig. 1). Any damage leading to interrupt electricity system was very costly and affects strongly to modern life.

To control wind induced vibration response of bundled conductors still depends on field trial and error procedure [1] [2]. Two types of the wind induced vibration response of high voltage electrical bundled conductors are the galloping and the gust response. The characteristics of galloping and gust response are entirely different, so that the way to control them would be different. It is, therefore, indispensable to identify the characteristics of high voltage electrical conductors.

For analysis of wind induced vibration response of electrical conductors developed in time, time domain gust analysis is considered. The feature of this approach is that the time dependent characteristics of unsteady aerodynamic forces and the nonlinearities of both aerodynamics and structural origins can be taken into account in estimating the vibration response electrical conductors. In the time-domain analysis, the time history of turbulence acting on structural nodes is input data. The turbulent field is considered as multivariate spatially-correlated random Gaussian processes. It is difficult to obtain the time series of turbulence in the field at all points of the bundled conductor. Therefore, the digital simulation techniques are often used to generate the time history of turbulence. The

decomposition techniques as the Cholesky’ decomposition [3] and modal one have been applied. The buffeting response analysis of bridges in coupling with the aero-elastic forces in the time domain have been carried out [4]. The proper orthogonal decomposition (POD) has been applied in order-reduced modeling of the random wind fields [5] [6]. The stochastic response of structures formulated in the time domain using the covariance proper transformation is very promising because of its direct and capable solutions for nonlinear problems and unsteady aerodynamics.

In this study, a finite element (FE) model of bundled conductors associated model of nodal wind forces is analyzed by using “Direct transient response analysis” solver. The comparison of field-measured data and simulation of wind induced vibration is presented to investigate the response developed in time. The result may be used in designing and controlling damages due to wind induced vibration of bundled conductors.



Figure 1. Damages of high voltage electrical bundled conductors

II. MATERIALS AND METHODS

A. Finite element model of bundled conductor

In order to evaluate dynamic characteristics of high voltage electrical bundled conductor systems, the eigenvalue analysis is performed. The FE model of bundled conductor is created and analyzed by using the computing software [7]. In creating the FE models of bundled conductor, the important part is to find

out the proper static equilibrium configurations of conductors subjected to the body loads. Catenary theory is a popular solution for static equilibrium configuration of conductors under its self-weight.

The details of FE models of bundled conductor are indicated in Fig. 2. The modeling of electrical conductors is most essential in the FE modeling of bundled conductor systems. In this study, three degree-of-freedom, two-node tube elements with zero bending stiffness apply to the conductors. The spacers in the transmission line systems have a function to maintain the distance between conductors in a bundled-conductors and each conductor is clamped at the end of spacer arm. The spacers are modeled by a two-node rigid tube element having the rigid connection with the conductors. The material properties of conductors and the spacer of the electrical bundled conductor system are shown in Table I.

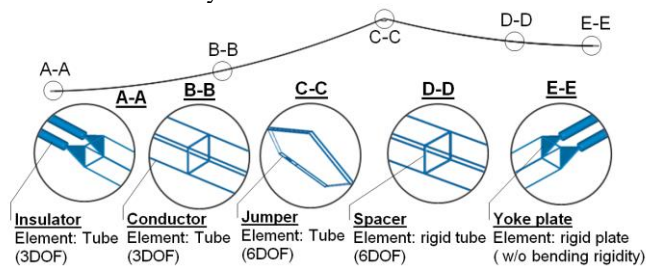


Figure 2. FE models of the of high voltage electrical bundled conductors

TABLE I. SPECIFICATION OF THE ELECTRICAL BUNDLED CONDUCTOR

Components	Parameter	Units	Values
Conductor	Elastic modulus	(109N/m ²)	90.6
	Diameter	(mm)	22.4
	Spacing	(m)	0.4
	Weight	(kg/m)	1.11
Spacer	Weight	(kg)	9.5
	Elastic modulus	(109N/m ²)	210

B. Method of vibration response analysis in time domain

Two different numerical methods can be used for a gust response analysis: modal and direct response analysis methods. The direction method performs a numerical integration of the complete coupled equations of motion. The modal method utilizes the mode shapes of the structure to reduce and uncouple the equations of motion. The solution is then obtained through the summation of the individual modal responses. In direct response analysis, structural response is computed by solving a set of coupled equations using direct numerical integration. In this study, the direction response method is used.

Multi-DOF motion equations of electrical bundled conductor subjected to the buffeting forces is expressed:

$$M\ddot{u}(x,t) + C\dot{u}(x,t) + Ku(x,t) = F_b(t) \quad (1)$$

where $u(x,t)$, $\dot{u}(x,t)$, $\ddot{u}(x,t)$ are deflection and its first, second order derivatives; M , C , K are mass, damping, stiffness matrices; $F_b(t)$ is full-scale buffeting forces.

The buffeting forces per unit length of the bundled conductor can be expressed and corrected by the frequency-dependent admittance functions as follows. (Eq.2).

$$L_b(t) = \frac{1}{2} \rho U^2 d_c n_c \left[C_L \chi_{Lu}(f) \frac{2u(t)}{U} + (C'_L + C_D) \chi_{Lw}(f) \frac{w(t)}{U} \right]$$

$$D_b(t) = \frac{1}{2} \rho U^2 d_c n_c \left[C_D \chi_{Du}(f) \frac{2u(t)}{U} + (C'_D - C_L) \chi_{Dw}(f) \frac{w(t)}{U} \right]$$

$$M_b(t) = \frac{1}{2} \rho U^2 (d_c n_c)^2 \left[C_M \chi_{Mu}(f) \frac{2u(t)}{U} + C'_M \chi_{Mw}(f) \frac{w(t)}{U} \right] \quad (2)$$

where C_L , C_D , C_M are aerodynamic coefficients at a balanced angle; C'_L , C'_D , C'_M are first-order derivatives with respect to angle of attack; d_c, n_c are the diameter of the bundled conductor and number of bundled-conductor; $\chi_{Fv}(F = L, D, M; v = u, w)$ is aerodynamic transfer functions between turbulent components and forces.

In current study, Eq. (1) will be solved by computing software by using "Direct transient response analysis" method based on FE model associated with nodal turbulent wind force acting on the nodes of models

Direct transient response analysis is the most general method for computing the forced dynamic response. The purpose of a transient response analysis is to compute the behavior of a structure subjected to time-varying excitation. The transient excitation is explicitly defined in the time domain. All of the forces applied to the structure are known at each instant in time. The important results obtained from a transient analysis are typically nodal translation in three directions.

For "Direct transient response analysis" solver, important information is selected as follows. Nonlinear properties on geometry, large displacement is selected in Nastran bulk data options. "Direct" solution type is selected in Nastran modal analysis setup. Full length of wind velocity time series is recorded in 600 second with time step of 0.02 second. However, vibration response analyzed in time domain is recommended to simulate in 100 second because of long enough of analysis time, capacity of computer and easily selecting wind velocity and vibration response in comparison. Therefore, in transient time step intervals, 1000 steps, 0.1 second time step and one output interval per one step of loading are selected. Due to the cable type structure, the overall structural damping coefficient is selected to be 1%. Loading case in the analysis is combining of body load and nodal wind force.

Nodal wind force is calculated by using Eq. (2) with their magnitude of nodal time-varying wind force depended on number of applied nodes along the span. Variant turbulent processes $u(t)$ and $w(t)$ are selected from field-measurement. In time domain analysis, nodal wind force varied in time is defined by using time depended function. In the current study, nodal wind forces are applied uniformly to all nodes at different location of nodes.

C. Wind field simulation

In some cases, without field-recorded wind velocity, empirical auto Power Spectral Density (PSD) is very usable. Some empirical formulae can be applied to simulate the longitudinal turbulence $u(t)$ and the vertical one $w(t)$. Von Karman (1948) firstly introduced a practical empirical formula of the auto power spectral density based on ongoing turbulent flow conditions such as mean velocity, intensities of turbulence, the length scale of turbulence and so on. This study

used Kaimal's spectra (Eq.3) to simulate the longitudinal turbulence $u(t)$ and the vertical one $w(t)$.

$$S_u(f) = \frac{a_u n u_*^2}{f(1+b_u n)^{5c/3}} \quad (3)$$

$$S_w(f) = \frac{a_w n u_*^2}{f(1+b_w n)^{5c/3}}$$

where $n = \frac{fz}{U}$ is the non-dimensional coordinates; f is frequency variable (Hz); U , z are mean velocity (m/s) and altitude z (m), respectively; $u_* = \frac{kU}{\ln(z/z_0)}$ is friction or shear velocity (m/s); k , z_0 are scale factor and roughness length (m).

The longitudinal $u(t)$, vertical turbulent components $w(t)$ are considered as two multivariate spatially-correlated Gaussian random processes with zero mean. The turbulent fields at "n" discrete nodes (Fig.3) are expressed as follows:

$$u(t) = \{u_1(t), u_2(t), \dots, u_N(t)\}^T \quad (4)$$

$$w(t) = \{w_1(t), w_2(t), \dots, w_N(t)\}^T$$

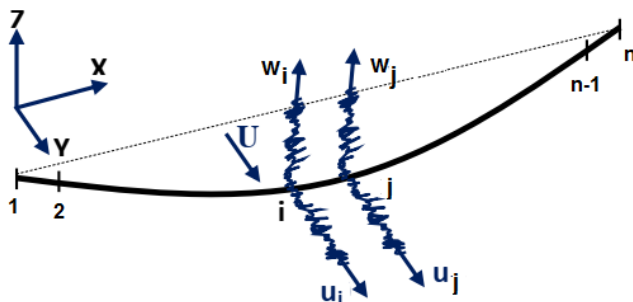


Figure 3. Turbulent wind at "n" discrete nodes of conductor model

D. Vibration response simulation in time domain

Model of wind force is shown in Eq. (2). In the equation, there are some parameters assumed in the following analysis. The air density depends on the temperature, pressure and presence of moisture, and is 1.204 kg/m^3 at 20°C under the standard atmospheric pressure and in the absence of moisture. In this analysis, its value is taken as 1.204 kg/m^3 because the possible change in its value may not affect the results of analysis significantly. The force coefficients for electrical conductors is provided by the company. In this study, an average value of 1.0 is assumed. The aerodynamic admittance is introduced to counter the effect of flow modification due to the motion of the structure on the force coefficients. Transmission line conductors, being very slender and moving with very small velocity as compared to the velocity of the oncoming wind, do not modify the flow significantly. Therefore, the aerodynamic admittance for the transmission lines is assumed as one. An appropriate value of k , which is the empirical constant in the frequency-dependent correlation of wind velocity, can be determined only through experimentation, but Holmes discusses on its general range from 10 to 20 [8]. The possible change in its value may not

affect the results significantly and therefore the value of k is taken as 15. The parameters are collected in Table II&III.

In preliminary time domain gust response analysis, along and vertical wind turbulence is selected from a field-measured wind velocity. Based on Eq. (2), time series of nodal wind force are applied uniformly to nodes.

TABLE II. ASSUMED PARAMETERS IN ANALYSIS.

Variable	Description	Units	Value
ρ	Air density	kg/m ³	1.204
$C_{D,L,M}$	Drag coefficient single conductor		1.0
χ	Aerodynamic admittance		1
k	Empirical constant in frequency dependant correlation of wind velocity		15

TABLE III. AERODYNAMIC DAMPING RATIOS

Mode	Horizontal	Vertical	Torsion
1	5%	2%	2%
2	4%	2%	1%
3	4%	2%	1%

In this study, variate along and vertical turbulent processes $u(t)$ and $w(t)$, respectively, are selected from the field-measurement in order to simulate the nodal wind force that is employed as input of time domain gust response analysis. Field-measured large amplitude fluctuation responses corresponding to those turbulences in two directions are also considered in comparison with simulation results. Scheme of time domain gust response analysis is shown in Fig. 4.

It should be noted that both vibration response and turbulent time series used in simulation and comparison extract from corresponding 600 second time series measured in the field. In this study, 100 second-time series is used in simulation and comparison because time series of 100 seconds is long enough for structural vibration response dominated by studying excitations. In simulation, FE model with huge number of node and element as long-span, large bundled-conductor transmission lines, long time series often leads to a big problem with analysis time, etc. Although simulated vibration responses in Fig. 4 is obtained from field-measured turbulences (input data), model of wind force and FE model of the transmission line system may be a bit different from the real ones due to the assumptions. Therefore, it is difficult to get exact vibration response time series as field-measured vibration response time series. The main objective of this analysis is to investigate the way of developing of large amplitude gust response in time. Based on the result, large amplitude of bundle-conductors due to gusty wind can be predicted for further works as in designing, structural health monitoring (phase to phase flashovers), etc.

In comparison, some points of discussion can be given as follows. Firstly, the agreement between field-measured response and simulation is unexpected at the beginning of 100 second vibration time series because lack of excitation before 100 second time series in simulation. Secondly, peak-to-peak and time period of response selected in a simulation should be considered in same sampling frequency (10Hz) with field-measured vibration response that may keep proper comparison.

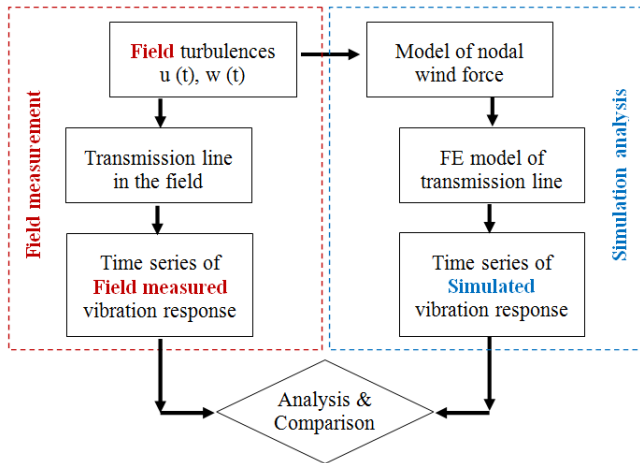


Figure 4. Scheme of framework in time domain gust response analysis

III. RESULTS AND DISCUSSIONS

A. Results of the eigenvalue analyses of FE model

The eigenvalue analyses are then conducted for the FE models of transmission lines with proper static equilibrium configurations, and the results of eigenvalue analysis are summarized in Table IV. It is confirmed, in the case of horizontal mode, the lowest natural frequency corresponds to one loop-per-span mode and that the higher natural frequencies are nearly equal to the integral multiple of the lowest one. Results of eigenvalue analysis present natural frequencies and mode shapes that are used to update by field-measured vibration in frequency domain for a realizable FE model of the electrical bundled conductor.

TABLE IV. NATURAL FREQUENCIES AND MODE SHAPES

Mode	Horizontal	Vertical	Torsion
1	0.099 Hz 	0.145 Hz 	0.131 Hz
2	0.156 Hz 	0.190 Hz 	0.183 Hz
3	0.197 Hz 	0.195 Hz 	0.212 Hz

B. Results of wind field simulation

The fitting result to Kaimal's spectra is conducted with $a=220$; $b=45$; $c=0.95$ with $k=0.4$; $z_1=0.01m$; $z_2=100m$; $u_* = 1.5$; $\alpha=0.2$ (terrain condition). The along turbulence spectra comparisons are plotted in Fig.5.

Fig.6 shows the nodal-wind time series at a sample grid point. The mean-wind velocity at the referred point is 19.4m/s (top of tower). It could be said that it is impossible to obtain the simulated wind field that is equal exactly to the measured-wind field because of the stochastic procedure. However, with the consideration of the fitting the spectra model to the measured spectra and the terrain condition of the site, the result of the wind simulation is assumed to be appropriate to the wind field.

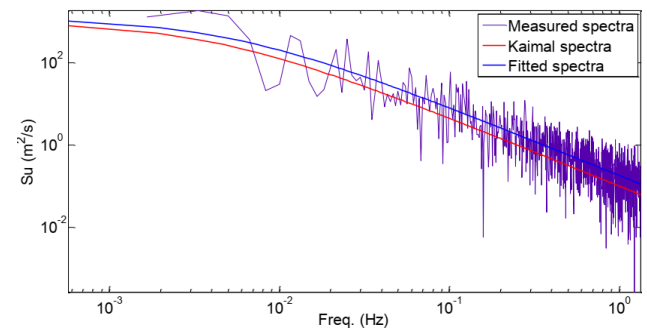


Figure 5. Fitting result to Kaimal's spectra

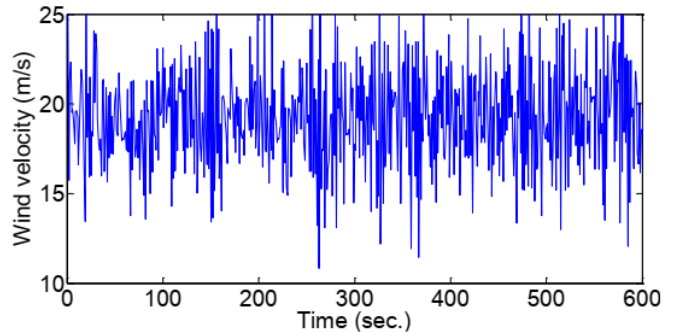


Figure 6. Wind time series at node

C. Vibration response analysis in time domain

In this analysis, the time-domain gust-response analysis subjected to the simulated-wind in previous part is conducted by using the basic computing software solver. The time series of drag wind force, lift wind force and moment wind forces are calculated by using Eq. 2. Based on the length of the elements, the nodal-wind-force time series is obtained. For example, by assuming parameters in Table V, the nodal-wind-force time series at mid-span is shown in Fig.7.

Vibration responses are simulated and compared with field-measured vibration data at the same position of middle span. The time series of longitudinal, vertical and torsional compared with the field-measured vibration responses turbulences are presented in Fig.8, Fig. 9 and Fig.10, respectively.

TABLE V. NODAL WIND FORCE PARAMETERS

ρ (kg/m ³)	U (m/s)	d_c (mm)	n_c	χ	C_D, C_L, C_M	C'_D, C'_L, C'_M
1.204	18.9	0.04	4	1	0.76, 0.05, -0.003	0.1, -0.006, -0.0002

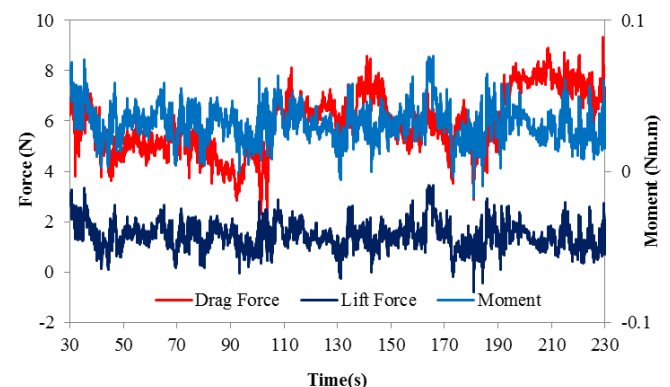


Figure 7. Nodal wind force of sub-conductor at mid span

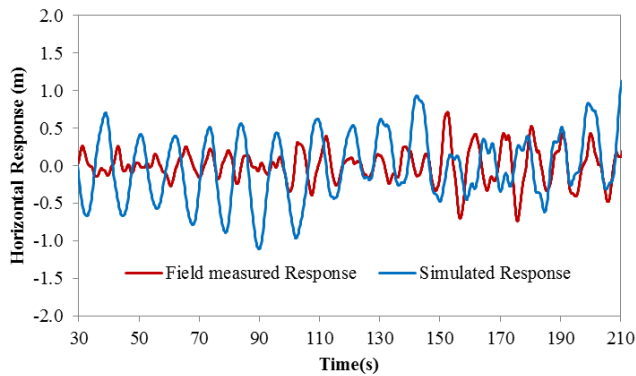


Figure 8. Time series of Horizontal vibration response

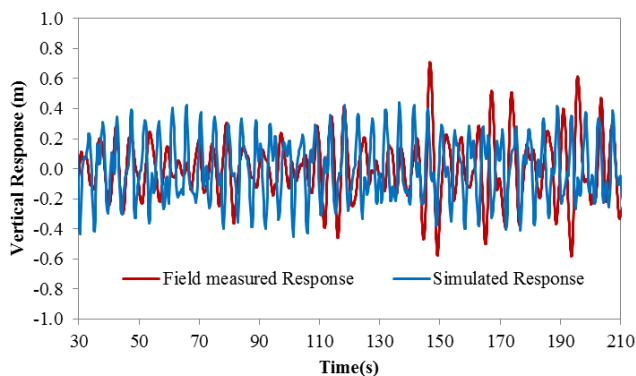


Figure 9. Time series of Vertical vibration response

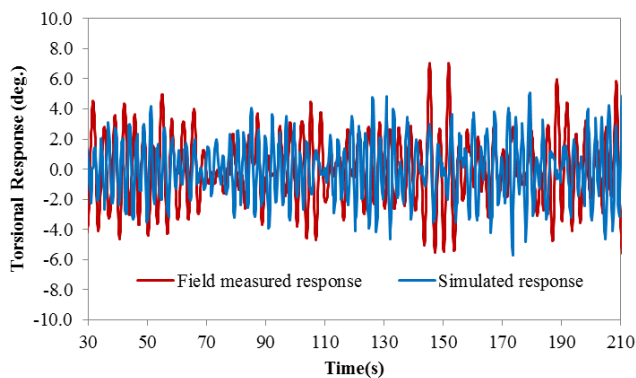


Figure 10. Time series of Torsional vibration response

In the figure, time series of simulated vibration responses of 3 directions seems to fit properly to time series of field-measured vibration responses. The MPPA of 3 directions is similar between the field response and simulated response. The shape of response amplitudes is similar in some period of time series. Especially, the torsional response in Fig.10 shows very good agreement.

To check the agreement of horizontal and vertical response, PSD comparison is calculated and presented in Fig. 11 and Fig.12, respectively. In the figures, both horizontal and vertical PSDs show shapes look quite similar and close peak responses in spectra around 0.1 Hz of horizontal PSD and 0.2 Hz of vertical PSD as obtained in the results of eigenvalue analysis.

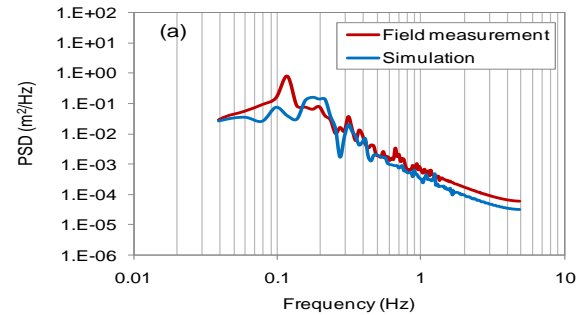


Figure 11. PSD of field and simulation fluctuation horizontal responses

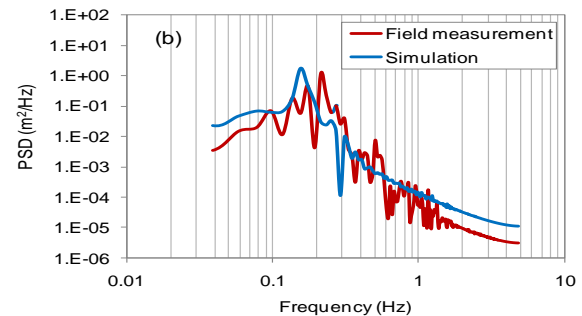


Figure 12. PSD of field and simulation fluctuation vertical responses

IV. CONCLUSIONS AND REMARKS

The study was conducted to predict the wind induced vibration response of high voltage electrical bundled conductors in time domain based on a comparison between the fields measured data and simulated vibration response analysis. The results lead to the following conclusions:

To deal with the spatial wind-field simulation for all nodes of the electrical conductors model, of which the nodal coordinates change in the two dimensions, the grid of finite locations of the wind-time series that covers all of the nodes of the conductor bundle is used.

By doing so, the wind time series at any coordinate can be easily obtained. Additionally, the grid of nodal wind time series makes the advance NX Nastran solver become more convenient due to interpolating the coordinates of the structural and aerodynamic model.

FE model of the high voltage electrical bundled conductors associated model of the spatial wind is analyzed in the NX Nastran computing software by using the basic solver, the "nonlinear-direct transient response analysis".

The simulated-response time series seem to be understandable. However, the basic solver is inconvenient for the aerodynamic analysis, especially for setting the damping matrix. Additionally, the structural node will change in time due to the continuous-movement of conductor in space leading change of the attacked angle as well as force coefficient.

In fact, it is not easy to simulate exactly the spatial-wind that can induce the vibration response of the transmission lines as observed in the field. However, by using the time-domain gust-response analysis, the time-dependent characteristics of unsteady aerodynamic forces and nonlinearities of the both aerodynamic and structural origins can be taken into account in characterizing the type of wind induced vibration response of high voltage electrical bundled conductors. The result may be used in designing and controlling damages due to wind induced vibration of bundled conductors.

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