# Numerical Simulation of Windage Yaw of Overhead Transmission Lines

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*Abstract:* To investigate the reasons of flashover accidents caused by windage yaw of overhead transmission lines and finally find a way to prevent this kind of accidents, finite element (FE) model of a typical transmission line section is set up by means of ABAQUS software in this paper. An efficient approach is proposed to determine the static equilibrium state of the cable under the action of its self-weight, based on which the dynamic responses of windage yaw of the FE model under other wind loads such as steady wind, gust wind and fluctuation wind are numerically simulated. The obtained numerical results demonstrate that the largest wandage yaw angle of the suspension insulator string during the operation may be larger than that determined by the traditional methods, which is probably one of the most important reasons of flashover accidents.

*Key-Words:* Overhead transmission line; flashover accident; windage yaw; finite element modeling; numerical simulation; wind load.

## 1 Introduction

More and more flashover accidents caused by windage yaw of overhead high voltage transmission lines took place in recent years in China [1,2], which have greatly affected the normal operation of power transmission system and in turn given rise to great economy loss. As the distance between conductor and tower is less than the critical discharge distance, accident may take place. Investigations on many on-site flashover accidents reveal that the actual largest distance between the conductor and tower caused by windage yaw in the case of strong wind may be less than that determined by means of the traditional design methods.

In the traditional design of overhead transmission lines, the windage yaw angle is simply calculated with static method [3], in which the suspension insulator string is modeled as a rigid straight rod and the load acting on the insulator string by the conductors is simplified as a static load. In this method, the dynamic characteristics of the wind load and the interaction between the insulator strings and the conductors are ignored. If porcelain or glass insulators are used in a transmission line, the insulators may rotate around their pins during swing of the string, and the simplification of the insulator string as a rigid straight rod may not be able to reflect real motion of the insulators. Moreover, it is also necessary to take account the interaction between the conductors and insulator strings in the analysis.

As the knowledge of the authors, little theoretical research on this type of problems is reported. However, some relevant dynamic response problems of transmission lines were studied, such as the dynamic analysis of transmission lines subjected to broken conductor loads [4,5,6] and the load caused by ice-shedding [7,8], and galloping of transmission lines [9,10], et al. It is noted that the static equilibrium state of a cable under the action of ts self-weight has to be found before the dynamic response analysis. However this problem has not been well settled down although Jamaleddine et al [7] and Desai et al [11] respectively proposed two methods to determine the positions of nodes of the cable in the static equilibrium state under the action of its self-weight load.

To analyze the windage yaw of transmission lines under the action of strong winds, a finite element (FE) model is set up in this paper. According to the physical and structural characteristics of porcelain and glass insulators, each insulator will rotate around the pin connecting with a neighboring insulator during the swing of the insulator string. It is reasonable to model the insulators by truss elements connected with connector elements. Furthermore, cable elements are used to model the cable and a new approach is proposed to determine static equilibrium state of the cable under the action of self-weight. A damping factor is chosen dependent on the work of Roshan Fekr [8]. Nonlinear geometric characteristics is taken account in the numerical simulation.

# 2 FE Model of a Line Section

The main structural components of a transmission line consist of conductors, shield wires, insulator strings, hardware and towers. The conductors are usually stranded cables composed of aluminum, galvanized steel or a combination of the two. The shield wires are grounded steel wires placed above the conductors for lightning protection. The suspension insulator strings attach the conductors via clamps to the suspension towers, and are vertical under normal operation and are free to swing whenever there is an unbalanced load. At dead-end towers, the insulator strings are anchored and in-line with the conductors. If a wind load acts on the line section, and the direction of the wind is not in-line with the conductors, the conductors and the suspension insulator string may swing, which may induce flashover accident when the distance between the conductor and the suspension tower is less than the critical discharge distance. To investigate the dynamic windage yaw of a transmission line section, a FE model including insulator strings, conductors and clamps is established, and the FE model of a typical two-span line section is shown in Fig.1.

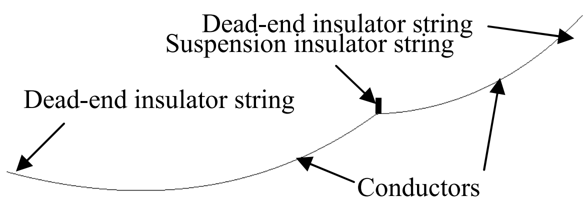


Fig.1 FE model of a two-span line section

## 2.1 Model of insulator strings and clamps

The most commonly used insulator strings in overhead transmission lines are porcelain, glass and composite insulator strings. Each two neighboring insulators in a porcelain or glass insulator string are connected with pin, around which one insulator rotates with respect to the other one during movement. For simplification reason, the porcelain and glass insulator strings can be modeled with truss elements and each two neighboring insulators in the strings are connected with connector elements modeling the pin connection behavior. Each of the insulators is represented by one truss element with the same weight as a single insulator. Moreover, the clamps are also simplified as truss elements.

## 2.2 Model of conductors

The conductors of the transmission line section are modeled with finite cable elements. It is a common knowledge that a cable can only sustain tensile but compressive stress and its bending modulus is so small that it is usually neglected. Truss element provided in ABAQUS software can be used to model cable behavior by simply setting the material property as no compression.

To simulate the dynamic response of a line section under the action of wind loads, an efficient approach is proposed here to determine the equilibrium state of the cable under the action of its self-weight. The configuration of an overhead transmission line under the action of its self-weight load can be depicted with catenary equation [3]. If the two ends of the cable are respectively suspended at points $O$ and $A$, as shown in Fig.2, the equation of this catenary curve can be expressed as [3]

$$y=\frac{\sigma_0}{\gamma}\mathrm{ch}(\frac{\gamma(x-a)}{\sigma_0})-\frac{\sigma_0}{\gamma}\mathrm{ch}(-\frac{\gamma a}{\sigma_0}) \qquad (1)$$

where $\sigma_0$ is the stress at the lowest point of the cable, $\gamma$ the specific load defined as the load (generated by self-weight in this case) acting on unit cross-section area of a cable segment with unit length, and $a$ can be written as

$$a=\frac{l}{2}-\frac{\sigma_0}{\gamma}\mathrm{sh}^{-1}\frac{\gamma h}{2\sigma_0\mathrm{sh}\dfrac{\gamma h}{2\sigma_0}} \qquad (2)$$

by means of the condition that as $x=a$, $y=h$ in Eq.(1).

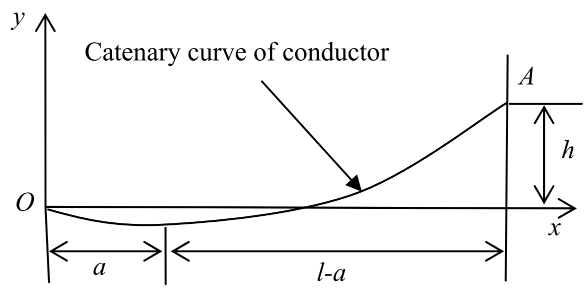


Fig.2 Catenary curve of a cable under self-weight

According to Eq.(1), the length of the deformed cable under the action of its self-weight can be determined by

$$L = \frac{\sigma_0}{\gamma}[\mathrm{sh}(\frac{\gamma(l-a)}{\sigma_0}) + \mathrm{sh}(\frac{\gamma a}{\sigma_0})] \tag{3}$$

where $l$ is the horizontal span. The original length of this cable without the action of any load can be approximately determined by [3]

$$L_0 = \int_0^L \Delta L_0 = L - \int_0^L \frac{\sigma_x}{E} \mathrm{d}L \tag{4}$$

in which

$$\sigma_x = \sigma_0 \mathrm{ch} \frac{\gamma(x\text{-}a)}{\sigma_0} \tag{5}$$

is the axial stress at a point of the deformed cable. Substituting $\sigma_x$ into Eq.(4), the original length $L_0$ of the cable is obtained as

$$L_0 = L - \frac{\sigma_0^2}{4E\gamma}[\mathrm{sh}(\frac{2\gamma(l-a)}{\sigma_0}) + \mathrm{sh}(\frac{2\gamma a}{\sigma_0}) + \frac{2\gamma l}{\sigma_0}] \tag{6}$$

where $L$ is determined by Eq.(3).

Theoretically any original configuration of the cable with the length $L_0$ can be assumed to determine the static equilibrium state under the action of self-weight with FE method. However, fast convergence rate may be obtained to arrive at its static equilibrium state if a catenary curve is assumed as the original configuration of the cable.

To define an original configuration of a cable with length $L_0$, we can assume the equation of the cable behaves the form of Eq.(1), in which the parameter $\sigma_0 / \gamma$ is numerically determined through setting $L$ equals to $L_0$ in Eq.(3) and substituting Eq.(2) into Eq.(3). It is noted that in this case $\sigma_0 / \gamma$ should be understood as a parameter without any physical meaning. It is worthwhile to be mentioned that the catenary curve is not the unique choice of the original shape of the cable.

A numerical example is studied to demonstrate the validation of the aforementioned method to determine the static equilibrium state of a cable under the action of its self-weight. A one-span conductor cable, with span $l$=400m, height difference $h$=0, Young's modulus $E$=7.264X10$^4$MPa, specific weight $\gamma' = 31066 \mathrm{N/m}^3$, cross-section area 4.25X10$^{-4}$m$^2$, and $\sigma_0 = 39.966$ MPa, is suspended at its two ends. Following the way described above, it is obtained that $L$=401.61m and $L_0$=401.39m. Let $L$ $L_0$=401.39m in Eq.(3), the parameter $\sigma_0/\gamma$=1392.93 is then obtained by means of Newton iteration numerical method, and the equation of the original configuration of the cable is obtained after substituting $\sigma_0/\gamma$ into Eq.(1). ABAQUS software is then used to analyze the static equilibrium state of the cable under its self-weight. The relative errors between the coordinates and stresses at the nodes of the deformed cable determined with FE method and those directly determined with Eq.(1), which is the catenary curve of the cable under the action of its self-weight, are less than 0.01%, which demonstrates the validation of the proposed method.

### 2.3 Damping of the system

In a typical line section without special damping devices, internal damping mainly comes from the cable and insulator strings. When a cable is subject to a dynamic wind load, the internal damping arises from the axial friction between the strands and friction induced by bending of the wire. However, it is usually very difficult to model the realistic damping of transmission lines. To our knowledge, a little research has been carried out on this subject and no satisfactory modeling has been proposed to depict the damping in a cable up to now.

A procedure to determine the appropriate damping constant of cable was described by Roshan Fekr[8] in relation with analysis of ice-shedding effects. Based on good numerical experience, but still lacking real-scale physical test validation, damping constants are set to represent equivalent viscous damping ratios of 2% critical for bare cables and 10% for iced cables. In this paper, damping ratio of 2% is used to model the damping of the conductor cables. However, the damping in insulator strings is ignored.

## 3 Wind load modeling

### 3.1 Wind pressure load

According to the characteristics of natural wind, it can usually be classified into steady wind, gust wind and fluctuation wind.

A simple relation between the wind speed and the pressure load acting on an insulator, which is extensively accepted in engineering, is [3]

$$P_J = 9.81C\frac{V^2}{16} \tag{7}$$

where $V$ is the wind speed and $C$ the section area of the insulator facing to wind. In addition, the wind pressure acting on a conductor in horizontal direction is determined by

$$P_d = \alpha KF \frac{\rho V^2}{2} \sin^2 \theta \qquad (8)$$

where $\rho$ is the density of the air and its standard value is 1.2255kg/m$^3$, $\alpha$ heterogeneous coefficient, $K$ the aerodynamic coefficient, $F$ the area of the conductor facing to wind equal to the product of diameter and length of the conductor, and $\theta$ the angle between the wind direction and the axis of the conductor cable.

In the design of overhead transmission lines, mean wind speed is usually used to determine the wind loads acting on the components.

### 3.2 Gust wind modeling

If the strength of a wind pressure load changes greatly in a short time, the wind is the so-called gust wind. Generally the speed of a gust wind is faster 50% than the mean speed defined as abovementioned, and the gust wind usually lasts a very short time. A typical gust wind with mean speed $v_0$ is shown in Fig.3, in which the wind speed arrives $1.5v_0$ from 0 in $t_0$ seconds, keeps constant for ($t_1$- $t_0$) second and finally decreases to 0 in ($t_2$- $t_1$) seconds.

To investigate the effects of the increase rate of wind speed on the dynamic response of transmission lines, three cases with different time parameters $t_i$ ($i$=0,1,2) are analyzed.

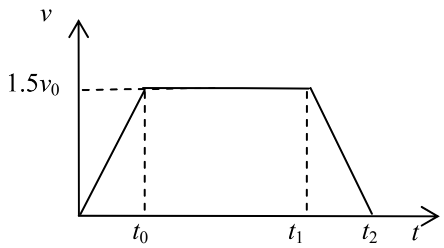


Fig.3 Speed variation of a typical gust wind with time

### 3.3 Fluctuation wind modeling

Generally, the speed of natural wind can be decomposed into two parts in the form as following

$$V(x,y,z,t) = \bar{v}(z) + v(x,y,z,t) \qquad (9)$$

where $\bar{v}(z)$ is the mean value of the wind speed at the height $z$ from the ground, and $v(x,y,z,t)$ the fluctuating component which is usually simplified as a stationary Gaussian stochastic process. The mean value $\bar{v}(z)$ is represented by

$$\bar{v}(z) = \bar{v}_s (\frac{z}{z_s})^a \qquad (10)$$

where $\bar{v}_s$ is the mean wind speed at the standard height $z_s$, which is usually chosen as 10m in most of the countries in the world.

It is known that a stationary Gaussian process can be numerically simulated with Monte Carlo method. If triangle series is used in the simulation, the stochastic process can be expressed as

$$v(t) = \sum_{j=1}^{N} a_j \cos(\omega_j t + \varphi_j) \qquad (11)$$

where $\varphi_j$ is uniform distribution random number in the range of [0, 2π], and

$$a_j = \sqrt{2S_v(\omega_j)\Delta\omega}$$

$$\Delta\omega = \frac{\omega_N - \omega_l}{N}$$

$$\omega_j = \omega_l + (j - \frac{1}{2})\Delta\omega \qquad j=1,2\ldots N$$

in which $S_v(\omega)$ is the power spectrum density of the stochastic process $v(t)$. In most of the wind engineering problems, Davenport power spectrum density function is usually used to depict the stochastic process of wind, which is formulated as [13],

$$S_v(n) = 4k\bar{v}^2{}_{10} \frac{x^2}{n(1+x^2)^{\frac{4}{3}}} \qquad (12)$$

In this formulation, $k$ is a coefficient reflecting the roughness of the ground, $x = 1200n/\bar{v}_{10}$, $n = \omega/2\pi$, and $\bar{v}_{10}$ is the mean wind speed at the standard height of 10m.

## 4 Numerical simulation of a typical line section

### 4.1 FE model of a typical line section

The two spans of a typical line section are 500m and 400m, and the height differences of the two spans are respectively -120m and 100m. Each of the three insulator strings, one suspension string and two dead-end strings, consists of 15 porcelain insulators of model XP-7 with self-weight 4.9kg. A single conductor LGJQ-300 and a clamp XGU-5 linking the suspension insulator string and the conductor are included in the model.

Assuming the diameter of the truss element representing a single insulator is 0.03m and its length is the same as that of the real insulator, its equivalent density is then determined as $3.557\times10^4$kg/m$^3$ based on the condition that the total weight of the insulator is the same as that of the truss element. Similar way is used to determine the parameters of the truss element representing the suspension clamp.

A typical maximum mean wind speed of 30m/s is applied to the established model to numerically simulate the windage yaw of the transmission line section, and the wind pressure loads acting on the insulator strings and the conductors are respectively determined by means of Eqs. (7) and (8), in which the parameters are: $C$=0.02m$^2$, $\alpha$=0.75, and $K$=1.1 in this case.

### 4.2 Windage yaw under steady wind

To demonstrate the validation of the FE model, a quasi-static problem of the model under the action of a steady wind with the speed of 30m/s is firstly analyzed with ABAQUS and its result is compared with that obtained with the traditional static method.

The windage yaw angle of the suspension insulator string in this transmission line section under the action of this steady wind load determined with FE method is 58.2$^o$, which is very close to that obtained with the traditional method, which is 58.5$^o$. The shape of the suspension insulator string in this case keeps string after the steady wind load is applied, and this is due to the uniform distribution of the wind loads acting on the insulators and the conductors. The coincident of the results obtained with the traditional method and the numerical method proposed in this paper demonstrates that the FE model is suitable to numerically simulate the dynamic windage yaw response of transmission lines.

It is noted that the action of wind load on the insulator string and conductor may not be uniform and the shape of the insulator string may not keep straight in reality.

### 4.3 Dynamic response under gust winds

To illustrate the effect of the increase rate of the wind speed on the dynamic windage yaw of the transmission line, several different increase rates of wind speed, varying with time as in Fig.3, are chosen in this case. To improve the dynamic response, Smooth Step is set as we define the load variation with time in ABAQUS/CAE.

The windage yaw of the typical line section under the action of a gust wind is shown in Fig.4. It is observed that the shape of the suspension insulator string changes to curve under the action of gust wind, although the wind load is uniformly applied on the insulator string and the conductor. The rotation angle of one insulator with respect to another neighboring one is not the same for each pair neighboring insulators. The variations of displacements of the suspension insulator string at the lowest point under the action of a gust wind are shown in Figs.5. In addition, the results illustrate that the quicker the wind speed increases at the initial stage, the larger the vertical and horizontal displacements of the string at the lowest point, which indicates that the inertia of the system under the action of dynamic wind load may greatly affect its swing amplitude of the insulator string. Therefore the determination method of windage yaw angle of transmission lines in design may be too rough to reflect its real characteristics.

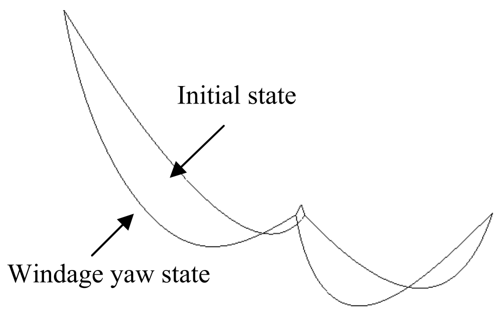


Fig.4 Windage yaw of the typical line section under gust wind ($t_0$=13s, $t_1$=25s, $t_2$=30s)

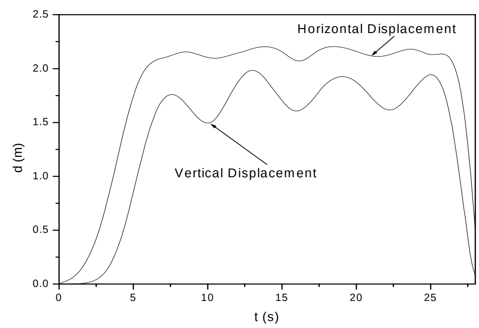


Fig.5 Variation of displacements of suspension string at the lowest point with time ($t_0$=13s, $t_1$=25s, $t_2$=30s)

### 4.4 Dynamic response under fluctuation wind

To numerically simulate a fluctuation wind varying with time by means of Monte Carlo method, a Fortran program is coded. The parameters are chosen as $k$=0.0043, $\bar{v}_{10} = 25\text{m/s}$, and the mean wind speed is 30m/s. The wind speed arrives at 30m/s from 0 in 2s at the inception, and the time range is 200s. In the simulation of the wind, the time step $\Delta t = 0.5\text{s}$, $\omega_{max}$=6.28 rad/s, and the division number of the frequency range is N=10000, $\Delta\omega = 0.000628\text{rad/s}$. The speed variation of the fluctuation wind, simulated with Monte Carlo method, with time is shown in Fig.6.

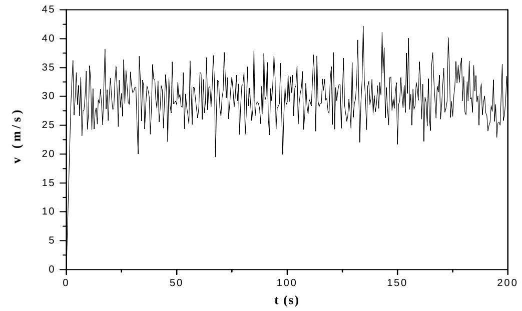


Fig.6 Speed variation of a typical fluctuation wind with time

ABAQUS is then used to simulate the dynamic response of the FE model. The variation of displacements of the suspension string at the lowest point during its swing in the vertical and horizontal directions in the plane transverse to the axis of the conductor are shown in Fig.7, in which only the responses in 25s is given out for clarity. It is discovered that the largest displacements of the suspension insulator at the lowest point in both vertical and horizontal directions are respectively 2.04m and 2.24m, which are far bigger than those determined with the traditional static method.

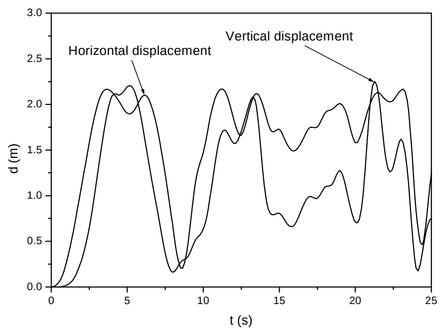


Fig.7 Variation of displacements of suspension string at the lowest point with time

### 4.5 Comparison of the results and discussion

The maximum horizontal and vertical displacements *dx* and *dy* and windage yaw angle $\theta$ at the lowest point of the suspension insulator string of the line section under different wind loads are listed in Table1. It is shown that the realistic swing of the suspension insulator string in reality may be larger than that determined with the traditional static method.

Table1 Maximum windage yaw of the line section

| Winds | *dx* (m) | | *dy* (m) | | $\theta$ (°) | |
|---|---|---|---|---|---|---|
| | FE | TM | FE | TM | FE | TM |
| Steady | 1.87 | 1.96 | 1.09 | 1.11 | 58.2 | 58.5 |
| Gust | 2.21 | -- | 1.99 | -- | 83.1 | -- |
| Fluct. | 2.24 | -- | 2.04 | -- | 84.7 | -- |

Note: TM-traditional method.

## 4 Conclusion

The windage yaws of transmission lines under the actions of various wind loads are investigated by means of FE method. From the numerical results, it is concluded that the wandage yaw determined with FE dynamic analysis is larger than that obtained with the traditional static method, and this may be one of the most important reasons inducing flashover accidents. However, the actions of the wind on transmission lines are still needed to be studied further.

**Acknowledgements**

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