A novel approach for wind tunnel modelling of transmission lines

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Abstract

This paper is concerned with the behaviour of transmission line cables in severe boundary layer winds. It examines the effect of the scale of turbulence on the response of a line-like structure (cable model) through wind tunnel tests and the comparison of wind tunnel tests with theoretical predictions made through the statistical method using influence lines. Consistency with theory allowed the development of a new modelling approach to conductor systems using a distorted horizontal length scale (span wise) to accommodate these systems in the wind tunnel. Transverse and oblique wind incidences were tested. From the results obtained in the experimental work, it is apparent that the new modelling approach to conductor systems in wind tunnels is a valid technique. It is necessary, however, that a correction be made in the values of the variance of the response measured in the distorted model. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Aeroelastic modelling; Wind tunnel; Transmission lines; Cables; Wind

1. Introduction

Although sophisticated theoretical models of the aerodynamic behaviour of transmission lines have been developed [1], and partially adopted in codes [2], they have been very difficult to verify. Full-scale measurement is a particularly difficult option. Wind tunnel testing is an attractive alternative; however it also poses considerable difficulties.
Currently, there are basically two different types of wind tunnel testing being performed. The first type of testing is referred to as static testing. In this, the mean aerodynamic forces are obtained from short lengths of full-scale conductor or conductor models. These are mounted in force balances and drag and lift coefficients are obtained. The other type is called dynamic testing, where again a two-dimensional modelling method is employed. The model is composed of a short length of rigid conductor having full-scale values of shape and weight. The elastic properties are simulated by a spring suspension system at each end of the rigid conductor.

In spite of a great number of wind loading studies of transmission lines, there is still not a complete understanding of their behaviour in wind nor complete agreement between wind tunnel testing and full-scale measurements [3]. Conductor drag forces obtained from full-scale tests have often been found to be smaller than the corresponding ones obtained in wind tunnel tests using section models [4]. Furthermore, certain full span motions cannot be simulated in these tests.

A more sophisticated approach is to model the full-span aeroelastically. This kind of test is seldom found in the literature. Some work has been done [5] although it was not the authors’ intention that the model be a small scale simulation of a prototype line. The correct modelling of this kind of structure is very difficult for many reasons which are discussed in this paper. This paper is an extension of an earlier paper on the effects of high winds on transmission lines [6]. It is the purpose of the present paper to describe the aeroelastic modelling of the conductors and to introduce a new approach for such modelling.

2. Aeroelastic modelling of the cables

In order to have the aeroelastic behaviour of the cables simulated in the models, the mass, drag forces, reduced frequency and aerodynamic damping should be simulated, together with the properties of the natural wind. Specifically, the conditions given below should be met. In the presentation, \( L \) is the line span, \( l \) the cable length, \( s \) the cable sag, \( m \) the mass per unit length, \( \rho_a \) the air density, \( C_D \) and \( d \) the cable’s drag coefficient and diameter, \( f \) the cable’s natural frequency, \( V \) the mean wind velocity and \( E \) the modulus of elasticity of the material. The subscript (m) refers to model and (p) to prototype.

2.1. Conventional modelling

(a) Geometric similarity (\( \lambda_L = \text{length scale} \))

The ratio between model and prototype dimensions should be preserved

\[
\frac{L_m}{L_p} = \frac{s_m}{s_p} = \lambda_L. \tag{1}
\]
(b) Mass modelling ($\lambda_m = \lambda^2_L$)

The requirement for the modelling of the mass of the structure is that the inertia forces of the structure and those of the flow be scaled consistently. When the aeroelastic tests are made through the use of equivalent models it is important to maintain the mass ratio the same in model and prototype [7]

$$\left( \frac{m}{\rho_a L^2} \right)_m = \left( \frac{m}{\rho_a L^2} \right)_p \quad (2)$$

(c) Drag force scaling

The drag force, $F$ in both model and prototype is given by

$$F = \frac{1}{2} \rho_a V^2 C_D dl. \quad (3)$$

The ratio $\lambda_F = F_m/F_p$ can then be written

$$(C_D d)_m = (C_D d)_p \lambda_L. \quad (4)$$

Due to the dependence of $C_D$ on the Reynolds number it is almost impossible to scale down geometrically the cable diameter, since drag coefficient would not correspond to the necessary $C_D$ to give a corrected scaled drag force. For this reason both $C_D$ and $d$ are scaled jointly.

(d) Reduced frequency

The relationship between length, time and velocity for a particular mode of vibration is based on the equality of the reduced frequency in model and full scale. For the cable the frequency depends a great deal on its sag, which is the important characteristic dimension.

$$\left( \frac{f_s}{V} \right)_m = \left( \frac{f_s}{V} \right)_p \quad (5)$$

(e) Aerodynamic damping

Cable motion is dominated by aerodynamic damping, the structural damping, $\zeta_S \approx 0.0005$ [8], being not so important, especially in strong winds. Aerodynamic damping is a retarding force which is derived from the relative motion between structure and air. It is a linear function of wind speed $V$ and, in the case of a uniform prismatic structure in uniform flow and in drag motion, can be given by the expression [9,10]

$$\zeta_a = \left( \frac{C_D}{4\pi} \right) \left( \frac{\rho_a d^2}{m} \right) \left( \frac{V}{f_d} \right). \quad (6)$$

So $(\zeta_a)_m = (\zeta_a)_p$, then

$$\lambda_L \frac{(C_D d)_m}{(C_D d)_p} = \frac{m_m}{m_p}. \quad (7)$$
(f) Wind/Gravity forces
It is necessary to maintain the ratio between wind and gravity forces for both model and prototype
\[ \lambda_V^2 \left( \frac{C_D d}{m} \right)_m = \frac{m_m}{m_p}. \]  
(8)

(g) Velocity scaling (Froude number)
For structures where resistance to deformation is influenced by the action of gravity, it is necessary to maintain Froude number, \( F_r \), similarity, which requires that
\[ \lambda_V^2 = \lambda_L. \]  
(9)

(h) Axial force scaling (Cauchy number)
To simulate the action of axial forces through the use of equivalent models, the Cauchy number, \( C_a \), must be maintained constant in model and prototype
\[ (Ed^2)_m = (Ed^2)_p \lambda_L^3. \]  
(10)

It should be remembered that all force scaling is given by \( \lambda_F = \lambda_L^3 \).

The axial tension is not very important for this purpose [11] and is not simulated here. The fulfillment of this requirement is somewhat difficult, especially if we recall that the symmetric in-plane modes also depend on the value of \( Ed^2 \) and have their own criteria to be satisfied, which do not necessarily match with Eq. (10).

2.2. Difficulties faced and adopted approach

Just to fix ideas we give a numerical example of a conventional cable modelling. The nominal prototype cable characteristics assumed are \( L_P = 300 \) m, \( s_p = 10 \) m, \( d_P = 300.9 \) m, \( d_P = 0.04 \) m, \( m_P = 3 \) kg/m and \( V_P = 45 \) m/s. From this \( Re \approx 1.2E5 \) and \( C_D \approx 1.0 \), which allows \( (C_D d)_p \approx 0.04 \) m. The first fundamental frequency is \( (f_c)_1 \approx 0.18 \) Hz. For this example, a geometric scale \( \lambda_L = 1/50 \) is chosen and therefore the velocity scale is \( \lambda_V = (\lambda_L)^{1/2} = 1/7.07 \). In this case we would have: \( L_m = 6 \) m, \( s_m = 0.2 \) m, \( l_m = 6.02 \) m, \( m_m = 0.0012 \) kg/m = 1.2 g/m, \( V_m = 6.4 \) m/s, \( (C_D d)_m \approx 8E - 4m = 0.8 \) mm and \( (f_c)_1 \approx 1.24 \) Hz.

Even with the relatively large scale ratio of 1/50 the mass per unit length has a very low value. This fact makes it difficult to actually build the model. If we compare the full-scale mass per unit length of a suspension bridge cable for example, which has \( m \approx 5000 \) kg/m, with the transmission line \( m \approx 3 \) kg/m or less, and look at the usual model dimensions of a bridge model, we can see the difficulties involved in simulating the transmission line in reduced scale. There is also the problem of simulating \( Ed^2 \) for axial forces and symmetric in-plane mode shapes. And because we are dealing with the line behaviour under design velocities, i.e., high wind speeds, we can be concerned only with the drag forces and avoid the problems related to cross-wind simulation [12]. Furthermore, with a model span as calculated it is very difficult (in our case impossible) to fit the model in conventional boundary layer wind tunnels that generally do not have such a wide section.
To accommodate such a span or even several spans of these systems in the wind tunnel, a new modelling approach to tower and conductor systems using a distorted scale was developed. Such approach is based on the idea that distorting horizontally the cable but maintaining the same sag and preserving the properties of the “normal” model (mass, drag, frequency), would not alter significantly its behaviour, since the natural frequencies of the cables are primarily a function of their sags when the cable tension is not high. That is, the modelling approach would be firstly to go from the full-scale to the “normal” model and from this to the “distorted” model, keeping the model sag the same. The flow conditions in the wind tunnel simulation are also kept the same.

The disadvantage of this approach is that it changes the correlation of the wind forces along the cable and this must be corrected. The correction is much smaller than that required by the usual sectional (two-dimensional modelling) wind tunnel cable testing, which results have to be adjusted by a span factor to take into account the variations of pressure along the cable length.

2.3. Distorted modelling

A reduced span $L_m^*$ obtained from the distortion of the original model span $L_m$ by an amount $\gamma$, is utilised, so that $L_m^* = \gamma L_m$, where the symbol * refers to a quantity used in the distorted model.

(a) The new length scale is then

$$\lambda^*_L = \frac{L_m^*}{L_p} = \frac{\gamma L_m}{L_p} = \gamma \lambda_L.$$  \hfill (11)

In order to have the same behaviour in both models the mass, drag forces, aerodynamic damping and reduced frequency must be kept the same.

(b) Mass

$$m^*_m = \frac{m_m}{\gamma}.$$  \hfill (12)

(c) Drag force

$$(C_Dd)_m^* = \frac{(C_Dd)_m}{\gamma}.$$  \hfill (13)

Distorting the mass per unit length and $C_Dd$ by the same amount $\gamma$ guarantees that the ratio between wind and gravity forces, Eq. (6), is also preserved.

(d) Reduced frequency and aerodynamic damping

$$f_m = f_m^*.$$  \hfill (14)

(e) Axial force

$$E^* d^2 = \gamma Ed^2.$$  \hfill (15)

The original average mass per unit length and average $C_Dd$ per unit length required have to increase by $1/\gamma$ if the total mass and drag force is to be maintained. The aerodynamic damping and reduced frequency are kept the same if the natural
frequency is not altered. This condition is satisfied since the natural frequency of a suspended cable is primarily a function of its sag (which is kept unchanged).

Strictly speaking, we should diminish $Ed^2$ by $\gamma$, although this would not make the strain of both models be the same (the reason being the difference in cable tension of the two models). However, due to the already mentioned difficulties in $Ed^2$ simulation, this condition will not be strictly followed. This gives more flexibility in the choice of the cable diameters for the design and construction of the models. The consequences of this assumption were verified to be acceptable in the experimental results [13].

As usual in aeroelastic studies, it is very difficult to satisfy all the requirements and some compromise has to be made. For the case of transverse wind loads transmitted by the cables to their supports, the conductor tension was found to have a negligible influence on the transverse loadings [11].

3. Testing distortion theory

3.1. Design of models 1 and 2

To initiate the study, two cable models corresponding to the same prototype were tested. One was a “normal” model (model 1) and the other a “distorted” one (model 2). The general characteristics are indicated in Table 1 together with the estimated first natural frequencies for a “no wind” condition. The predicted natural frequencies for other modes of vibration for both, tension due to its own weight (or a “no wind” condition) and resultant tension due to the combination of the own weight and the mean wind speed based on the velocities considered were also calculated [13]. The values of $Ed^2$ adopted are considered as well.

The models were built by employing a technique broadly used in wind tunnel modelling of bridge cables and also used in a simulation of elevator cables [14]. It consists in using a basic cable of very small diameter to simulate, if desired, the axial stiffness and flexibility, over which are attached lumped pieces (cylinders or spheres) of a certain material to give, together with the basic cable, the required average mass per unit length and the required average $C_D d$ per unit length.

Both models were built using as basic cable a steel piano wire with diameter $\Phi = 2.29E - 4$ m over which lumped foam cylinders (3 mm diameter, 10 mm length) were attached. It was decided to keep the mass as low as possible in the first models.
for two reasons: (a) to test if it was possible to make a model work in a lower extreme case (corresponding smaller values for transmission lines are not expected to be found in full-scale), and (b) to keep the influence of the mass and related properties a minimum.

The natural frequencies of the distorted and the normal models are very close and can be assumed to be the same. The actual values obtained for the total mass of the cable models was $M_1 = 1.3 \text{ g}$ and $M_2 = 1.1 \text{ g}$, what gives $m_1 \approx 0.43 \text{ g/m}$ and $m_2 \approx 0.71 \text{ g/m}$. The value of $C_D d$ is chosen from a smooth flow regime and therefore the correctness of the model design will be checked using the results from exposure 3—smooth flow.

4. Experimental results

The tests were done in the low-speed section of the BLWT II, in which the length of the working section upstream of the model is 43 m. Three different exposures were used in the study: smooth flow and turbulent flow with turbulence intensities of 0.11 and 0.14. Detailed information regarding the adopted exposures, wind profiles, span-wise cross-correlation of the wind, wind spectra and coherence are shown elsewhere [13]. One of the reasons to use the low speed section is its large width (4.88 m) and its lower wind velocities (Froude number requirement), making it the best option to test the transmission lines.

The testing of the cable model included measurements of the time history of the drag force over a period of time (500 s) corresponding to approximately 60 min in full-scale for the desired wind speed. From these, the mean, root-mean-square (RMS), maximum and minimum values of the response as well as the force spectra were obtained. The spectra were also measured independently, through a specific software, and have compared very well with those obtained from the time series. Force balances were used to measure the drag forces at the cables extremities.

Two angles of incidence were tested: $0^\circ$ incidence (transverse wind) and $45^\circ$ incidence (oblique wind). The models were also tested for a slightly higher velocity and a slightly lower velocity than the design values of 45 m/s in the case of the time series, plus 3 extra lower velocities in the measurements of the force spectra. Although the model was not designed for those wind speeds, they serve the purpose of qualitative information. The values obtained are shown in Tables 2 and 3.

From the analyses of the values measured it can be observed that the mean values from the normal model agree fairly well with the mean distorted values and are in general slightly smaller for the more turbulent wind. The values of the variance were in general very small and, in the case of the normal cable values, roughly half its corresponding value from the distorted model. This leaves the RMS values for the distorted model overestimated by roughly between 1.4 and 1.5 times the normal value for transverse wind ($0^\circ$), and roughly between 1.3 and 1.4 for the oblique incidence ($45^\circ$). The reason for that may be due to the fact that, because the wind characteristics remain unchanged, the turbulence is “seen” as having a larger
correlation in the case of the distorted model and, therefore, the variance is bigger. The maximum values followed the same trend and therefore were bigger for the distorted model. The minimum values, however, were almost all smaller for the distorted model.

These results are very important since they demonstrate the effect of turbulence in the dynamic response. Theory says that the variance is directly proportional to the ratio between turbulence length scale and the structure’s span, and that is exactly what is demonstrated in these experiments by changing the structure and leaving the wind flow characteristics unchanged.

The values from exposure 3 were used to calculate the model values of $C_D d$ and check if the design was correct. From those it was observed that the expected design values of $C_D d = 0.0006$, for the normal model, and $C_D d = 0.0012$, for the distorted one, were closely matched, although slightly larger values were obtained. The ratio

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### Table 2
Cable model drag force at one extremity in turbulent flow for transverse wind incidence ($0^\circ$)

<table>
<thead>
<tr>
<th>Model</th>
<th>Exposure</th>
<th>Velocity (m/s)</th>
<th>Max (N)</th>
<th>Min (N)</th>
<th>Mean (N)</th>
<th>RMS (N)</th>
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<td>5.8</td>
<td>29.8E-5</td>
<td>12.4E-5</td>
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<td>6.4</td>
<td>38.1E-5</td>
<td>14.7E-5</td>
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<td></td>
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<td>40.6E-5</td>
<td>16.1E-5</td>
<td>27.1E-5</td>
<td>2.85E-5</td>
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<td>34.4E-5</td>
<td>9.0E-5</td>
<td>20.5E-5</td>
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### Table 3
Cable model drag force at one extremity in turbulent flow for oblique wind incidence ($45^\circ$)

<table>
<thead>
<tr>
<th>Model</th>
<th>Exposure</th>
<th>Velocity (m/s)</th>
<th>Max (N)</th>
<th>Min (N)</th>
<th>Mean (N)</th>
<th>RMS (N)</th>
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<tr>
<td>Distorted</td>
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<td>9.5E-5</td>
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between normal and distorted $C_D$ values, however, kept practically the same ($\approx 0.50$). These results were considered satisfactory.

The force spectra for the drag at one extremity of the cable for a few cases are shown in Figs. 1–5. From the analyses of Figs. 1–3 spectra we can observe that

![Fig. 1.](image1.png)  
(a) Spectra of drag force (N) at one end of cable 1 for exposure 1 and transverse wind ($0^\circ$) for several wind speeds. (b) Spectra of drag force (N) at one end of cable 2 for exposure 1 and transverse wind ($0^\circ$) for several wind speeds.

![Fig. 2.](image2.png)  
(a) Spectra of drag force (N) at one end of cable 1 for exposure 2 and transverse wind ($0^\circ$) for several wind speeds. (b) Spectra of drag force (N) at one end of cable 2 for exposure 2 and transverse wind ($0^\circ$) for several wind speeds.

![Fig. 3.](image3.png)  
(a) Spectra of drag force (N) at one end of cable 1 for exposure 1 and oblique wind ($45^\circ$) for several wind speeds. (b) Spectra of drag force (N) at one end of cable 2 for exposure 1 and oblique wind ($45^\circ$) for several wind speeds.
cable2 (distorted model) had larger values of $fS(f)$, which agrees with the time series values for the force variance, and, repeating the observation, may be due to the larger correlation of the gusts for the distorted model in relation to the normal one. The difference is larger for exposure 1 (more turbulent). Another observation is that

Fig. 4. Normalised spectrum of drag force (N) at one end of cables 1 and 2 for exposure 1 and transverse wind ($\theta^\circ$) $V = 6.4$ m/s.

Fig. 5. Normalised spectrum of drag force (N) at one end of cables 1 and 2 for exposure 2 and transverse wind ($\theta^\circ$) $V = 6.4$ m/s.
the normal cable had the peaks in the spectra more distinct than the distorted. This can be due to the slightly smaller aerodynamic damping of cable 1. At the model design velocities it was almost impossible to see any distinct peaks in the spectra, those becoming more distinct as the velocity decreases. This could be attributed to the aerodynamic damping which is directly proportional to the wind velocity and inversely proportional to the mass per unit length. From the smaller velocity spectra we can infer the natural frequencies of the cable, which are in the range of the expected theoretical predictions.

Figs. 4 and 5 show the spectra of the drag forces normalised by its variance and present the normal and distorted models in the same plot. Although $fS(f)$ and the variance are bigger for the distorted model, the normalised spectra of both models have a good match, indicating the validity of the technique.

The angular displacement of the cables under those severe wind conditions were expectedly high. These extreme angular displacements have been found in real lines under extreme winds [15].

The statistical method using influence lines [6] has been employed for the theoretical prediction of the cable responses and comparison with experimental values. Table 4 presents RMS values of the drag force at one extremity of the cable obtained from the measurements and calculated from theory using the estimated values of the transverse length scale of turbulence. Theory predicts well the mean responses and overestimates the experimental findings for the fluctuating part of the response. For the cables tested, only the value of the background response obtained by the statistical method using influence lines was enough to predict the measured fluctuating response. There are however, uncertainties in the determination of the transverse length scale of turbulence ($L_V$). The value used was from the fit of the correlation curve by an approximate

<table>
<thead>
<tr>
<th>Model</th>
<th>Exposure</th>
<th>Velocity (m/s)</th>
<th>Intensity of turbulence</th>
<th>RMS calculated (N)</th>
<th>RMS measured (N)</th>
<th>RMS ratio calc./meas.</th>
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exponential function and the area under the real curve seems to be actually lower than the area given by the fitting curve. A lower value of \((L_V)\) in the calculation would mean a background response coinciding with the measurements. The resonant response does not seem to be important in this case, which can also be seen from the spectra, although it may be very important for more massive cables or when cable characteristics and flow conditions dictate a smaller value for the aerodynamic damping [6].

5. Conclusions

The effect of turbulence scale on the behaviour of transmission line cables has been examined. Wind tunnel results and theoretical predictions have validated a new modelling approach to conductor systems using a distorted horizontal length scale (span wise) to accommodate these systems in the wind tunnel. It is necessary, however, that a correction be made in the values of the variance of the response measured in the distorted model. Specifically, the findings were:

1. Mean values measured from normal and distorted models agree well among themselves and with those predicted from theory.
2. The variance of the response measured from the distorted model was roughly double its corresponding value in the normal model. The horizontal distortion of the cable was \(\gamma = 50\%\). In agreement with theory, the variance obtained from the distorted models should be multiplied by \(\gamma\), the horizontal geometric distortion of the cable model, to obtain the real values of the variance of the response. However, further research may indicate the necessity of a non-linear correction, related to the variance.
3. From the resulting spectra of the models tested (low mass per unit length) it can be seen that, at the model design velocities, the response is all background. The theoretical predictions in this case overestimated the fluctuating response; but due to the fact that there are uncertainties in the determination of the turbulence length scale, it can be said that the statistical method using influence lines is a good tool in the theoretical prediction of the cable responses.
4. Aerodynamic damping plays an important role in the dynamic behaviour of the cables. This was demonstrated in the experimental results obtained for the lines with different characteristics and also in full-scale experiments made by other researchers.
5. The results obtained demonstrate the effect of turbulence in the dynamic response. Theory says that the variance of the response is directly proportional to the ratio between turbulence length scale and the structure’s span, and that is exactly what is demonstrated in these experiments by modifying the structure and leaving the wind characteristics unchanged.
References


