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Dynamic analysis of an overhead transmission line subject to gusty wind loading predicted by wind–conductor interaction

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ABSTRACT

The authors present a new method to determine wind loading on transmission line conductors based on fluid–structure interaction (FSI) analysis. FSI results yield a more accurate representation of pressure loads acting on moving conductors than provided by the pseudo-static pressure calculation based on Bernoulli's equation, which is the current approach used in design. The results based on the proposed method are compared to those obtained using the Bernoulli load model using four natural wind records to perform a nonlinear dynamic analysis of a three-span transmission line section. The quasi-static approach significantly overestimates the conductor motion and the cable tensions.

1. Introduction

Transmission line structures are designed to withstand several different load cases they may experience during their service life. Among these load cases, those involving extreme wind and combined wind and icing in cold climates are typically governing the design for lateral loads. In design practice wind loading on transmission line conductors is applied following simplified static procedures that are meant to be conservative. Such procedures, described in national and international codes and standards or in utility guidelines, are very similar and essentially based on Bernoulli equation. Referring to Eq. (1) provided by Canadian standards CSA-C22.3 No. 60826-10, Design criteria of overhead transmission lines [1], the wind pressure on towers and conductors, q, is obtained by multiplying the reference dynamic wind pressure, q_o – actually the equivalent pseudo-static pressure predicted by Bernoulli equation, by a gust effect factor proposed by Davenport in the late 1970s [2] to account for tower resonant response and wind gustiness. The incident wind speed nominally specified at 10 m elevation is also modified to account for terrain roughness and height according to the classical boundary layer wind model. Finally, a span coefficient is used to consider the random unevenness of wind gust speed along the span.

$$q = q_0 C_{xc} G_c G_L \quad (1)$$

Where, C_{xc} is the drag coefficient of the conductor (considered in the un-iced condition), G_c is the combined wind factor for the conductors, which depends on height above ground and terrain roughness categories, and G_L is the span factor. Other standards such as IEC 60826, Design criteria of overhead transmission lines issued by International Electrotechnical Commission [3] and ASCE Manual No. 74 [4] use similar approaches.

Among the different mechanical components of transmission lines, conductors have the largest area exposed to wind, especially in high and ultra high voltage lines where bundles of four or more conductors are used. Line conductors are particularly sensitive to wind effects as they are long and relatively flexible compared to their supports. Because of their flexibility, conductors may experience large motions under wind loading: depending on wind speed, line parameters and span length, horizontal (swinging) displacements at the mid span may reach 10–20 m in high voltage lines. In cold climates, atmospheric ice accretions of various types, from light rime to dense glaze, further increase the effects of wind loads on lines and give rise to the most severe design loading conditions. Although simplified static methods are expected to be conservative for design, economy brings other incentives to better understand and quantify the effects of wind loads on line conductors, especially in the context of older line assessment where overly conservative load estimates may lead to costly retrofit measures that are not necessary. It is clear that in extreme wind conditions conductors experience large displacements and interact with the wind flow: is this interaction contributing to increasing or decreasing the net pressures on the conductor span and consequently the loads transferred to their supporting towers? This is the main question that motivated this research. A refined computational

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model of the conductor cross section on flexible supports in surrounding moving air is used to investigate the dynamic interaction between wind and conductor motion. The net wind load resulting from fluid–structure interaction (FSI) analysis is then applied to detailed three-dimensional models of a line section to determine the loads transferred to line supports.

2. Fluid–structure interaction analysis

Considering the conductor motion in the wind flow, an accurate computational evaluation of wind pressure on overhead conductors requires FSI analysis. In this analysis, a two-dimensional model of the conductor cross section is coupled to its surrounding air flow (fluid) domain, as illustrated in Fig. 1. In the solid domain, only the outer cable boundary is modeled with 450 2-node Hermitian beam elements with constant cross-sectional properties. A very high flexural stiffness (high Young's modulus) is prescribed to prevent deformation of the conductor cross section. It is assumed that large displacements/rotations can occur, but only small strains. The stiffness matrix and internal force vector of this element are evaluated in closed form [7]. The mass of the conductor is attributed to individual elements of its contour while the support stiffness is distributed along the contour with spring elements assigned in two orthogonal directions. In other words, the cross section is assumed mounted on elastic springs with equivalent vertical and horizontal linearized stiffnesses that can be adjusted for various line parameters. In the application presented here, these equivalent stiffness properties were determined for a mid-span cross section using a detailed large kinematics nonlinear static analysis of a level 355-m span suspended in still air, with a horizontal tension of 19.2 kN in the bare condition (cable self-weight 14.9 N/m). A viscous damping constant equivalent to 2% of critical is also assigned at the support in each orthogonal direction to approximate internal material damping in the conductor. Interface boundary conditions are assigned to the solid and fluid elements to ensure that in each iteration the fluid domain displacements on the contour are updated to correspond to the beam element displacements. The corresponding fluid pressures determined by CFD analysis in the fluid domain are also transferred to the beam elements of the solid domain as external nodal point loads. These two-dimensional models provide a tool to evaluate the effects of several parameters such as the magnitude of incident wind speeds, conductor shape, surface roughness and ice accretion on resultant wind loading of overhead line conductors.[5]

In the solid domain, direct time-step integration is used to solve the incremental form of the nonlinear equations of motion (Eq. (2)) of the cable cross section on spring supports and dashpots, and the equilibrium iterations are carried using the Full Newton method for stiffness updates. In the following equation u is the cable displacement vector; K, M and C are stiffness, mass and damping matrices respectively, and $F_{t+\Delta t}$ represents the fluid force applied on the conductor nodes at time $t + \Delta t$.

$$M\Delta\ddot{u} + C\Delta\dot{u} + K\Delta u = F_{t+\delta t} - M\ddot{u} - C\dot{u} - Ku \quad (2)$$

For computational fluid dynamics, the modeling parameters that were found to have the most influence on accuracy are the fluid domain dimensions and the mesh fineness. Thereafter, these were iteratively adjusted with several numerical experiments until the computational domain was found adequate to minimize blockage and boundary effects on cable response while keeping the computational cost reasonable. The fluid domain is discretized with quadrilateral FCBI-C elements [6], using a structured "O" shape mesh (see Fig. 1). To capture the fluid response with reasonable accuracy 450 elements are used at the fluid–solid interface. The fluid elements' thickness is reduced when approaching the interface and a refined mesh is used in a ring zone of about $1 \times D$ thickness around the cable surface of diameter D to keep at least 5 layers of elements with Y^+ under 1.00. An extensive mesh study has been conducted in the initial stage of modeling to determine the appropriate size and shape of the mesh that would yield good convergence and accuracy while keeping the numerical effort manageable: finer meshes were tested and improved to the pressure calculations by less than 5%. The CFD analysis is based on the direct time-step integration of the unsteady Reynolds-averaged Navier–Stokes equations (Eq. (3)) using the Euler α-method of first order, and a constant time-step size of 0.1 ms was found optimal for the problem at hand.

$$\rho\bar{u}_j\partial\bar{u}_i/\partial x_j = \rho\bar{f}_i + \partial/\partial x_i\left[-\bar{p}\delta_{ij} + \mu\left(\partial\bar{u}_i/\partial x_j + \partial\bar{u}_j/\partial x_i\right) - \rho\overline{u'_i u'_j}\right] \quad (3)$$

In Eq. (3), ρ is the air density, $\bar{u}_i$ and u'_j are the mean and fluctuating components of i-th component of the fluid velocity, $\bar{p}$ is the mean static pressure, μ is the air viscosity and $\bar{f}_i$is a vector representing the mean external forces applied on the control fluid domain. The iterative solver for the linearized incremental equations is the Algebraic Multi-Grid method (AMG). Airflow turbulence is modeled with the Spalart–Allmaras one-equation approach and vortex-shedding effects are introduced with the Detached Eddy Simulation (DES) algorithm. In FSI analysis, the Arbitrary-Lagrangian–Eulerian (ALE) formulation is used to allow for compatible mesh deformations and displacements for the air surrounding the cable in motion in each solution step. Note that these features are available in commercial software ADINA which was used in the study. [7]

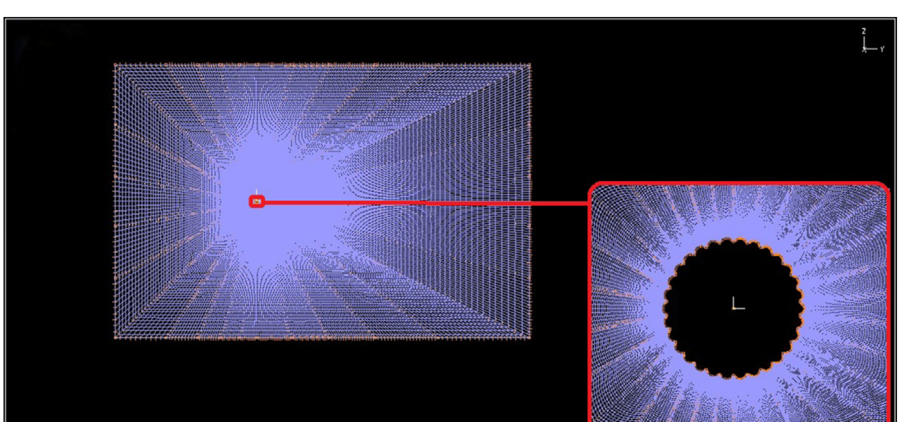

Fig. 1. Two-dimensional model of stranded conductor cross section coupled to its surrounding air flow.