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Numerical Modeling and Small-Scale Experimental Simulation of Ice Shedding Propagation on Bundled Conductors

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***Abstract*—Ice shedding propagation on bundled conductors is simulated numerically and experimentally. A numerical model was built using a commercial finite element software ADINA, whereas experiments were carried out on a small-scale setup in laboratory. The numerical and the experimental models simulate the propagation of ice shedding from one cable in a twin bundle together with the resulting vibration. The calculated and measured parameters are time histories of vertical and transverse vibrations of the cable and time histories of the angle of bundle rotation in the middle of the span when the number of spacers is varied. Ice load is modeled by applying concentrated loads at constant distances along the cables, and then they are released consecutively from either cable in order to simulate ice shedding propagation. The numerical model is validated by comparing the computed and measured results. This model may easily be modified to simulate ice shedding propagation and the induced vibration on bundled conductors in real-scale transmission lines.**

Keywords-cable vibration; conductor bundle; ice shedding; numerical modeling; small-scale experiment

I. INTRODUCTION

Ice shedding from transmission line cables occurs as a source of dynamic load on the line due to the resulting high-amplitude vibration and excessive transient dynamic forces. Such vibration is usually the most severe in the vertical plane; however, when the ice-shedding phenomenon appears in a conductor bundle, the transverse vibration and the bundle rolling may also be significant. The dynamic effects of ice or wet snow on overhead lines are reviewed in [1].

Ice may shed suddenly as a large chunk from the whole span or from a part of it, or the fall of smaller ice chunks may propagate along the span. The observation of natural ice shedding is a difficult task, but the consequences may lead to serious damage in the line elements. Ice shedding from conductor bundles was simulated applying the finite element method [2, 3]. The dynamic effects of ice shedding on spacers in conductor bundles were studied in [4]. The above models considered sudden ice shedding; but more recently, propagating ice shedding was also simulated on a full-scale test line [5]. Reference [6] examined the twisting phenomenon of bundled conductors due to the application of external forces, although icing as a source of an external force was not considered particularly. The torsional behavior of conductor bundles was modeled theoretically as well as on a full-scale line in [7].

This study presents a small-scale experimental model for shedding propagation from one span of a twin bundle. A numerical model of this experimental setup is also constructed and applied to simulate propagating shedding. The validation of numerical model is carried out by comparing experimentally and numerically obtained time histories of vertical and transverse cable vibration as well as bundle rotation.

II. EXPERIMENTAL SETUP

The idea of simulating ice shedding experimentally is based on [8], where sudden ice shedding was modeled on a single conductor of a full-scale test line by load dropping tests.

A. *Small-Scale Model of a Twin Bundle*

The experimental setup was constructed in one of the cold chambers in the CIGELE laboratories for modeling one span of a twin bundle with spacers in the horizontal plane. Fig. 1 shows the main elements of this setup. The distance between the cables was 5 cm. Two identical Vanguard 7x19 construction stainless steel cables were connected at each end to aluminum plates hinged to the suspensions. Cables with diameter of 3.2 mm were used in the tests. The sum of strand cross-sections in this cable is 5.5 mm^2, the mass per unit length is 0.043 kg/m, and the tensile strength is 9 kN. The span length was 6.4 m, which is limited by the dimension of the laboratory chamber. The sag of the unloaded cable was 29 cm. In the set-up, Teflon bars acted as spacers which maintained a constant distance between the subconductors. However, the bars could not simulate the damping effects of the spacers. Experiments were carried out with up to 5 spacers. Although sub-span lengths are usually unequal in practice, equal sub-span lengths were applied in these tests for the sake of simplicity.

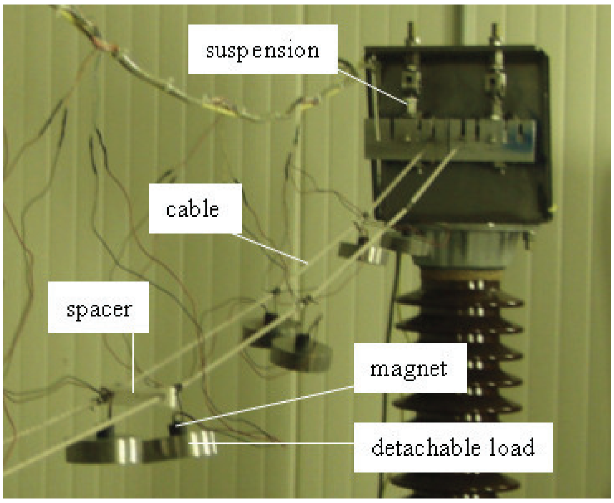

Figure 1. Main elements of the experimental setup

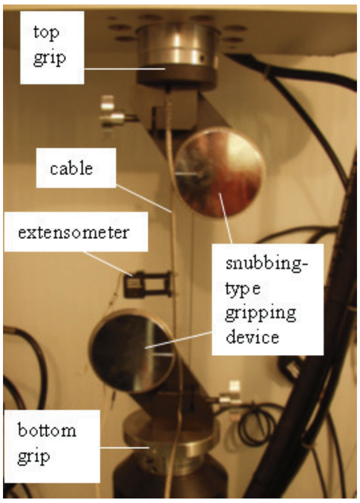

Figure 2. Setup for cable tensile tests

B. Simulation of Ice Shedding

The ice load was modeled by weights attached to the cables via electromagnets manufactured by AEC Magnetics. Eight weights of 0.812 kg each were attached to both cables with approximately constant distances in between, representing a load of 8 times 0.812 kg in 6.4 m, i.e. 1.015 kg/m. The current in the electromagnets was switched on before the weights were attached, meaning that switching off the current released the weights thereby simulating ice shedding from the corresponding area of the cable. When simulating shedding propagation along the span, the eight weights on either cable were released with short time intervals between the releases of two consecutive loads so that the whole span shed in about 2 s.

The time history of vertical displacement of cables following load shedding was observed at mid-span by fixing a scale behind the cables and recording cable movement by a Panasonic digital video camcorder (model no. PV-GS400). The angle of bundle rotation was also determined at mid-span by using the horizontal and vertical coordinates of the spacer attachment points. In order to achieve this goal, a scale was placed horizontally above the cables, another scale was fixed vertically near the cables, and the vibration was recorded by the same camera. The highest jump was occurring at mid-span when there was no spacer there, so that a vertical vibration was observed in the configurations without spacers (i.e. single cable), and with 2 and 4 spacers. However, bundle rotation was measured at mid-span by using the spacer attachment points; therefore bundle rotation was observed when applying 1, 3 or 5 spacers.

III. NUMERICAL MODEL

A numerical model of the experimental setup described in the previous section was also constructed for simulating ice shedding propagation from a twin bundle of conductors. This model is implemented using the finite-element analysis software ADINA [9].

A. Cable

The cable model is based on the model of [10], where it is described in more detail. The stress-strain curve of the cable was determined in tensile tests carried out according to the ASTM SA-370 Standard [11] by using an MTS material test machine. The elongation of the sample was measured by an extensometer fixed to the cable. Fig. 2 illustrates the set-up at the beginning of a tensile test. The deformation rate was kept at $5 \cdot 10^{-4}$ 1/s, which meant a displacement rate of approximately 6 mm/min with 200-mm long samples. Measurements were repeated with 2 to 3 samples, and the stress-strain curve was approximated by a piecewise linear relationship for tension, and no compression was allowed.

The cable damping is considered by Rayleigh damping as proposed and explained in [12]. The damping ratios were estimated to be 0.02 following the observation of the decay of vertical cable vibration in the small-scale laboratory model.

B. Suspension

The subconductors in the experimental set-up are connected to an aluminum element which is hinged to the suspension. This aluminum element is modeled by one truss element at each cable attachment with a simplification of its geometry obtained by defining a uniform area of cross section. This element is associated with elastic isotropic material representing aluminum. Rotation around the transverse axis is allowed at the points where the cable is attached to the aluminum element, and where the latter is hinged to the suspension.

C. Spacer

The spacer is modeled by a two-node truss element associated with an elastic isotropic material representing Teflon. Structural damping of spacer is considered by a nonlinear spring element with exponent 1 and with damping constant calculated from

$$c_s = 2\zeta_s \sqrt{E_{s1} A_s m_s}$$

where $\zeta_s = 0.005$ is the spacer damping ratio, E_{s1} is the tangent of the first piece of the stress-strain curve, and A_s and m_s are the cross section and mass per unit length of the spacer element, respectively.

D. Ice Load and Shedding Propagation

The model of ice shedding propagation is developed in a parallel study [13]. Although ice load usually appears on conductors as a distributed load, it is simulated by several concentrated loads applied at constant distances along the loaded span. Therefore, the numerical model considers the ice load by concentrated loads at the locations where they are attached in the experimental setup. Modeling ice load this way makes the simulation of shedding propagation possible by removing any of the concentrated loads at arbitrary time instants. The propagation velocity is controlled by associating each concentrated load with a time function which determines the removal time of that specific load. Since 8 loads act along the span and the wave propagation time along the span is 2 s, the time between the removals of two consecutive loads is 0.25 s.

IV. RESULTS

The numerical model is validated by simulating the small-scale experiments and comparing the calculated and measured static sag of the loaded cable, the vertical and transverse components of cable vibration and the angle of bundle rotation after the load sheds from one of the cables. The numerical model is applied for simulating propagation of ice shedding from a single span of a real-scale transmission line elsewhere [13].

The numerical model simulates ice shedding in two steps. First, the geometry of the experimental set-up is constructed, and the loads representing ice are added in the static analysis. The result of this step is the profile of the loaded cables. Then, the propagation of ice shedding is simulated in the dynamic analysis, which provides the resulting vibration of both cables.

The time histories of vertical cable displacement at mid-span are shown in Fig. 3. The static sag of the cables is increased by 3.9 cm in the experiments, and 3.3 cm according to the numerical model. Thus, the model underestimates the static sag by about 15%, but the time histories obtained numerically and experimentally show similar tendencies. When the first two loads shed, i.e. about a quarter of the span is unloaded, the vibration is not severe at mid-span. Small peaks appear in the curves after further loads are released (at each 0.25 s intervals after 0.5 s). The maximum displacement of a single cable occurs after the whole span is unloaded; however, this maximum occurs earlier for bundles, when about ¾ of the span is shed. Fig. 3 also shows clearly that the jump height decreases significantly by increasing the number of spacers (or reducing sub-span length).

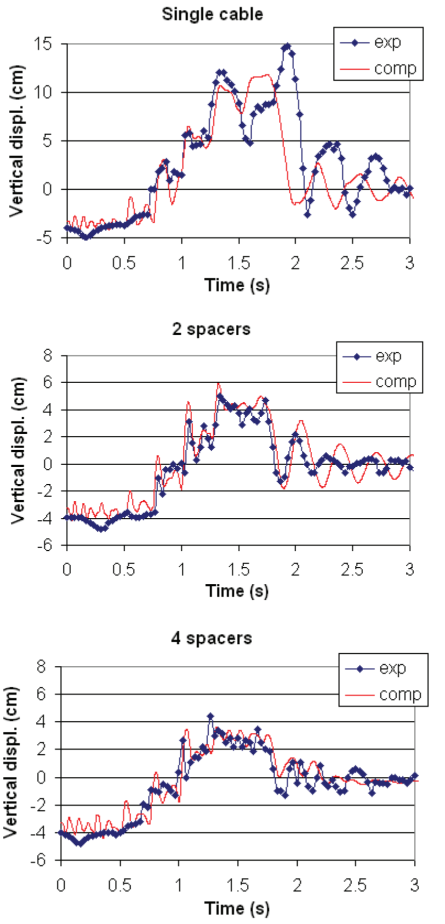

Figure 3. Vertical cable displacement at mid-span for 0, 2 and 4 spacers

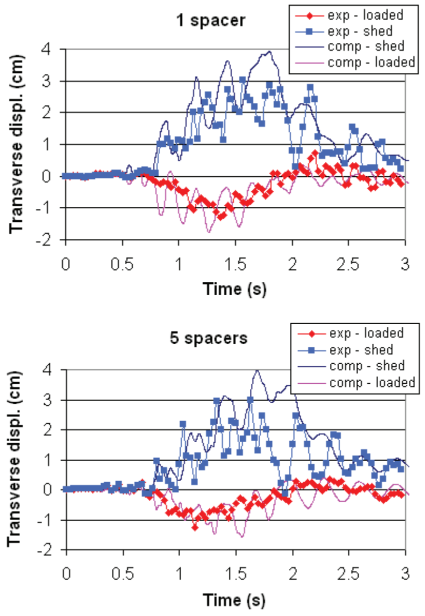

Figure 4. Transverse cable displacement at mid-span for 1 and 5 spacers

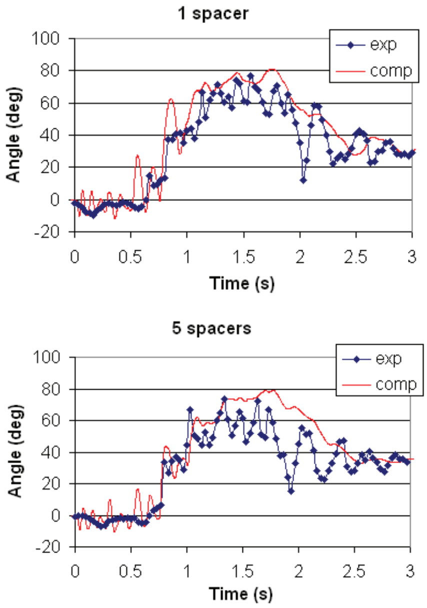

Figure 5. Bundle rotation at mid-span for 1 and 5 spacers

Fig. 4 compares transverse cable displacements at mid-span as obtained numerically and experimentally when applying 1 and 5 spacers along the span. The numerically computed time histories follow the tendencies obtained experimentally, but the maximum displacements are overestimated. The maximum transverse displacement is independent of the number of spacers, which is a significant difference as compared to what was observed for the vertical motion. However, similarly to the vertical motion, the maximum displacements occur when the last quarter of the span sheds (between 1.5 s and 2 s).

The bundle rotation due to ice shedding propagation is presented in Fig. 5 for the cases of 1 and 5 spacers. The computed and measured curves show closer agreements which was observed for the transverse displacement. Similar tendencies may be seen: (i) the maximum angle of rotation is independent of the number of spacers; and (ii) this maximum occurs when the last quarter of the span sheds.

V. CONCLUSION

Ice shedding propagation along a subconductor in a twin bundle has been modeled numerically and experimentally in a small-scale setup. The ice load was considered by several concentrated loads applied along the span, and its shedding was simulated by their consecutive removal. The static sag of the loaded cable, the vertical and transverse components of cable vibration, and the angle of bundle rotation were calculated and measured. Numerical and experimental results show the same tendencies, and the numerical model approximates closely the vertical cable displacement and bundle rotation, but it underestimates the static sag and overestimates the transverse displacement. Results show that the increasing number of spacers along the span reduces the vertical cable jump; however, it does not decrease the transverse displacement and the angle of bundle rotation at the spacer attachment. The vibration is the most severe when the last quarter of the span sheds. A future goal is to apply this model to simulating ice shedding propagation from a real-scale conductor bundle.

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