# Electric transmission line wire deformation dynamics

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# Electric Transmission Line Wire Deformation Dynamics

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**Abstract.** Loading dynamics of a transmission line (TL) with a joint weight, wind and ice deposits loading is being studied. For exploring of icing restapling the equations of dynamics and heat conduction are resolved. The mechanism of the appearance of «the dance of wires» is revealed.

Wires of high-voltage lines are subject to significant mechanical stresses. They are permanently loaded with their own weight and wind load. Weather conditions in the autumn-spring season in many regions of our country result in icing of power transmission lines. Icing detection of power lines is described in the work [1]. The wires are a deformable body which diameter can be considered negligible compared to its length. The wire is modeled by an absolutely flexible linear connection [2-8].

## THE VECTOR EQUATION OF MOTION

The vector equation of motion of a high-voltage line under the influence of normal, tangential linear forces and the weight force with linear density has the form

$$\rho_0 \, \partial^2 \mathbf{r} / \partial t^2 = \partial \mathbf{T} / \partial s_0 + \mathbf{F}_n + \mathbf{F}_\tau + \mathbf{g}\rho_0 \tag{1}$$

The motion of the wire is considered in the Cartesian coordinate system $Ox_1x_2x_3$ , (Fig. 1)

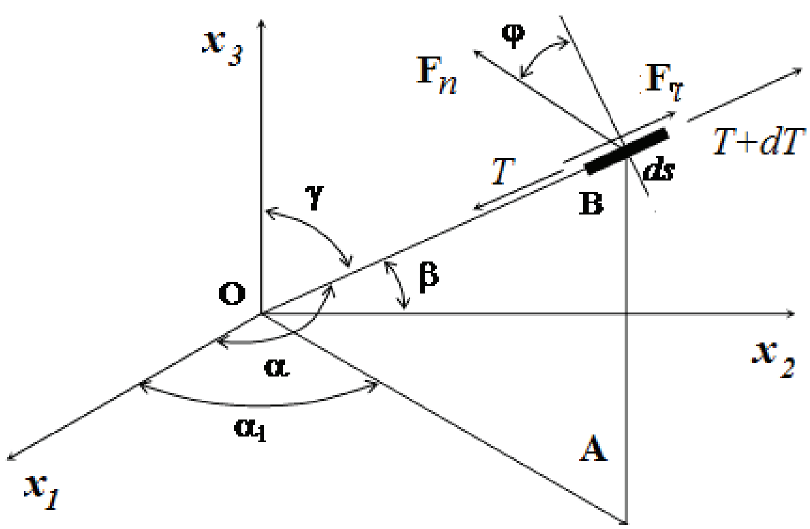


**FIGURE 1.** Loading diagram (TL)

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$$\rho_0 \frac{\partial v_1}{\partial t} = \frac{\partial}{\partial s}\left(\frac{T}{\lambda}\frac{\partial x_1}{\partial s}\right) - F_n \cos\varphi \cos\alpha_1 \frac{\partial x_3}{\partial s} + F_\tau \frac{\partial x_1}{\partial s}$$

$$\rho_0 \frac{\partial v_2}{\partial t} = \frac{\partial}{\partial s}\left(\frac{T}{\lambda}\frac{\partial x_2}{\partial s}\right) - F_n \cos\varphi \sin\alpha_1 \frac{\partial x_3}{\partial s} + F_\tau \frac{\partial x_2}{\partial s}$$

$$\rho_0 \frac{\partial v_3}{\partial t} = \frac{\partial}{\partial s}\left(\frac{T}{\lambda}\frac{\partial x_3}{\partial s}\right) + F_n \lambda \cos\varphi \sin\gamma + F_\tau \frac{\partial x_3}{\partial s} - \rho_0 g \tag{2}$$

$$\cos\alpha = \frac{1}{\lambda}\frac{\partial x_1}{\partial s},\ \cos\beta = \frac{1}{\lambda}\frac{\partial x_2}{\partial s},\ \cos\gamma = \frac{1}{\lambda}\frac{\partial x_3}{\partial s}$$

$$tg\alpha_1 = \frac{\partial x_2}{\partial x_1} = \left(\frac{1}{\lambda}\frac{\partial x_2}{\partial s}\right) \Big/ \left(\frac{1}{\lambda}\frac{\partial x_1}{\partial s}\right) = \frac{\cos\beta}{\cos\alpha},\ \cos\alpha_1 = 1\Big/\sqrt{1+tg^2\alpha_1} = \cos\alpha\Big/\sqrt{\cos^2\alpha + \cos^2\beta}$$

$$\sin\alpha_1 = \cos\beta\Big/\sqrt{\cos^2\alpha + \cos^2\beta}$$

The components of the aerodynamic forces - (Devnin S.I.)

$$F_n = \frac{\rho U_\infty^2}{2} d\left(c_n \sin^2\alpha + c_\tau \sin\alpha\right),\ F_\tau = \frac{\rho U_\infty^2}{2} d\, c_\tau \cos^2\alpha \tag{3}$$

$$c_n = 1{,}8446,\ c_\tau = 0{,}0554$$

Influence of transverse oscillations [3]

$$F_n(s,t) = F_n^0(s,t)\left[1 - \mu V_n / U_\infty\right]^2 sign\left[1 - \mu V_n / U_\infty\right] \tag{4}$$

Correction of speeds [3]

$$\bar{v}_k = v_k + \beta \partial^2 v_k \big/ \partial s^2 \tag{5}$$

The physical relationships (Kelvin-Voigt)

$$T = E \cdot e + \eta \cdot \dot{e} \tag{6}$$

Courant-Friedrichs-Levy conditions

$$\Delta\tau = \alpha_k \Delta s \sqrt{\rho_0 / E} \tag{7}$$

## The verification of the elastic part of the problem

The verification of the elastic part of the problem is carried out by comparison with analytical solutions: a) weight acts along the axis $Ox_3$, in the work [4] an analytical solution was obtained for the static state of a power line and a numerical solution. For a static problem, the relative error, as compared with the exact solution, is $\theta \approx 0.12\%$:

$$x_3 = -l^2 \rho_0 g\left[(1+\varepsilon)/(E\varepsilon)\right]/8,\ \varepsilon = \sqrt[3]{\gamma/2 + \left[(\gamma/2)^2 - (\gamma/3)^3\right]^{1/2}} + \sqrt[3]{\gamma/2 - \left[(\gamma/2)^2 - (\gamma/3)^3\right]^{1/2}}$$

$$\gamma = (\rho_0 g)^2 l^2 / \left(24E^2\right)$$

b) under the wind load, the pressure change acts along the normal to the deformed wire. For this case, a numerical comparison of the equations with an approximate analytical solution was compared in [6]. The relative error is less than $\theta \approx 0.007\%$:

$$r = l/(2\sin\varphi),\ \varphi = (3pl/E)^{1/3}\left[1 + (3pl/E)^{2/3}/60\right],\ x_1 = r\left[1 - \sqrt{1 - (l/(2r))^2}\right].$$

## THE WIRE DANCE

On the basis of numerical simulation, the mechanism for the appearance of "the Wire Dance" under the influence of a variable wind load is shown, (Fig. 2)

Consider a gust of wind that acts in a horizontal plane $Ox_1x_2$ with a sinusoidal law of variation

$$p(\tau) = q_0 d\left|\sin(\pi\, n/\delta)\right| \tag{8}$$

Where $q_0$ is the speed head at wind speed $V_0$, $d$ the wire diameter, $n = \tau/\Delta\tau$, $\tau$ - current time, $\Delta\tau$ - integration step, $n/\delta = 1,2,3..$ - zero points of the sinusoid.

Figure 2, a–d show the results of calculating the motion of the midpoint of the span in accordance with the algorithm (2-7). The initial state of the span at time $\tau = 0$ is taken as a straight line. From this state, under the influence of the weight of the wire, a transient process is realized up to the shape of the equilibrium state (Fig. 2, a). The maximum deflection is $x_3 = -4.54\times10^{-2}$. At a time $\tau \geq 4$ there is a gust of wind in accordance with (8). The oscillations of the midpoint of the wire are shown in the plane $Ox_1x_2$ , Fig. 2, b).

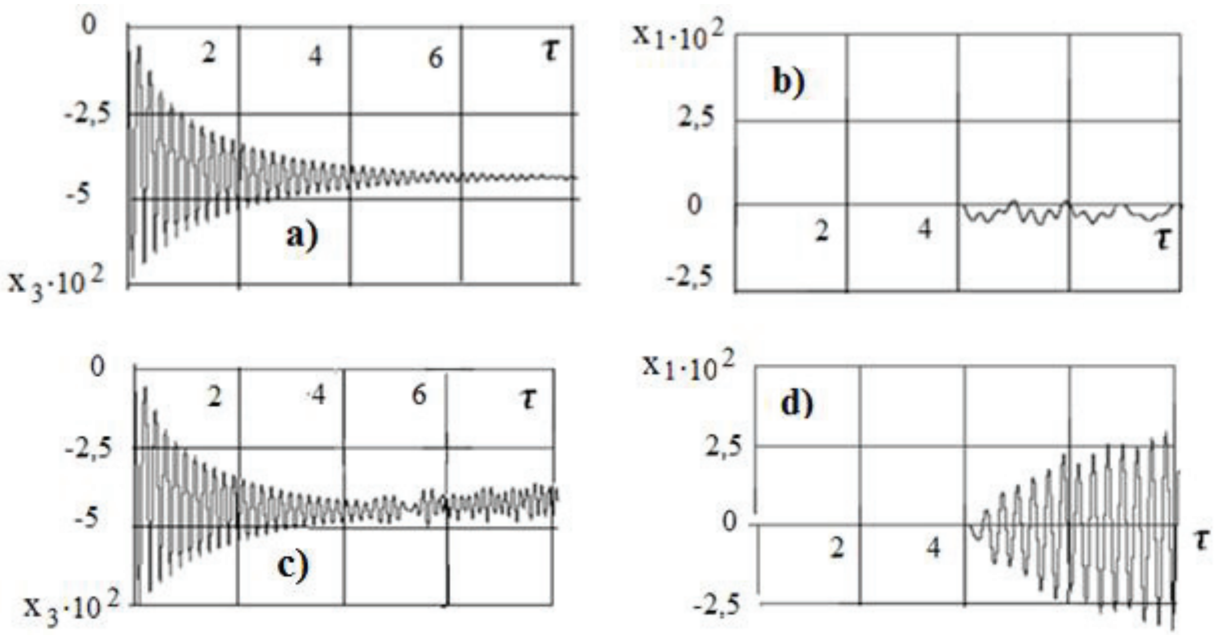


**FIGURE 2.** Dancing wires: a) transient process of equilibrium state; b) $\tau \geq 4$ operates a gust of wind; c), d) at a time $\tau \geq 4$ and coincides with the motion at the speed of the wire elements $v_{x_{1i}} \leq 0$ , and when the wire element moves $v_{x_{1i}} > 0$, it is zero

Letka consider the following option, when the wind pressure varies according to the law (8) at time $\tau \geq 4$ and coincides with the motion at the speed of the wire elements $v_{x_{1i}} \leq 0$, and when the wire element moves $v_{x_{1i}} > 0$, it is zero. That is, a gust of wind helps to wobble the wire in a horizontal plane $Ox_1x_2$. These results are shown in Fig. 2, c, d. The amplitude of the oscillation in the plane increases. These oscillations are reflected in the oscillations of the wire in the vertical plane $Ox_2x_3$, Fig. 2, c.

Thus, the increasing amplitude of oscillations contributes to the appearance of oscillations such as “dancing wires”.

## THE EQUATION OF THERMAL CONDUCTIVITY

The equation of thermal conductivity for a linear element has the form:

$$c\rho\, u_t = (ku_s)_s + f_0(s,t) \tag{9}$$

### Checking the algorithm of the heat conduction (9)

The insulated wire, 160 meter long, is divided into two parts. Left part is heated to 200°C, right part has temperature of -5°C. In a dimensionless form these temperatures are 1.7322 and 0.9817. The process continues to the temperature (1.7322 + 0.9817)/2 = 1.35695. Calculations according to (9) give 1.35689 for 2.1 second.

## THE RESULTS OF THE NUMERICAL EXPERIMENT OF THE POWER LINE

The results of the numerical experiment of the power line with regard to the weight of the wire, the weight of ice and thermal conductivity [5]. In accordance with the solution of the equation of motion, the wire under the influence of its own weight moves to the sag max $f$ = 3.4 meter, with the tension being $T$ = 12 kN, then, as a result of the transient process, after a time of about 30 seconds self-adjusting to the form of an equilibrium state with a deflection max $f$ = 2.3 meter. This shape of the equilibrium state is affected by a uniform by length icing. The system again comes to an equilibrium state with a mass of wire and icing, this state at time $t$ = 51 second is shown on Fig. 3 (–•–).

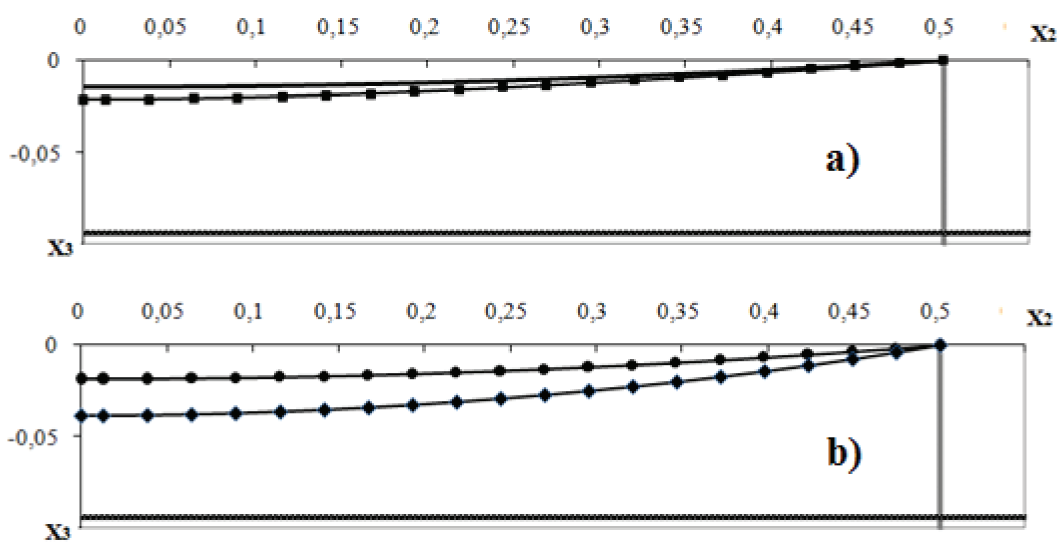


**FIGURE 3.** Dynamics of loading (TL): a) equilibrium and dynamic state of the wire when loading only the weight of the wire; b) equilibrium shape of wires with light icing (–•–) and shape after heating (–♦–)

Maximum sag is $f$ = 2.95 meter and tension $T = 9{,}8\,\mathrm{kN}$. It is assumed that at the time $t = 51\,\mathrm{sec}$ 1/10 part of the span is instantly heated to temperature 150°C, and this temperature keeps unchanged on this part and heats the rest of the span due to thermal conductivity for 5 seconds. During this time, this temperature spreads and equalizes to 150 °

C along the entire wire length. Wire elongates due to thermal expansion. At the end of the heating, the sag reaches a value max $f = 6.2$ meter (–♦–), and the temperature tension in the wire is 38 kN .

After that the mass of icing is considered to be reset immediately, within one second the temperature is equalized with the ambient temperature equal to minus 5°C. Further movement is calculated, the system passes into a new equilibrium state with the maximum deflection 2.3meter and tension of the wire 6.2 kN.

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