Dynamic vibration absorber in robot for inspection of electrical transmission lines with unequal height elevations

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Abstract. The aim of this paper is to study the use of a dynamic vibration absorber in a robot for inspection of electrical transmission lines. To achieve this, in this paper, a mathematical model used to study the motion of a robot for inspection of electrical transmission lines. In this model, the electrical line, which is located on a different level of elevations, is considered as a thread. The robot considered a moving load on the line. First, the configuration and tension in the thread have been calculated. Then the equation of motion is written using the Lagrange method. As a result, vibrations in the horizontal plane of the motion appears. These vibrations might serve as a source of parametric oscillations' appearance in the perpendicular plane of motion. To avoid dangerous oscillation in the vertical plane of motion and achieve dynamical stability during the operation of the robot on the electrical line, dynamic vibration absorber has been used and its performance evaluated.

1. Introduction

Population growth, industrial developments, etc. leads to an increase in demand for electrical power. Electricity producing in power plants transmitted to end-users (industrial sectors, cities, etc.) through electrical transmission lines. Any failure to this may influence on the performance of industrial sectors and human lives. Therefore, supplying sustainable energy is the main goal of power companies around the world. In order to achieve this goal regular inspection of electrical transmission lines is planned and executed. One way of inspection is by using robots for this task. Figure 1(a) illustrates the proposal concept of a novel design of an electrical transmission line inspection machine [10].

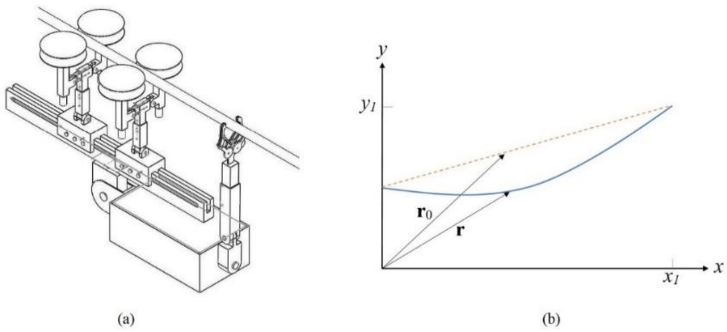


Figure 1. (a) Schematic of a robot inspector and (b) conductor as a thread [16].

In works [11-15], the electrical line conductor considered as a stretched string with a moving load, robot, on it. In these works, as proved in [11] the tension in the conductor is constant. In work [16], the conductor considered as a thread, since assumed that the electrical towers, supports, are located in different elevation levels and as shown, the tension, in this case, is not constant. In [16], showed that even the motion of the robot is constantly led to extensive fluctuations in the horizontal plane of motion. The consequence of these fluctuations might cause parametric oscillation in the vertical plane of motion as shown in [12-16].

In this paper, a mathematical model developed to study the dynamic vibration absorber system use in order to avoid dangerous oscillation in the vertical plane of motion.

2. Vibration in an electrical line

2.1. Modeling of an overhead electrical line as a thread

In this section, the dynamics of the conductor with a moving load is considered (figure 1(b)). This is the model in which the conductor is considered as a thread, and the robot inspector is considered as a moving object along with it. Here, we use the method explained in [11, 16].

In figure 1(b), $\mathbf{r_0}$ and $\mathbf{r}$ are the arc coordinate in the initial state and after the deformation.

The tension force is calculated $T = b\varepsilon$ since the initial state is unstressed. Here, b is the tensile stiffness ($b = E\pi R^2$) and ε is the elongation, calculating by $\varepsilon = |r'| - 1$ (prime means differentiation with respect to x).

The equation of the balance of forces from [16] is:

$$\mathbf{T}' = -\mathbf{q}, \mathbf{T} = T\mathbf{r}' / |\mathbf{r}'| \Rightarrow \mathbf{r}' = \mathbf{T}(b^{-1} + |\mathbf{T}|^{-1}). \tag{1}$$

In (1) q is distributed force and with boundary conditions is $x(0) = 0, x(L) = x_1, y(0) = y_0, y(L) = y_1$ where L is the initial length of the electrical line.

Now one can present the nonlinear boundary problem posed for the ODE system in matrix form,

$$\begin{aligned} &Y = [T_x \quad T_y \quad x \quad y]^T, \\ &Y' = F(\xi, Y) = [-q_x \quad -q_y \quad Y_0 G(Y) \quad Y_1 G(Y)]^T, \\ &G(Y) = \left(\frac{b + \sqrt{Y_0^2 + Y_1^2}}{b\sqrt{Y_0^2 + Y_1^2}} \right), \end{aligned} \tag{2}$$

and solve it.

Here, we use an aluminum wire of radius R=2.5 cm and E=7e10 N/m2 (E is Young's modulus) for calculation. Parameters for calculation are l=150 m, x_1=150 m, y_0= 40 m, y_1 =80 m q_x=0, q_y=-ρg (linear weight, distributed loads). The calculated wire configuration is shown in figure 2(a) and in figure 2(b) the tension force, $T(\xi) = \sqrt{T_x^2 + T_y^2}$, is presented.

2.2. Oscillation in the horizontal plane of motion

The equation of the deflection in thread problems, $u(x,t)$, is known [11]:

$$\begin{aligned} &EJu'''' + T(x)u'' + f(x,t) = \rho\ddot{u}, \\ &f(x,t) = P(t)\delta(x - \xi(t)), \end{aligned} \tag{3}$$

with initial conditions $u(0,t) = u''(l,t) = 0, u(x,0) = \dot{u}(x,0) = 0$. Here, l is the length of the electrical transmission line. In (3), the tension in the thread is denoted by T, the linear load is designated f, and the density is denoted by ρ. It should be noted that the prime and dot mean differentiation by coordinate x and time t. Function $P(t)$ is point load, moving with an arbitrary law defining by $\xi(t)$. In this article $P(t)$ is constant and equals the weight of the robot inspector, $P = mg$, and it moves with a constant speed i.e. $\xi(t) = vt$.

To solve (3) we use the results obtained by the Lagrangian method in [11]. The defining approximate solution, $u(x,t)=\sum_{n=1}^{\infty}u_n(t)\varphi_n(x)$, leads to the final solution:

$$(M+\mu)\ddot{q}+[C+\dot{\xi}^2\kappa(\xi)]q+2\dot{\xi}\eta^T(\xi)\dot{q}=F, \tag{4}$$

where

$$\varphi_n=\sqrt{\frac{2}{l}}\sin\lambda_n x,\ \ \lambda_n=\frac{n\pi}{l},\ \ \kappa=m\varphi\varphi''^T, M=\int_0^L\rho\varphi\varphi^T\mathrm{d}x, \mu=m\varphi\varphi^T,$$
$$\sigma=m\varphi'\varphi'^T,\ \ \eta=m\varphi'\varphi^T,\ \ F=P\varphi, C=\int_0^L(T\varphi'\varphi'^T+EJ\varphi''\varphi''^T)\mathrm{d}x. \tag{5}$$

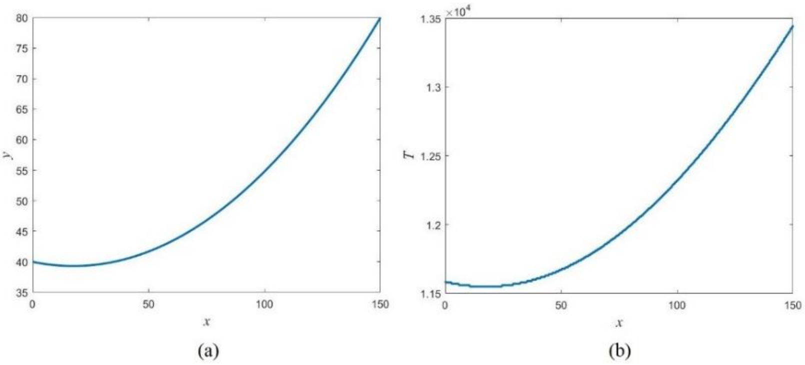


Figure 2. (a) Configuration and (b) tension of the conductor of an overhead line.

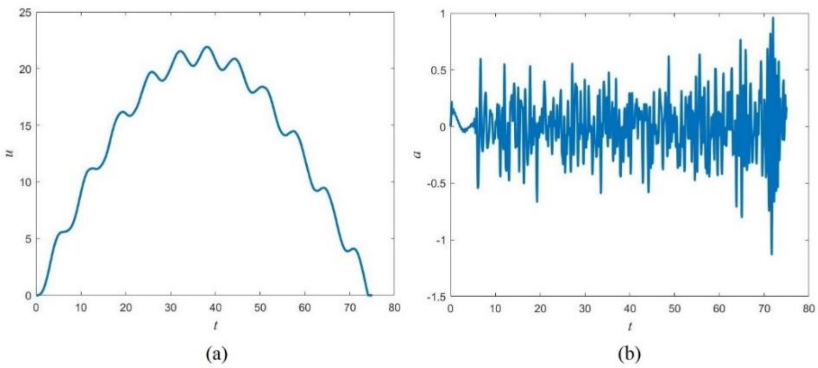


Figure 3. (*a*) Deflection and (*b*) acceleration of the conductor of an overhead line.

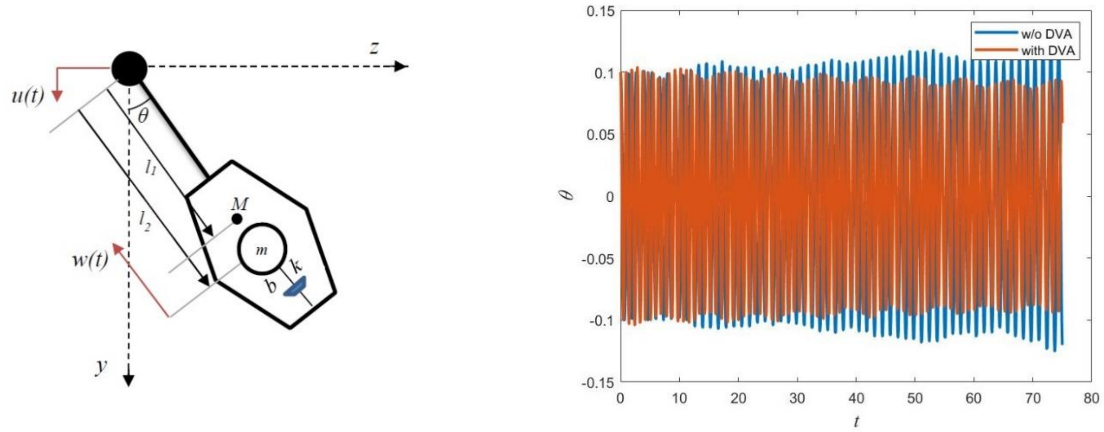
Equation (4) has been solved with the help of a mathematical computer program. For calculation the following parameters are used: T=10 kN, F=1 kN, v=2 m/s, ρ= 5 kg/m, l= 150 m. The deflection and acceleration of the electrical line conductor are presented in figure 3. Figure 3(*a*) presents the appearance of oscillations in the vertical plane, even the speed of traveling load was constant. Acceleration (figure 3(*b*)) might cause an inertial load on the robot construction.

3. Dynamic vibration absorber for electrical line robot inspector

As shown in [12] the vibrations in the horizontal plane may cause parametric oscillations in the vertical plane of motion. [16] presents an example of the appearance of dangerous vibrations (an increase of the amplitude of oscillations by the time of process).

In this work, in order to prevent such dangerous oscillation (not classical parametric oscillations) in the vertical plane of motion (presented in [14-15]), dynamic vibration absorber (DVA) has been used and its performance has been studied.

Figure 4(a) shows the concept for DVA [15] to decrease the pendulum sway motion (we considered the robot as a pendulum with a suspension base).



(a) (b)

Figure 4. (a) Dynamic vibration absorber scheme and (b) vibration of a pendulum with a suspension base with and without DVA.

In figure 4(a), M and m are designated to the main and tuned masses respectively. Here, θ is the deflection angle from the vertical axis. The center of mass of the pendulum and tuned mass are shown by l_1 and l_2 respectively. The spring stiffness and the damping coefficient of the DVA system are indicated by k and c. The base of pendulum moves with the function $u(t)$ in the vertical direction (obtained from the previous section). $w(t)$ describes the motion of the tuned mass of the DVA system.

Using positions of the main system mass (z_1, y_1) and the DVA mass (z_2, y_2) and the velocities of both masses, one can write the kinetic energy and potential energy as:

$$\begin{aligned}
&2K = M(\dot{z}_1^{\,2} + \dot{y}_1^{\,2}) + m(\dot{z}_2^{\,2} + \dot{y}_2^{\,2}) \Rightarrow \\
&2K = M\left(l_1^2\dot{\theta}^2 + \dot{u}^2 - 2l_1\dot{u}\dot{\theta}\sin(\theta)\right) + \ldots \\
&\ldots + m\left\{\dot{\theta}^2(l_2 - w)^2 + \dot{u}^2 + \dot{w}^2 - 2\dot{u}\dot{w}\cos(\theta) - 2(l_2 - w)\dot{u}\dot{\theta}\sin(\theta)\right\}, \\
&U = \frac{1}{2}kw^2 + g(1 - \cos\theta)(Ml_1 + m(l_2 - w)).
\end{aligned} \tag{6}$$

Using general forces, $Q_w = -c\dot{w}, Q_\theta = 0$, one can obtain the system of equations using (6) for the general coordinate's θ and w:

$$\begin{aligned}
&\frac{d}{dt}\left(\frac{\partial K}{\partial \dot{q}_i}\right) - \left(\frac{\partial K}{\partial q_i}\right) + \frac{\partial U}{\partial q_i} = Q_i \Rightarrow \\
&\ddot{\theta}[Ml_1^{\,2} + m(l_2 - w)^2] - 2m\dot{\theta}\dot{d}(r_2 - d) + (g - \ddot{u})(Ml_1 + m(l_2 - w))\sin(\theta) = 0, \\
&m\ddot{w} + b\dot{w} + kw + m\dot{\theta}^2(l_2 - w)^2 = m\cos(\theta)\ddot{u} + mg(1 - \cos(\theta)).
\end{aligned} \tag{7}$$

Here, initial conditions are $\theta(0) = 0.1,\ \dot{\theta}(0) = 0$ and $a(t)$ as shown in figure 3 (b). Equation (7) has been solved numerically. Parameters for calculation are M=100 kg, m=2 kg, l_1=0.3 m, l_2= 0.5 m, k= 0.5 N/m, b=15 N.s/m. Figure 4(b) shows the results.

As illustrated in figure 4(b) (blue graph) the amplitude of fluctuations increased by the time of process when there is no DVA involved, but with DVA (figure 4(b) (orange graph)) became limited by the time of the process. This example shows the possibility of usage of DVA in electrical transmission inspection robots.

4. Conclusion

As a result of mathematical modeling, it is shown that even by the constant speed of the robot on the line vibrations appear in the horizontal and vertical planes of motion. These vibrations influence the stability of the performance of the robot on the line. To avoid these instabilities, a dynamic vibration absorber has been used and investigated. This article is a good example that shows the possibility of usage of DVA in electrical transmission inspection robots.

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