Digitally controlled forced vibration of suspended conductors

Security and data protection in the fields of material technology, industry 4.0 and energy

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Nemzeti Kutatási, Fejlesztési és Innovációs Hivatal

AZ NKFI ALAPBÓL MEGVALÓSULÓ PROJEKT

Transmission line protection by vibration control

Methodology

- Analyze the effects of natural phenomena (wind, ice) that transmission lines are exposed to
- Simulate the resulting vibrations
- Develop solutions in order to attenuate vibration, and thereby reduce the harmful effects of the phenomena studied

Parallel projects

- Flow-induced vibration of elastic cables (D. Dorogi)
- Buckling of conductors during vibration following ice shedding
- Bending vibration of a beam modelling wind turbine blade
- Effects of thermodynamic parameters on icing of a wind turbine blade
- Processing technologies (J. Sidor)

Digitally controlled forced vibration of suspended conductors

Goals

- Develop model of vibration control that is applied locally on the conductor
- Apply the model to attenuate wind-induced vibration
- Study the dynamics of controlled system considering time delay due to sampling and backlash at the driving

Methodology

- Theoretical and numerical modelling
- Model validation by former experimental results

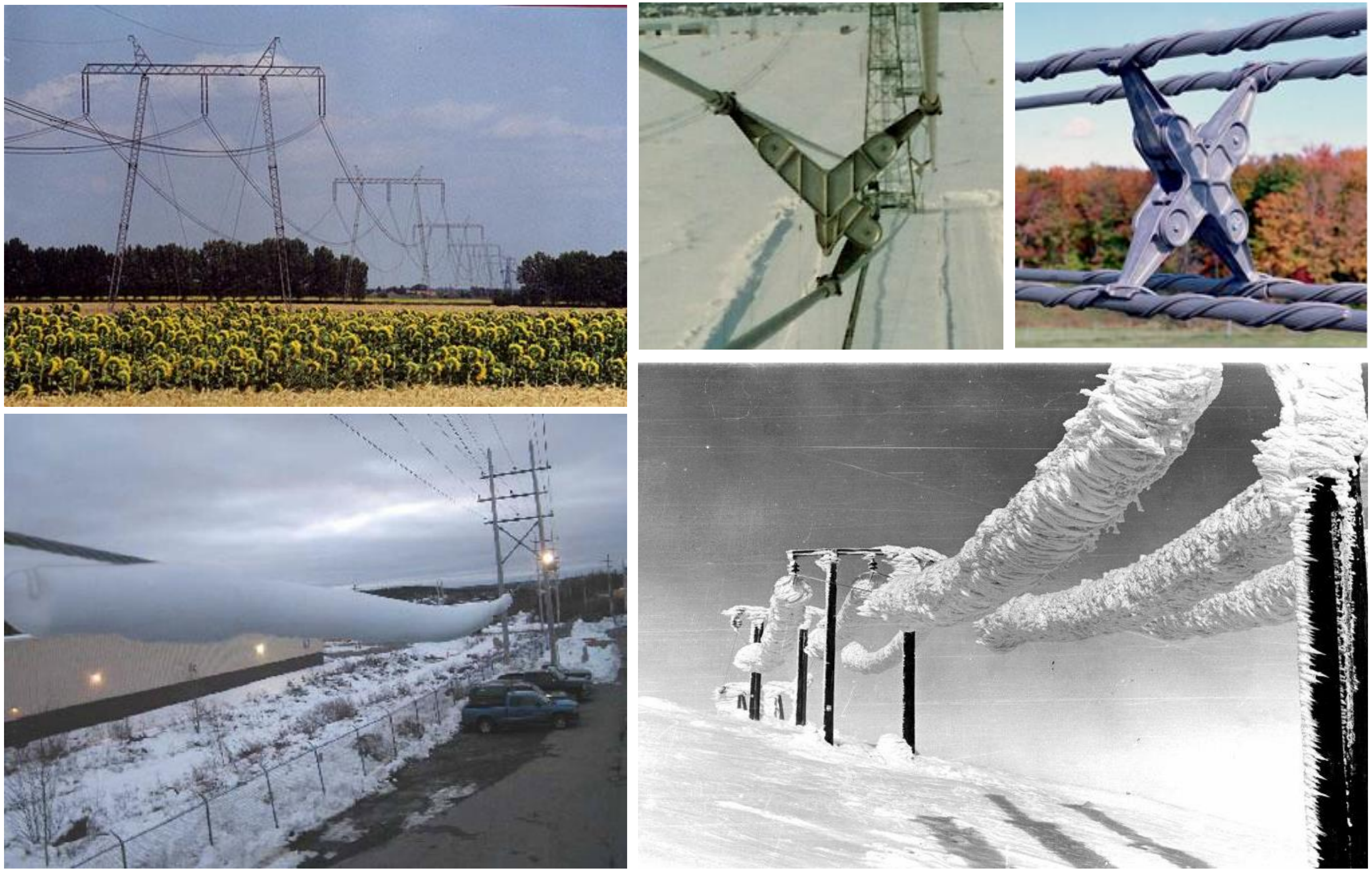
Effects of natural phenomena

Natural phenomena

- Wind
- Ice accretion and ice shedding
- Impacts

Loads on transmission lines

- High sag
- Vibration (high-frequency or high-amplitude)
- Rotation of conductor bundle



Damages on transmission lines

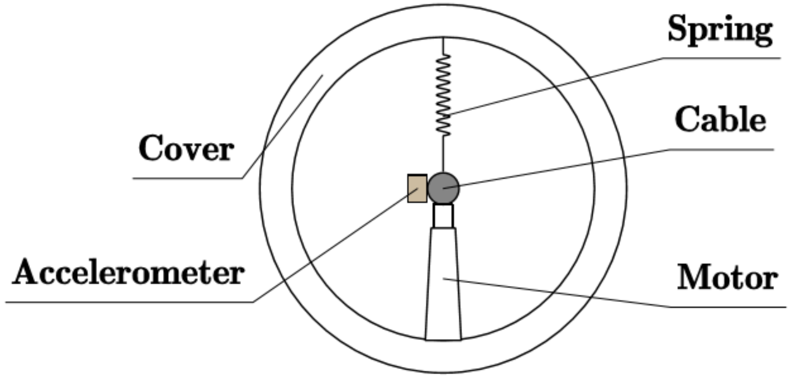
Damages

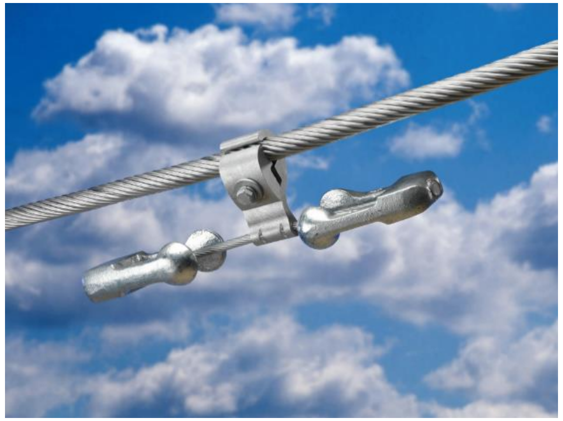
- Flashover
- Insulator breakage
- Conductor damage
- Tower collapse

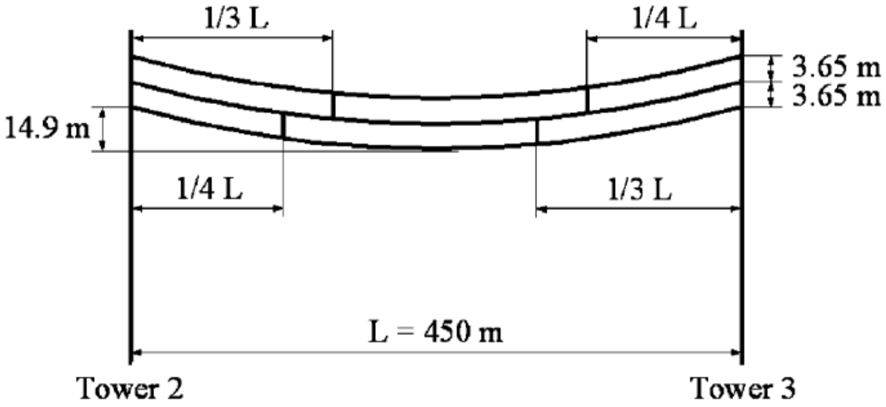
Line protecion methods

Methods for attenuation of vibration

- Vibration absorbers
- Interphase spacers
- Active control







Simplified model for vibration control

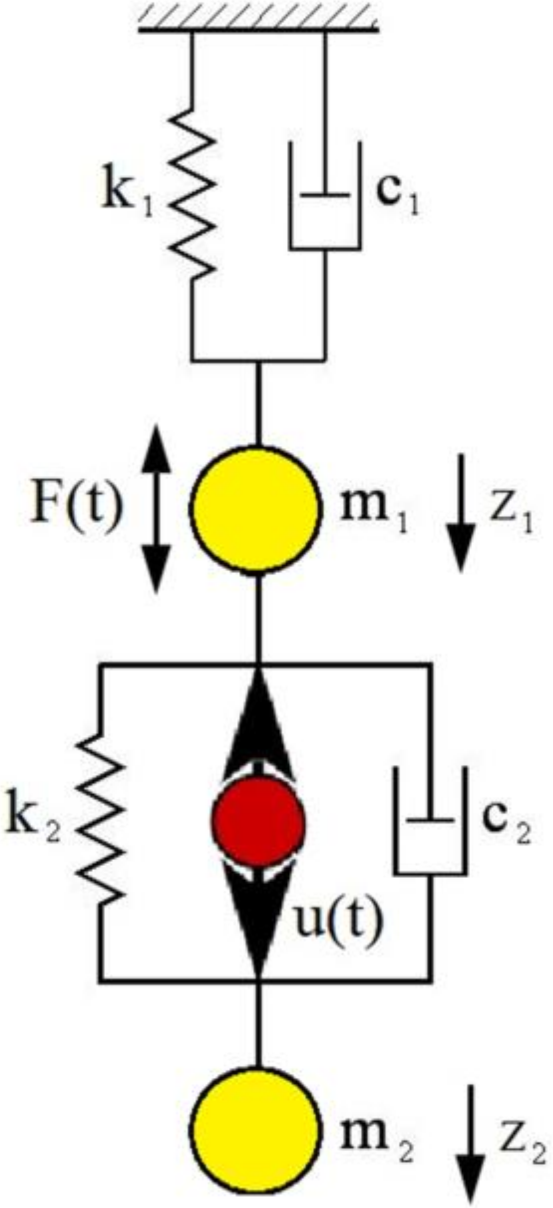
2DOF model of conductor with absorber

- Conductor: m_1, k_1, c_1
- Vibration absorber: m_2, k_2, c_2
- Excitation (wind): $F(t) = F_m \cos(\omega t)$
- Control force: $u(t) = P z_1(t-\tau) + D\dot{z}_1(t-\tau)$

Model parameters

- Spring stiffness k_1 from relationship between vertical displacement and concentrated force (Irvine, 1981) – linear approximation (small displacements)

$$w_p(x) = \begin{cases} \dfrac{P_z L}{H+h}\left[\left(1-\dfrac{x_p}{L}\right)\dfrac{x}{L} - \dfrac{\mu g L h}{2HP_z}\dfrac{x}{L}\left(1-\dfrac{x}{L}\right)\right] & 0 \le x \le x_p \\ \dfrac{P_z L}{H+h}\left[\dfrac{x_p}{L}\left(1-\dfrac{x}{L}\right) - \dfrac{\mu g L h}{2HP_z}\dfrac{x}{L}\left(1-\dfrac{x}{L}\right)\right] & x_p \le x \le L \end{cases} \rightarrow \quad k_1 = \frac{\Delta P_z}{\Delta w_p}$$



Simplified model for vibration control

Model parameters

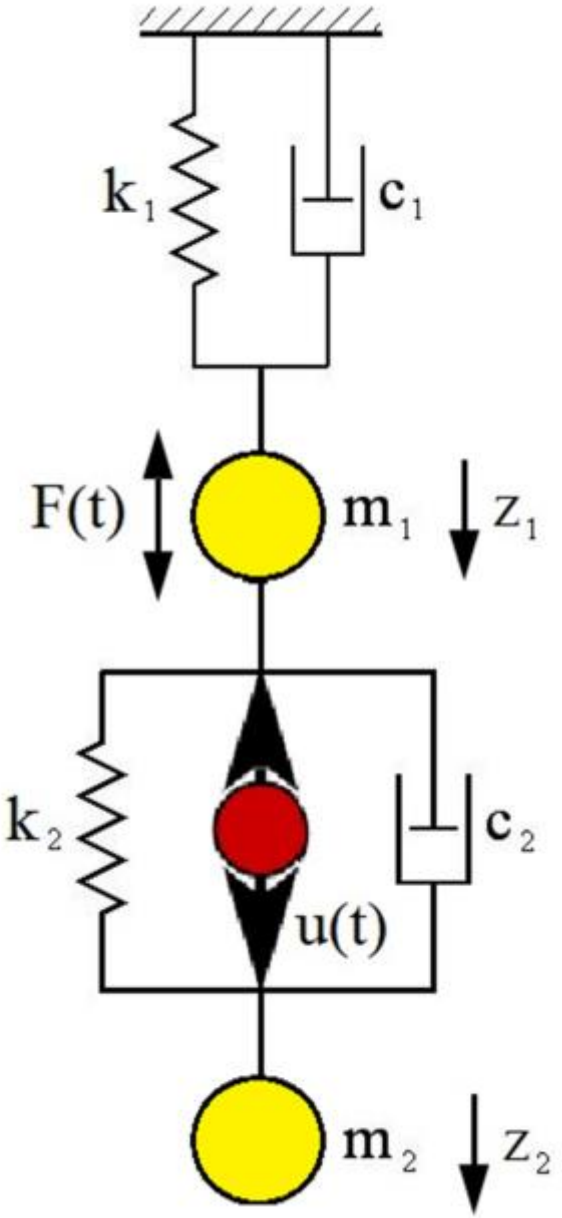
- Damping coefficient c_1 obtained from measured damping ratio
- Mass m_2: mass of absorber
- Damping coefficient c_2 obtained from decay of vibration
- Mass m_1 and spring stiffness k_2: natural frequencies of the 2DOF system are equal to two natural frequencies in vertical vibration modes, of the conductor with vibration absorber

Control

- Proportional gain: chosen so that together with the spring stiffness k_2, they provide the adequately tuned vibration absorber for the actual excitation frequency

$$P = k_2 - m_2\omega^2$$

- Differential gain: relatively small compared to proportional gain.



Equations of motion

Equations of motion with backlash at the driving

$$\dot{\mathbf{z}}(t) = \mathbf{A}\mathbf{z}(t) + \mathbf{b}u(t) + \mathbf{c}F(t)$$

where **z** is the vector including the coordinates and their derivatives. The control force is determined by

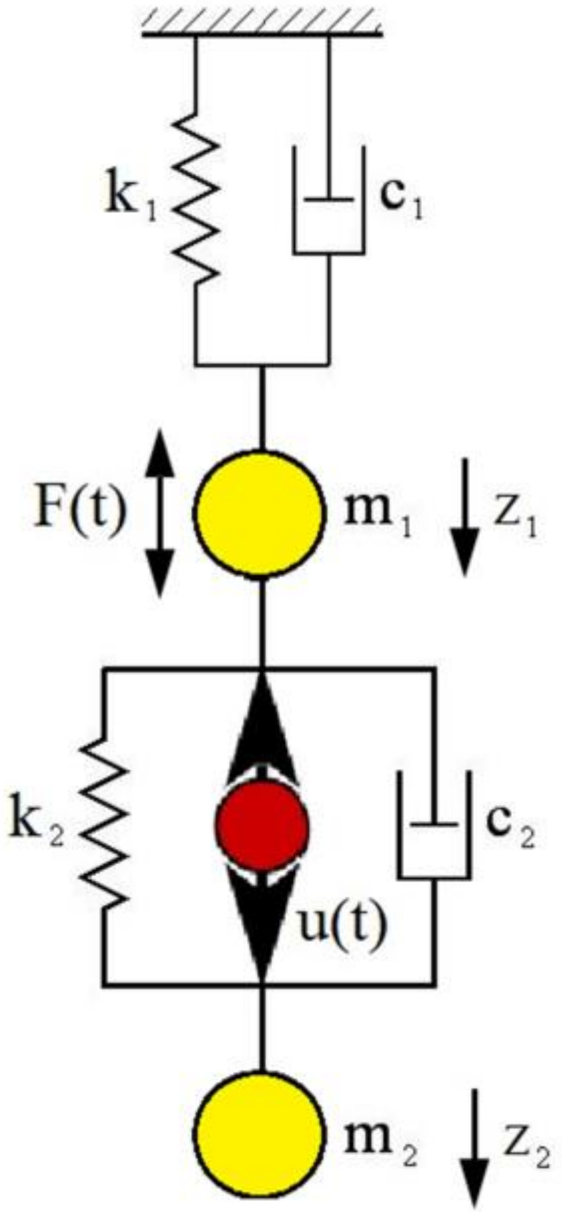
$$u(t) = \begin{cases} \mathbf{D}\mathbf{z}(t-\tau) & \text{outside backlash} \\ 0 & \text{domain of backlash} \end{cases}$$

where $\mathbf{D} = [P \;\; D \;\; 0 \;\; 0]$.

Discrete-time model

$$\mathbf{z}_{j+1} = \mathbf{A}_\mathbf{d}\mathbf{z}_j + \mathbf{b}_\mathbf{d}u_j + \mathbf{c}_\mathbf{d}F_j$$

$$u_{j+1} = \begin{cases} \mathbf{D}\mathbf{z}_j & \text{outside backlash} \\ 0 & \text{domain of backlash} \end{cases}$$

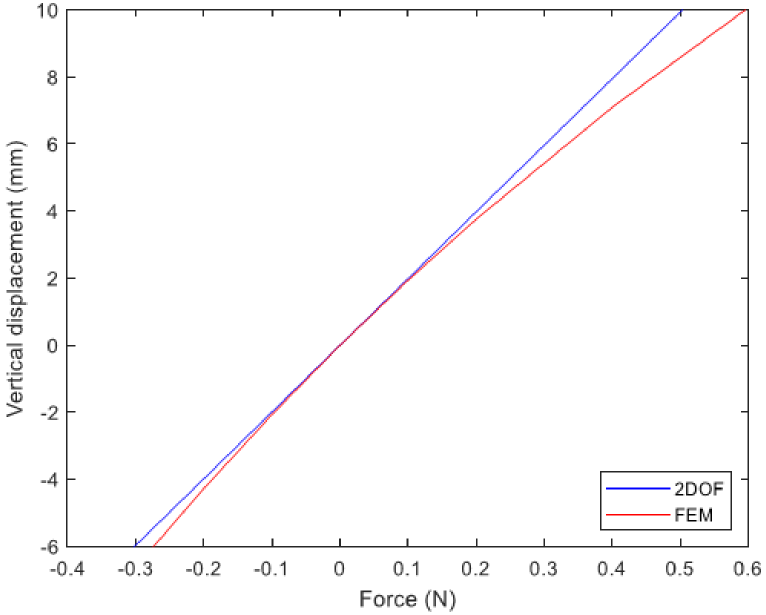


Model validation

Model is validated by comparing results with those obtained by a finite element model that was already validated by experiments

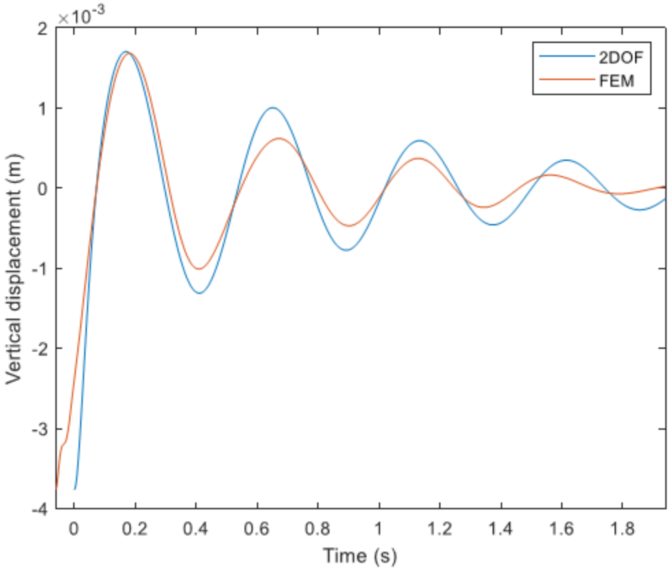
Static behaviour

- Displacements due to the application of concentrated force



Dynamic behaviour

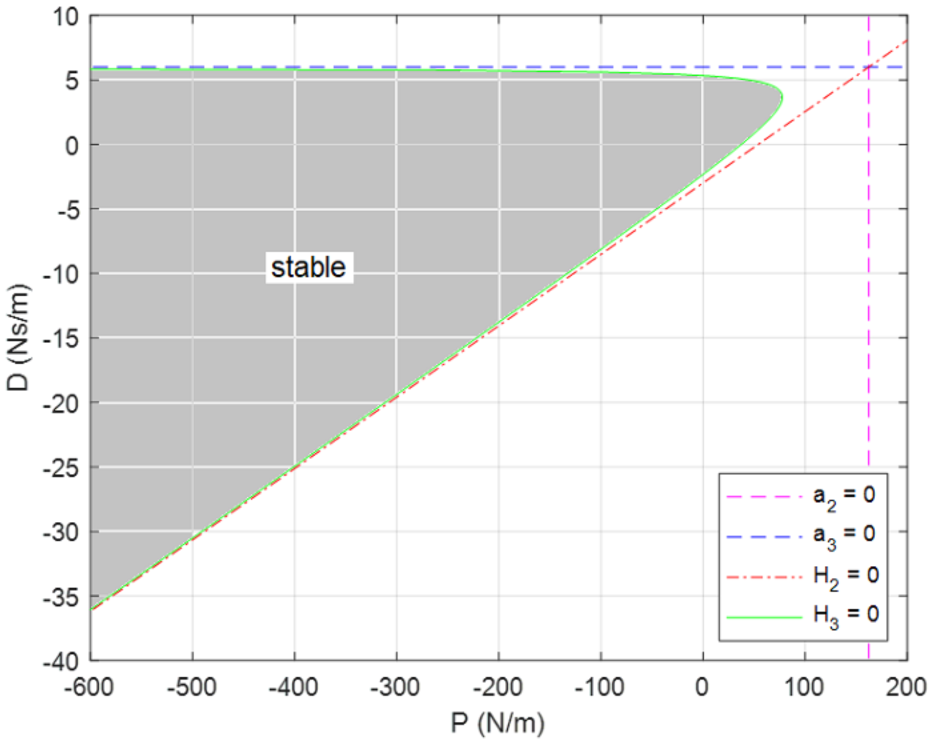
- Vibration following the removal of concentrated force



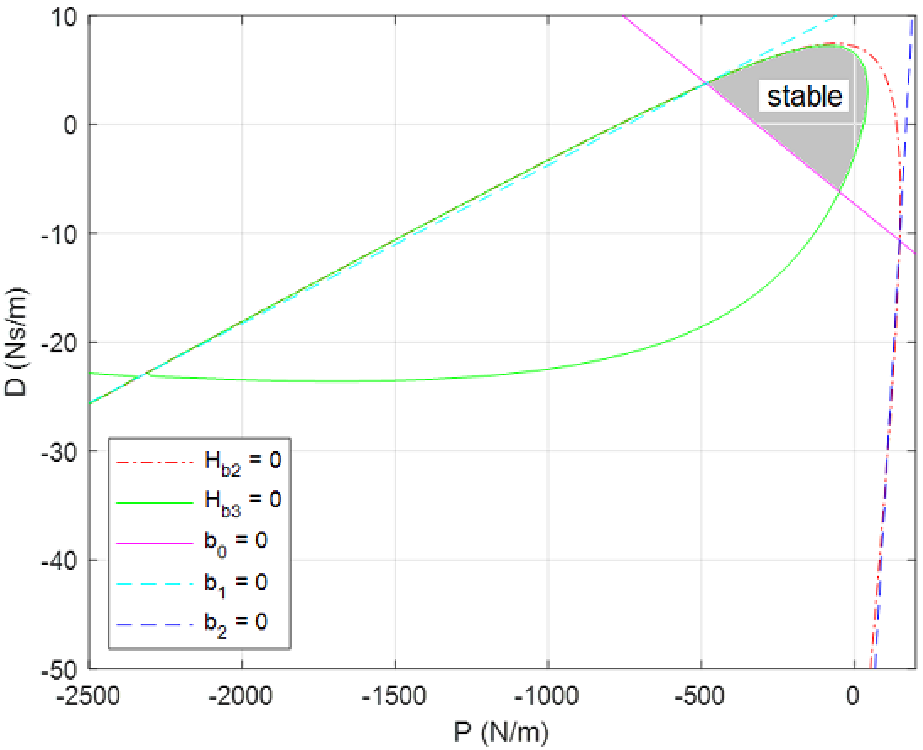
Stability of the digitally controlled vibration system

Stability domain on the plane of control parameters

No time delay



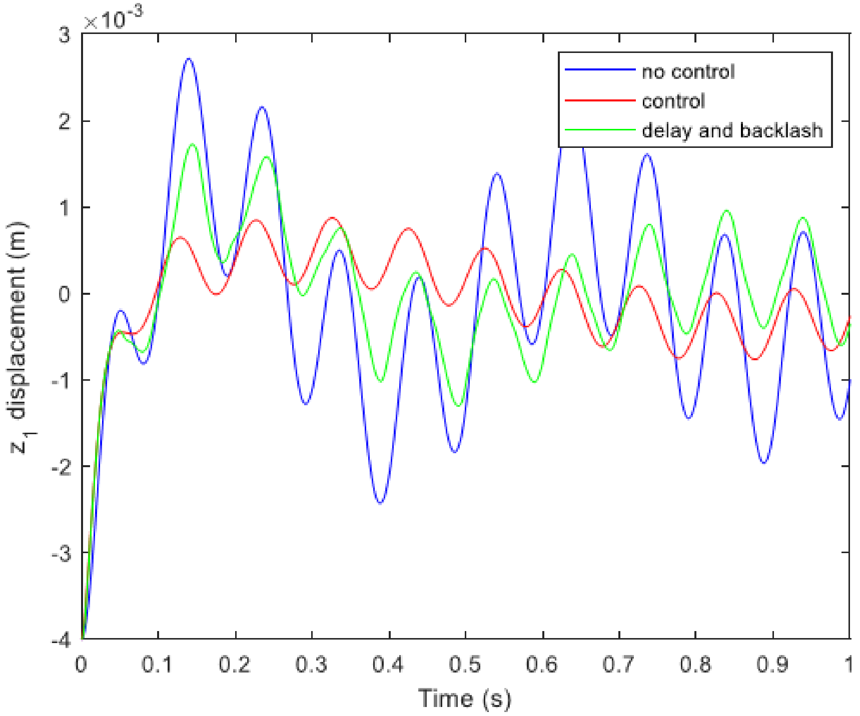
Time delay is 50 ms



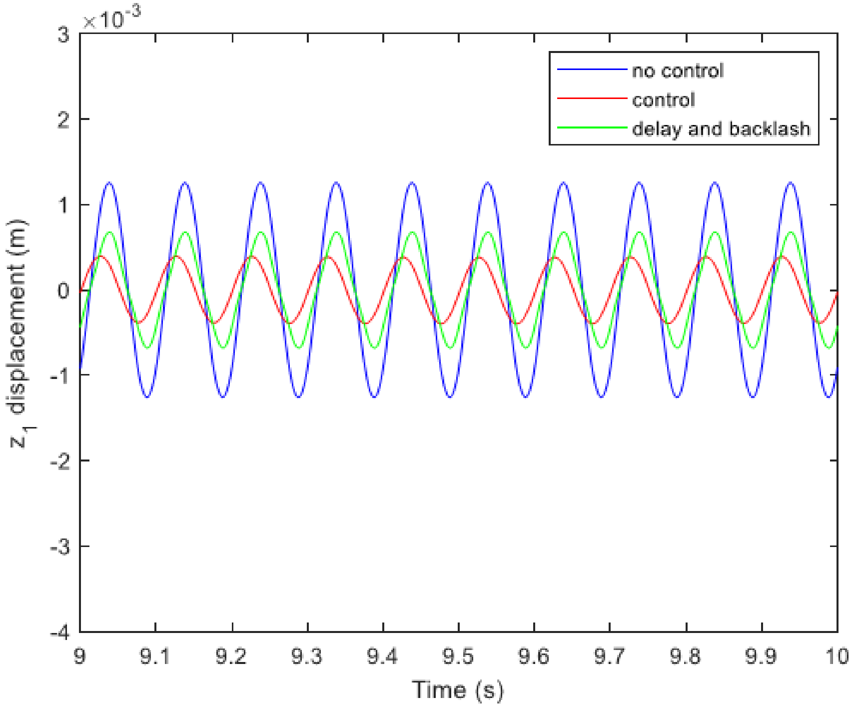
Dynamics of controlled vibration system
Time histories

Excitation: F_0 = 0.5 N; f = 10 Hz; Control: P = –557 N/m; D = –13 Ns/m;
Time delay: τ = 1 ms; Backlash: r_0 = 0.5 mm

Initiation of vibration



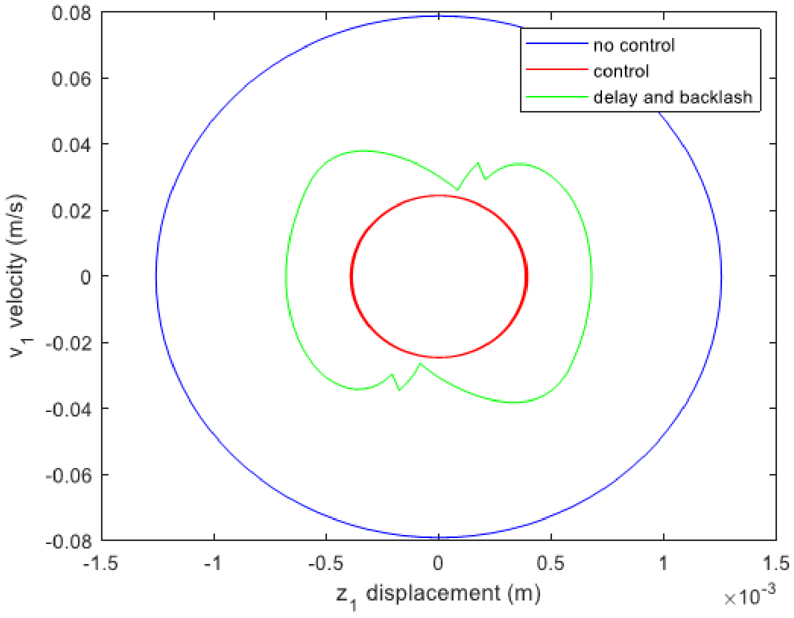
Steady state



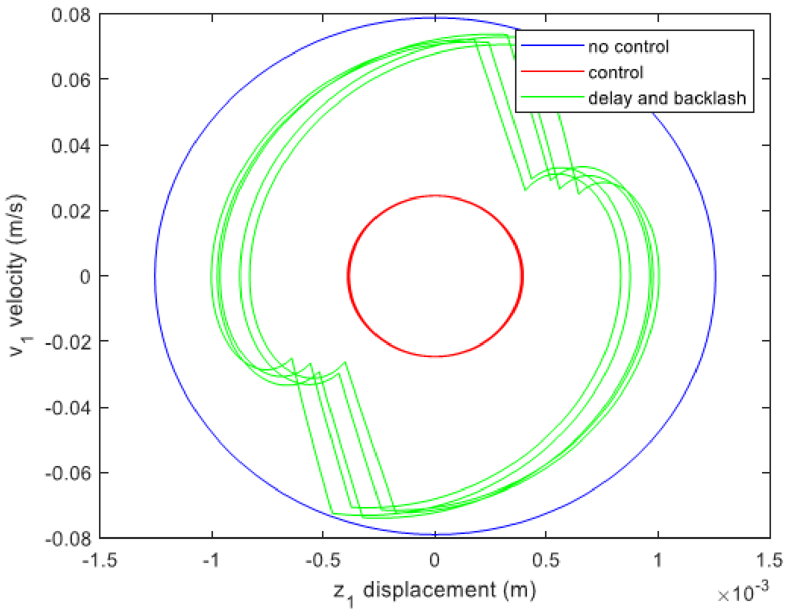
Dynamics of controlled vibration system
Phase diagrams

Excitation: F_0 = 0.5 N; f = 10 Hz; Control: P = –557 N/m; D = –13 Ns/m

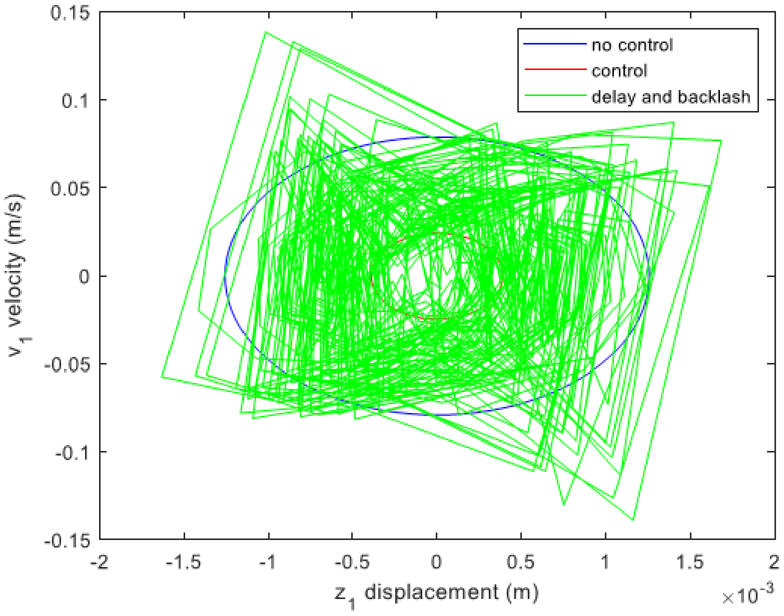
τ = 1 ms; r_0 = 0.5 mm



τ = 1 ms; r_0 = 2 mm



τ = 11 ms; r_0 = 2 mm



Dynamics of controlled vibration system
Investigation of irregular motion

Excitation: F_0 = 0.5 N; f = 10 Hz; Control: P = –557 N/m; D = –13 Ns/m
a) τ = 1 ms; r_0 = 2 mm; b) τ = 11 ms; r_0 = 2 mm

Investigation of the behaviour of irregular motion

- Fourier spectrum (FFT): peaks at the dominating frequencies, further small peaks for case b)
- Deviation between nearby trajectories (sensitive dependence on initial conditions):
  Case a): nearby trajectories neither approach nor stretch each other
  Case b): nearby trajectories approach each other
- Dense trajectories (topological transitivity): trajectories would not become arbitrarily dense
- Lyapunov exponents: all of them are negative

Conclusion: although irregular motions exist, these motions are periodic, no chaotic motion was observed.

Conclusions

Simplified model of controlled forced vibration of suspended conductors have been developed

- Model simulates vibration at a specific position along the conductor where the vibration absorber is attached
- Forced vibration considers the effects of high-frequency wind-induced vibration
- Time delay occurs due to sampling
- Backlash occurs at the driving (control force is not transmitted in the domain of backlash)

Results

- Stability domain in the plane of control parameter shrinks with increasing time delay
- Irregular motion occurs in the digitally controlled vibration with backlash at the driving – detailed investigation of such motion revealed that the motion is periodic, no chaotic motion was observed
- Practical observations: presence of backlash my require quick change (i.e. in the range of few ms) in the direction of rotation of the driving motor; irregular motion occurs for high values of backlash (i.e. in the range of 1 mm)

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