

# Out-of-plane vibration mitigation of wind turbine blade using highly efficient nonlinear energy sink

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## ABSTRACT

Nowadays, the use of wind as one of the main sources of low carbon and renewable energy is expanding rapidly all around the world. Recently, by development of wind farms and increase in the size of wind turbines, the wind loads on them has increased, and as a result, they have become more difficult and expensive to maintain. Therefore, researchers have deeply focused on the analysis and the control of their vibration. In this study, a wind turbine blade with a type of nonlinear absorber, called highly efficient nonlinear energy sink is analyzed, furthermore the interaction between the heavy and long blade and the nonlinear energy sink (NES), under the influence of gravity in the vertical plane and time dependent wind force, which is due to its height dependency is examined. For this purpose, the equations of motion of the system are obtained by energy method and solved numerically. The blade-NES system behavior is compared to that of the blade and linear absorber system. Also, the sensitivity of the parameters affecting the performance of the NES is analyzed and the vibration of the system with optimized NES are compared with the alone blade and the blade with the optimal linear absorber behaviors.

## KEYWORDS

Wind turbine, Mechanical vibration of blade, energy method, Sensitivity analysis, Nonlinear energy sink

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## 1. Introduction

Due to increasing in demand of electricity and higher productivity expectations, modern wind turbines are being built in larger dimensions in order to produce more electricity, which may generate higher force and significant vibrations.

In literature, considerable attention has been paid to the structural control of wind turbines and to reduce wind vibrations and improve the dynamic response of the structure, various control methods including the use of tuned mass dampers, Tuned liquid column damper and Active vibration control devices provided, while nonlinear energy sink has not been employed yet.

The present research has studied the control of out of plane vibration of a wind turbine blade, by using nonlinear energy sink (NES). For this purpose, the turbine blade is considered as an elastic beam rotate in the vertical plane. The model generated in [1] is applied for wind turbine structure and the highly efficient NES introduced in [2] is utilized as absorber. Accordingly, equations of blade and blade with absorber are extracted using Euler-Lagrange equation and the effect of NES is compared with the effect of optimal linear absorber [3].

## 2. Equations

A wind turbine blade is considered as an elastic beam so that one end is fixed perpendicular to the horizontal main shaft, and the other end is free. The wind blows in the horizontal direction, and the wind force acts on the rotating blade in out of plane direction, while its force ( $Q_y$ ) varies depending on the height from the ground.

By deriving kinematic energy, potential energy and non-conservative forces and applying the Lagrange's equation, the equations of motion of blade with a NES are obtained as:

$$\begin{aligned}
 & (1 + 4(\alpha_1 + \alpha(\delta)^2 f_{n11})z_l^2)\ddot{z}_l + c_l \dot{z}_l - c_{nes} \frac{h_\delta}{h_l} (\dot{z}_{nes} - \frac{h_\delta}{h_l} \dot{z}_l) + [4(\alpha_1 + \alpha(\delta)^2 f_{n12})z_l^2 + 2w^2(\alpha_2 - \alpha_1 z_l^2)]z_l \\
 & + [2w^2(\alpha(\delta) f_{n13} - \alpha(\delta)^2 z_l^2 f_{n14}) + 1 - g(1 + f_{n15}) \sin wt]z_l + k_{nes1} \frac{h_\delta}{h_l} (z_{nes} - \frac{h_\delta}{h_l} z_l - z_c) - k_{nes2} \frac{h_\delta}{h_l} \\
 & (z_{nes} - \frac{h_\delta}{h_l} z_l - z_c)^3 + k_{nes3} \frac{h_\delta}{h_l} (z_{nes} - \frac{h_\delta}{h_l} z_l - z_c)^5 \\
 & - k_{nes4} \frac{h_\delta}{h_l} (z_{nes} - \frac{h_\delta}{h_l} z_l - z_c)^7 = Q_c + \Delta Q \sin wt
 \end{aligned} \quad (1)$$

$$\begin{aligned}
 & f_{n21} \ddot{z}_{nes} + c_{nes} (\dot{z}_{nes} - \frac{h_\delta}{h_l} \dot{z}_l) - k_{nes1} (z_{nes} - \frac{h_\delta}{h_l} z_l - z_c)^7 + \\
 & k_{nes2} (z_{nes} - \frac{h_\delta}{h_l} z_l - z_c)^3 - k_{nes3} (z_{nes} - \frac{h_\delta}{h_l} z_l - z_c)^5 + \\
 & k_{nes4} (z_{nes} - \frac{h_\delta}{h_l} z_l - z_c)^7 = 0
 \end{aligned} \quad (2)$$

While:

$$f_{n11} = m_{nes} \alpha / \rho A h^2 \quad (3)$$

$$f_{n12} = f_{n14} = f_{n11} \quad (4)$$

$$f_{n13} = m_{nes} \delta / \rho A h \quad (5)$$

$$f_{n5} = m_{nes} \alpha(\delta) \alpha_3 / \rho A \beta_3 h^2 \quad (6)$$

$$f_{n21} = m_{nes} / \rho A \alpha_3 \quad (7)$$

Moreover, the equations of motion of the blade and linear absorber are as equations 8 and 9:

$$\begin{aligned}
 & (1 + 4(\alpha_1 + \alpha(\delta)^2 f_{n11})z_l^2)\ddot{z}_l + c_l \dot{z}_l - c_{abs} \frac{h_\delta}{h_l} (\dot{z}_{abs} - \frac{h_\delta}{h_l} \dot{z}_l) \\
 & \dot{z}_l + [4(\alpha_1 + \alpha(\delta)^2 f_{n12})z_l^2 + 2w^2(\alpha_2 - \alpha_1 z_l^2)]z_l + [2w^2
 \end{aligned} \quad (8)$$

$$\begin{aligned}
 & (\alpha(\delta) f_{n13} - \alpha(\delta)^2 z_l^2 f_{n14}) + 1 - g(1 + f_{n15}) \sin wt]z_l - \\
 & k_{abs} \frac{h_\delta}{h_l} (z_{abs} - \frac{h_\delta}{h_l} z_l) = Q_c + \Delta Q \sin wt
 \end{aligned}$$

$$f_{n21} \ddot{z}_{abs} + c_{abs} (\dot{z}_{abs} - \frac{h_\delta}{h_l} \dot{z}_l) + k_{abs} (z_{abs} - \frac{h_\delta}{h_l} z_l) = 0 \quad (9)$$

## 3. Solving the equations

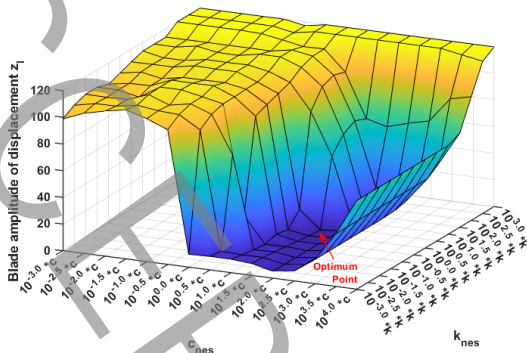
Above equations are solved numerically using Runge Kutta method by considering following values for the parameters:

**Table 1. Blade Parameters**

Parameter	Qty.	Unit
Density	7870	Kg/m <sup>3</sup>
Module of elasticity	200	GPa
Length	1.0	m
Width	0.04	m
Thickness	0.0025	m
$c_l$	0.001	N.s/m
$Q_c$	0.3	N
$\Delta Q$	0.1	N

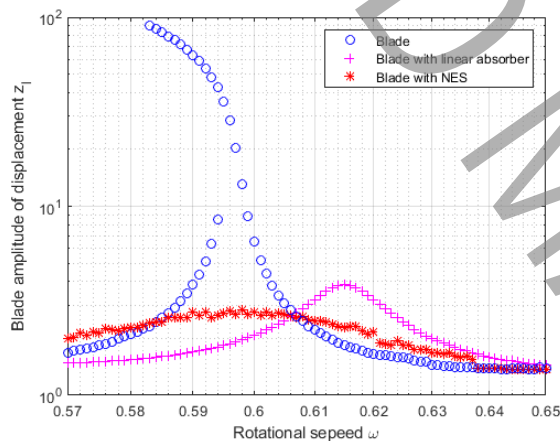
Sensitivity analysis of the effect of stiffness and damping coefficients of the NES on the blade displacement is performed to extract the optimal system

as shown in Figure 1. The initial spring stiffness and damping coefficient for the NES is such that the NES linear frequency is equal to the blade frequency and the damping is 10 times of the blade damping coefficient.



**Figure 1. Blade Vibration amplitude versus stiffness and damping coefficients of NES**

The frequency response diagrams of the wind turbine blade with NES, the blade with the optimal linear absorber, and the alone blade around the second super-harmonic resonance region are shown in Figure 2 as:

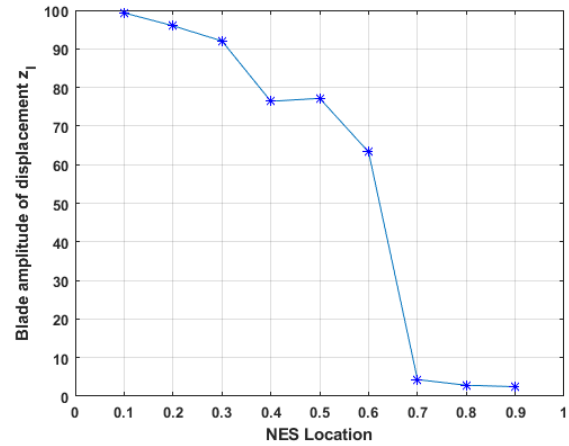


**Figure 2. Frequency response of the blade with NES, optimal linear absorber and without them**

Figure 2 shows that both linear and nonlinear absorbers have significant effects in reducing the amplitude of displacement of wind turbine blade vibration, so that its value from 90.01 in the alone blade reduces to 2.81 with NES and 3.85 with optimal linear absorber. In this way, the NES, due to the use of non-linear springs, in addition to the ability to further reduce in vibration amplitude, causes robust changes.

In the literature, it is shown that the best connection point of the NES is at the location of the maximum amplitude of structure. However, since the primary system were considered linear in these papers, and the nonlinearity of blade structure as a primary system in this study sensitivity analysis for installing position of

NES is performed for more assurance. In this way, the NES is connected to a one-meter-long blade at 0.1 m intervals. As shown in Figure 3, the maximum absorbent is obtained at a point of 0.9 m from the blade root. However, it can be seen that it is almost similar in the range of 0.7 m to 0.9 m.



**Figure 3. Maximum vibrations amplitude of blade around the second super-harmonic resonance depending on the location of the absorber on the blade**

#### 4. Conclusion

Based on the presented results, the following main points can be concluded as:

- A. The use of highly efficient NES could reduce the amplitude of blade vibrations in the resonance conditions by 96% from 90.01 to 2.81.
- B. The reduction of blade vibration with NES is 31% more than when using an optimal linear absorber, which indicates better performance of the NES.
- C. The effect of spring stiffness and damping coefficients of NES on its performance is so effective, and therefore, by considering inappropriate parameters, the amplitude of vibration could decrease.
- D. The best performance of NES is achieved when it is installed at the farthest possible distance from the root the blade.

#### 5. References

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