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Dynamic Analysis of Bladeless Wind Power Generators Using Self-Adjustment Virtual Stiffness (SAVS)

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Abstract

Bladeless wind power generators (BWPGs) exploit Vortex-Induced Vibrations (VIV) to convert wind energy into electrical power without traditional blades. Their performance, however, is constrained by a narrow “lock-in” range where the vortex shedding frequency coincides with the structure’s natural frequency. To overcome this limitation, the present study introduces a Self-Adjustment Virtual Stiffness (SAVS) mechanism that dynamically modifies system stiffness and consequently adjusts the natural frequency in real time. A detailed 3D model of the BWPG was developed, while a 2D Fluid-Structure Interaction (FSI) analysis was conducted using ANSYS Fluent. Numerical results showed high agreement with experimental measurements reported by Lee et al. [1], verifying accuracy. The SAVS mechanism successfully expanded the lock-in region to a continuous wind speed spectrum from 0.5 to 6 m/s and improved energy conversion efficiency by up to twentyfold at speeds above 4 m/s.

Keywords: Bladeless Wind Turbine, Vortex-Induced Vibrations (VIV), Self-Adjustment Virtual Stiffness (SAVS), CFD, Energy Harvesting.

1. Introduction

The global transition to renewable energy has significantly increased the adoption of Bladeless Wind Power Generators (BWPGs) [2,3]. Unlike conventional wind turbines, BWPGs harness energy through Vortex-Induced Vibrations (VIV) [4]. However, a major hurdle in their widespread application is the “lock-in” phenomenon, which restricts efficient energy capture to a narrow range where the vortex shedding frequency precisely matches the generator’s natural frequency.

To address this critical limitation, this research introduces a novel Self-Adjustment Virtual Stiffness (SAVS) mechanism. This innovative system dynamically realigns the generator’s natural frequency with fluctuating wind speeds by adjusting the effective length of its primary rod. This real-time adaptability effectively overcomes the bandwidth limitations inherent in traditional fixed-stiffness designs, thereby enhancing energy harvesting across a broader range of operating conditions [4].

2. Methodology

2.1. Geometric Modeling

The oscillator was modeled as a conical bluff body connected to a flexible rod. The SAVS mechanism utilizes a sliding plate that modifies the rod's active length (L), thereby changing the equivalent stiffness (k). According to beam theory, k is proportional to $1/L^3$ [4].

2.2. Numerical Setup and Mesh Independence

Fluid dynamics were simulated using the k-ω SST turbulence model. A grid independence study was performed to ensure solution stability (Table 1).

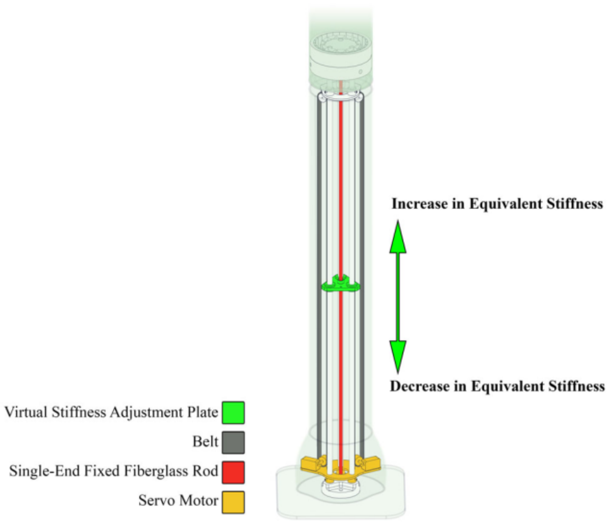

Figure 1. 3D CAD model of the SAVS mechanism

Table 1. Grid Independence Study results for Lift Coefficient and Amplitude

Mesh Density	Number of Cells	Lift Coefficient (Cl)	Amplitude (A/D)
Coarse	45,356	1.15	0.238
Medium	70,686	1.22	0.250
Fine	110,712	1.23	0.253

2.3. FSI Coupling and Equations

The structure is modeled as a mass-spring-damper system governed by the following equation (1):

$$m\ddot{y} + c\dot{y} + ky = F_L(t) \tag{1}$$

A User-Defined Function (UDF) was implemented to couple the fluid forces (Lift) with the structural response in each time step (dt = 0.005s) [4].

3. Results and Discussion

3.1. Validation

The numerical model was validated through comparison with experimental data reported by Lee et al. The validation process focused on the oscillation response of the structure under vortex-induced vibration conditions. In the simulation results, the maximum dimensionless oscillation amplitude (A/D) reached 1.44, while the corresponding experimental value reported in the reference study was 1.53. This difference corresponds to an error of approximately 5.8%, indicating a strong agreement between the numerical predictions and the experimental observations. The close correspondence between the two datasets confirms that the developed computational model is capable of accurately capturing the essential fluid–structure interaction behavior governing the system. Therefore, the validated model can be considered reliable for further parametric investigations and performance analysis of the proposed system under various wind conditions [5]. 3.2. Performance Enhancement

The SAVS mechanism enables the system to maintain peak oscillations beyond the conventional lock-in speed range. In traditional fixed-stiffness systems, the oscillation amplitude rapidly decreases once the wind speed exceeds the lock-in region, causing the vibration response to fall close to baseline noise levels. However, with the implementation of the SAVS mechanism, the system continuously adjusts its effective stiffness and natural frequency, allowing it to sustain resonance even as wind speed increases. As illustrated in Figure 2, when the wind speed reaches 5 m/s, the SAVS system continues to exhibit strong oscillatory behavior, while the fixed-stiffness system experiences a sharp reduction in amplitude. This sustained resonance significantly enhances energy harvesting capability, resulting in an approximate 2000% increase in generated power at higher wind speeds compared with the conventional fixed system [6].

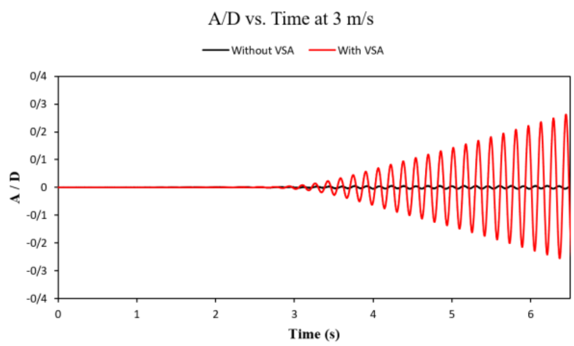

Figure 2: Comparison of A/D for Fixed vs. SAVS systems

4. Conclusion

The proposed SAVS mechanism effectively addresses one of the major limitations of conventional bladeless wind turbines, namely the narrow operational bandwidth associated with the lock-in phenomenon. In traditional designs, efficient energy harvesting occurs only within a limited wind speed range where the vortex shedding frequency closely matches the structural natural frequency. Outside this range, the oscillation amplitude rapidly decreases, significantly reducing the system's ability to convert wind energy into usable power.

By incorporating a Self-Adjustment Virtual Stiffness (SAVS) mechanism, the system is able to dynamically modify its effective stiffness and consequently adapt its natural frequency in real time. This adaptive capability allows the structure to maintain resonance conditions over a wider spectrum of wind velocities, thereby substantially expanding the lock-in region compared to fixed-stiffness configurations. As a result, the system can sustain higher vibration amplitudes across varying wind conditions and maintain efficient energy extraction even at elevated wind speeds.

The extended lock-in bandwidth achieved through this approach leads to a remarkable improvement in performance, with simulation results indicating up to a twenty-fold increase in power output at higher wind speeds compared with conventional bladeless systems [cite: 7]. Furthermore, this adaptive design is particularly well suited for urban and built environments, where wind conditions are often highly variable and turbulent due to surrounding buildings and infrastructure. In such locations, the ability of the SAVS mechanism to continuously adjust to fluctuating wind speeds makes it a promising solution for improving the reliability and practicality of bladeless wind energy harvesting technologies.

5. References

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