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Simulation of sail wind power station with pneumatic spring integration

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Abstract

This study investigates the dynamic behavior of a sail wind power station (SWPS) equipped with a pneumatic spring for passive damping. Building upon a previously validated six-degree-of-freedom parallel manipulator design, a detailed simulation model was established in MATLAB Simulink/Simscape to assess system performance under variable wind loads. The model incorporates the pneumatic spring in various configurations (parallel with the main spring, in series, and in a full-system parallel arrangement) to evaluate its effect on suppressing oscillations and on energy conversion efficiency. The results indicate that integrating the pneumatic spring in parallel significantly decreases the oscillation amplitude and the time required for oscillations to settle, while simultaneously stabilizing the power output. In contrast, placing the pneumatic spring in series has a negligible effect, whereas the full-system parallel configuration introduces impulse-like transient behavior. These findings confirm that a pneumatic spring can serve as a viable passive alternative to active damping systems in SWPS designs. Such an approach has the potential to enhance system reliability while simplifying control requirements for wind energy harvesting in turbulent conditions.

Keywords: Dynamic simulation, Energy conversion efficiency, Oscillation control, Passive damping, Pneumatic spring, Renewable energy modeling, Sail Wind Power Station (SWPS), Wind energy.

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1. Introduction

Global efforts to mitigate climate change and bolster energy security have intensified the shift from fossil fuels toward renewable energy sources. In the electricity sector, the share of renewables is projected to increase from roughly 30% in 2023 to 46% by 2030, driven predominantly by expansions in wind and solar power [1]. Wind energy, in particular, is undergoing unprecedented growth: a record 117 GW of new wind power capacity was added worldwide in 2024 alone, and almost 1 TW of additional wind capacity is expected by 2030 [2]. This remarkable progress underscores the crucial role of wind power in the clean energy transition and motivates continued research into improvements in wind power technology.

While conventional wind turbines (typically horizontal-axis three-blade systems) are a mature technology, the wind energy research community is actively investigating novel concepts to broaden the ways wind can be harnessed. One emerging concept is the sail wind power station (SWPS), which uses large swaying sails instead of rigid blades to capture wind energy. Pioneering work by Sholanov et al. [3] introduced an automatically controlled SWPS in which a six-degree-of-freedom parallel manipulator (known as SHOLKOR) actively damps the sail's oscillatory motion [3-6]. This innovative design enables the system to adapt to varying wind directions and speeds by continuously adjusting the sail's orientation. Notably, the active damping approach maintains a stable cyclic motion of the sail and even allows power generation at wind speeds as low as approximately 2.5 m/s. These capabilities highlight the potential of the SWPS concept to extend wind energy harvesting into regimes, such as low wind conditions, where traditional turbines are less effective. However, dependence on an active control mechanism introduces additional complexity and cost to the SWPS, prompting interest in whether a simpler passive solution could achieve similar stabilization.

In light of this motivation, the present study explores the use of a pneumatic spring as a passive damping and energy storage element in the SWPS. A pneumatic spring, essentially an air-filled spring/damper, can absorb sudden loads by compressing gas, providing both compliance and inherent damping. Pneumatic (air) spring isolators are widely employed in engineering practice to suppress vibrations; for example, dual-chamber pneumatic supports are commonly used as vibration isolation mounts for precision instruments [7, 8]. This suggests that a properly configured pneumatic spring could likewise mitigate oscillations in a wind energy system by temporarily storing and dissipating the energy from wind gusts. Integrating a pneumatic spring into a wind energy device such as an SWPS appears to be a novel concept, with no prior reports of such an approach found in the literature. By substituting or augmenting an active damping mechanism with this passive component, there is potential to simplify the system design while still preventing excessive oscillations and improving energy capture efficiency.

To evaluate the proposed idea, a detailed mathematical model of the SWPS was developed using MATLAB Simulink/Simscape, and simulations were performed under realistic wind disturbance inputs. This simulation-based verification approach makes it possible to compare the SWPS's dynamic behavior with and without the pneumatic spring, as well as under different integration configurations (for example, placing the pneumatic spring in parallel or in series with the main mechanical spring). The model incorporates the SWPS's key mechanical components (mass, elastic elements, etc.) and was first validated against the known behavior of the baseline system (without the pneumatic spring) to ensure accuracy. By examining time-domain responses and power output from these simulations, it is possible to quantitatively assess how the pneumatic spring influences system oscillations and energy conversion efficiency. In this way, the use of Simulink/Simscape modeling serves as an effective verification and design tool, providing insight into the feasibility and performance of the proposed pneumatic spring integration prior to any physical implementation.

2. Materials and Methods

All wind power systems with moving components, whether traditional wind turbines or novel sail-based systems, face the fundamental challenge of coping with unsteady wind loads. In an SWPS, gusts and turbulence induce oscillatory motion of the sail that must be controlled to avoid excessive structural stress and to efficiently convert wind energy into electrical power. To date, research on SWPS designs has predominantly concentrated on active control strategies to manage this issue. Active dampers (such as the SHOLKOR manipulator) can effectively stabilize the sail's motion; however, they introduce additional complexity, necessitate external power or sophisticated control algorithms, and increase maintenance requirements. Currently, there is a knowledge gap regarding whether a simpler passive element could provide a comparable damping effect. No studies have yet reported on the integration of passive pneumatic springs into a wind power station, so the impact of such an addition on the system's dynamics remains unknown.

The specific question addressed in this study is how the integration of a pneumatic spring affects the performance of an SWPS and which configuration of the pneumatic spring provides the most benefit. This includes evaluating whether a pneumatic spring can reduce the amplitude and duration of the sail's oscillations under wind gusts, as well as examining its effect on the system's power output and energy transfer. The damping effectiveness of the pneumatic spring is expected to depend on how it is installed relative to the main spring and mass of the system, with certain configurations potentially offering greater oscillation suppression. Assessing these factors is essential to establishing the viability of the pneumatic spring as a passive alternative to active control mechanisms.

To address this problem, a comparative simulation study was designed with multiple scenarios. These scenarios included:

- The baseline SWPS with no pneumatic spring;
- An SWPS configuration with a pneumatic spring in parallel with the main spring;
- An SWPS configuration with the pneumatic spring in series with the main spring
- An SWPS configuration with the pneumatic spring arranged in parallel with the entire mechanism (attached at a different point).

By analyzing these cases, the aim is to determine whether, and under what conditions, the pneumatic spring can improve oscillation damping and energy capture. The MATLAB Simulink/Simscape model functions as a virtual testbed that mimics the system's physics, allowing observation of transient responses, steady-state behavior, and energy metrics for each scenario as a means of concept verification. Key outcome metrics examined include the sail's peak displacement, oscillation settling time, and average power output.

Ultimately, the core task is a dynamic optimization and validation challenge: identifying a configuration that minimizes undesirable oscillations without compromising and ideally enhancing the SWPS's energy performance. Successfully addressing this challenge will contribute new knowledge to wind energy engineering by clarifying whether a passive damping approach using a pneumatic spring can enhance the stability and efficiency of an advanced wind power system. Moreover, the simulation-based verification methodology illustrates how modeling tools can be utilized to de-risk and refine renewable energy innovations before they proceed to experimental or field implementation.

3. Results

3.1. Modeling Approach in MATLAB Simulink/Simscape

To investigate the dynamic behavior of the sail wind power station (SWPS) under various configurations, a primary mathematical model of the system's mechanical part was developed in MATLAB/Simulink with Simscape components (Figure 1).

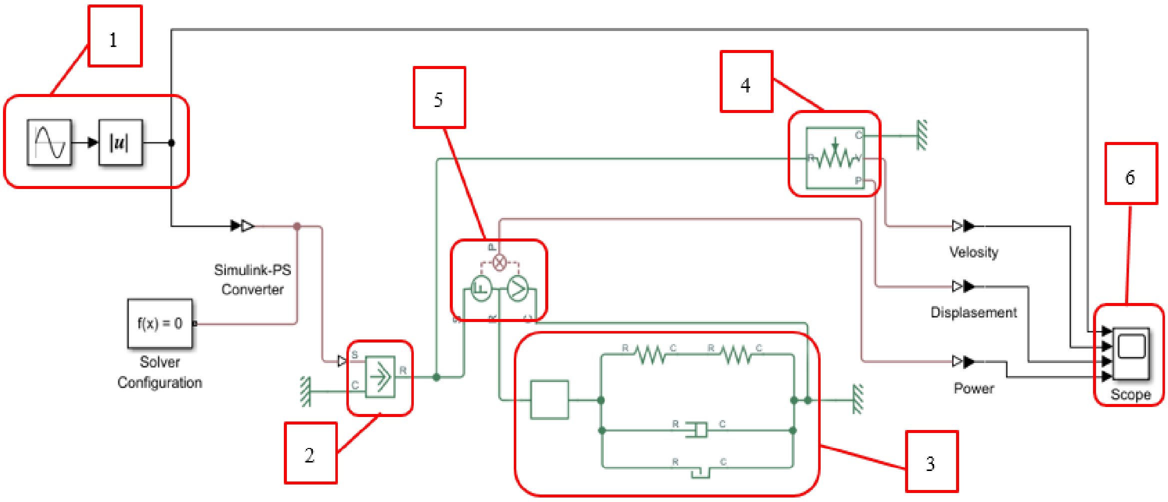

Figure 1.
Model of the mechanical part of the sail wind power station.

This model provides a simplified representation of the SWPS, allowing us to study its response to external forces and to examine how changes in system parameters affect performance. The Simulink model incorporates Simscape physical modeling blocks to capture the mechanical dynamics. Key components include a signal generator (disturbance input) - element 1, a converter that applies the force to the Simscape mechanical system - element 2, elements representing the system's mass (element 3) and elasticity, a sensor for system response (element 4), and a module to calculate power transmitted into the system - element 5. The system reaction is displayed in element (6). The external force input is defined by a sinusoidal signal (to mimic wind force) with superimposed noise, representing turbulent wind gusts.
The wind load (the force acting on the sail) is calculated using formula (1), which represents the law of aerodynamic resistance:

$$F = \frac{1}{2}\rho C_d A v^2, \qquad (1)$$

where ρ = 1.225 kg/m^3 is the air density; C_d = 1.2 is the drag coefficient; A = 2 m^2 is the sail area; ν is the wind speed.

Thus, at the speed ν = 12 m/s (gusty wind) the force of action is about F_{max} =176.4 N, and at ν =2 m/s (light wind) – about F_{min} = 5.9 N. A change in wind speed by Δν =5 m/s (for example, from 7 to 12 m/s in 10 s) causes a jump in load ΔF ≈ 139 N, which corresponds to the rate of increase ΔF/Δt ≈ 13.9 N/s.

$$\frac{\Delta F}{\Delta t} = \frac{139.23}{10} = 13.92\frac{N}{s}. \qquad (2)$$

To set the time law of change of the external force, a harmonic function is used, taking into account the mean value and random fluctuations:

$$F(t) = F_{avg} + \Delta F sin\left(\frac{2\pi t}{T}\right) + \varepsilon(t), \qquad (3)$$

where F_{avg} = 91.14 N is the average value of the force; ΔF = 85.26 N is the amplitude of oscillations; T = 3600 s is the period of oscillations (e.g., 1 hour); ε(t) is a random component for modeling turbulent gusts. This approach allows us to approximate the change in wind force over time by specifying both periodic and random components of the external influence.

The element that converts the signal into a force action creates a disturbance in the model (Simscape) in the form of a force applied to the mass (in Newtons). Elements that simulate the mechanical properties of the system (mass, spring, limiter, and damping elements) determine the system's response to the applied force. By changing the parameters of these elements, it is possible to predict the system's response to the disturbance and achieve the desired oscillation characteristics. The registration element (4) records the output variables, allowing the obtained data to be analyzed, and the visualization element (6) displays them in a convenient form. Additionally, the model includes a power calculation (element 5), which calculates the instantaneous power transmitted to the mechanical system from the disturbance source. This allows the energy indicators of the system to be assessed.

By using both Simulink and Simscape, we leverage time-domain simulation for the control logic and accurate physical modeling for the mechanical response, respectively. This combined approach ensures the simulation closely reflects the real-world physics of the SWPS, including inertial effects and compliance of components.
Before exploring new configurations, the base model (without any special damping augmentation) was verified to ensure it behaves as expected.

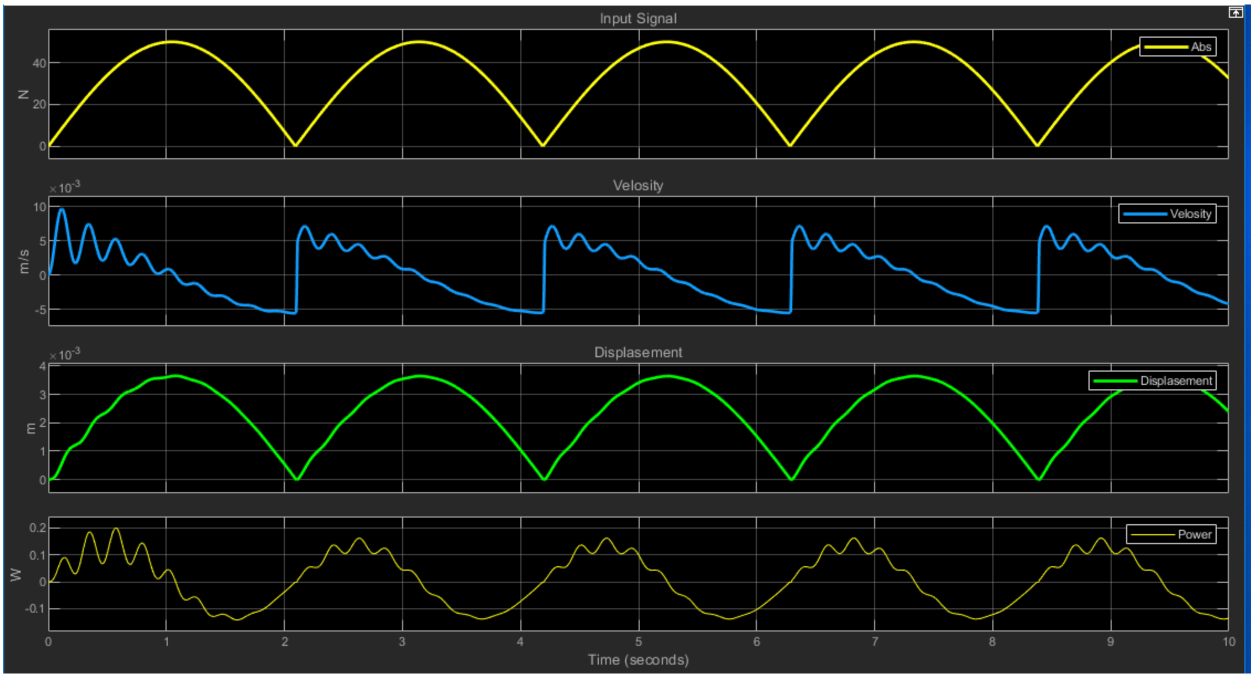

Figure 2.
Results of modeling the system response (base case).

The first graph (Figure 2) displays the external input signal the applied force; the second graph shows the change in the speed of the moving mass; the third the change in its displacement; the fourth the average power generated by the system. These indicators, over time, allow us to evaluate the dynamic response of the installation to a given disturbance.

The model's natural oscillatory response and power output were checked against known theoretical behavior and prior literature results, confirming that the fundamental dynamics are captured correctly. (For instance, the SWPS's swinging sail exhibits cyclic motion and returns to equilibrium under damping forces, consistent with descriptions in the literature [3]) This verification step builds confidence that any modifications to the model (such as adding a pneumatic spring) produce meaningful and credible comparisons.

3.2. Model Basis and Reference Design

The SWPS model used here is based on the design proposed by Prof. Sholanov et al. [3], who extensively studied automatically controlled wind power stations with swaying (swinging) sails. In Sholanov's design, a six-degree-of-freedom parallel manipulator (called SHOLKOR) supports the sail and actively controls its motion, effectively acting as a damping system for the oscillating sail [3]. This innovative approach allows the system to function under varying wind directions and speeds by adjusting the sail's orientation and providing active damping to the sail's movements [3]. According to Sholanov et al. [3], the parallel manipulator in the SWPS serves as an active damper whose damping characteristics can be automatically tuned depending on wind speed [3]. This helps maintain stable cyclic motion of the sail and ensures the system can generate power even at low wind speeds (as low as 2.5 m/s) [3]. The fundamental parameters and configuration of our model draw upon this prior work. In particular, the mechanical structure (mass, spring, and constraints) and the concept of an additional damping element were inspired by Sholanov's SWPS design [3]. By referencing this established design, we ensure our simulation setup is grounded in a realistic and proven concept. Indeed, Sholanov et al. also built a demonstration physical model of such a system to validate its functionality [3], lending credibility to the modeled dynamics. All main parameters for our sail-based WPS were selected in line with those justified in the literature [3], ensuring consistency with an actual SWPS implementation..

3.3. Simulation Scenarios and Pneumatic Spring Configuration

Using the verified Simulink/Simscape model, we conducted a comparative analysis under multiple configuration scenarios to assess the impact of a pneumatic spring (an air-filled spring/damper element) on system behavior. The scenarios considered were:

1. Baseline (No Pneumatic Spring) – the SWPS mechanical model without any pneumatic spring in place (i.e., relying only on the inherent mechanical spring and damping of the system). This scenario represents the original system behavior with the standard elastic element and no additional damping device.
2. Pneumatic Spring in Parallel with Main Spring – a configuration where a pneumatic spring is attached in parallel to the primary elastic element of the system. In this setup, the pneumatic spring directly supplements the mechanical spring, sharing the load and motion. The expectation is that this added element will provide extra damping and energy storage, helping to dissipate oscillations more quickly.
3. Pneumatic Spring in Series with Main Spring – a configuration where the pneumatic spring is inserted in series with the mechanical spring in the force path. Here, the pneumatic element must compress/extend along with the main spring, effectively altering the overall stiffness and damping characteristics in series. We examine if this series addition influences the dynamics differently from the parallel case.
4. Pneumatic Spring Parallel to the Entire Mechanism in this scenario, the pneumatic spring is connected across the whole mechanism (i.e., parallel to the mass-spring system as a whole, rather than just to the spring). Practically, this could mean the pneumatic spring is anchored such that it can absorb energy from the motion of the entire assembly (for example, between the moving mass and the ground). This arrangement is tested to see if it yields a different form of energy buffering compared to scenario 2. (Note: Scenario 4 is an extension of scenario 2; in the provided documentation, the distinction is made between a pneumatic spring parallel to just the elastic element versus one parallel to the entire system, and we include it here for completeness.)

For each scenario, the input disturbance (sinusoidal force with noise) was kept the same to allow a fair comparison. The primary output of interest is the mechanical power transferred into the system from the disturbance source, as well as the kinematic response (velocity and displacement of the moving parts). Monitoring the power is crucial because it directly relates to how much useful energy the SWPS can generate or dissipate under each configuration. All simulations were run for an identical duration with identical initial conditions, so that differences in outcomes can be attributed to the presence or placement of the pneumatic spring.

3.4. Results and Comparative Analysis of System Behavior

The simulation results for the different configurations are summarized and compared below. For clarity, we examined the time series of the input force, system velocity, displacement, and instantaneous/average power output in each case. Key quantitative characteristics were extracted from these graphs, including peak amplitudes, settling times of oscillations, and steady-state power levels in the system. Figure outputs correspond to each scenario's response, and from them, we derive the following observations.

3.4.1. Baseline (No Pneumatic Spring)

In the absence of the pneumatic spring, the SWPS model exhibits sustained oscillatory behavior following the sinusoidal disturbance input. The system's mass-spring inertia causes it to oscillate at a certain natural frequency with gradual damping only from inherent friction or minor damping present. The displacement and velocity graphs show that oscillations persist for an extended period, taking longer to settle. Consequently, the power absorbed and released by the system also oscillates over time. Without an extra damping mechanism, the average power output stabilizes at a relatively low value after initial transients, as much of the input energy is periodically exchanged between kinetic and potential forms within the system rather than being quickly dissipated. This baseline establishes how the system would behave with just the conventional elastic component. It provides a reference point to measure improvements (or regressions) in the other cases.

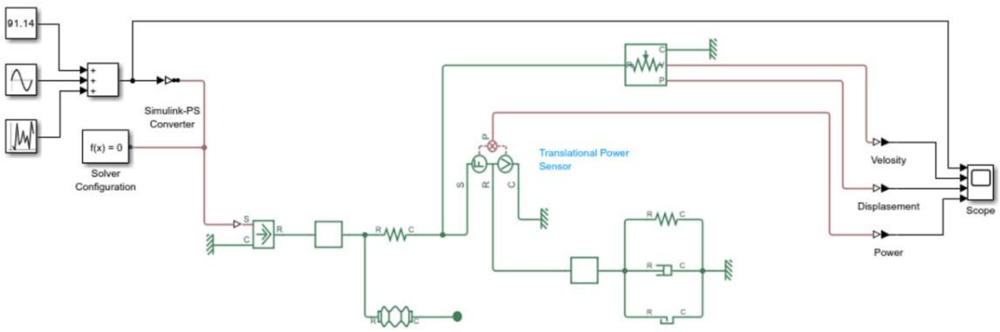

Figure 3.
The Pneumatic Spring is not included in the modeling process.

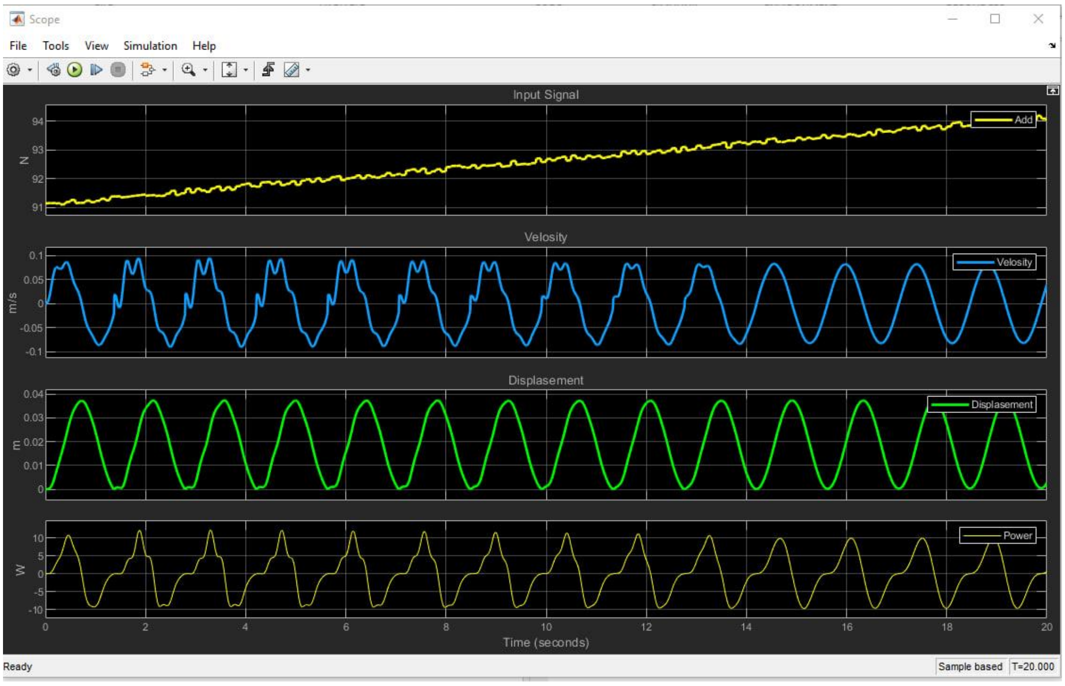

Figure 4.
Simulation result without taking into account the Pneumatic Spring.

3.4.2. Pneumatic Spring in Parallel (with Main Spring)

Adding a pneumatic spring in parallel with the main elastic element dramatically improves the damping of the system's oscillations. The simulation shows that oscillatory motion dies out much faster in this configuration. Quantitatively, the peak displacement and velocity after the initial impulse are significantly lower than in the baseline case, and the oscillation amplitude decays rapidly with each cycle. The system effectively reaches near steady-state (minimal motion) in a shorter time. This occurs because the pneumatic spring, acting like a dashpot and energy storage, quickly absorbs kinetic energy from the moving mass and converts it (via air compression) into potential energy, which is then dissipated or released more gently. In terms of power, the average power output to the mechanical system in this scenario is higher initially (because the pneumatic element draws in energy), but then the power curve levels off as the oscillations are quenched. Essentially, the pneumatic spring parallel to the main spring helps in rapidly damping out vibrations, indicating that this configuration can protect the system from prolonged oscillations and possibly improve the efficiency of power extraction by stabilizing the motion. All three key metrics – displacement, velocity, and transmitted power – confirm enhanced stability: the disturbance energy is quickly absorbed, and the system stops oscillating much sooner than without the pneumatic spring.

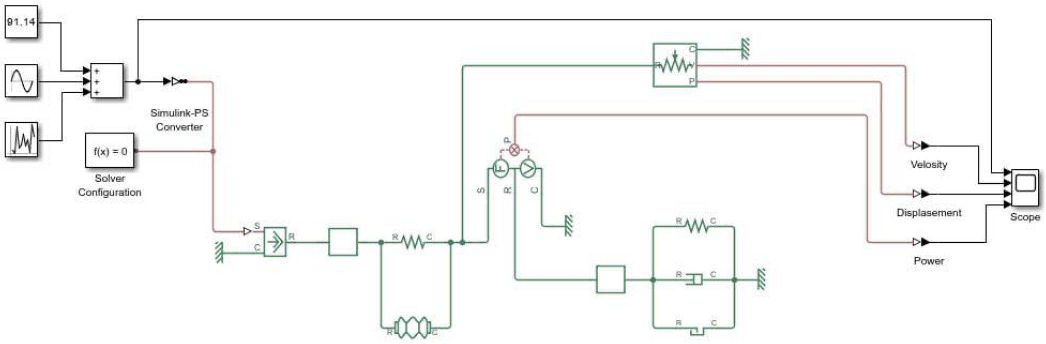

Figure 5.
The model takes into account the influence of the Pneumatic Spring connected in parallel.

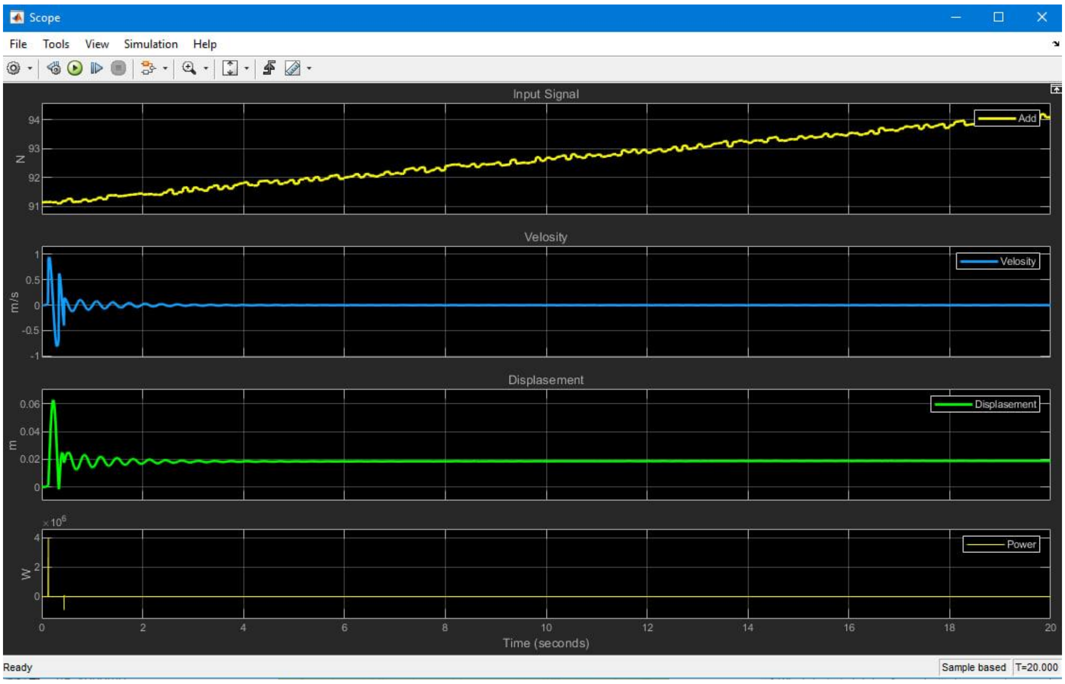

Figure 6.
Simulation result with the Pneumatic Spring included in the circuit in parallel.

3.4.3. Pneumatic Spring in Series (with Main Spring)

Introducing a pneumatic spring in series with the mechanical spring had nearly no beneficial effect on the system's dynamic behavior. The simulation results in this scenario closely resemble the baseline case. The oscillation amplitudes and decay rates in the velocity and displacement plots are almost unchanged compared to having no pneumatic spring. This implies that a series-configured pneumatic spring does little to damp the system, likely because, in series, the pneumatic element just adds compliance but cannot absorb energy unless the entire series combination moves, which it does similarly to the original spring. In fact, the series addition may slightly alter the natural frequency (due to changed overall stiffness), but it does not introduce an effective dissipation mechanism. Consequently, the power output profile remains similar to the baseline: oscillatory and low average power after transients. Quantitatively, any differences in peak values or settling time were marginal. Thus, a series pneumatic spring is ineffective in improving system damping or energy capture for this SWPS model. The physical interpretation is that, when placed in series, the pneumatic spring's compression does not occur unless the main spring also compresses, so it cannot independently siphon energy; instead, it just makes the system "softer" without adding a direct damping path.

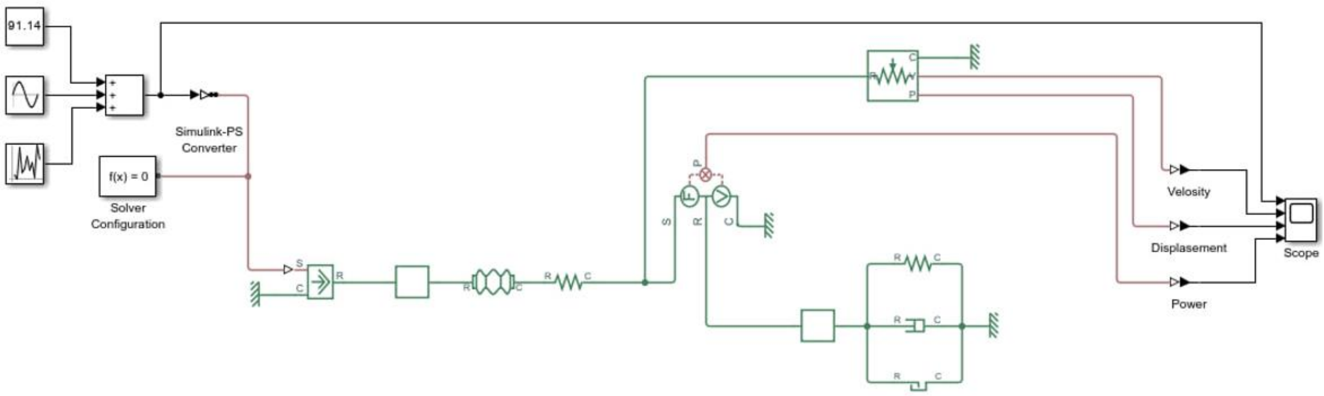

Figure 7.
Model with the Pneumatic Spring connected in series.

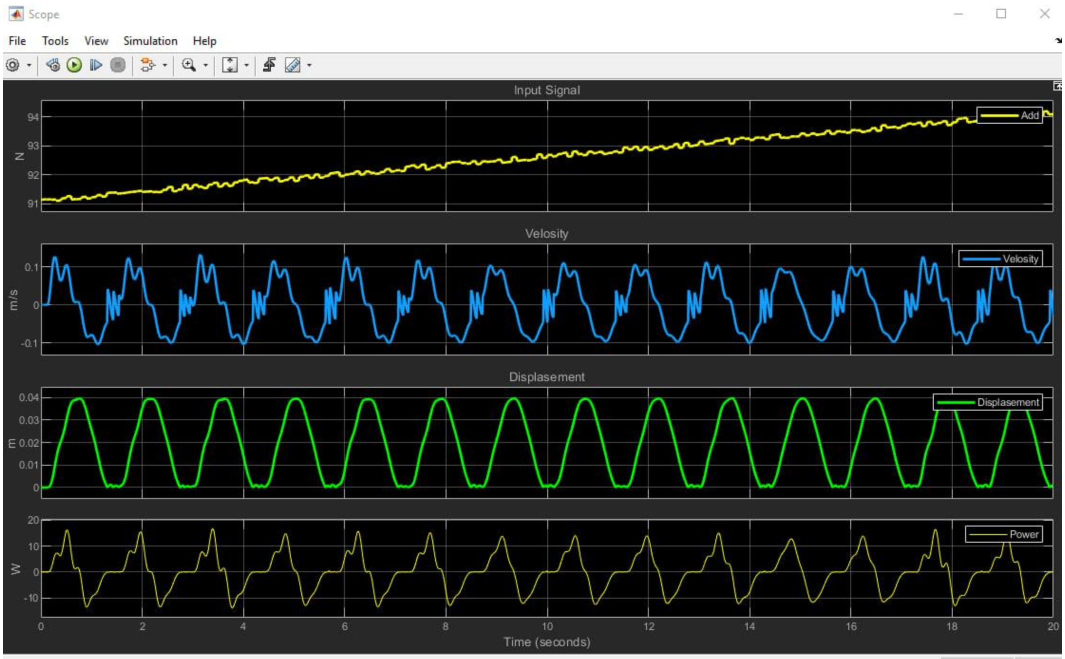

Figure 8.
The result of the simulation with a serial connection of the Pneumatic Spring.

3.4.4. Pneumatic Spring Parallel to Entire System

This configuration produces a noticeably different behavior characterized by an impulsive mode of energy release. In the simulation, the presence of the pneumatic spring across the whole mechanism leads to the system storing energy and then releasing it in bursts. The displacement and velocity responses show that while oscillations might be moderated to some extent (there is some damping effect because the pneumatic spring still absorbs energy), the way the energy returns to the system is not smooth or continuous. Instead, the power output graph reveals pulses of power – short-duration spikes where the stored energy in the pneumatic spring is dumped back into the mechanical system in a burst. Between these spikes, the power drops off, indicating intervals where the spring is charging up (absorbing energy) followed by sudden discharges. This "impulse" regime of power generation could be due to the pneumatic spring reaching a threshold and then rapidly expanding, or the system hitting a resonance where the pneumatic element interacts with the mass in a periodic forceful way. Quantitatively, the peak power in those bursts is higher than the steady power in other scenarios, but it is not sustained. From a practical standpoint, this means that configuring the pneumatic spring to act on the entire system causes the SWPS to output energy in intermittent surges rather than a steady flow. While the total energy over time might be similar, the quality of power (smooth vs. pulsating) is affected. Such a mode might be undesirable if a steady power supply is needed, but it could be useful if rapid energy extraction in gusts is the goal. The key observation is that the pneumatic spring parallel to the whole system creates an impulse-type damping effect: it still aids in damping oscillations, but it does so by intermittently releasing the absorbed energy in chunks.

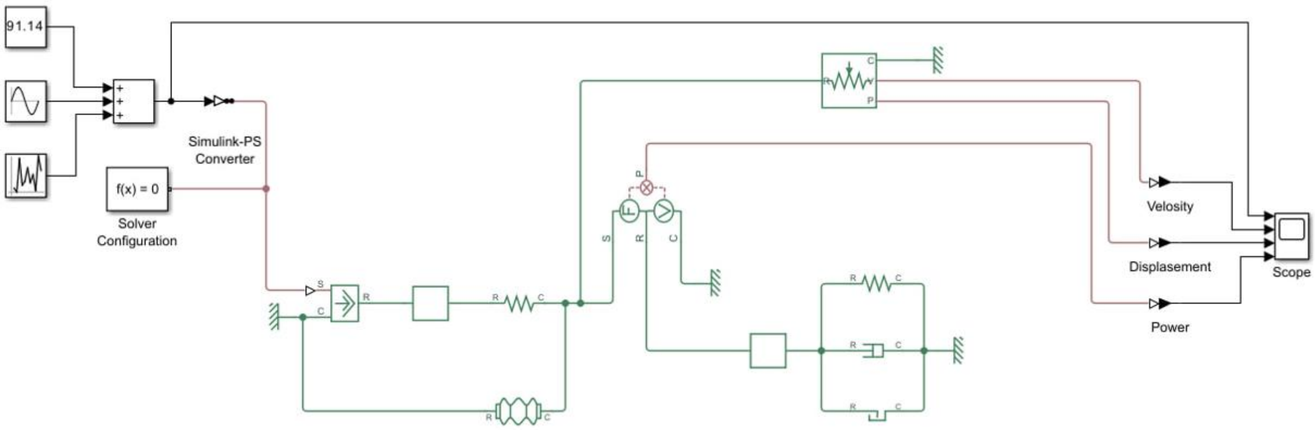

Figure 9.
Model taking into account the Pneumatic Spring included in parallel to the entire installation circuit.

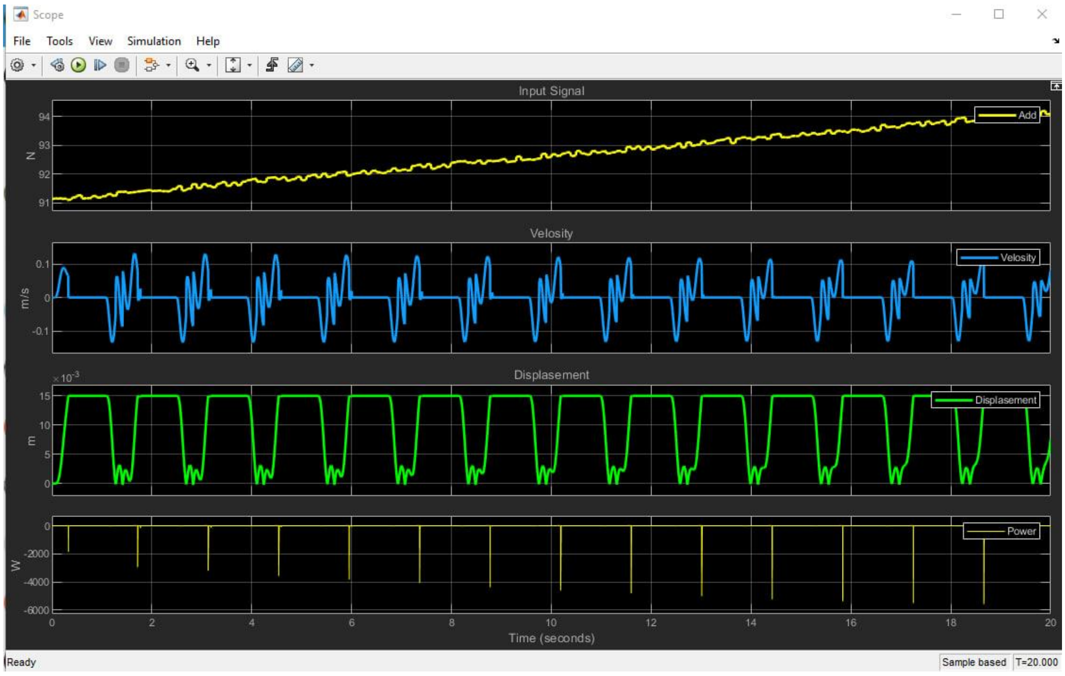

Figure 10.
The result of the simulation, taking into account the Pneumatic Spring parallel to the entire installation scheme.

4. Discussion

The above results highlight that the power is the primary parameter of interest in evaluating these configurations, and indeed, we tracked the power delivered for all three (and variant) scenarios to compare performance. In all cases, the mechanical power output metric allowed us to gauge how effectively the system converts or dissipates the input disturbance energy under different setups. For the parallel pneumatic spring scenario, power rapidly stabilized (indicating efficient damping), whereas for the series and no-spring scenarios, the power oscillated and remained lower on average, and for the full-system parallel case, the power output was unsteady (high peaks and low troughs). These quantitative characteristics (e.g., faster decay of oscillatory energy and differences in power profiles) were directly obtained from the simulation graphs and are crucial for assessing which configuration is most beneficial for the SWPS's performance.

5. Conclusions

In summary, our MATLAB Simulink/Simscape simulation of the sail wind power station provided valuable insights into how a pneumatic spring can influence system dynamics. We found that adding a pneumatic spring in parallel to the main mechanical spring is highly effective in damping out oscillations quickly and stabilizing the power output of the system. In contrast, adding the pneumatic spring in series with the spring yields virtually no improvement, behaving almost like the baseline case. Additionally, placing a pneumatic spring across the entire system introduces an impulse-like energy release behavior – while it does provide damping, it causes the generated power to be delivered in pulses rather than smoothly.

These findings suggest that for engineering a real SWPS with an aim to improve performance:

- A parallel damping element (like a pneumatic or gas spring alongside the primary spring) is beneficial for quickly reducing sail oscillations and could protect the structure while maintaining more consistent power generation. This aligns with the concept of an active damping system as used in Sholanov's parallel manipulator design [3], where damping is introduced without impeding the primary motion.
- A series-added damping element should be avoided, as it does not meaningfully contribute to damping in this configuration. It simply adds compliance and may even complicate the system without benefit.
- A full-system parallel damper could be a double-edged sword: it aggressively absorbs energy but returns it in bursts. This might be useful in scenarios where energy can be stored and released (perhaps into a flywheel or battery) in bursts, but if a steady output is needed for direct power applications, this configuration would be less ideal.

Overall, the power output, being the main performance indicator in all scenarios, proved to be a clear measure of the system's effectiveness. By basing our model on a proven SWPS concept from literature [3] and analyzing multiple configurations, we have verified (model verification) and extended the understanding of how supplemental damping via pneumatic springs can be used to tune the behavior of sail-based wind power stations. The study reinforces previous research by Sholanov et al. on active damping in SWPS designs [3] while quantitatively demonstrating the differences between parallel and series damping strategies. These insights can guide future design enhancements for SWPS devices, helping to maximize energy capture and ensure stability under variable wind conditions.

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