

Design Optimization of Vortex-Induced Vibration Bladeless Wind Turbines for Urban Energy Harvesting

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Urban environments require innovative solutions for clean energy generation, as conventional wind turbines are often limited by space and noise constraints. Vortex-Induced Vibration (VIV) bladeless wind turbines present a promising alternative by converting oscillatory motion into electricity without rotating blades. This study investigates the influence of mast height, upper diameter, and lower diameter on turbine flexibility and performance under the low wind speeds typical of urban settings. Computational fluid dynamics and static structural analysis in ANSYS, combined with Response Surface Methodology (RSM) and Central Composite Design (CCD), were used to develop an optimization model aimed at maximizing mast deflection—a critical factor in energy harvesting efficiency. Results reveal that mast height and upper diameter significantly influence deformation, while lower diameter has a relatively minor impact. The optimal configuration achieved a mast deflection of 9.15 mm, validating the model's predictive accuracy. These findings provide practical design insights for enhancing bladeless wind turbine performance in urban settings, paving the way for more sustainable and space-efficient renewable energy solutions.

Keywords: Bladeless Wind Turbine; Vortex Shedding; Resonance; Static Structural Analysis; Response Surface Methodology

Introduction

The global demand for energy has surged dramatically since the Industrial Revolution, driven by rapid urbanization, population growth, and technological advancements. Historically, this demand has been met primarily through the exploitation of fossil fuels such as petroleum and coal. However, these non-renewable resources are finite and are major contributors to environmental degradation, including global warming, air pollution, acid rain, ozone layer depletion, and disruption of ecosystems [1]. These adverse impacts have heightened public awareness and underscored the urgent need to transition toward sustainable energy solutions. Renewable energy technologies are therefore essential for building a resilient and environmentally responsible future [2].

Recognizing this imperative, the United Nations has established 17 Sustainable Development Goals (SDGs), which provide a comprehensive framework for achieving sustainability across social, environmental, and economic dimensions. Among these, “Affordable and Clean Energy” emphasizes the critical role of clean energy in shaping a sustainable future [3].

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Common renewable energy sources include solar, wind, and hydropower. According to the U.S. Department of Energy, in 2022, wind power generated 10.3% of all U.S. electricity, indicating the importance and potential of wind power [4].

Conventional wind energy systems primarily employ Horizontal-Axis Wind Turbines (HAWTs) and Vertical-Axis Wind Turbines (VAWTs). However, these designs face significant challenges in urban environments. Limited open space, noise restrictions, and complex wind patterns caused by densely packed buildings make large-scale wind farms impractical in cities. Urban wind conditions are characterized by low wind speeds, turbulence, and eddies, which further reduce the efficiency of traditional turbines.

To overcome these limitations, Vortex-Induced Vibration (VIV) bladeless wind turbines (BWTs) have emerged as a promising alternative. Unlike conventional turbines, VIV BWTs generate electricity by converting oscillatory motion induced by vortex shedding into electrical energy, eliminating the need for rotating blades. This design offers advantages such as reduced noise, compact size, and insensitivity to wind direction, making it particularly suitable for urban applications.

The primary contribution of this study is to enhance the performance of VIV BWTs under low wind speed conditions typical of urban settings. Specifically, the research focuses on maximizing mast deflection, which is a critical factor influencing energy harvesting efficiency. To achieve this, a series of three-dimensional simulations were conducted using ANSYS, and the results were analyzed through Response Surface Methodology (RSM) implemented in JASP software.

Literature Review

A vortex-induced vibration (VIV) bladeless wind turbine (BWT) differs fundamentally from conventional bladed wind turbines. It is a type of wind power generator that generates energy by harnessing the wind induced oscillatory mechanical energy caused by wind induced vortex shedding.

When the VIV BWT is exposed to a fluid flow, the mast is primarily subjected to pressure exerted by the flow. It can be calculated by using Eqs. 1 and 2 [5, 6]

$$P=F/A \quad (1)$$

where F is the force experienced by the mast and A is the cross-sectional area.

$$F = 0.5\rho u^3 DLC \quad (2)$$

where F is the dynamic drag force, ρ is the density of fluid, u is the velocity of the fluid, D is the average diameter, L is the height, and C is the coefficient of lift force.

Vortex shedding is a fluid dynamics phenomenon. When a fluid flow passes a bluff body, the pressure of fluid rises to the stagnation pressure from the stream pressure. The fluid pressure remains symmetrical at low flow rates [6], more specifically, when the Reynolds number $Re \leq 40$ [8]. The equation of Reynolds number (Re) characterizes the state of fluid flow and can be estimated by using Eq. 3 [9].

$$Re = \frac{\rho v \phi}{\mu} \quad (3)$$

where Re is the Reynolds number, ρ is the density of the fluid, v is the average velocity of incident wind flow, Φ is the characteristic length, and μ is the fluid viscosity.

However, when the Reynolds number reached the critical value, the pressure on both side of the object becomes unstable. The instability leads to the formation of vortices in the wake region of the object. These vortices result in a periodical alternating pattern called Kármán Vortex Street, creating a fluctuating force perpendicular to the direction of the fluid flow [10]. This transverse force, primarily contributed by the lift force, can be expressed by Eq. 4 [9]

$$F_L = \frac{1}{2} \rho \phi v^2 C_L \sin(2\pi f_v t) \quad (4)$$

where C_L is the lift force coefficient and f_v is the vortex induced vibration/ vortex shedding frequency.

The frequency of vortex shedding can be expressed as Eq. 5 [10]:

$$f = \frac{St \cdot v}{\phi} \quad (5)$$

where St is the constant of proportionality (Strouhal Number) and f is the frequency of vortex shedding

Vortex induced vibration occurs when the frequency of vortex shedding matches or is close to the natural frequency of vibration of the body. This condition induces resonance, amplifying the harmonic vibration of the body. Within the ‘synchronization range’, the vibration amplitude increases significantly [8]. Even when the shedding frequency does not precisely match the natural frequency, the body will still vibrate if the incident velocity falls within the lock-in range, which can be expressed by Eq. 6 [9]

$$v_{lock} \approx \frac{\phi}{St} f \quad (6)$$

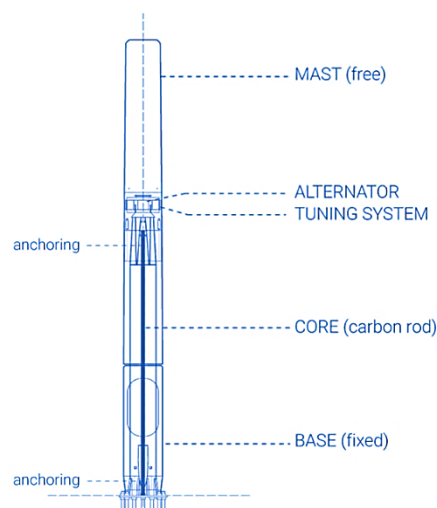


Figure 1. Schematic Diagram of current commercialized VIV BWT [10]

The VIV BWT leverages this phenomenon by using a flexible mast that oscillates due to vortex shedding and the resulting vortex induced vibration (Fig. 1). As the wind flows past the mast, the turbine captures wind energy by harvesting the vibrational kinetic energy of the mast into electrical energy by electromagnetic induction. A combination of a coil and a magnet is employed within the mast, where the relative motion of the magnet with respect to the coil induces an electromagnetic field, generating electrical current as the mast oscillates (Faradays Law) [12]. Thus, during the resonance vibrations, greater the deflection angle that the mast can achieve, greater the energy that can be generated.

In practical applications, a tuning system is also implemented with respect the vibration phenomena (Fig. 1). Although the "lock-in range" enables synchronisation, this range is narrow and cannot accommodate the variations in non-constant wind velocities experienced in real-world conditions. As a result, a tuning system comprising two circular permanent magnets will be installed to the original damped oscillator. The tuning mechanism could dynamically 'adjust' the device's natural frequency by extending the lock-in range and increasing the synchronisation workable range with peak/ near peak performance. The magnetic repulsive force between two permanent magnets is inversely proportional to the square of the average distance between their poles. Consequently, as deflection increases, the gap between the magnets in one side decreases, leading to greater repulsion. The system enables the vibration frequency increases with the degree of deflection during oscillation [11], leading to energy harvesting more frequently and intense. The frequency equation can be given by Eq. 7 [11]

$$f(x) = \frac{1}{2\pi} \sqrt{\frac{(k+k'(x))}{m} - \left(\frac{c}{2m}\right)^2} \quad (7)$$

Currently, VIV BWT only generate 30% of power that conventional wind turbines generate [13]. To improve the turbine performance of wind energy harvesting, two primary approaches are either maximising the vibration frequency or increase the magnitude of the deflection of the mast. Since vortex shedding frequency depends on variables such as incident wind speed — which cannot be continuously controlled to match the natural frequency of the body — this study focuses on maximizing the deflection that the mast can achieve during vibration to improve turbine performance.

As it pertains to vibration of the cylinder in an incident wind flow, vortex formation is significantly different based on the type of cylinder — Uniform cylinder and tapered cylinder, and these significantly affect VIV turbine performance. The current commercially available VIV bladeless (Fig. 2) are primarily designed with nearly uniform cylindrical shapes [11].

From the review articles on various VIV BWT models, the turbine parameters can preliminary be divided into rod (base) height, mast height, and diameter. Tapered cylindrical designs are worth exploring further, as tapered cylinder performs greater degree of deflection under same the same airflow [14].

Reviews were also conducted to explore existing approaches to optimisation problems in wind turbine research. Common methods include computational fluid dynamics (CFD), numerical analysis, metaheuristic algorithms, morphological/ geometric optimisation, *etc.* These approaches are widely used to analyse the dynamic response and fluid flow in both BWT and conventional wind turbines.

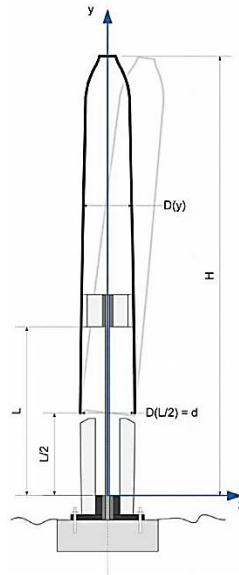


Figure 2. Current BWT design of Vortex Bladeless [10]

The most common and essential approach for studying the stability and performance of wind turbines is CFD and numerical analysis. They enable studies in dynamic response and fluid flow in both BWT and conventional turbines. For instance, past research has employed CFD to examine the stability of vortex-induced vibrations in conventional wind turbines by analysing mode shapes at different inclinations, providing valuable insights into turbine stability [15]. In the context of VIV BWT, CFD has also been employed to explore the effect of separation distance between tandem cylinders on vortex shedding frequency. The airflow passing through the first cylinder generates wakes, and CFD has proven instrumental in determining the optimal separation distance by providing maximum amplitude and frequency of vibration for the downstream one, thus to improve performance and stability of the overall system [16].

Metaheuristic Algorithms are also widely utilised in engineering design for solving complex optimisation problems. These algorithms explore large search spaces to identify global optima. Methods include evolutionary algorithms, particle swarm optimisation, and simulated annealing. They have been applied to a range of wind turbine problems, including blade design and layout optimization [17, 18]. Past research has used this method for investigating the optimal number of turbines in a certain area [19] and the layout of wind farm for maximising energy output. Computational random testing and coding were employed to generate plots and diagrams as shown in references [20]. Furthermore, past research in conventional wind turbine also used this method to address aerodynamic design, structural design, damage detection, optimal onshore and offshore location, control optimisation, and wind energy assessment optimisation problems. One study consolidated and analysed these findings to address various operational and control issues, improving and providing better turbine performance [21].

In the context of VIV BWT, static and modal analyses are commonly used to evaluate performance. These methods are particularly relevant as BWT generates energy through deformation and the vibration dynamic behaviour. Static and modal analyses provide critical information on deformation and resonance, which serve as a foundation for further performance optimization [5, 7].

Methodology

The fundamental principle for vortex induced vibration (VIV) bladeless wind turbine is to harvest the energy of wind induced vibration that occur transverse to the incident airflow. Maximising the degree of deflection of the turbine's mast can enhance the vibrational kinetic energy that can be harvested.

The primary objective is to maximize mast deflection within specified constraints. In urban settings, the size of the turbine is a dominant constrain due to the compact and open/ free space-restricted characteristic of city environments. Optimising the deflection degree then involves finding the best set of parameters that yield the local maximum of deflection while adhering to the size constrains.

To conduct this optimisation analysis, various methods were considered. From the reviewed studies on VIV BWT deflection and vibration optimisation, computational fluid dynamics (CFD), static structural analysis, and modal analysis were commonly employed on their models. These methods provided valuable insights on how changes in different factors influence deformation outcomes. However, these studies typically relied on a small sample size, often examining only few parameter configurations and focusing on a single design shape [7, 22]. Such limited sample sizes and parameter variations are neither systematic nor adequate for developing a comprehensive optimisation model for static deformation or modal analysis.

Repeated testing and plots generation methods used in conventional wind turbine and wind farm analyses have provided inspiration for us to develop a more systematic simulation plan. By combining the common approaches used for analysing VIV BWT with methodologies applied in conventional wind turbine and wind farm studies, design of experiment (DOE) is finally chosen. DOE provides a structured method for planning and conducting experiments, as well as data analysis and interpretation for complex systems [23]. It enables clear identification of relationship between variables and their influence on the outcome.

Response Surface Methodology is selected for doing the optimisation analysis, as it can use wide range of model fitting (first order (linear), second order (quadratic), or even higher order (cubic and quartic)). The typical model equation for response surface design, which explains different model terms corresponding to the degree of interactions between the factor levels is shown in Eq. 8 [23]

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_1^2 + \beta_4 X_2^2 + \beta_5 X_1 X_2 \quad (8)$$

where Y is the response variable, β_0 is the constant term, β_1 , β_2 are the coefficients of the linear model terms, β_3 , β_4 are the coefficient of quadratic model terms, and X_1 , X_2 are the model terms.

Central composite design (CCD) is chosen for conducting response surface methodology (RSM). It applies a second order (quadratic) model to the response outcome (Fig. 3), extending beyond a first order (linear) factorial design to second order design that capture potential curvatures in the response surface. The inclusion of centre points and axial points within CCD allows for a more accurate estimation of the curvature of the response surface, enabling better optimisation [23].

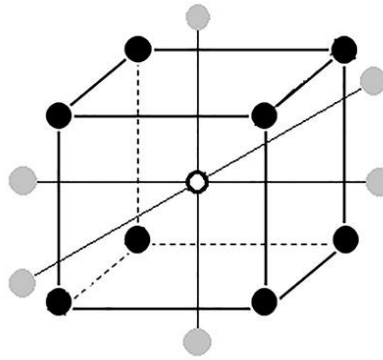


Figure 3. Visualised model of central composite design. The white point is the centre point; grey points are the axial points; black points are the corner points.

For multiple factors involved in this optimisation analysis, CCD and RSM are ultimately chosen as they minimise runs of experiments but can still capture the critical information and the factors and outcome interactions.

The choice of CCD and RSM is based on their ability to balance efficiency and accuracy in optimisation studies involving multiple factors. This method minimise the number of experimental runs required while still capturing critical information about the interactions between variables and their effects on the outcome. A response surface plot can be created at last. By visualising the results, it can make the result and analysis more easy understanding.

In our study, three factors were selected as the primary objectives in CCD: mast height (MH), mast upper diameter (UD), and mast lower diameter (LD), represented as factors X_1 , X_2 , and X_3 , respectively. Consequently, three combinations were formed for conducting the RSM, *i.e.* X_1 and X_2 , X_1 and X_3 , and X_2 and X_3 . Meanwhile, the response variable Y , mentioned in Eq. (8), is the maximum deflection/maximum deformation.

Parameters are being set up with reference to the dimensions of a commercially available vortex-induced vibration bladeless wind turbine developed by Vortex Bladeless. The dimensions of their testing device are used as the centre point in the CCD. To simplify future hardware simulations and ensure scalability, the dimensions have been uniformly reduced by a factor of two. This adjustment maintains the proportional relationships for software simulation in ANSYS while making future possible physical prototyping and simulation more practical and manageable.

Experimental Data and Results

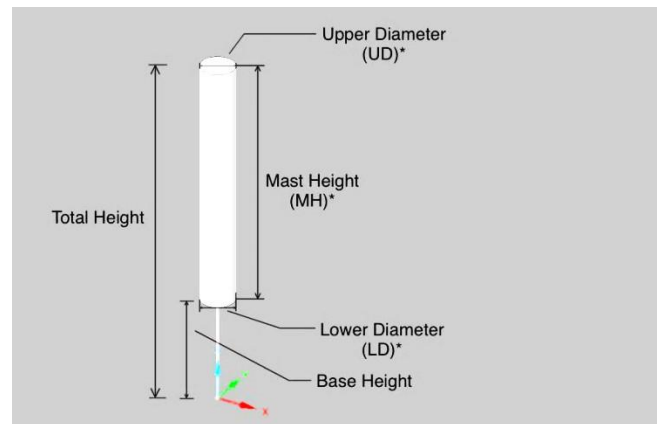
Experimental Data

In the context of harvesting urban wind energy, the velocity of the incident wind flow is a critical factor in ensuring that the simulation results are of practical and reference value. For this study, Central, Hong Kong, a world-class central business district renowned for its densely packed skyscrapers, was selected as the reference location for wind speed data. This typical urban environment provides a realistic basis for evaluating the performance of the VIV bladeless wind turbine under typical urban wind speed.

Table 1. Mean Wind Speed of Selected Site

Mean Wind Speed of Central Pier in 2024 [23]	
Month	Wind Speed (m/s)
January	3.714
February	3.665
March	3.993
April	3.144
May	4.361
June	3.3
July	3.145
August	2.51
September	3.329
November	3.852
December	3.268
Overall Mean	3.439

Considering the wind tunnel effect that may brought by densely packed buildings in urban districts, wind would accelerate between tall buildings and structures. Moreover, the Vortex Bladeless VIV bladeless wind turbine begins generating power at a minimum wind speed of 3 m/s [25]. To reflect realistic operating conditions while ensuring reliable simulation results, a wind speed of 5 m/s (to the positive x direction) was chosen for the ANSYS Fluent computational fluid dynamics (CFD) simulation.

**Figure 4.** Simplified model used for simulation. The labels with “*” are the study objectives.

Parameters analysis is designed to study their effect on the vibration ability of the turbine’s mast. As previously mentioned, the dimensions of the testing device from Vortex Bladeless are used as the centre point in the CCD. Three parameters are selected as the study objective (Fig. 4) — Mast Height (MH), Mast Upper Diameter (UD), and Mast Lower Diameter (LD). These parameters collectively represent most of the critical dimensional attributes of the turbine, including mast height, mast upper and lower diameter, rod (base) height, taper ratio. The upper and lower limits for each parameter are set to $\pm 20\%$ of the centre point, with alpha value 1.682 as the axial point. The alpha value is given by this Eq. 9.

$$\alpha = (2^k)^{1/4} \quad (9)$$

where α is the alpha value and k is the number of factors.

This configuration ensures that parameter variations remain within a reasonable range for accurate results, while also allowing for the study of parameter interactions and their influence on turbine's mast deflection.

Table 2. Design Summary Table of CCD

Design Summary	
Variable	Value
Continuous predictors	3
Discrete predictors	0
Base runs	20
Replicates	1
Total runs	20
Centre points in cube	6
Centre points in axial	0
α	1.682

Table 3. Design Table of CCD

Response Surface Design – Central Composite Design				
		Continuous predictors		
Run order	Standard order	A	B	C
1	6	1	-1	1
2	20	0	0	1.682
3	19	0	0	-1.682
4	18	0	1.682	0
5	12	0	0	0
6	1	-1	-1	-1
7	9	0	0	0
8	3	-1	1	-1
9	14	0	0	0
10	11	0	0	0
11	13	0	0	0
12	8	1	1	1
13	16	1.682	0	0
14	17	0	-1.682	0
15	2	1	-1	-1

16	4	1	1	-1
17	5	-1	-1	1
18	7	-1	1	1
19	15	-1.682	0	0
20	10	0	0	0

The raw CCD design generated by JASP (<https://jasp-stats.org/>) is shown in Table 3, where 1 and -1 represent the upper limit and lower limit, respectively.

The reference parameter values for the centre point are derived from a literature paper available on the Vortex Bladeless official website [11]. The testing device described in the literature has a height of 1 m and a diameter of 95 mm. For the purposes of this simulation, these dimensions were scaled down by a factor of two, and our model is then with a height of 0.5 m and a diameter of 0.0475 m. As our study focus is on the mast height, upper mast diameter, and lower mast diameter, the total height of the device is fixed at 0.5 m. This fixation allows us to specifically analyse how variations in mast height influence the outcomes. The mast-to-rod height ratio in the reference device is 2:1 [26], and for simplicity in calculations, the mast height and rod height in centre point were set to 0.35 m and 0.15 m, respectively.

The upper and lower limit for each parameter is set to $\pm 20\%$ of the centre point value. So, for the upper limit (+20%), the MH, UD, and LD would be 0.42 m, 0.057 m, and 0.057 m, respectively; for the lower limit (-20%), the MH, UD, and LD would be 0.28m, 0.038m, and 0.038m, respectively. The CCD experimental plan, incorporating these parameter ranges, generated by JASP, is summarised in Table 4 below:

Table 4. Response Surface Worksheet

<i>Response Surface Design - Central Composite Design</i>				
		Continuous predictors		
Run order	Standard order	Mast Height (m)	Upper Diameter (m)	Lower Diameter (m)
1	10	0.35	0.0475	0.0475
2	12	0.35	0.0475	0.0475
3	11	0.35	0.0475	0.0475
4	5	0.28	0.038	0.057
5	15	0.232	0.0475	0.0475
6	1	0.28	0.038	0.038
7	16	0.468	0.0475	0.0475
8	2	0.42	0.038	0.038
9	8	0.42	0.057	0.057
10	14	0.35	0.0475	0.0475
11	3	0.28	0.057	0.038
12	17	0.35	0.032	0.0475
13	20	0.35	0.0475	0.063
14	6	0.42	0.038	0.057

15	7	0.28	0.057	0.057
16	4	0.42	0.057	0.038
17	18	0.35	0.063	0.0475
18	19	0.35	0.0475	0.032
19	9	0.35	0.0475	0.0475
20	13	0.35	0.0475	0.0475

With the other parameters of the model fixed as follows:

- Total Height: 0.5 m
- Rod Diameter: 0.004 m (4 mm)

This ensures consistency through the whole simulation while only varying the selected study parameters.

Experimental Results

A static structural analysis was performed by selecting carbon fiber as the structural material, with a modulus of 230 GPa. Results from ANSYS Fluent and the static deflection are shown in Table 5. Modal analysis was also conducted, and the results of modal deformation in Y direction (mode shape) and modal frequency are shown in Table 6.

Table 5. Fluent and Static Structural Simulation Result

Run	Total pressure (Pa)(m ²)	C _d	C _l	Maximum Deformation (mm)
1	0.28146781	0.19222508	0.060053516	6.0795
2	0.28146781	0.19222508	0.060053516	6.0831
3	0.28191598	0.19038404	0.072198843	6.2554
4	0.22881341	0.16902544	0.038351499	6.6807
5	0.18260136	0.15215051	-0.031795178	7.0342
6	0.17405874	0.13278225	0.033721399	5.2847
7	0.37378878	0.24677277	0.071273073	1.8531
8	0.24786523	0.19436052	0.040703837	3.3829
9	0.40296264	0.26814913	-0.052038397	5.1753
10	0.28146781	0.19222508	0.060053516	6.0831
11	0.21617909	0.18733908	-0.03952183	8.3022
12	0.22389221	0.16219897	-0.021429441	4.5774
13	0.31739769	0.25221641	0.032131833	7.2835
14	0.31992216	0.24410209	-0.008118619	4.0578
15	0.26402788	0.20574843	0.026202234	8.5333
16	0.32495557	0.22356115	-0.033877016	4.1081
17	0.33065364	0.21953961	-0.084153551	7.3881
18	0.22784349	0.16939196	-0.040941837	5.6533
19	0.28146781	0.19222508	0.060053516	6.241
20	0.28146781	0.19222508	0.060053516	6.0831

Table 6. Modal Analysis Result

Run	Modal deformation (mm)	Modal Frequency (Hz)
1	46.891	0.76562
2	46.895	0.76539
3	46.895	0.76549

4	51.955	0.76074
5	50.945	0.71309
6	61.205	0.89379
7	44.109	1.3572
8	56.481	1.1669
9	37.666	0.77826
10	46.895	0.76539
11	45.874	0.67121
12	60.332	0.9864
13	42.533	0.69738
14	49.422	1.0211
15	40.828	0.60032
16	41.352	0.8541
17	38.177	0.62354
18	51.89	0.84611
19	46.895	0.76539
20	46.895	0.76539

Result Analysis and Interpretation

Static structural analysis involves applying static loads to the structure and studying the corresponding deformation. From our simulations, it serves as a baseline for understanding the dynamic behaviour of the system by providing insight into how the structure responds to static wind pressure. A larger degree of deformation indicates the turbine's potential to deflect under wind stress, which is crucial for amplifying the dynamic effects of resonance during vortex shedding [5].

To optimise the design parameters, analysis of response surface design in JASP was employed. The experimental data has been shown in the previous section. The tables, residues plots, as well as response surfaces, and their corresponding contour plots are shown below.

Table 7. Model Summary Table from JASP

<i>Model Summary</i>			
S	R ²	Adjusted R ²	Predictive R ²
0.196	0.992	0.986	0.936

Table 8. ANOVA Report from JASP

<i>ANOVA</i>					
Source	Sum of squares	df	Mean square	F	p
Model	10.176	9	1.131	29.4	< .001
Linear terms	3.773	3			
Mast Height (m)	2.814	1	2.814	73.162	< .001
Upper Diameter (m)	0.936	1	0.936	24.327	< .001

Lower Diameter (m)	0.024	1	0.024	0.613	0.452
Squared terms	5.181	3			
Mast Height (m) ²	4.89	1	4.89	127.157	< .001
Upper Diameter (m) ²	0.02	1	0.02	0.513	0.49
Lower Diameter (m) ²	0.271	1	0.271	7.055	0.024
Interaction terms	1.222	3			
Mast Height (m) × Upper Diameter (m)	1.146	1	1.146	29.79	< .001
Mast Height (m) × Lower Diameter (m)	0.002	1	0.002	0.043	0.84
Upper Diameter (m) × Lower Diameter (m)	0.075	1	0.075	1.94	0.194
Error	0.385	10	0.038		
Total	10.56	19			

Note. Type III sums of squares.

Table 9. Coded Coefficients Table from JASP

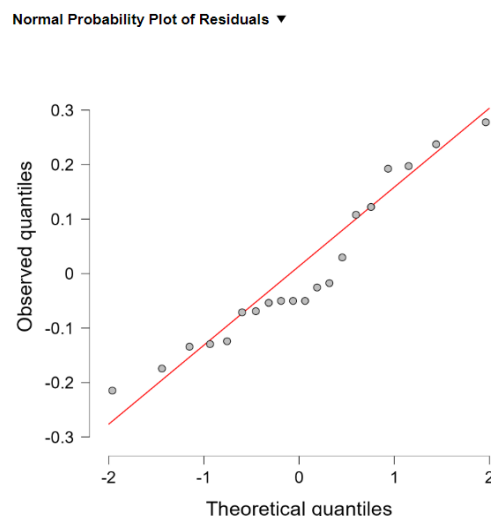
<i>Coded Coefficients</i>							
Alias	Term	Effect	Coefficient	Standard error	t	p	VIF
(Intercept)	(Intercept)		6.133	0.08	76.815	< .001	
A	Mast Height (m)	-5.128	-2.564	0.089	-28.688	< .001	1
B	Upper Diameter (m)	2.767	1.384	0.088	15.784	< .001	1
C	Lower Diameter (m)	1.477	0.738	0.088	8.422	< .001	1
A ²	Mast Height (m) ²	-3.29	-1.645	0.146	-11.276	< .001	
B ²	Upper Diameter (m) ²	-0.206	-0.103	0.144	-0.716	0.49	
C ²	Lower Diameter (m) ²	0.765	0.382	0.144	2.656	0.024	
AB	Mast Height (m) × Upper Diameter (m)	-2.082	-1.041	0.191	-5.458	< .001	1
AC	Mast Height (m) × Lower Diameter (m)	0.079	0.04	0.191	0.207	0.84	1
BC	Upper Diameter (m) × Lower Diameter (m)	-0.514	-0.257	0.185	-1.393	0.194	1

Table 10. Equation to Calculate the Approximate Response Value from JASP

<i>Regression equation in Coded Units</i>
Maximum Deflection = 6.133 (Intercept) - 2.564 A + 1.384 B + 0.738 C - 1.645 A ² - 0.103 B ² + 0.382 C ² - 1.041 AB + 0.04 AC - 0.257 BC

In RSM model summary (Table 7), there are two notations, where S stands for Standard error of the estimation, and R² stands for Coefficient of determination. S represents the average distance that the experimental value apart from the fitted value. S was found to be 0.196, indicating reasonable errors between observed and predicted values. R² was 0.992, demonstrating that 99.2% of the variance in the parameters could be explained by the model, showing a great fit of predictions. Extended from R², the adjusted R² value of 0.986 suggested a tendency for overfitting, meaning the overreliance on preexisting data and low accuracy on new data [27], while the predictive R² of 0.936 confirmed the model's strong predictive capabilities.

The analysis of variance (ANOVA, Table 8) further reinforced the model's reliability, with F-statistic value of 29.400, and p-value <0.001, showing the model is statistically significant (A small p-value (around <0.05) indicates statistical significance). More specifically, among linear terms, mast height (MH) is the most significant predictor (SS = 2.814, F = 73.162, p < 0.001), followed by upper mast diameter (UD) (SS = 0.936, F = 24.327, p < 0.001). Lower mast diameter (LD), however, showed minimal significance (SS = 0.024, F = 0.613, p = 0.452 (statistical insignificant)). Among squared terms, MH (SS = 4.890, F = 127.157, p < 0.001) and LD (SS = 0.271, F = 7.055, p < 0.05) are significant, while UD (SS = 0.02, F = 0.513, p = 0.490) is insignificant. Furthermore, among the interacting terms, only MH×UD (SS = 1.146, F = 29.79, p < 0.001) shows significant interactions, highlighting their combined impact on deflection. Overall, the analysis suggested that MH is the most critical parameter, with both strong linear and quadratic effects. UD also plays an important role, particularly in its linear term and its interaction with MH. LD, however, has a much smaller influence on deflection.

**Figure 5.** Probability Plot of Residuals

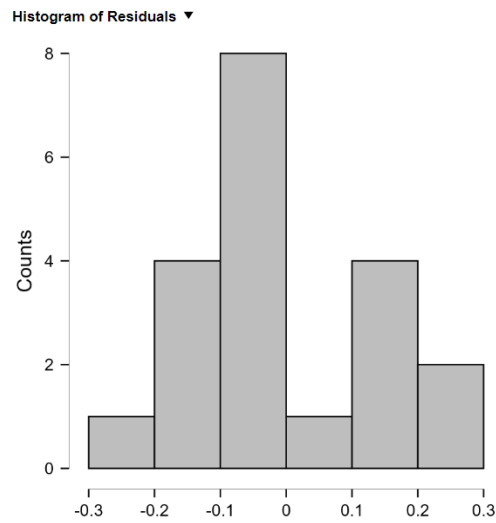


Figure 6. Histogram of Residuals

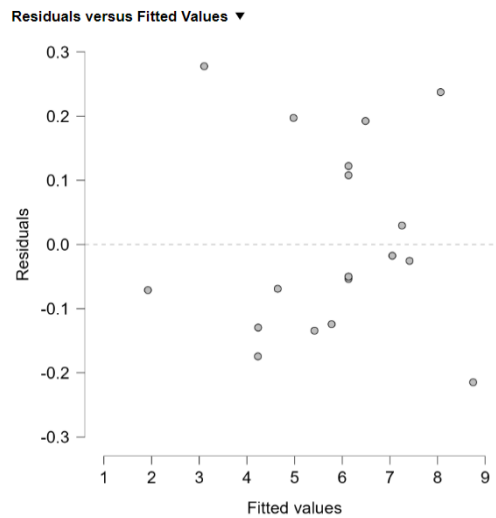


Figure 7. Residuals vs Fitted Values

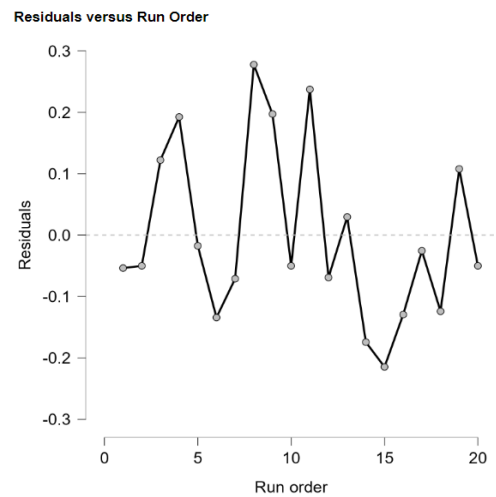
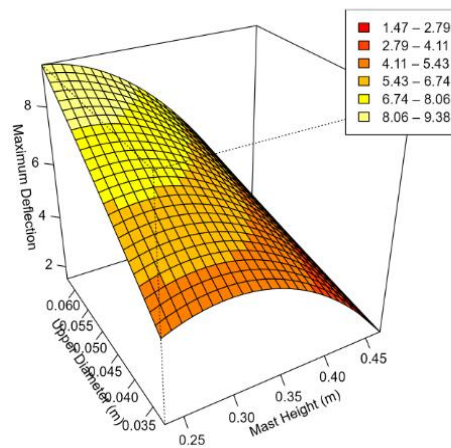


Figure 8. Residuals vs Run Order

In the residuals four in one plot (Figs. 5-8), the normal probability plot (Fig. 5) showed that the residuals were approximately normally distributed, as they fell closely along a straight line. The histogram (Fig. 6) indicated that the residuals were within a small range of ± 0.3 , with most values concentrated between ± 0.2 , confirming the accuracy of the model with reasonable errors. Both the residuals versus fitted values and residuals versus run order plots (Figs. 7-8) showed no discernible patterns, indicating independence and homoscedasticity of the residuals. These observations suggest that the model predictions are robust and free from time-dependent bias.

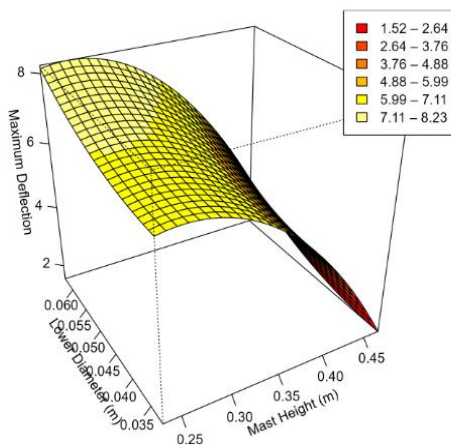
Surface plot of Maximum Deflection vs Mast Height (m) and Upper Diameter (m)



Slice at Lower Diameter (m) = 0.048

Figure 9. Response Surface of Maximum Deflection vs MH vs UD

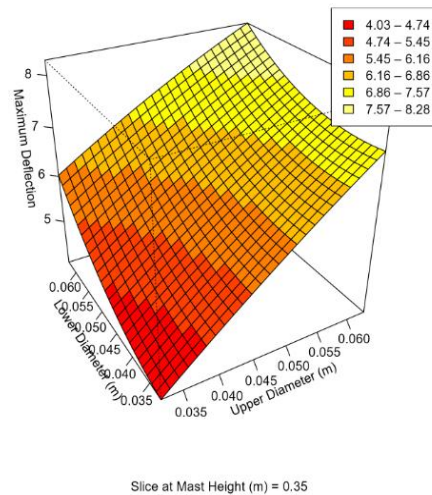
Surface plot of Maximum Deflection vs Mast Height (m) and Lower Diameter (m)



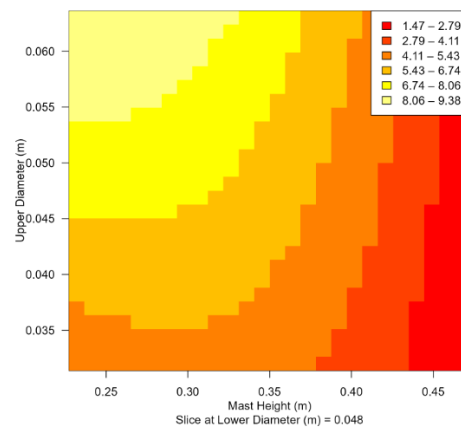
Slice at Upper Diameter (m) = 0.048

Figure 10. Response Surface of Maximum Deflection vs MH vs LD

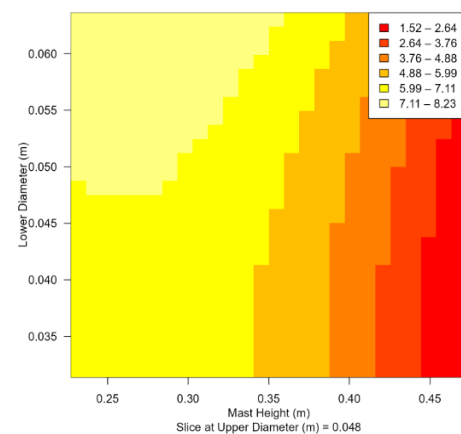
Surface plot of Maximum Deflection vs Upper Diameter (m) and Lower Diameter (m)

**Figure 11.** Response Surface of Maximum Deflection vs UD vs LD

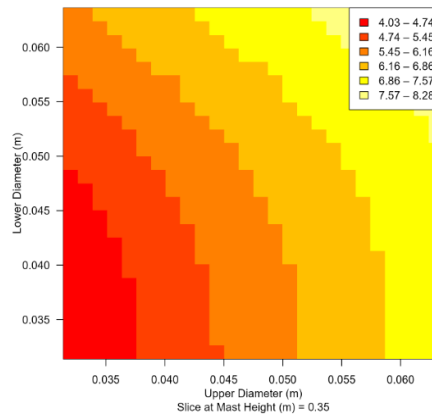
Contour plot of Maximum Deflection vs Mast Height (m) and Upper Diameter (m)

**Figure 12.** Contour Plot of Fig. 9

Contour plot of Maximum Deflection vs Mast Height (m) and Lower Diameter (m)

**Figure 13.** Contour Plot of Fig. 10

Contour plot of Maximum Deflection vs Upper Diameter (m) and Lower Diameter (m)

**Figure 14.** Contour Plot of Fig. 11

By observing three of the response surfaces (Figs. 9-14), it is observed that the approximate location of the optimal solution, as well as they are sharing the same findings mentioned in the report above. As there are three parameters, the response surfaces were presented in 3D plots, with one parameter held constant at its midpoint value each.

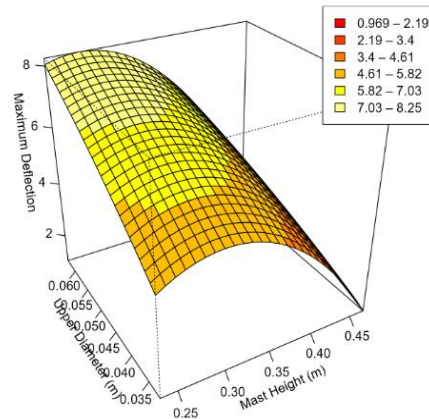
In the Maximum Deflection vs MH vs LD surface plot (Fig. 10) and Maximum Deflection vs MH vs UD surface plot (Fig. 9), it is observed that the shorter the MH, the greater the deflection. This is likely because a shorter mast height raises the system's centre of gravity, making it more prone to deformation under wind stress. We can also observe that LD is playing a less significant role when compared to UD, whereas the dominant parameter is the MH. Similar findings were found in the Maximum Deflection vs LD vs UD plot (Fig. 11). With MH being fixed, the change in UD resulted in a much steeper slope compared to the change in LD. Larger diameter values were associated with greater deflections, which can be attribute to Eq. 1.

To validate the accuracy of the three surfaces, repeated verifications were conducted. For most of the points of verification are fall within a minor and reasonable residual range, two points exhibit significant errors: The two points are:

1. For MH = 0.25 m, UD = 0.06 m, LD = 0.0475 m, the expected deflection was ≥ 8.06 mm, but the observed value was 7.162 mm.
2. For MH = 0.25 m, UD = 0.0475 m, LD = 0.06 m, the expected deflection was ≥ 7.11 mm, but the observed value was 6.3475 mm.

These results represent that in both Maximum Deflection vs MH vs LD surface plot and Maximum Deflection vs MH vs UD surface plot, a downward slope should be presented in the upper left corner instead of the current continuous upward slope. Having considered that two points into our analysis, new response surfaces are generated.

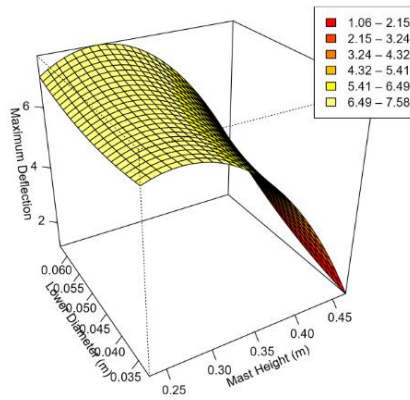
Surface plot of Maximum Deflection vs Mast Height (m) and Upper Diameter (m)



Slice at Lower Diameter (m) = 0.048

Figure 15. Refined Response Surface of Maximum Deflection vs MH vs UD

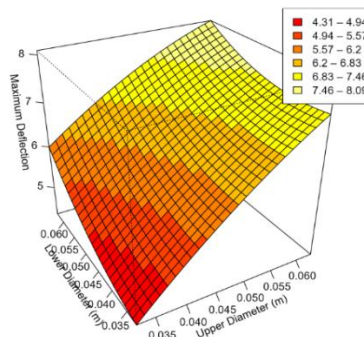
Surface plot of Maximum Deflection vs Mast Height (m) and Lower Diameter (m)



Slice at Upper Diameter (m) = 0.048

Figure 16. Refined Response Surface of Maximum Deflection vs MH vs LD

Surface plot of Maximum Deflection vs Upper Diameter (m) and Lower Diameter (m)



Slice at Mast Height (m) = 0.34

Figure 17. Refined Response Surface of Maximum Deflection vs UD vs LD

Although the adjusted response surfaces still could not precisely predict deflection at these two points, they provided valuable insights into the overall trends and robust zones in the new surfaces. For both plots (Fig. 15, 16), the robust zones for optimal performance were identified as follows:

1. In the Maximum Deflection vs MH vs LD plot (Fig. 15), the optimal region was found at $LD = 0.060$ m and $MH = 0.27\text{--}0.33$ m.
2. In the Maximum Deflection vs MH vs UD plot (Fig. 16), the optimal region was at $UD = 0.060$ m and $MH = 0.27\text{--}0.33$ m.

From the analysis of the three response surface plots, a potential optimal region was identified. The optimal mast height (MH) was observed to lie between 0.27 m and 0.33 m, as indicated from the Maximum Deflection vs MH vs LD (Fig. 16) and Maximum Deflection vs MH vs UD (Fig. 15) surface plots. Furthermore, the optimal values for the lower mast diameter (LD) and upper mast diameter (UD) were found to be 0.060 m, as indicated by the Maximum Deflection vs UD vs LD plot (Fig. 17).

Based on these observations, a potential optimal combination of parameters was tested, with $MH = 0.3$ m, $LD = 0.06$ m, and $UD = 0.06$ m.

The static structural analysis of this configuration achieved the highest response, with a maximum deformation of 9.1497 mm (Fig. 18). This result validates the accuracy and effectiveness of the optimization model in predicting static deformation behavior and confirms the robustness of the identified optimal parameter combination. The results indicate that the optimum ratio of mast height to rod height is approximately 3:2. Additionally, while a larger mast diameter corresponds to greater deflection, the taper ratio does not significantly influence the degree of deflection in static structural analysis (Fig. 17). However, it is likely to play a more critical role in shedding frequency (a dynamic aspect) with reference to past studies [14, 28].

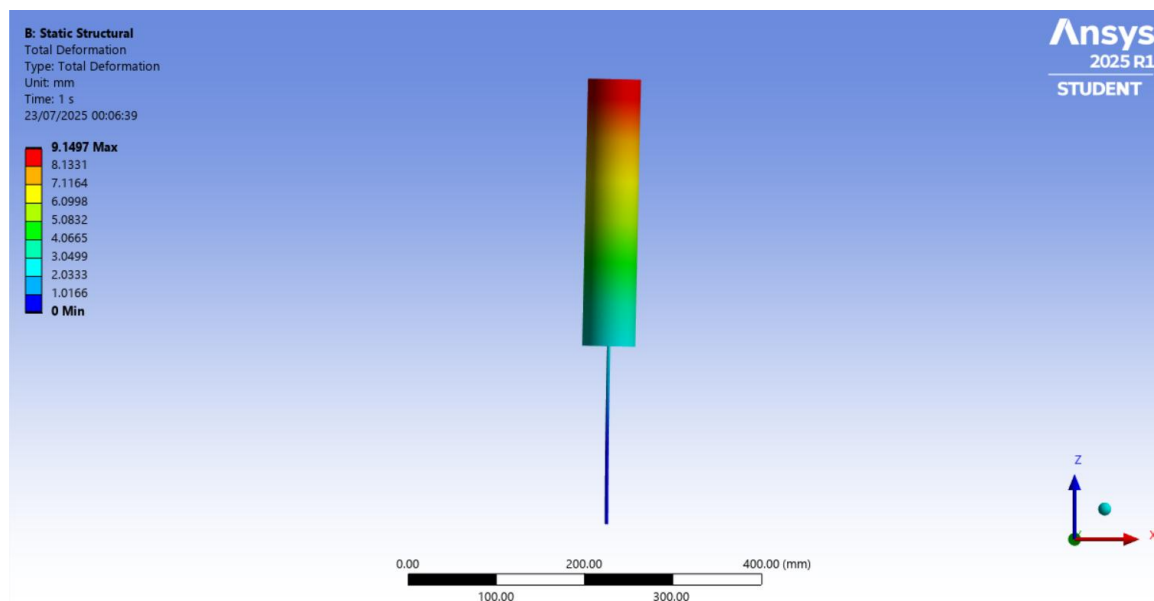


Figure 18. Result of the Optimal Model in Static Structural Analysis

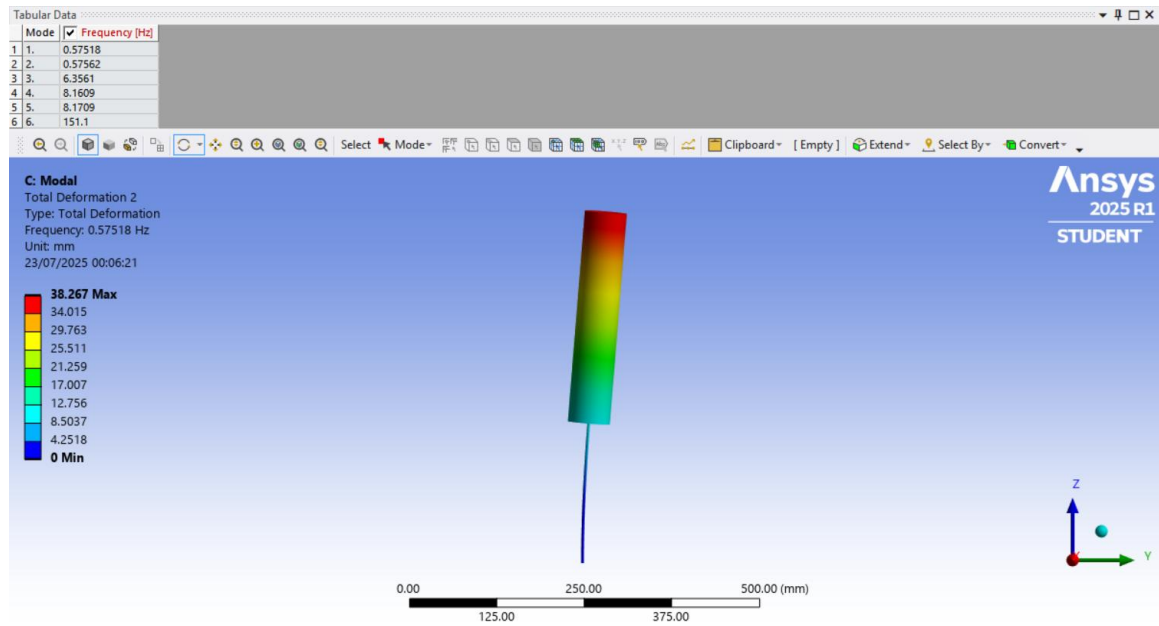


Figure 19. Result of the Optimal Model in Modal Analysis

The results from Table 11 also indicate that, when compared with the findings from the modal analysis, an opposite trend is observed in modal frequency. Specifically, a trend of greater the degree of deformation, the smaller the modal frequency is observed. Structural stiffness plays a critical role in determining both deformation and modal frequency. Lower stiffness allows for greater deformation but also reduces the natural (modal) frequency of the structure [29]. From the static structural analysis, the maximum deflection provides an approximate indication of the relative stiffness between the models. Based on the results, it can be concluded that Run 7 exhibits the greatest stiffness, while Run Max demonstrates the least stiffness, with the other models falling between these extremes under this constant wind speed. Since modal frequency is directly proportional to the stiffness of the structure, (*i.e.*, greater the stiffness greater the frequency), the trend observed in modal frequency is the complete inverse of the trend in maximum deflection obtained from the static structural analysis, which also validates the accuracy of the collected in static structural analysis and reinforces that greater deflection can be achieved under greater flexibility.

While frequency is a key factor in assessing the performance of VIV BWT, it is not the primary focus of this study. For a more comprehensive evaluation in maximising VIV BWT performance, it is necessary to balance both factors. Further research on BWT shedding frequency, including considerations such as material properties, damping, and tuning systems, is required to extend beyond the scope of this study.

Table 11. Comparison Between Static Structural Deflection and Modal Frequency

Run Number	Static Structural – Max. Deflection (mm)	Modal Analysis Frequency [Hz]
Run7	1.8531	1.3572
Run8	3.3829	1.1669
Run14	4.0578	1.0211
Run16	4.1081	0.8541

Run12	4.5774	0.9864
Run9	5.1753	0.77826
Run6	5.2847	0.89379
Run18	5.6533	0.84611
Run1	6.0795	0.76562
Run2	6.0831	0.76539
Run10	6.0831	0.76539
Run20	6.0831	0.76539
Run19	6.241	0.76548
Run3	6.2554	0.76549
Run4	6.6807	0.76074
Run5	7.0342	0.71309
Run13	7.2835	0.69738
Run17	7.3881	0.62354
Run11	8.3022	0.67121
Run15	8.5333	0.60032
Run Max	9.1497	0.57518

Conclusion

This study optimized the design of Vortex-Induced Vibration (VIV) bladeless wind turbines to enhance energy harvesting in urban environments. By applying static structural and modal analyses combined with Response Surface Methodology (RSM), we identified mast height (MH) as the most influential parameter, followed by upper diameter (UD), while lower diameter (LD) had minimal impact. The optimal configuration achieved a maximum static deflection of 9.15 mm, corresponding to an approximate mast-to-rod height ratio of 3:2. Larger mast diameters improved flexibility, whereas taper ratio showed limited effect under static conditions.

These findings provide valuable insights into structural optimization; however, the study primarily addresses static deformation. Future research will address dynamic aspects such as vortex shedding frequency, damping, and tuning mechanisms to achieve a balance between flexibility and resonance. Such advancements are essential for improving the efficiency and reliability of VIV bladeless wind turbines in real-world urban applications. In addition, our future effort will be devoted to the robust design of VIV bladeless wind turbines under uncertainties and disturbance [30-31].

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this paper.

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