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INVESTIGATING AND IMPROVING THE DYNAMIC CHARACTERISTICS OF OMNI -DIRECTIONAL ANEMOCONE USING VIBRATIONAL ANALYSIS

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Abstract
Wind energy is being used for various other purposes for ages. In the modern era, it is being used to produce electricity. The aim of this work is to minimize vibrations in an Omni-directional Anemocone operating at its peak performance of 4m/s, while simultaneously improving its structural design to reduce weight and cost. The ODA represents an innovative wind energy solution that utilizes a unique funnel-shaped design to capture wind from all directions and direct it through a narrowing duct towards the turbine rotor to rotate it even at low outside wind speeds, resulting in increased energy capture efficiency and reduced vibrational amplitudes. However, this distinctive design introduces challenges related to vibrations, which can adversely affect the turbine's performance, structural integrity, and overall lifespan. To address this issue, a modal analysis technique is employed to identify and minimize resonance frequencies and modes in the Anemocone components. By conducting a detailed analysis of the duct structure, rotor assembly, and supporting infrastructure, the project aims to identify potential sources of vibrations and develop effective mitigation strategies. Furthermore, the project seeks to optimize the turbine's structural design to reduce weight while keeping costs minimal. This involves exploring different design configurations, material choices, and manufacturing processes to achieve a lighter and more efficient structure. The successful reduction of vibrations and weight will not only enhance the turbine's reliability and longevity but also contribute to increased energy conversion efficiency, decreased maintenance requirements, and improved economic viability. Overall, this work endeavors to advance the ODA technology, making it a more sustainable and economically competitive wind energy solution in the global push towards renewable energy adoption.

INTRODUCTION

The world needs to produce electricity from different forms of energy. Among them, fossil fuels have played a significant role. Many renewable energy sources are also used widely, which include wind and solar power. Utilizing wind energy is not a new concept that has been used for ages for different purposes. In the modern era, it is used to produce electricity by making various wind farms. Omni-directional Anemocone (ODA) is a

type of shrouded wind turbine which, due to its innovative design, is cable of producing significantly greater energy than conventional wind turbines. G.

A. Gohar et al. showed the comparison of two different INVELOX models to examine pressure and velocity distributions. The results demonstrate that the velocity and pressure drop of Model-1 at venturi is 10.42 m/s and -1.722×10^{1} Pa, and of Model-2 are 45.5 m/s and -6.938×10^{2} Pa, respectively [1]. Sotoudeh et al. studied that adding a block to the INVELOX wind turbine increases the power output of the turbine, by increasing its height from 10 m to 40 m the output power increased by 87.5%, and the power acoustic level increased by 39.3% [2]. N.Maftouni et al. presented a numerical study of two different designs of INVELOX, the first design has long flanges, and the second design has holes in the venturi section to allow more mass flow rate, the results show that using the long flange increases the wind velocity (about 15.45%). Also, the pair of holes in the venturi results show a slight improvement in the output power [3]. S. Shayestehnezhad et al. showed the utilization of CFD tools to evaluate the inlet parameters of the INVELOX, the results show that by increasing the diameter and inlet of turbine two times, the output power increases by 35% as compared to the original design of INVELOX [4].F. Nardecchia et al. proposed multiple design enhancements resulted in a 20% improvement in performance in CFD simulation; in addition, the effect of omni-directional capability and wind stream speed on the speed ratio was examined. They concluded that INVELOX is not omni-directional for wind incident angles of 135°, 225°, and 180°. Moreover, the wind stream speed relation to the Venturi section speed is almost linear; thus, the wind speed effect on the speed ratio is negligible [5]. N. Aravindhan et al. demonstrated in this study that a further increase in wind speed is achieved by optimizing the profile of the shroud using the Taguchi method. A modified INVELOX is affixed to the shroud's exit. The shrouded INVELOX increases wind speed by 1.52 times when installed on low-rise buildings and 1.68 times when installed on the highest building [6]. P.Snehal Narendrabhai et al. showed that Numerical simulation and analysis have been performed on the INVELOX wind turbine system to determine its benefits over traditional turbines in terms of power generation. The INVELOX achieved a wind speed of 11.9 m/s at the venturi section, which is 6–8 times more powerful than conventional wind energy. The INVELOX system generated more energy than conventional wind turbines [7]. D. Allaei et al. objective of this study is to demonstrate the comparison between INVELOX wind turbine and conventional wind turbine based on various parameters. Both computational and measured test results were described in this study, the results showed that it is possible to concentrate, capture and accelerate wind using an omnidirectional intake. [8]. A. Golozar et al., in his study offered an innovative roof mechanism that was controlled by a fuzzy system to lessen the fleeing stream. This method showed a 12% increase in efficiency when tested using a CFD simulation [9]. L. Ding et al. in his study showed that when the wind direction is greater than 90° from the axis of the venturi conduit, the system's power generation efficiency will drop dramatically. When the angle is greater than 120°, the system ceases to produce electricity. After contemplating Atmospheric Boundary Layer (ABL) the system's speed ratio (SR) will decrease [10]. In this article, support structure has been introduced the practical implementation of ODA. It has been structurally stabilized for the smooth functioning and power generation.

II. METHODOLOGY

ODA was modeled using Solidworks. There are various ways in which it can be modeled but the spline command was used to obtain a complete model with fewer points so that it can be applied for machine learning in the future. After designing the ODA, a supporting structure was designed keeping in view that the design remains cost-effective and structurally stable. There was a limitation in utilizing the amount of material as it directly affects the cost. A design made using support structure is shown in figure 1. It consists of ODA along with the supports which provide base for its implementation.

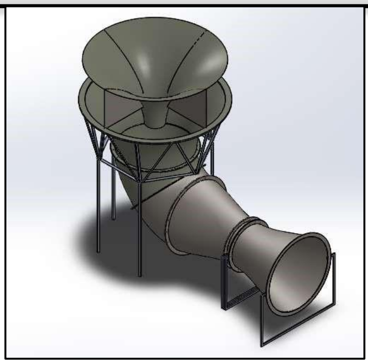

Figure 1: ODA First Design

The methodology includes first performing modal analysis followed by structural analysis. There was no need for harmonic analysis as it is aimed to move the natural frequencies out of the operating frequency range. The following chart(figure2) best describes the methodology utilized.

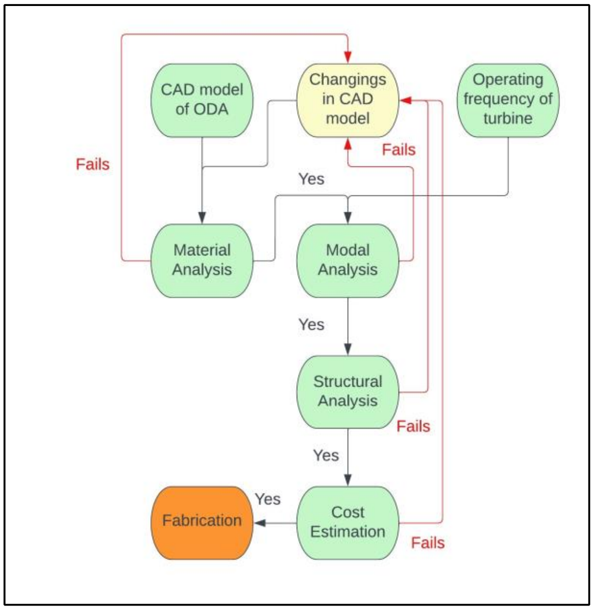

Figure 2: Flow chart of the methodology

The red lines represent that the structure fails and is sent back for the redesigning of the CAD model and the methodology repeats.

The operating frequency of an ODA refers to the range within which the turbine rotates. For this particular work, the operating frequency is specified to be in the range of 100 – 500 rpm. This range ensures optimal performance and power generation within the turbine's design parameters. However, it is important to note that when the speed exceeds 500 rpm, an auto-braking mechanism activates to prevent the turbine from reaching higher frequencies.

The specified operating frequency range and the implementation of auto braking are determined based on the manufacturer's handbook [11]. The handbook provides essential guidelines and specifications to ensure the safe and efficient operation of the ODA. By adhering to these recommendations, the project aims to maintain the turbine's integrity and performance while minimizing vibrations. To determine the optimal operating frequency range and the need for auto braking, data from the manufacturer's handbook is used. A flow chart, shown in Figure 2, displays the recommended operating parameters provided by the manufacturer.

This chart serves as a valuable reference for understanding the relation between rpm, wind speed, and power generated. By considering the operating frequency range and implementing an auto-braking system when necessary, the work aims to ensure that the turbine operates within its specified parameters and minimizes the risk of excessive vibrations or mechanical stress.
By reading the graph, the operating frequency is found to be between 2-6 Hz, with 2 Hz being cut in speed whereas 6 Hz is the maximum achievable.

III. NUMERICAL METHOD

A. CAD methodology

Different supporting structures were designed based on the ease of their availability. Angled bars and squared bars are commonly used to support these kinds of structures. Therefore, the same supports were used for the stability of ODA. The shape of ODA was designed to have a good velocity ratio at the throat area where the turbine is placed for power extraction. The weight of the initial design was 9000 kg. The height of the models is fixed to be around 32-33 ft. There was a little flexibility in the length of the designs which ranged from 35-45 ft. The throat diameter was selected to be 7.6 ft so that a turbine capable of producing 2KW can be placed. Within this height range, the turbine is capable of producing a 2-2.5KW.

B. Simulations and Results

The first design, being lightweight, was unable to bear static load due to its weight. It failed due to less thickness. Various other designs were also analyzed. Here the results of three designs are analyzed which differ in their values.

1) Design-1

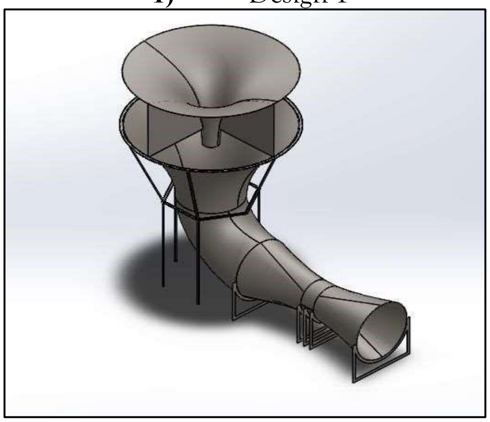

Figure 3: Design- 1

The CAD model shown in Figure 3 is the initial CAD model which was designed to bear static load only at the cost of 10.046 M Pak Rs. The model was a result of continuously improved CFD design to achieve a peak velocity ratio at the throat. Its modal analysis (first eight modes) showed that the 1st four natural frequencies were close to zero and the next four frequencies were between the operating ranges of the turbine, i.e., 2-6 Hz. The potential reasons for these issues were, either the model was too lightweight compared to its size or improper CAD model/discontinuity in structure. The use of thick sheet metal for wrapping and the use of thicker pillars and rebar was the viable solution to improve dynamic response at the expense of increased cost. The support structure was then changed depending on the deformation results from the 1st and 2nd natural frequencies. The modal analysis was run with alterations till the results were satisfied.

2) Design-2

By using the hit-and-trial method and doing various analyses, the final design was selected. Different supporting mechanism and cross-section bars contributed to new design. This design, shown in figure 4, is better solution and cost-effective, and the model frequencies lie within the safe range of operating frequencies.

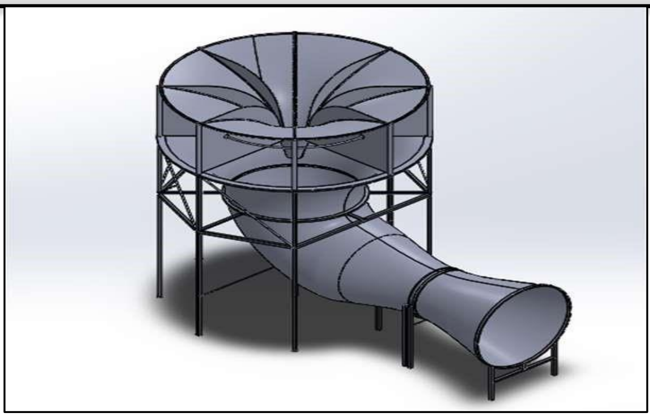

Figure 4: ODA with better modal frequencies

3) Stiffened Structure

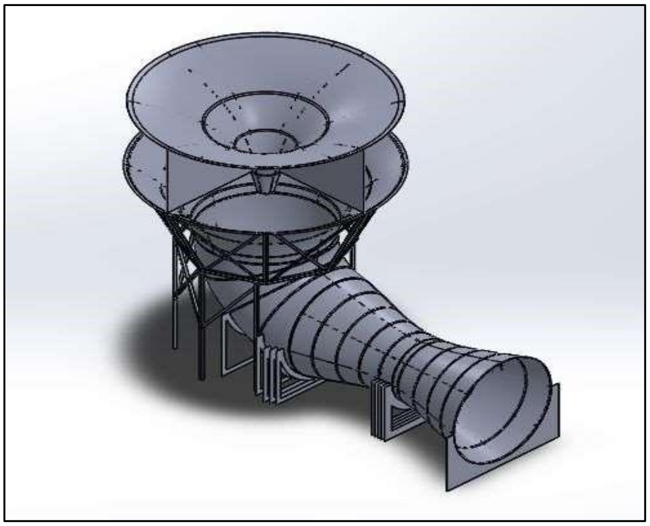

Figure 5: Design- 2 with ribs

To enhance the stiffness and structural integrity of the ODA model, a rib structure, as shown in figure 5, was introduced at specific intervals of 1.5-2 feet. The purpose of this addition was to improve the overall performance of the turbine and reduce vibrations. The ribs were strategically placed within the turbine assembly to achieve optimal results. One of the primary goals of incorporating the ribs' structure was to increase the natural frequencies of the turbine along with strength. By stiffening the model, the rib structure effectively raised the resonance frequencies, leading to a more stable operation. The increase in natural frequencies was crucial in minimizing the risk of vibration-induced failures and improving the overall reliability of the turbine.

Remarkably, the addition of the ribs structure resulted in a significant increase of 1Hz in the natural frequencies of the ODA. This increment demonstrates the effectiveness of the ribs in achieving the desired level of stiffness and vibration reduction.

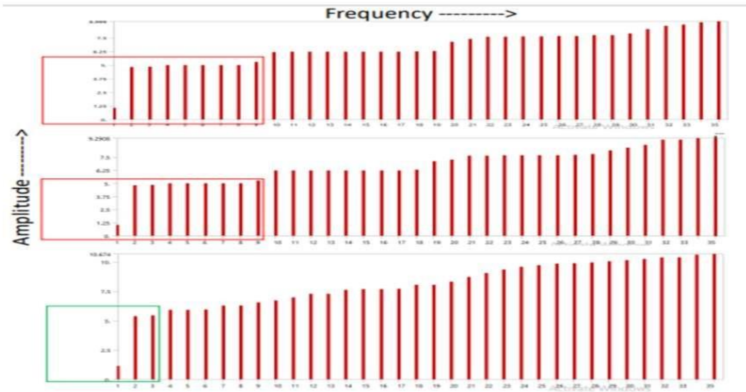

Figure 6: Frequency vs Amplitude

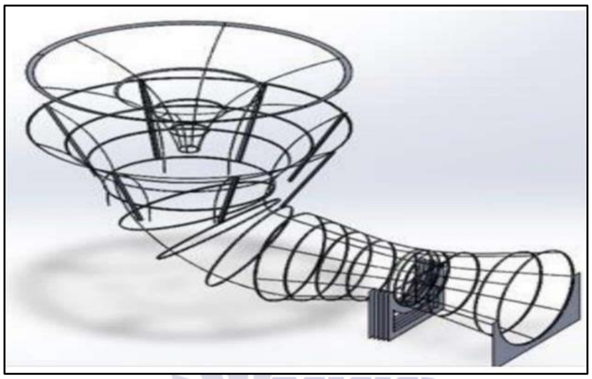

Figure 7: Ribs Structure only

The higher natural frequencies obtained through the ribs structure contribute to a more stable and efficient operation of the turbine. The comparison between the modal frequencies of all the three cases has been shown in figure 6 for better understanding. From this figure it is evident that the design 2 model and stiffened model gave almost same and satisfactory frequencies. The rib structure alone is shown in figure 7. However, it is important to consider the cost implications associated with incorporating the ribs' structure. The cost of implementing the ribs' structure was found to be approximately 800k to 900k. While the increase in natural frequencies was notable, the associated cost was determined to be relatively high in comparison. So instead of going for more ribs, other designs based on amplitudes/deflections obtained from previous designs were created to achieve relatively acceptable results while optimizing cost.

IV. RESULTS

Figure 7 shows a comparison of frequencies of Design-1, Design-2, and stiffened design. The highlighted boxes show the range of frequencies falling in the operating range of the turbine. The results show that the most suitable range of frequencies is for the stiffened design, but the cost has increased significantly as well. There is not much change in the results of Design-2 and stiffened design. These results vary by 1Hz frequency only. Therefore, instead of going towards the stiffened design, Design-2 is selected. The overall cost of both the designs are shown in Table 1 along with their shroud thickness.

Model	Thickness (mm)	Cost (Rs.)
Design-1	5	10M
Design-2	1.2	2.4M

Stiffened Design	1.2	3.3M

Table 1:Cost Comparison

The following are the modal results for the first two natural frequencies.

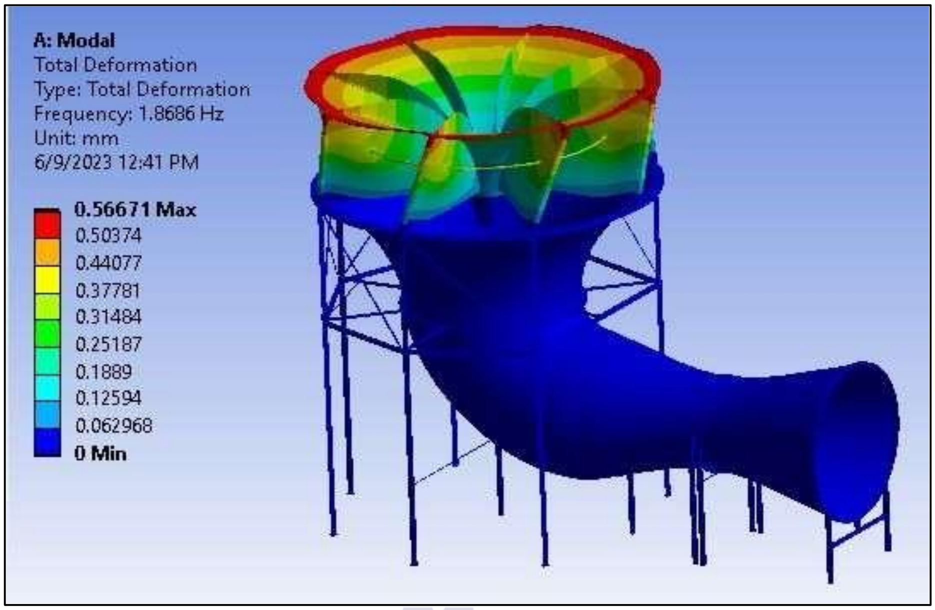

Figure 8: 1st Frequency

The results of figure 8 show the first modal frequency which lies outside the operating frequency range. Therefore, its impact can be neglected.

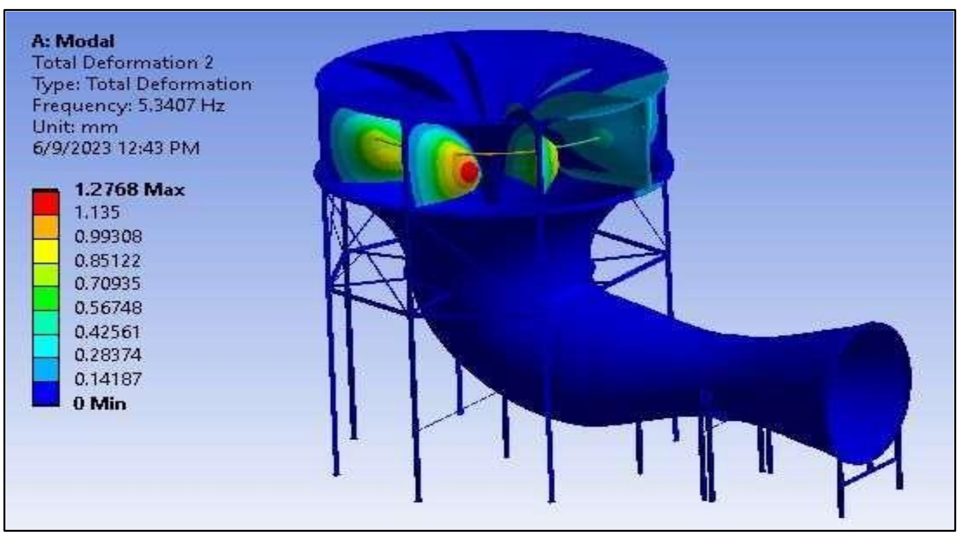

Figure 9: 2nd Frequency

The results of the second frequency lie at the edge of the frequency range of the operating frequency. It shows 1mm deflection on the six upper flanges as can be evident from the figure 9.

V. DISCUSSIONS

Based on the analysis and the values obtained, using the maximum speed of 500 rpm and the maximum displacement of 4 mm, a chart from the book "Condition Monitoring of Rotating Machines" by Robert Bond Randall must be followed to determine the vibration velocity. According to the chart [12], the calculated vibration velocity indicated that the turbine would be running in a "Good state" under these conditions.

The classification of the turbine as being in a "Good state" suggests that the vibration levels at the specified RPM and displacement are within acceptable limits. This implies that the turbine would be safe under its operating conditions. It is important to note that continuous monitoring and periodic assessments are necessary to ensure the long-term reliability and performance of the turbine. Regular condition monitoring practices enable the early detection of any changes or anomalies in vibration patterns, allowing for timely maintenance or corrective actions to be taken.

The results obtained from the analysis indicate important findings regarding the operating frequency and the natural frequency to safeguard the turbine system. The operating frequency range was determined to be between 2 Hz and 6 Hz. Notably, it was observed that the upper limit of the operating frequency coincided with the natural frequency of the structure with a difference of 0.62 Hz. To increase the natural frequency by this amount and ensure a safe operating range, a significant cost increase of approximately Rs. 1 M was estimated. However, such a substantial cost escalation was deemed financially unfeasible for this work. As a result, an alternative approach is suggested to incorporate the half auto braking mechanism when the turbine's speed exceeds 335 rpm, and full braking is applied as the speed reaches 500 rpm. It will limit the rotational speed and prevent the turbine from higher operating frequencies, thus mitigating the risk of excessive vibrations and potential structural damage. By controlling the rotational speed within a safe range, the proposed approach ensures the turbine operates within its structural limitations and minimizes the risk of failure. Further verification and validation through testing and simulations are necessary to confirm the effectiveness and feasibility of the proposed braking system. Additionally, continuous monitoring and evaluation of the turbine's performance are crucial to ensure that vibrations are effectively controlled and that the overall operation remains safe and reliable. In conclusion, the presented results highlight the identification of the operating frequency range, the determination of a safe range based on the dynamic analysis, and the proposal of an auto braking system to prevent the turbine from operating at frequencies that could pose risks.

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