NUMERICAL STUDY OF TWIN-ROTOR VERTICAL AXIS WIND TURBINE

SANDEEP YADAV

DEPARTMENT OF APPLIED MECHANICS

INDIAN INSTITUTE OF TECHNOLOGY DELHI

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by

SANDEEP YADAV

DEPARTMENT OF APPLIED MECHANICS

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Dedicated to my loving family, who have supported me unconditionally throughout this journey. Their encouragement and belief in me have been my guiding light.

THESIS CERTIFICATE

This is to certify that the thesis titled "**Numerical Study of Twin-Rotor Vertical Axis Wind Turbine**", being submitted by **Sandeep Yadav (2016AMZ2259)** is a report of the bonafide research work carried out by him under our supervision. The thesis has been prepared in conformity with the rules and regulations of Indian Institute of Technology, New Delhi, India. We further certify that the thesis has attained a standard required for a PhD degree of the Institute. The research reported, results presented in the thesis have not been submitted, in part or full to any other Institute or University for the award of any degree or diploma.

Dr. Srinivas V Veeravalli
Professor
Dept. of Applied Mechanics
IIT-Delhi, 110016

Dr. S.N. Singh
Professor
Dept. of Applied Mechanics
IIT-Delhi, 110016

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Place: New Delhi

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-Sandeep Yadav

ABSTRACT

With the continuously increasing population, their raised household comforts, and the growing industrialization, there has been a significant rise in energy demands. These rising energy demands, coupled with the rapid depletion of fossil fuels and the resulting increase in CO_2 emissions, have highlighted the urgent need for the transition towards clean and renewable energy sources like solar and wind power. Among these alternatives, our focus has been on harnessing wind power.

Wind power is captured through the use of wind turbines, which are broadly classified into two categories: Horizontal Axis Wind Turbines (HAWTs) and Vertical Axis Wind Turbines (VAWTs). In the past decade, the resurgence of interest among researchers in lift-type VAWTs due to their demonstrated potential for higher power density compared to their HAWT counterparts, as the operation of these turbines in closer proximity to each other in a counter-rotating configuration would produce more power in a farm. In alignment with the same, this thesis presents the computational study conducted to investigate the effect of aerodynamic interference between rotors in a non-overlapping twin-rotor configuration (having center-to-center relative inter-turbine spacing (S) ($\frac{S}{D} > 1$) and overlapping twin-rotor ($\frac{S}{D} \leq 1$), where D represents the rotor diameter) on the performance and wake recovery. The relevance of this piece of work lies in understanding the performance characteristics and interaction dynamics of twin-rotor VAWTs, which will allow for their successful incorporation into a wind farm (onshore or offshore).

The work commenced with a two-dimensional study using Unsteady Reynolds Av-

eraged Navier Stokes (URANS) Equations, employing the commercial solver ANSYS Fluent 19.2. The selection of a numerical modeling technique for an isolated rotor involved the comparison of two different dynamic meshing techniques: sliding mesh and overset mesh. Both techniques produced similar results but deviated from the experimental findings. However, due to the limitations of the sliding mesh technique in handling overlapping rotors, the overset mesh technique was chosen for further investigations. The subsequent phase focused on the performance and wake validation study of both single rotors and counter-rotating pairs of rotors at a $\frac{S}{D} = 1.65$. By building upon established criteria, the modeling process was extended to include paired and twin-rotor configurations with different relative spacings.

A systematic simulation campaign was carried out for overlapping twin-rotor ($\frac{S}{D} \leq 1$) and non-overlapping twin-rotor ($\frac{S}{D} > 1$) for varied tip speed ratios. The key results indicate that overlapping rotors exhibit unique interaction effects, influencing the performance and wake characteristics of each rotor. Analysis of the obtained data indicates that the overlapping twin-rotor with $\frac{S}{D} = 0.9875$ demonstrates approximately 25% better performance compared to a single-rotor. Furthermore, the twin-rotor with $\frac{S}{D} = 0.89$ exhibits a remarkably smooth power output (nearly independent of the azimuthal position) with an enhancement of approximately 8% over the single rotor. This has significant practical implications from the point of view of power generation and transmission. Additionally, the wake recovery is observed to be faster for the $\frac{S}{D} = 0.89$ case in comparison to other configurations.

Further, the thesis provides details of several attempts made to conduct experimental studies, which are outlined in the appendix. The reasons for the lack of success in these attempts are thoroughly discussed, shedding light on the challenges encountered during the research process. In conclusion, this thesis encompasses the numerical investigation of overlapping and non-overlapping twin-rotor VAWTs, focusing on their performance, wake validation, numerical modeling techniques, and the insights gained. The study contributes to our understanding of the resulting interaction effects between twin-rotor VAWTs and offers valuable insights into their optimal design and performance. The findings and analysis presented in this work serve as a foundation for the development of efficient and reliable twin-rotor VAWTs.

सारांश

निरंतर बढ़ती जनसंख्या, उनकी बढ़ी हुई घरेलू सुविधाएँ, और बढ़ते औद्योगीकरण के साथ, ऊर्जा मांग में व्यापक वृद्धि हुई है। यह बढ़ती ऊर्जा मांग, जलवायु परिवर्तन के कारण खनिज ईंधनों के त्वचाई होने और उसके परिणामस्वरूप CO2 उत्सर्जन में तेजी से बढ़ोतरी को दिखाती है, इससे साफ और नवीनीकृत ऊर्जा स्रोतों की ओर जल्दी से आवश्यकता का संकेत मिलता है, जैसे सौर और पवन की ऊर्जा। इन विकल्पों में, हमारा ध्यान पवन की ऊर्जा को प्राप्त करने पर रहा है।

पवन की ऊर्जा को पवन टर्बाइन के उपयोग से पकड़ा जाता है, जो विस्तृत रूप से दो श्रेणियों में वर्गीकृत होते हैं: क्षैतिज एक्सिस टर्बाइन (HAWTs) और अनुलंब एक्सिस टर्बाइन (VAWTs)। पिछले दशक में, खुद को लिफ्ट-प्रकार के VAWTs में रुचि के पुनर्जीवन के कारण जागरूकता का पुनः उत्पन्न होने के कारण, इनके HAWT समकक्षों की तुलना में उनकी उच्च ऊर्जा घनत्व की संभावित क्षमता के कारण, जैसा कि ये टर्बाइन एक दूसरे के निकट संयोजन में अधिक ऊर्जा उत्पन्न करेंगे। इसी दिशा में, यह थीसिस एक गणनात्मक अध्ययन प्रस्तुत करती है जो रोटर्स के बीच हवाई अवरोध के प्रभाव की जांच करने के लिए किया गया है (जिसमें केंद्र से केंद्र अधिक बीच का अनुत्तर टर्बाइन स्थानिक इंटर-टर्बाइन अंतर (S) ($S/D > 1$) और ओवरलैपिंग ट्विन-रोटर ($S/D \leq 1$), जहां D रोटर व्यास को प्रस्तुत करता है) प्रदर्शन और वेक उपचार पर। इस काम की प्रासंगिकता ट्विन- रोटर VAWTs के प्रदर्शन विशेषताओं और अंतर्क्रिया गतिकी को समझने में है, जो उनके सफल समावेशन की अनुमति देगा एक पवन टर्बाइन फार्म (ऑनशोर या ऑफ़शोर) में।

काम दो आयामी अध्ययन के साथ आरंभ हुआ, जिसमें अनस्थिर रेनोल्ड्स औस्तामित नवीयर-स्टोक्स (URANS) समीकरणों का उपयोग किया गया, व्यावसायिक सॉल्वर ANSYS Fluent 19.2 का उपयोग करते हुए। एक अलग रोटर के लिए आंकिक मॉडलिंग तकनीक का चयन करने में दो विभिन्न गतिशील मैशिंग तकनीकों: स्लाइडिंग मैश और ओवरसेट मैश की तुलना की गई। दोनों तकनीकें समान परिणाम उत्पन्न करतीं हैं, लेकिन प्रयोगशालात्मक अनुसंधान से अलग होती हैं। हालांकि, स्लाइडिंग मैश तकनीक की सीमाओं के कारण, ओवरसेट मैश तकनीक को आगे की जांच के लिए चुना गया। अगले चरण में, दोनों

एकल रोटर्स और एक S/D = 1.65 पर बादी रोटरों की प्रदर्शन और वेक मान्यता अध्ययन पर ध्यान केंद्रित था। स्थापित मानकों को बढ़ाकर, मॉडलिंग प्रक्रिया को जोड़ा गया ताकि विभिन्न संबंधित अंतरालों के साथ जोड़े और ट्विन-रोटर कॉन्फ़िगरेशन शामिल किया जा सके।

एक व्यवस्थित अनुकरण अभियान का आयोजन किया गया था ओवरलैपिंग ट्विन-रोटर ($S/D \leq 1$) और गैर-ओवरलैपिंग ट्विन-रोटर ($S/D > 1$) के लिए विभिन्न टिप गति अनुपातों के लिए। प्रमुख परिणाम सुझाते हैं कि ओवरलैपिंग रोटर्स अनोखी अंतर्रेखित प्रभाव प्रदर्शित करते हैं, जो प्रत्येक रोटर के प्रदर्शन और वेक विशेषताओं को प्रभावित करते हैं। प्राप्त डेटा का विश्लेषण दिखाता है कि S/D = 0.9875 के साथ ओवरलैपिंग ट्विन-रोटर लगभग एक-रोटर की तुलना में लगभग 25% बेहतर प्रदर्शन प्रदर्शित करते हैं। इसके अतिरिक्त, S/D = 0.89 के साथ ट्विन-रोटर एक अत्यधिक इंचले विद्युत उत्पादन (आज़िमुथियल स्थिति के लगभग स्वतंत्र) प्रदर्शित करते हैं जिसमें एक-रोटर की तुलना में लगभग 8% का वृद्धि होता है। यह विद्युत उत्पादन और प्रसार के दृष्टिकोण से महत्वपूर्ण आवश्यकताओं को ध्यान में रखता है। इसके अलावा, S/D = 0.89 मामले में वेक पुनर्वस्ती अन्य कॉन्फ़िगरेशनों की तुलना में अधिक फास्ट होती है।

इसके अतिरिक्त, थीसिस में कई प्रयासों का विवरण प्रदान किया गया है जो प्रायोगिक अध्ययनों का आयोजन करने के लिए किए गए हैं, जिन्हें परिशीलित किया गया है अपेंडिक्स में। इन प्रयासों में सफलता की कमी के कारणों का विस्तृत विवेचन किया गया है, जो अनुसंधान प्रक्रिया के दौरान प्रस्तुत चुनौतियों पर प्रकाश डालता है। समापन में, यह थीसिस ओवरलैपिंग और गैर-ओवरलैपिंग ट्विन-रोटर VAWTs की संख्यात्मक जांच को समाप्त करती है, जो उनके प्रदर्शन, वेक मान्यता, संख्यात्मक मॉडलिंग तकनीकों, और प्राप्त दर्शनों पर ध्यान केंद्रित करती है। इस अध्ययन से हमारे ट्विन-रोटर VAWTs के बीच होने वाले परिणामकारी प्रभावों की समझ में योगदान होता है और उनके उत्कृष्ट डिज़ाइन और प्रदर्शन के लिए मूल्यवान दर्शन प्रदान करता है। इस काम में प्रस्तुत अनुसंधान और विश्लेषण एक प्रभावी और विश्वसनीय ट्विन-रोटर VAWTs के विकास के लिए एक आधार के रूप में कार्य करते हैं

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ABBREVIATIONS

VAWT	Vertical Axis Wind Turbine
HAWT	Horizontal Axis Wind Turbine
CFD	Computational Fluid Dynamics
RPM	Revolution Per Minute
URANS	Unsteady Reynolds Averaged Navier Stokes
DES	Direct Numerical Simulation
LES	Large Eddy Simulations
SST	Shear Stress Transport
TSST	Transition Shear Stress Transport
GWEC	Global Wind Energy Council
IEA	International Energy Agency
CPU	Central Processing Unit
FVM	Finite Volume Method
RMSE	Root Mean Square Error
BR	Blockage Ratio
PIV	Particle Image Velocimetry
SPIV	Stereo Particle Image Velocimetry

NOTATION

x or X X coordinate [m]

y or Y Y coordinate [m]

c Chord of the aerofoil blade [m]

D Rotor Diameter [m]

H Height of the rotor [m]

$A = D \times H$ Swept Area [m^2]

ρ Density of the fluid [$\frac{kg}{m^3}$]

p Pressure [Pa]

P Modified pressure [Pa]

V_∞ Free-stream Wind Speed [m/s]

$\bar{U}$ Ensemble-average velocity [$\frac{m}{s}$]

n Number of blades

ν Kinematic viscosity of Air[m^2/s]

N Revolutions per minute

I_u Turbulence Intensity [%]

θ Azimuthal increment [° degrees]

ω Angular velocity of the rotor [rad/s]

θ_τ Azimuthal Incremental size [°]

Δt Time step size [s]

$\sigma \equiv \frac{nc}{D}$ Solidity Ratio based on diameter

$\sigma_D \equiv 1 - \frac{1}{2\pi\sigma\lambda}$ Dynamic Solidity

S center-to-center spacing between the rotors[m]

$\frac{S}{D}$ Relative spacing ($>$1 for uncoupled, $\leq$ 1 for coupled)

$K_o = \frac{D-S}{D}$ Overlap Ratio

$A_{\text{eff}} = \left(\frac{D+S}{2}\right) \times H$ Effective Swept Area for each rotor of twin rotor [m^2]

$y^+ \equiv \frac{yu_\tau}{\nu}$ Dimensionless wall-normal coordinate

$\text{Re}_c \equiv \frac{(V_\infty + R\omega)c}{\nu}$ Reynolds Number based on Chord Length

$\text{TSR}, \lambda \equiv \frac{R\omega}{V_\infty}$ Tip Speed Ratio

B_L Blockage Ratio

$F_t(\theta)$ Tangential Force as a function of azimuthal position [N]

$C_D \equiv \frac{\text{Drag force}}{0.5\rho A V_\infty^2}$ Drag Coefficient

$C_{\text{Pr}} \equiv \frac{p_s - p_\infty}{0.5\rho V_\infty^2}$ Pressure Coefficient

$C_L \equiv \frac{\text{Lift force}}{0.5\rho A V_\infty^2}$ Lift Coefficient

$C_M \equiv \frac{\text{Moment}}{0.5\rho A R V_\infty^2}$ Moment Coefficient about axis of rotation

$C_P \equiv \frac{\text{Power output}}{0.5\rho A V_\infty^3}$ Mean Power Coefficient

$C_P(\theta) \equiv \frac{P(\theta)}{0.5\rho A V_\infty^3}$ Phase-Averaged Power Coefficient as function of azimuthal position

$C_P^{\text{Twin}} \equiv \frac{(P_{\text{Rotor-1}} + P_{\text{Rotor-2}})/2}{0.5\rho A_{Eff} V_\infty^3}$ Twin-rotor Mean Power Coefficient

$C_P^{\text{Twin}}(\theta) \equiv \frac{(P_{\text{Rotor-1}}(\theta) + P_{\text{Rotor-2}}(\theta))/2}{0.5\rho A_{Eff} V_\infty^3}$ Twin-rotor Phase-Averaged Power Coefficient as a function of azimuthal position