WIND TUNNEL TEST TO INVESTIGATE TRANSITION TO TURBULENCE ON WIND TURBINE AIRFOIL

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To my adorable *parents* for all their best things and for their priceless support

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ABSTRACT

The choice of the airfoils with excellent aerodynamics characteristics is an essential step in the design of wind turbine blade in order to obtain optimal performances. Wind tunnel test to investigate transition to turbulence on wind turbine airfoil was performed in the Universiti Teknologi Malaysia Low Speed Tunnel. Aerodynamic characteristics of a NACA 64(4)-421 airfoil in a two-dimensional setup, such as lift, drag and pressure coefficients were measured for two main cases. In the first case, tests were carried out on a clean airfoil (no turbulator) and in the second case, three configurations with three different positions of turbulator at x=10%, 20% and 50% of chord were tested. A Steady-state, two-dimensional CFD calculations were also carried out for the airfoil in same scale as experimental test using commercial CFD code, Ansys FLUENT 14. The surface coordinates of the experimental airfoil model were measured by coordinate measurement machine (CMM) and optimized in ICEM CFD software included in the Ansys package to create the related geometry and mesh. All experimental and numerical analysis were performed at velocities of V=22, 33, 45, 56, 61 *m/s* and at angle of attacks ranges between -6° to +30°. For the simulation, a minimum of 85000 grids was used to get a grid independent solution. To simulate the transition phenomena, K-ω-SST turbulent model was used. Different types of mesh were analyzed in detail by comparing agreement between the simulated aerodynamic characteristics with experimental results. There are good agreement between experimental results and numerical results by using K-ω-SST model. Both lift coefficient and pressure coefficient in experimental and numerical studies have good agreement with each other but it is not true for drag coefficients. Also according to different meshes, we found that a mesh with unit zone which contains K-ω-SST model is the best model according to the convergence speed and accuracy. The effects of turbulator used in the experiment was not significant. In conclusion the study is partly successful.

ABSTRAK

Ujian terowong angin digunakan untuk menyiasat kesan pergerakan udara dari bentuk transisi kepada gelora ke atas airfoil turbin udara jenis NACA 64(4)-421 dibangunkan dengan skala 70% di Universiti Teknologi Malaysia. Sifat aerodinamik seperti pekali angkatan, seretan dan tekanan diukur untuk dua kes utama. Bagi kes yang pertama, NACA 64(4)-421 airfoil dalam kes bersih (tiada penggolak) telah ditetapkan di dalam terowong angin berkelajuan rendah dan dalam kes yang kedua, tiga kedudukan penggolak yang berbeza iaitu x=10%, 20% and 50% telah dipilih setiap satu. Selain itu, perkiraan CFD dalam dua dimensi dan dalam berkeadaan tetap juga dijalankan untuk NACA 64(4)-42 dalam skala yang sama dengan eksperimen di mana koordinat yang diperlukan, telah diukur dengan menggunakan mesin pengukuran coordinate (CMM) dan dioptimumkan dalam perisian ICEM CFD yang terdapat dalam pekej Ansys untuk membuat geometri dan rangkaian yang berkaitan. Semua ujian secara eksperimen mahupun secara berangka telah dijalankan pada kelajuan V=22, 33, 45, 56, 61 *m/s* dan dalam sudut capaian dalam julat -6° to +30°. Keadaan awal, bentuk dan bahan pada kedua-dua hujung aerofoil plat dalam eksperimen memberi kesan pada keputusan ujian, yang diukur dengan alat untuk pengukuran daya dan tekanan. Kesan penggolak yang digunakan dalam eksperimen tidak begitu ketara. Bentuk, tinggi dan kedudukan penggolak yang digunakan pada airfoil perlu diberi perhatian dan pemilihan penggolak perlu diambil perhatian. Penetapan grid dan juga ujian grid bebas telah dijalankan dan didapati jaringan dengan 85000 grid boleh digunakan untuk simulasi. K-ω-SST model untuk simulasi dicadangkan untuk mengkaji fenomena transisi yang berlaku. Jenis jaringan yang berbeza dianalisis dengan mendalam dengan membandingkan sifat aerodinamik dengan dapatan daripada ujian eksperimen. Terdapat keputusan yang baik antara keputusan eksperimen dan juga kaedah berangka dengan menggunakan K-ω-SST model. Kedua-dua pekali angkatan dan tekanan dalam kedua-dua experiment dan simulasi menunjukkan keputusan yang baik. Walau bagaimanapun, bagi pekali

seretan, ia menunjukkan sebaliknya. Tambahan pula, dengan menggunakan jaringan yang berbeza, satu jaringan dengan zon unit yang menggandungi K-ω-SST model adalah yang terbaik dari segi kelajuan dan ketepatan.

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P	-	Pressure
T	-	Temperature
ρ	-	Density , kg/m^3
V	-	Velocity , m/s
M	-	Mach number
t	-	Time
γ	-	Specific heat ratio
C_P	-	Pressure coefficient
C_l	-	Lift coefficient
C_d	-	Drag coefficient
C or L	-	Chord line length
Re	-	Reynolds number
λ	-	Tip speed ratio
ε_{sb}	-	Solid Blockage
ε_{wb}	-	Wake Blockage
$\Delta C_{l_{sc}}$	-	Stream line curvature
d	-	Diameter , m
μ	-	Viscosity , kg/m.s
R	-	Gas constant , J/mol.K
AOA or α	-	Angle of Attack , degree
q	-	Dynamic Pressure , Pa
y+	-	Non dimensional distance

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Wind energy as a renewable energy has been lionized since the past decades, due to the increase in cost of fossil fuels as they are being used up very fast and they hardly get replaced. On the other hand, this is also due to a considerable advancements of wind energy, such as to be renewable, distributed in the whole world, plentiful, clean and without any pollution [1].

Since most of countries in the world does not have access to fossil fuels conveniently, wind energy can be a good offer as an alternative to the use of fossil fuels. In wind turbine researches, the most important objective is to design and build larger and more efficient wind turbines to gain more power from energy from the wind [1].

1.1.1 Wind Turbine

Wind turbines are commonly divided to two different categories:

- Horizontal-Axis Wind Turbines (HAWT).
- Vertical-Axis Wind Turbines (VAWT).

Between them, the HAWT due to their ability to generate more electrical energy than VAWT at different wind speeds, are the most commercially developed wind turbines in the world. They are mostly use especially in the wind farms where the wind speed is alternative [2].

HAWTs produce a power which is related to the number of blades of turbine (B), the ratio of blade tip speed to the wind free stream velocity which is called tip speed ratio (λ) and the ratio of lift coefficient to drag coefficient C_L/C_D [2].

Airfoils for these types of application are usually different thick section airfoils types such as the S, DU, FX, Flat-back and NACA 6-series of airfoils is being used. These airfoils in HAWT by their different value of (B), (λ) and C_L/C_D will generate different power [2].

Inboard sections of modern mega-watt scale wind turbines consist of thick airfoils to maintain the structural integrity of the blade [1].

1.1.2 NACA Airfoil

According to various advancements of wind energy and the using of wind turbines to generate this type of energy, different airfoils sections especially NACA (developed by the National Advisory Committee for Aeronautics) series airfoils have been used. NACA have developed airfoils suitable for wind turbine blades to generate reasonable energy and were tested at higher Reynolds number up to 9 million. Between the different series of NACA airfoils the 4 and 5 series have been disused because they are sensitive to the roughness. On the other hand, NACA 63 and 64 six digit series are still being used in wind turbine blades as a result of the availability of two-dimensional aerodynamic characteristics, even for airfoils with a fairly large relative thickness [3].

Airfoil designer have planned to make a NACA airfoil to have a maximized region over which the airflow remains laminar, and this causes the drag over a small range of lift coefficients to be substantially reduced. With respect to this objective the NACA 6 series were developed and being used.

1.1.3 Transition on airfoil surface

Fluid flow that is slow tends to be laminar. As it speeds up a transition occurs and it crinkles up into complicated, random turbulent flow. It is desirable to be able to quantify under what conditions it occurs. Experiments suggest that laminar flow occurs for low speeds, small diameters, low densities and high viscosities, while turbulent flows occur for the opposite conditions: high speeds, large diameters, high densities and low viscosities. Viscosity is a measurable fluid property (as is its density, temperature, etc.). We often use the "kinematic viscosity," which is the viscosity divided by the density. Its unit is m^2/s. Notice its dimensions are the same as a length multiplied by a velocity. If the fluid speed is V m/s, the airfoil length or the orifice diameter is d (m) then we can write the following dimensionless ratio:

$$Re = \frac{\rho V d}{\mu} = \frac{V d}{\vartheta}$$

Re is the Reynolds number, named after Osborne Reynolds who did systematic experiments one hundred years ago. Notice that if V or d (or both) are small and the viscosity is large, Re will be small. For this case the flow will be laminar. Increase d or V or decrease the viscosity, and Re will increase. Reynolds found that for flow in a pipe it did not matter which of the three particular parameters he varied in this dimensionless group: as long as Re was less than approximately 2300, the flow was laminar. Above this value, turbulence would invariably occur. This is a general result since it allows us to vary the type of fluid, flow speed and pipe diameter without having to use the words "large" or "fast", etc. Moreover, since Re is dimensionless, it does not matter which system of units is used (S.I., Engineering, etc.) so long as they are the same throughout [4].

While the transition from laminar to turbulent flow in pipe occurs at a Reynolds number of approximately 2300, the precise value depends on whether any small disturbances are present. If the experiment is very carefully arranged so that the pipe internal surface is very smooth and there are no disturbances to the velocity and so on, higher values of Re can be obtained with the flow still in a laminar state. However, if Re is less than 2300, the flow will be laminar even if it is disturbed. Thus 2300 is the value the Re below which turbulence will not occur in the pipe. Moreover, if the flow has a different geometry, such as flow in a square duct, airfoil or etc, transition will occur at different values of Re. The essential point is that flows become turbulent at high Reynolds numbers where “high” means much greater than unity [4]. For airfoil transition Reynolds number is between 3×10^5 to 2×10^6.

1.1.4 Turbulent Flow

When the flow is turbulent, the flow contains eddying motions of all sizes, and a large part of the mechanical energy in the flow goes into the formation of these eddies which eventually dissipate their energy as heat. As a result, at a given Reynolds number, the drag of a turbulent flow is higher than the drag of a laminar flow. Also, turbulent flow is affected by surface roughness, so that increasing roughness increases the drag [4].

Transition to turbulence can occur over a range of Reynolds numbers, depending on many factors, including the level surface roughness, heat transfer, vibration, noise, and other disturbances. To understand why this is so, and to appreciate the role of the Reynolds number in governing the stability of the flow, it is helpful to think in terms of a spring-damper system such as the suspension system of a car. Driving along a bumpy road, the springs act to reduce the movement experienced by the passengers. If there were no shock absorbers, however, there would be no damping of the motion, and the car would continue to oscillate long after the bump has been left behind. So the shock absorbers, through a viscous damping action, dissipate the energy in the oscillations and reduce the amplitude of the oscillations. If the viscous action is strong enough, the oscillations will die out very quickly, and the passengers can proceed smoothly. If the shock absorbers are not in good shape, the oscillations may not die out. The oscillations can actually grow if the excitation frequency is in the right range, and the system can experience resonance. The car becomes unstable, and it is then virtually uncontrollable [4].

In fluid flow, we often interpret the Reynolds number as the ratio of the inertia force (that is, the force given by mass x acceleration) to the viscous force. At low Reynolds numbers, therefore, the viscous force is large compared to the inertia force, and the flow behaves in some ways like a car with a good suspension system. Small disturbances in the velocity field, created perhaps by small roughness elements on the surface, or pressure perturbations from external sources such as vibrations in the surface or strong sound waves, will be damped out and not allowed to grow. This is the case for pipe flow at Reynolds numbers less than the critical value of 2300 (based on pipe diameter and average velocity), and for boundary layers with a Reynolds number less than about 200,000 (based on distance from the origin of the layer and the free-stream velocity). As the Reynolds number increases, however, the viscous damping action becomes comparatively less, and at some point it becomes possible for small perturbations to grow, just as in the case of a car with poor shock absorbers. The flow can become unstable, and it can experience transition to a turbulent state where large variations in the velocity field can be maintained. If the disturbances are very small, as in the case where the surface is very smooth, or if the wavelength of the disturbance is not near the point of resonance, the transition to turbulence will occur at a higher Reynolds number than the critical value. So the point of transition does not correspond to a single Reynolds number, and it is possible to delay transition to relatively large values by controlling the disturbance environment. At very high Reynolds numbers, however, it is not possible to maintain laminar flow since under these conditions even minute disturbances will be amplified into turbulence [4].

Turbulent flow is characterized by unsteady eddying motions that are in constant motion with respect to each other. At any point in the flow, eddies produce fluctuations in the flow velocity and pressure. If we were able to measure the stream wise velocity in turbulent pipe flow, we would see a variation in time as shown in Figure 1.1.

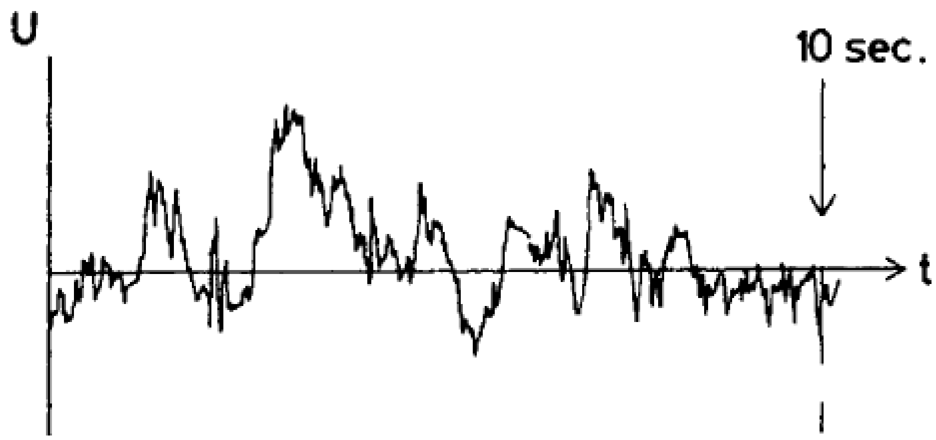

Figure 1.1 Velocity at a point in a turbulent flow as a function of time

The important point is that turbulent flows are very effective at mixing: the eddying motions can very quickly transport momentum, energy and heat from one place to another. As a result, velocity differences get smoothed out more effectively than in a laminar flow, and the time-averaged velocity profile in a turbulent flow is much more uniform than in a laminar flow [4].

1.2 Research Objective

Objectives of this study can be specified as follows:

i. To investigate the NACA 64(4)-421 airfoil different characteristics in order to produce the transition phenomena. This gives us various information about how to create forced transition over this airfoil.
ii. To experimentally study the aerodynamic characteristics on natural / forced transition.
iii. To numerically analysis the aerodynamic characteristics under different turbulence models by using commercial software.

1.3 Problem Statement

The goal of developing of NACA 6-series was to design airfoils that maximized the region over which the airflow remains laminar. The effect achieved by this type of design of airfoils is to maintain the laminar flow of air throughout a greater percentage of the chord of the airfoil and to control the transition point. Drag is therefore considerably reduced since the laminar airfoil takes less energy to slide through the air. The pressure distribution on the laminar flow airfoil is much more even since the camber of the airfoil from the leading edge to the point of maximum camber is more gradual than on the conventional airfoil. However, at the point of stall, the transition point moves more rapidly forward [5]. In this project we try to find out the answer of these questions:

- How to create transition phenomena for laminar airfoil to prevent aerodynamic stall?
- Accessibility to the lot of airfoils characteristics data have been restricted by designers due to military secrets or designer copyright therefore we need to obtain our data by doing our own experiment on the NACA 64(4)-421 airfoil.

1.4 Research Scopes

The scope in this project will be classified into six different areas:

- ✓ Study about various NACA airfoil characteristics by using XFOIL software.
- ✓ Produce the airfoil by fiberglass and install measurement sensors in UTM aeronautics laboratory.
- ✓ Pressure taps diameter will be 1.6 mm.
- ✓ Perform wind tunnel tests in UTM-LST.
- ✓ Angle of attack rang will be -5 to +15 degree.
- ✓ Numerically analysis by using Ansys15.

This chapter clarifies the problem identification in this project. In addition, background of this project, scope of this project, purposes and objectives are explained in this chapter. It briefly gives readers a clear understanding and review about the research in this project.

REFERENCES

1. Narsipur, S., Computational Analysis of Multielement Airfoils for Wind Turbines, in Aerospace Engineering2012, University of Illinois at Urbana-Champaign.
2. Xiaomin Chen, R.A., Assessment of the performance of various airfoil sections on power generation from a wind turbine using the blade element momentum theory. Energy and Environment, 2013. 4(5).
3. Timmer, W., An Overview of NACA 6-Digit Airfoil Series Characteristics with Reference to Airfoils for Large Wind Turbine Blades. American Institute of Aeronautics and Astronautics, 2009: p. 13.
4. Warhaft, Z., An Introduction to Thermal-Fluid Engineering. 1997.
5. A. M. Kuethe , J.D.S., Foundations of Aerodynamics. 2 ed. 1959: John Wiley & Sons, Inc.; 2nd edition. 464.
6. Akmandor, I. and K. Ekici, Airfoil analysis for horizontal axis wind turbines. 1998.
7. The NACA airfoil series.
8. Libii, J.N., Wind Tunnels in Engineering Education. 2011.
9. Selig, M., R. Deters, and G. Wiliamson, Wind Tunnel Testing Airfoils at Low Reynolds Numbers. 2011.
10. Ren, X., et al., Investigation of NACA 0012 Airfoil Periodic Flows in a Transonic Wind Tunnel. 2013.
11. Lian, Y. and W. Shyy, Laminar-Turbulent Transition of a Low Reynolds Number Rigid or Flexible Airfoil. 2006.
12. Katam, V., Simulation of low-re flow over a modified naca 4415 airfoil with oscillating camber, in Mechanical Engineering2005, University of Lexington Kentucky. p. 159.
13. Duris, M., Numerical Simulation of the Transitional Flow on Airfoil, in National Conference with International Participatio2006: Svratka, Czech Republic. p. 8.
14. Fuglsang, P., et al., Wind Tunnel Tests of the FFA-W3-241,FFA-W3-301 and NACA 63-430 Airfoils, ed. R.N. Laboratory. 1998, Roskilde: Riso National Laboratory. 163.
15. Selig, M.S., Low Reynolds Number Airfoil Design. 2003.
16. Papadakis, M. and L. Miller, Experimental and computational investigation of wind tunnel effects on airfoil flow fields. 1992.
17. Shang, D.Y., Basic Conservation Equations for Laminar Convection, in Theory of heat transfer with forced convection film flows. 2011, Springer: Verlag Berlin Heidelberg. p. 346.
18. Amir Faghri, Y.Z., John Howell, Advanced Heat and Mass Transfer. 2010: Global Digital Press.

19. Moin, P.a.M., K, Direct numerical simulation: A tool in turbulence research. ANNUAL REVIEWS, 4139 EL CAMINO WAY, PO BOX 10139, PALO ALTO, CA 94303-0139 USA, 1998. 30: p. 39.
20. Huidan, Y., S.G. Sharath, and L.S. Luo, DNS and LES of decaying isotropic turbulence with and without frame rotation using lattice Boltzmann method. Journal of Computational Physics, 2005(209): p. 17.
21. Menter, F.R., Two-EquationEddy-ViscosityTurbulence Models for Engineering Applications. AIAA Journal, 1994. 32: p. 8.
22. Iskandar, S.I., M.L. Tholudin, and M. Shuhaimi, Wind tunnel tests on a generic eurocopter 350z helicopter, Universiti Teknologi Malaysia. p. 7.
23. Barlow, J.B., W.H. Rae, and A. Pope, Low-Speed Wind Tunnel Testing, 3rd Edition. Third ed. 1999, The University of Michigan: Wiley.
24. Reches, M., et al., Thread as a matrix for biomedical assays. ACS Appl Mater Interfaces, 2010. 2(6): p. 1722-8.
25. Johansen, J., Prediction of laminar/turbulent transition in airfoil flows, ed. R.N. Laboratory. Vol. 987. 1997, Roskilde Denmark: Riso National Laboratory. 25.