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AERODYNAMIC PERFORMANCE ANALYSIS OF CORRUGATED DRAGONFLY-WING AIRFOIL FOR SMALL WIND TURBINE BLADE APPLICATION

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ABSTRACT

A biomimetic design was investigated to enhance the performance of small horizontal-axis wind turbine. The aerodynamic performance of a corrugated dragonfly-wing airfoil was evaluated using wind tunnel experimentations and CFD simulations. At Reynolds number of 40000 to 370000, the corrugated dragonfly-wing blade had the highest lift coefficient and lift-to-drag ratio among the airfoils tested. It was evident that at high angles of attack, the corrugated dragonfly-wing blade exhibited the best aerodynamic performance because of its unique capability of delaying the onset of flow separation due to the effects of corrugation. A better wind turbine design was achieved because of the high lift generated and the added structural integrity to the rotor blades provided by the corrugated configurations of the dragonfly-wing airfoil.

Keywords: Dragonfly-wing, Wind turbine, Wind tunnel experimentation, Computational Fluid Dynamics.

1. INTRODUCTION

Global warming is a pressing problem experienced in the world today. According to the Intergovernmental Panel on Climate Change, the globally averaged surface temperature is projected to increase by 1.4° to 5.8° C over the period of 1990 to 2100, with nearly all land areas warming more rapidly than the global average. An increase in global temperature will cause sea levels to rise, changing the amount and pattern of precipitation, and a probable expansion of subtropical deserts (Lu, et al. 2007). One of the renewable resources that may help slow down the process of global warming is wind energy because it is widely distributed and produces no greenhouse gas emissions during operation. Wind energy is a form of solar energy due to the earth's rotation and the uneven heating of its irregular surface. Wind turbines of various designs have been used to convert the kinetic energy in the wind into mechanical power or electricity. In remote

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areas or areas with weak electrical grid, wind energy can be used for charging batteries or can be combined with a conventional power source to save fuel whenever wind is available. Figure 1 shows an idealized wind turbine. In contrast to large horizontal-axis wind turbines (HAWTs) located in areas dictated by optimum wind conditions, small wind turbines are required to produce power without necessarily the best wind conditions (Ozgener and Ozgener, 2007). These non-optimal locations can be urban areas where the wind flow patterns may be turbulent and obstructed by vegetative coverings or buildings. An important factor determining the efficiency of a turbine is the profile of the rotor blades, how effectively the profile performs at various wind speeds and especially at high angles of attack that may exist locally on a wind turbine (Hansen, 2008). The blade profiles dictate not only the efficiency of the rotor in increasing the lift to generate sufficient torque for power production, but also the cost, method of construction of the blades and the necessary pre and post assembly support of the wind turbine. In small wind turbine installations, the choice of blade profile is greatly influenced by simplicity and the ease of blade fabrication and installation. Blade twisting (span wise changing of blade profiles to conform to the optimal effective angle of attack) is seldom practiced in small wind turbine installation; thus, further lowering the output power. The study aims to evaluate the aerodynamic performance of a biomimetic blade design for small wind turbine application. This blade design is patterned after a dragonfly-wing (*Aeshna Cyanea*) cross-section that has well-defined corrugated configurations. Such corrugated design is important for the stability of ultra-light wings in handling the span wise bending forces and mechanical wear that the wing experiences during flapping (Kesel, 2000).

2. AIRFOIL-BLADE AERODYNAMICS

Aerodynamic analysis is one of the most helpful methods in the process of designing wind turbine blades. By improving the efficiency of the wind turbines, they would continue to generate electricity even when the wind velocity drops to near-undetectable levels.

2.1 Sample Size Determination

An airfoil or aerofoil is the shape of a wing or blade or sail as seen in cross-section of the wind turbine blade or aircraft wings or propellers. Figure 2 shows an airfoil moving through a fluid, where force is exerted upon it as a result of the motion. This force is called the fluid dynamic force. As in the case of an airplane wing, propeller blade, or rotor blade, where the fluid is air, the resultant force will be called aerodynamic force acting on the aerodynamic center. The aerodynamic force is caused by the pressure gradient around the profile of an unbalanced nature so that there is a net pressure difference. For a cambered airfoil as shown in Figure 2, even if the angle of attack, α, is zero, the lift force will still exist. This happens because at the stagnation point *A* where the flow separates, the velocity of moving fluid at the top surface is higher as it reaches point *B*. By Bernoulli's equation, where velocity and pressure are dependent on each other, an increase in velocity at the upper surface results in the decrease of ambient pressure. The lower surface having greater pressure tends to go up since it is the nature of the flow to move from higher to lower pressure, producing lift.

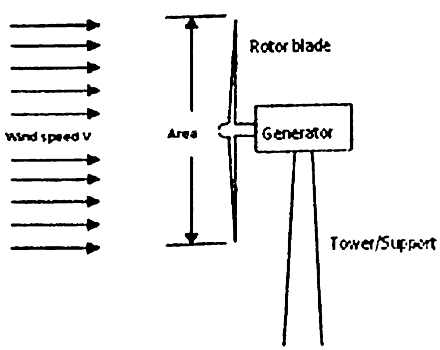

Fig. 1 Horizontal-axis wind turbine

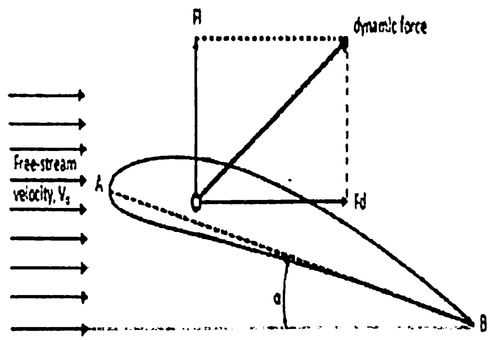

Fig. 2 The aerodynamic force on a smooth airfoil

2.2 Coefficient of Lift

The lift coefficient is a dimensionless coefficient that relates the lift generated by a lifting body, the dynamic pressure of the fluid flow around the body, and a reference area associated with the body. A lifting body is a foil or a complete foil-bearing body such as a fixed-wing aircraft. The coefficient of lift, C_L, is given as

$$C_L = \frac{F_L}{\frac{1}{2}\rho V^2 A} \quad (1)$$

where F_L is the lift force, ρ is the fluid density, V is the velocity of the air, and A is the surface area of the airfoil.

2.3. Coefficient of Drag

The drag coefficient is a dimensionless quantity used for quantifying the drag or resistance of an object in a fluid environment such as air or water. It is used in the drag equation, where a lower drag coefficient indicates the object will have less aerodynamic or hydrodynamic drag. The coefficient of drag, C_D, is given as $C_D = \frac{F_D}{\frac{1}{2}\rho V^2 A}$ (2)

where F_D is the drag force, ρ is the fluid density, V is the velocity of the air, and A is the surface area of the airfoil.

2.4. Lift to Drag Ratio

In aerodynamics, the lift-to-drag ratio, or L/D ratio or consequently the CL/CD ratio, is the amount of lift generated by a wing or vehicle, divided by the drag it creates by moving through the air. A higher or more favorable L/D ratio is typically one of the major goals in aircraft design. Since a particular aircraft's required lift is set by its weight, delivering that lift with lower drag leads directly to better fuel economy, climb performance, and glide ratio.

2.5 *Corrugated Dragonfly-Wing*

Dragonfly wings are not smooth or simple cambered surfaces. The cross-sectional camber of the wing has a well-defined corrugated configuration. This structure produces whirling vortices in the creases, which push air back, generate lift and give the wings "virtual" volume without adding bulk or weight.

Figure 3 shows a diagram of an airflow pattern on a corrugated plate. Several researches have pointed out that the corrugated dragonfly airfoil has much better performance over the streamlined airfoil and the flat plate in preventing large-scale flow separation and airfoil stall. Tamai, et al. (2007) showed the detailed particle image velocimetry (PIV) measurements near the noses of the airfoils, illustrating the underlying physics about why the corrugated dragonfly airfoil could suppress flow separation and airfoil stall at low Reynolds numbers. Their study showed that instead of having laminar separation, the protruding corners of the corrugated dragonfly airfoil act as "turbulators" to generate unsteady vortices rapidly promoting the transition of the boundary layer from laminar to turbulent. These unsteady vortex structures trapped in the valleys of the corrugated cross section could pump high-speed fluid from outside to near wall regions. This provides sufficient energy for the boundary layer to overcome the adverse pressure gradient, thus discouraging flow separations and airfoil stall.

Fig. 3 Flow pattern on a corrugated plate

3. METHODOLOGY

3.1 The Blade Airfoil Geometry and Construction

Figure 4 shows the three airfoils used in the present study: a corrugated plate (corrugated dragonfly airfoil), a streamlined airfoil NACA 0015, and a flat plate airfoil. The shape of the corrugated plate corresponds to the forewing of a dragonfly (*Aeshna Cyanea*) acquired at the mid-section of the wing which was digitally extracted from the profiles given in Kesel (2000). The NACA 0015 airfoil has maximum thickness of 15% of the chord length. The flat plate has a rectangular cross section without any rounded treatment at the leading edge and trailing edge. The NACA 0015 and the flat plate is made of wood, where the flat plate is 3.5 mm thick. The corrugated plate is made of Galvanized Steel Sheet Gauge 19, and bent to create the corrugated design. The corrugated plate, NACA 0015, and flat plate had the same chord length of 60 mm with the same span length of 260 mm. Figure 5 shows the geometry of the corrugated dragonfly-wing blade used in this study.

Fig. 4 Photo of the actual test airfoils

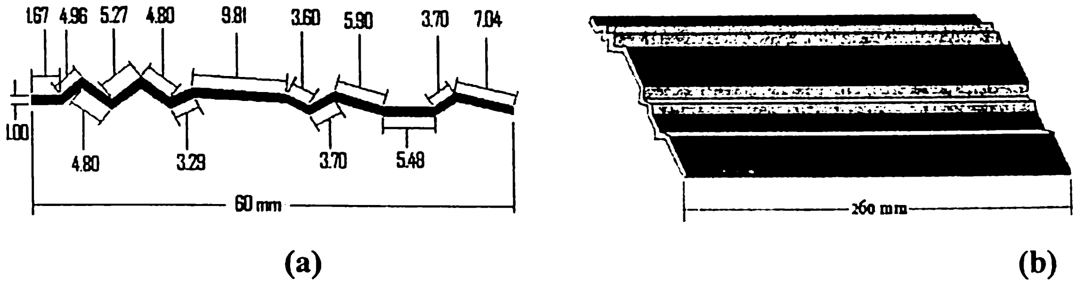

Fig. 5 Corrugated dragonfly-wing blade geometry

3.2 Wind Tunnel Experimentation

A wind tunnel is a tool used in aerodynamic research to study the effects of air moving past solid objects. The three specimen models had been tested in the subsonic wind tunnel of the MSU-IIT Mechanical Engineering Laboratories shown in Figure 6. The tunnel has a test cross section of 308x288 mm with all the walls optically transparent. The test airfoil was mounted in the lift and drag balances and locked by a set screw at the chosen angle of attack and air velocity. During the tests, the angle of attack ranged from 0_ to 30_ with 2_ interval. For the flat plate, however, much higher values for the angle of attack were also explored. The wind velocity ranged from 2m/s to 20m/s. Atmospheric pressure and temperature were also measured during the experiment using a barometer and a thermometer. These parameters were later used for the calculations of the lift and drag coefficients. Computational Fluid Dynamics (CFD) simulations were also performed to further investigate the flow patterns of the blades.

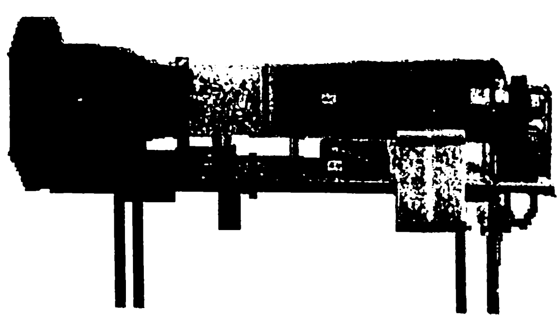

Fig. 6 MSU-IIT ME Subsonic Wind Tunnel

4. RESULTS AND DISCUSSIONS

Figures 7 and 8 show the lift coefficient and lift to drag ratio (CL/CD) of the flat plate blade, respectively. As the angle of attack increased the lift also increased. The increase in lift at high angles of attack also induced too much drag forces resulting to very low CL/CD. This indicates a poor aerodynamic performance. Figure 9 also shows a CFD flow simulation result for a flat plate blade at 120° angle of attack and 8m/s wind velocity. The results strongly suggest that this type of blade should not be used for wind turbine blades in the absence of blade twisting. Flat plate blades will result to both poor aerodynamic performance, translating directly to low power output and efficiency, and poor structural integrity because of the excessive bending stresses due to large drag forces along the blade span.

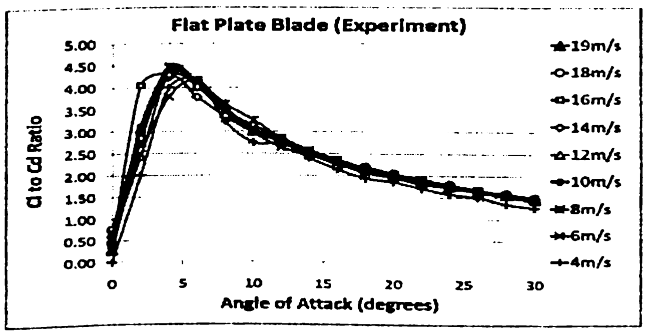

Fig. 7 Coefficient of lift of the flat plate blade

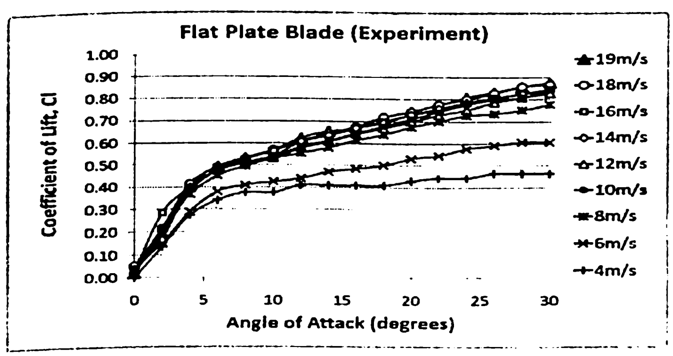

Fig. 8 Lift to drag ratio of the flat plate blade

Fig. 9 CFD flow profile for flat plate blade at 12 AoA, 8m/s

The aerodynamic performance of the blade using NACA0015 airfoil can be seen in Figures 10 and 11. The coefficient of lift, CL, for the NACA 0015 blade obviously started at zero value for zero angle of attack because of its uncambered (symmetric) profile with respect to the flow direction, similar to the flat plate. As shown in Figure 10, however, the coefficient of lift suddenly decreased at an angle of attack close to 10 degrees and was attributed to a phenomenon called "stall" which is associated to a sudden loss of lift usually creating very undesirable effects to aircraft or wind turbine. Figure 12 shows a CDF flow simulation result for a NACA 0015 blade at 120° angle of attack and 8m/s wind velocity.

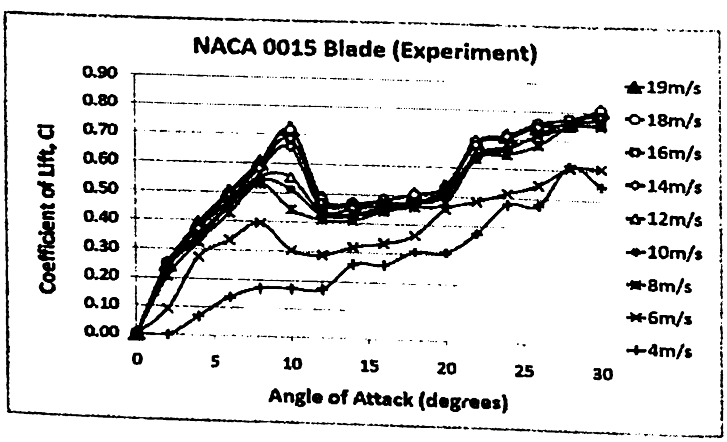

Fig. 10 Coefficient of lift of the NACA 0015 blade

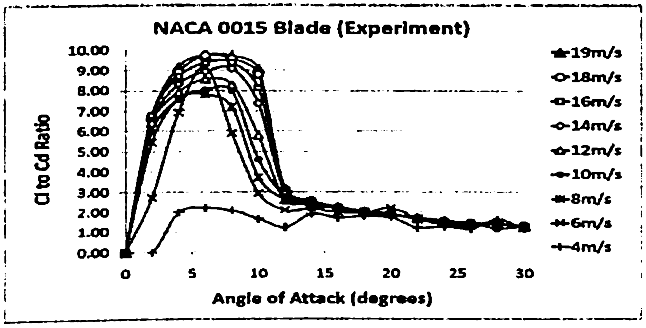

Fig. 11 Lift to drag ratio of the NACA 0015 blade

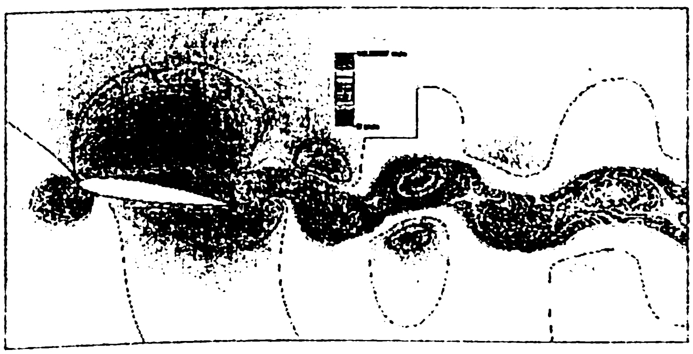

Fig. 12 CFD flow profile for NACA 0015 blade at 12 AoA, 8m/s

Figure 13 shows the lift coefficient plot of the corrugated dragonfly-wing plate. Because of the corrugation effects, the blade produced lift even at zero angle of attack. At the same time, the graphs show that the lift coefficient values are higher compared with that of the two previous test blades. At an angle of attack close to 150°, the flow separation around the blade was about to propagate but was arrested by the positive effects of the corrugation configuration. This mechanism of delaying the flow separation or stall is a very important development in high angle of attack fluid flow applications such as in untwisted wind turbine blades and wings, and control surfaces of micro aerial vehicles. Figure 14 shows the very wide range of decent CL/CD ratio for the corrugated blade. A CFD flow simulation result showing the effects of corrugation in the flow separation can be seen in Figure 15. In Figures 16 and 17, the aerodynamic performances of the three test blades are compared. The graphs show the good performance of the corrugated dragonfly-wing blade in contrast with the two other test blades. It is also important to note that for small horizontal-axis wind turbine applications, the coefficient of lift of the blade is the primary consideration in the selection process, since it directly dictates the turbine efficiency and power output. Drag reduction in almost all components is obviously needed but this concern diminishes as the turbine size decreases.

at 12° AoA, 8m/s.

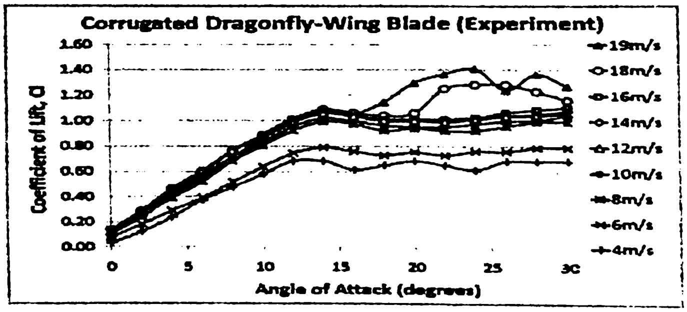

Fig. 13 Coefficient of lift of the corrugated blade

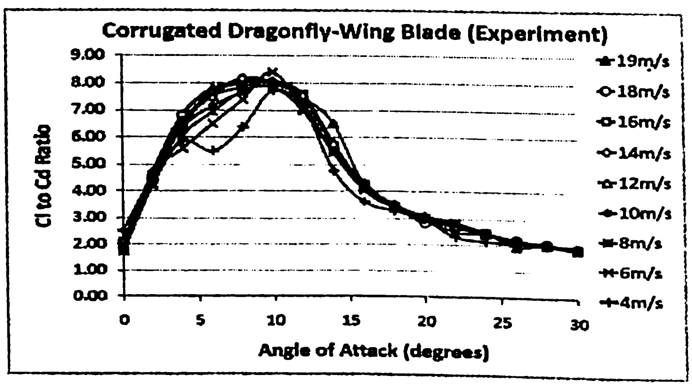

Fig. 14 Lift to drag ratio of the corrugated blade

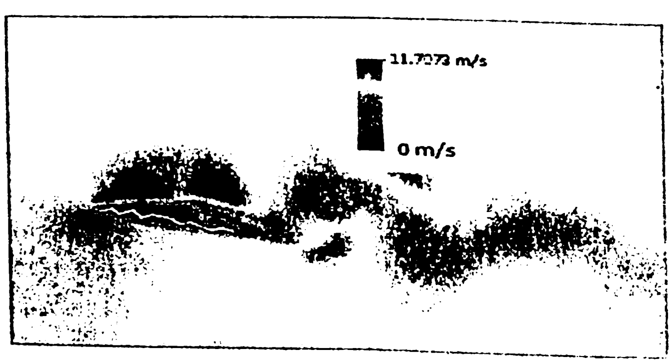

Fig. 15 CFD flow profile for corrugated blade at 12 AoA, 8m/s

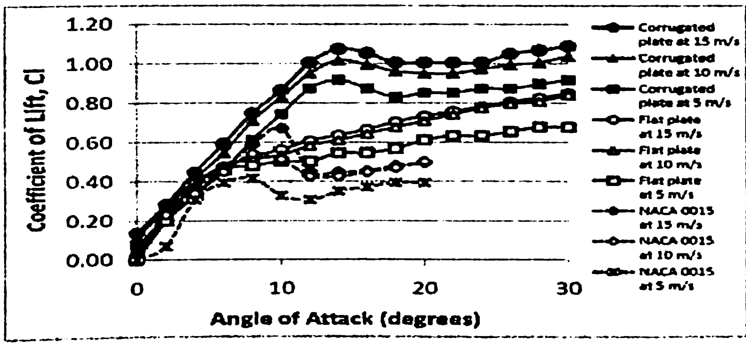

Fig. 16 Coefficients of lift of the different blades

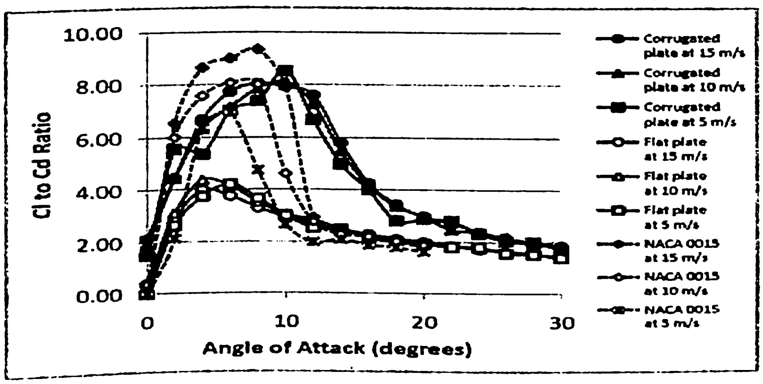

Fig. 17 Lift to drag ratio of the different blades

5. CONCLUSION

The results from both experimental studies and CFD simulations showed that the corrugated dragonfly-wing blade had the best aerodynamic performance among the three test blades intended for small wind turbine blade application. The corrugated dragonfly-wing blade showed superior aerodynamic performance for a very wide range of attack angles because of its unique capability of delaying the onset of flow separation due to the positive effects of the corrugation configuration. In designing a small wind turbine where the primary concern is high and stable lift generation over a very wide range of attack angles (typical for untwisted blading), corrugated dragonfly-wing is an excellent airfoil shape for the rotor blades since it provides very good structural integrity and exhibits very good aerodynamic performance.

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