Experimental and numerical analysis of the flow characteristics and performance of micro-scale horizontal axis wind turbines

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学位論文要旨

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Abstract

The performance of different micro scale wind turbines have been evaluated. Also characteristics influencing performance are identified. This was accomplished by means field tests, wind tunnel experiments and numerical simulations.

The field tests that were included in the analysis measured wind speed and power generated. The data was gathered using a data logger system. Due to the scatter of data points caused by wind turbulence the bins method was implemented. The bins method basically averaged values of power and wind speed in a specified range of velocity.

Wind tunnel experiments were carried out for three different rotors with blades using the Clark Y, MEL 002 and MEL 081.airfoils. Performance and also boundary layer behavior were evaluated. The effect of the boundary layer in performance is also described. Boundary layer behavior was visualized using two well known techniques: the tufts method and the oil film visualization techniques. Results showed influence of the formation of laminar separation bubbles in performance.

CFD calculations were performed using the commercial code CFX-TASCflow. The code employs Reynolds Averaged Navier-Stokes (RANS) equations for the solution of the flow in the computational domain. Results showed flow behavior in the blades surface, wake development behind the rotor and axial velocity behavior. Performance was also calculated and compared with experimental results. Flow separation was observed.

keywords Flow visualization, Boundary layer, performance, flow separation, Computaional Fluid dynamics, Laminar separation bubble

1.Introduction

Research into wind power generation is increasing. Interest is also focused on micro scale wind power generation systems. Micro scale horizontal axis wind turbines (HAWTs) are highly efficient machines when it comes to capturing wind energy. A wind turbine under 1kw of rated power and less than 1m in rotor diameter is considered a micro scale wind turbine. A better aerodynamic understanding of phenomena present in micro scale wind turbines is the key to better designs that will improve performance and other important characteristics. To obtain basic data that should help to increase the efficiency of micro HAWT systems, field performance measurements, wind tunnel experiments and numerical simulations were carried out. The wind tunnel experiments included flow visualization with an oil-film applied on the rotor blades surface.

Numerical computations are a way of visualizing and quantifying phenomena, which are not possible to analyze with conventional experiments. It is common practice in the numerical analysis of any type of HAWTs to use BEM (blade element/momentum) methods , but BEM methods can underestimate the angle of attack at the hub and the tip sides where 3D flow effects are strong. In recent years, CFD computations have become a widely use method to provide consistent and physically realistic simulations of HAWTs flow fields.

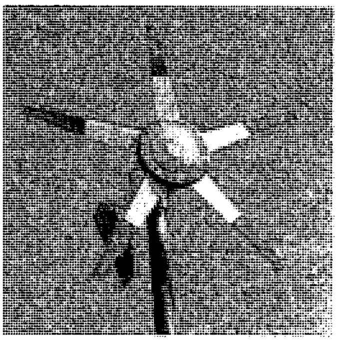


Fig. 1 Rotor configuration used in field and wind tunnel experiments

This paper demonstrates the numerical CFD analysis of a variable speed micro scale HAWT and results of performance experimental and computational data. are compared.

2. Field tests and wind tunnel experiments

Fig. 1 shows the rotor configuration of the micro scale wind turbines used in the field and wind tunnel experiments. The airfoils sections are shown in Fig. 2.

2.1 Field tests

The micro scale wind turbine used in the field measurements has the Clark Y airfoil. From August 1999 to March 2000 field measurements of wind velocity and power generated were taken. Using the bins method of akins averages of wind velocity and power were calculated. Results obtained results allowed the plotting of the power against wind velocity and power coefficient against tip speed ratio as Fig.3 shows. The curves present fairly normal tendencies such as: power coefficient decrement as tip speed ratio increases

Tip speed ratio and power coefficient were calculated with the following equations respectively

$$C_p = \frac{P_{net}}{\frac{1}{2}\rho A V^3} \quad (1) \qquad \lambda = \frac{R\Omega}{V} \quad (2)$$

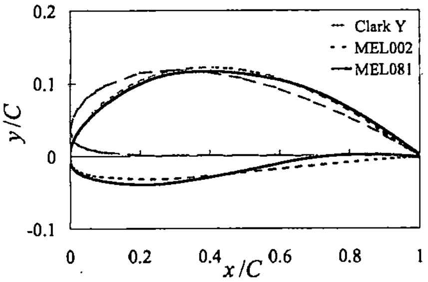


Fig. 2 Airfoils shapes used in experiments and field tests

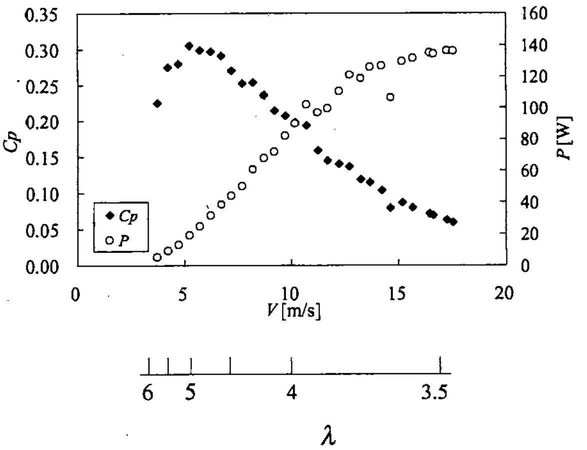
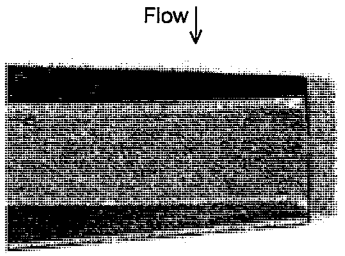
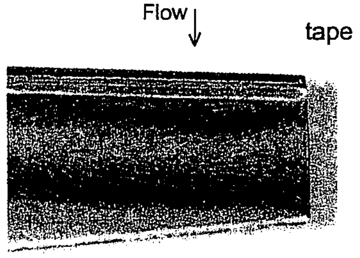


Fig. 3 Performance parameters obtained using the bins method



(a)V=4m/s, λ=4.6 α_{tip}=9.8°, Re_{tip}=3.5x10^4



(b)V=4m/s, λ=4.6, α_{tip}=9.8° Re_{tip}=3.5x10^4, with tape

Fig. 4 Comparison of the tip boundary layer with and without forced transition

where ρ is the density A the rotor swept area, V is the wind velocity, R the turbine radius and Ω the rotor angular speed

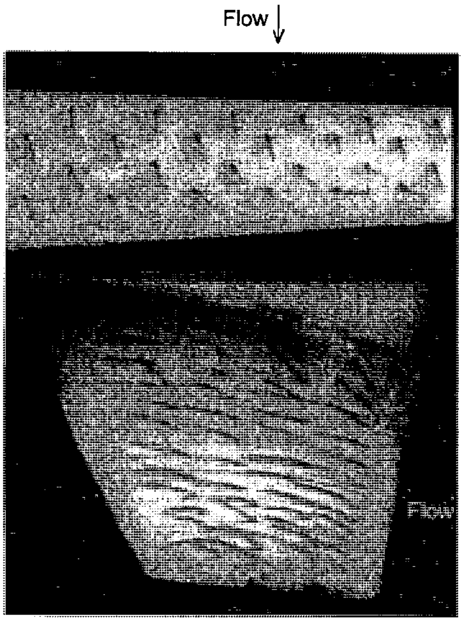
2.2 Wind tunnel experiments

Wind tunnel experiment and flow visualization were performed for three different wind turbines rotors using the Clark Y, MEL 002 and MEL 081 airfoils respectively.

The flow visualization experiments of the rotor using the Clark Y airfoil were carried out with free transition and forced transition. Fig.4(a) shows for a tip speed ratio λ= 4.6 and an incoming wind speed of 4 m/s the formation of a laminar separation bubble in the blade tip region, which is suppressed in Fig. 4(b) with a forced transition. The forced transition energizes the boundary layer eliminating the laminar separation bubble. Also , using the tufts visualization technique the separation of the flow was confirmed as It can be seen in Fig.5. for a tip speed ratio value of λ=3.1 Tufts can aerodynamically act as a trip and sometimes visualization of separation is not possible.

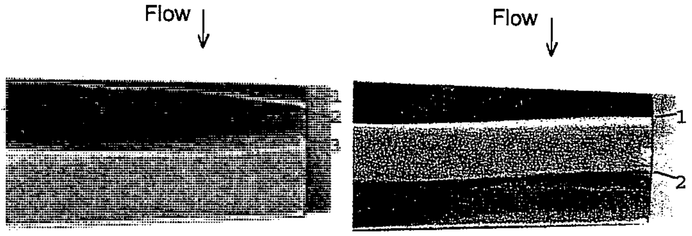
Fig. 6(a) shows that for blades using the MEL 002 airfoil at a tip speed ratio value of λ=3.8, there is the formation of three well marked points: laminar separation, reattachment and turbulent separation. It can be observed that there is the formation of a short laminar separation bubble near to the leading edge. The bursting and formation of a long laminar separation bubble can be observed in Fig6(b) at a tip speed ratio of λ=5.2. It can be also observed in Fig. 6(a) and 6(b) the reduction in angle of attack as the tip speed ratio increases

For the rotating blades using the MEL 081 it also can be observed that there is the formation of a short laminar separation bubble at a tip speed ratio of λ=3.3 (Fig 7(a)). The laminar separation, reattachment and turbulent separation are present. Fig. 7(b) for a higher tip speed ratio (λ=5.9) a lon laminar separation bubble is formed. Again the increment in tip speed ratio values reduces the angles of attack



V=6m/s, λ=3.1, α_{tip}=11.8°, Re_{tip}=3.9x10^4

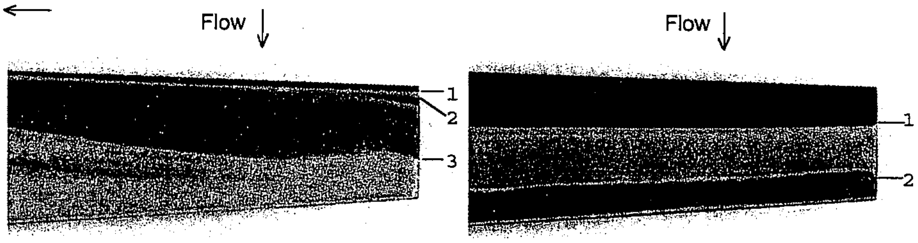
Fig. 5 visualization using the tufts method for blades using the Clark Y airfoil



(a)λ=3.8, α_{tip}=14.0°, Re_{tip}=6.9x10^4 (b) λ=5.2, α_{tip}=10.0°, Re_{tip}=9.3x10^4

1)*Laminar flow separation* 2)*Reattachment* 3)*Turbulent flow separation*

Fig. 6 Boundary layer behavior in the tip region of blades using the MEL 002 airfoil at different tip speed ratio values



(a) λ=3.3, α_{tip}=14.4°, Re=5.1x10^4 (b) λ=5.9, α_{tip}=7.1°, Re=8.9x10^4

Fig. 7 Boundary layer behavior in the tip region of blades using the MEL 081 airfoil at different tip speed ratio values

Performance is evaluated using the power coefficient and the tip speed ratio. Fig. 8 shows the comparisons of rotor power coefficient with blades using the Clark Y airfoil. For wind velocities of 4,6 and 7 m/s free transition and forced transition are compared. Results showed that, as expected thera was a better blade performance with forced transition. The forced trasnition carries a penalty in drag.

Fig 8 compares the power coefficient variation at different tip speed ratio for blades using the MEL 002 and the MEL 081. The performance superiority of the MEL 081 airfoil is evident. The MEl 002 powwer coefficients curves present a particular behavior. Around tip speed ratio values of 4 to 6, the power coefficient reduces its value from a peak and then returns to the peak. It is believed that the bursting of short laminar separation bubbles produces this phenomenon.

3.Numerical simulations

Also to corroborate experimentals results numerical calculations using CFD were carried out. The commercial code CFX-TASCflow was used for the simulations. This code employs Reynolds Averaged Navier-Stokes (RANS) equations for the solution of the flow.

As a first step, a three dimensional grid was created in a sector of 120^0 as it is shown in Fig. 10. It consists of 900,000 nodes and 55 blocks. The simulations was performed until the residuals values of the RANS equation reached 1x10^{-5}

Results for the different cases studied revealed pressure distribution on the blades surface, separation and wake development.

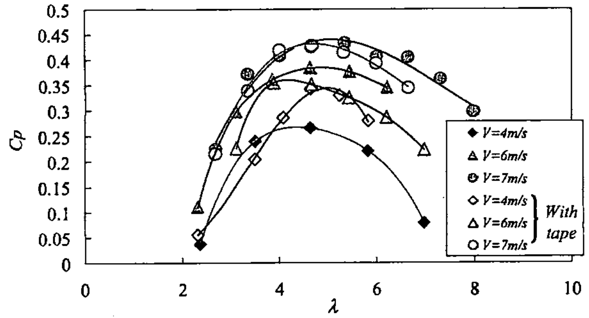


Fig. 8 Comparison of power coefficient variation at different tip speed ratio for blades using the Clark Y airfoil with free and forced transition,

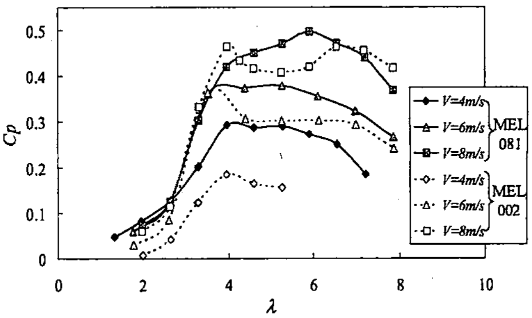


Fig. 8 Comparison of power coefficient variation at different tip speed ratio for blades using the MEL 002 and MEL 081 airfoils

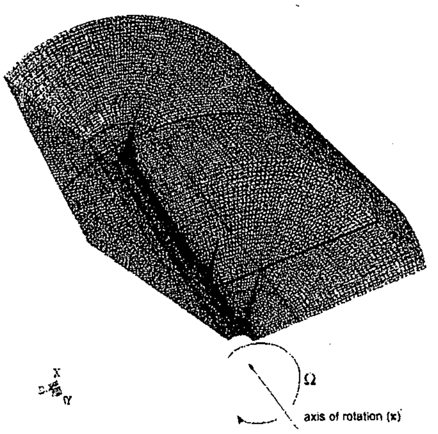


Fig. 10 three dimensional grid of the 120 degrees section used for the computations

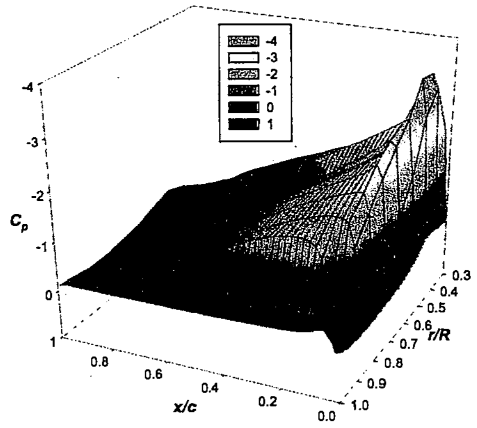


Fig. 11 3D Pressure coefficient distribution along the blade span and the chordwise direction in the suction side at λ= 6.16

A three dimensional pressure coefficient distribution for the suction side is showed in Fig. 11 for a tip speed ratio value of l=6.16. It can be observed in the non dimensional radial direction (r/R) in areas near the leading edge that a suction peak which is formed due to the large angle of attack at the inboard section. In the outboard sections, near the tip, due to rotational effects this peak dissapears. Separation is also observed in the radial positions of r/R=0.3 to 0.5 and in the chordwise positions of x/c=0.6 to 1.

Wake development is showed in Fig. 11. In the wake the formation of a central vortex sheet region and an external vortex sheet region is evident. The central region is formed from the vortex shedding in the inboard section of the blades,while the external region is formed due outboard section vortex shedding.

Numerical power coefficient results were compared with experimental data. and the agreement was good. a small difference is found for a tip speed ratio of λ=6.16. Phenomena not acounted for the numerical simulation, such as blade roughnes, wind unsteadiness, transition and low Reynolds number effects are explain the differences

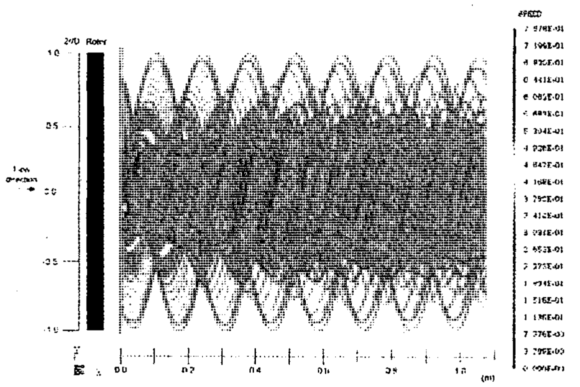


Fig. 11 Rotor wake visualization at a tip speed ratio of λ= 6.16

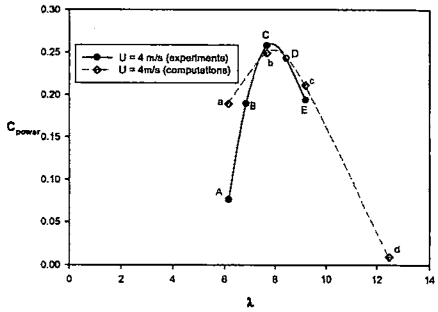


Fig.12 Power coefficient (C_{power}) vs. tip speed

学位論文審査結果の要旨

第 1，2 回の学位論文審査委員会を平成 17 年 1 月 24 日、28 日に開催し、口頭発表を 1 月 28 日に行い、同日最終審査委員会を開催した。協議の結果、以下の通り判定した。申請者は 1996 年 12 月パナマ工科大学機械工学科を卒業し、2000 年 4 月本研究科機械科学専攻に国費留学生として入学し、2002 年 4 月本研究科地球環境科学専攻に進学した。申請論文はプロペラ式マイクロ風車の流れと性能特性に関する実験及び数値解析の研究であり、まず実際の市販風車を例としてその性能試験を自然風におけるフィールド実測試験によって行い、実際の風車性能に及ぼす影響係数を特定した。数値解析は、圧縮機設計などの汎用計算コード（CFX-TASCflow）を風車の流れ解析に適用し、実際の 3 枚翼の風車諸元を基に回転風車流れの乱流計算を行った。回転風車から放出される渦の様相及び性能特性を数値シミュレーションし、その計算結果は風洞における風車回転試験やフィールド実測試験によって得られた風車性能と良い一致を示し、計算方法および導入した仮定などの有効性を立証した。さらに、改良翼形の回転翼面上の流れの剥離パターンの様相を風洞における回転翼試験で油膜法によって可視化して従来型の流れパターンと比較し、マイクロ風車では、運転状態のレイノルズ数範囲に特有の剥離バブルが存在することを明らかにした。以上、申請論文は、数値解析及びフィールド実測試験と風洞実験によって風車の性能改善のため風車流れと性能特性を研究したもので、今後プロペラ式マイクロ風車の研究、特に性能改善のための風車の流れ解析の分野に寄与するところ大であり、博士（工学）論文として値するものと認定した。