International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:10, No:1, 2016

Aerodynamic Models for the Analysis of Vertical Axis Wind Turbines (VAWTs)

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Abstract**—**This paper details the progress made in the development of the different state-of-the-art aerodynamic tools for the analysis of vertical axis wind turbines including the flow simulation around the blade, viscous flow, stochastic wind, and dynamic stall effects. The paper highlights the capabilities of the developed wind turbine aerodynamic codes over the last thirty years which are currently being used in North America and Europe by Sandia Laboratories, FloWind, IMST Marseilles, and Hydro-Quebec among others. The aerodynamic codes developed at Ecole Polytechnique de Montreal, Canada, represent valuable tools for simulating the flow around wind turbines including secondary effects. Comparison of theoretical results with experimental data have shown good agreement. The strength of the aerodynamic codes based on Double-Multiple Stream tube model (DMS) lies in its simplicity, accuracy, and ability to analyze secondary effects that interfere with wind turbine aerodynamic calculations.

Keywords**—**Aerodynamics, wind turbines, VAWT, CARDAAV, Darrieus, dynamic stall.

I. Introduction

WHILE human have been harnessing the energy of the wind for thousands of years the interest in wind power was reborn during the energy crises of the 1970s period in which the economy of the major industrial countries of the world, particularly the United States was affected by the 1973 oil crisis and the 1979 energy crisis. Since then many countries turned to renewable energy in particular wind energy where the power collected from wind machines is fed into the existing electricity grid, combined with electricity from other power plants, and finally distributed to utility customers. The J.-A. Bombardier Aeronautical Chair at Ecole Polytechnique has developed computer codes to predict aerodynamic loads and performance of a Darrieus rotor including viscous, stochastic wind and dynamic-stall effects [1]. A fundamental study of the dynamic-stall phenomenon has also been performed using the unsteady Navier-Stokes equations in a stream function-vorticity formulation [2], [3]. For fast and accurate predictions of vertical-axis wind turbines performances can be obtained using momentum models based on the conservation of momentum principle in a quasi-steady flow. The present paper reviews the main aerodynamic models that have been developed to predict the aerodynamic loads and performance of wind turbines.

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II. Development of Wind Energy in Canada

Early developments of wind energy in Canada were located primarily in Ontario, Quebec, and Alberta. Throughout the late 1990s and early years of the 21st Century every Canadian province has pursued wind power to supplement their provincial energy grids. Indeed, in Canada the energy is a provincial responsibility not a federal one. The federal government introduced a series of greenhouse gas (GHG) emission regulations which would support shifting to clean energy sources like solar, wind and geothermal, but industry is putting more efforts on provincial policies and programs that will help in improving the development of wind energy. In Quebec alone, more than 100,000 MW of wind potential exist in sites within 25 km of Hydro Quebec's existing transmission lines [4]. The number of wind turbines in Quebec exceeds 1600 turbines, with a total installed capacity of 2883 MW, and has one of the country's largest wind farm, the 350 MW at Rivière-du-Moulin. Quebec ranks second among Canadian provinces in terms of wind power installed powering 1,000,000 Quebec homes. The Global Wind Energy Council [5] reported that each year the average of new wind farm construction is about 1.4 GW, this trends is expected to be maintained for the next couple of years. CanWEA, the Canadian Wind Energy Association recently published the new vision for wind energy in Canada for 2025 discussing and showing how wind energy in Canada will create new jobs and reduce the impact on the environment [4]. Canada's electricity system can integrate large amounts of wind energy and by 2025 Canadians can get 20 percent of their electricity from wind that would require installing 22,000 wind turbines in 450 locations. In 2014, as of September 2015 Canada had a total wind installed capacity of nearly 10,425 MW, Fig. 1 [6]. The quality of Canada's wind resource is as good as or better than any of the world's leading wind energy nations such as Germany and the United States. For the coming four years, Canada will see an average of 1,500 MW of new projects creating 68,000 additional person-years of employment and attracting $15 billion in new investment, in addition, by 2025, Canada would reach a capacity of 55,000 MW, meeting 20% of the country's energy needs [4].

While the cost to build wind energy continues to decline, the improvements made in wind turbine through advanced technology had significant effects on the efficiency of the machines and become an important commercial option for large scale power production. Current turbine technology has enabled wind energy to enter the electric power mainstream and become a viable power source in today's energy market [4], [7], [8]. Over the past few years' novel designs are taking wind power to the next level where the efficiency is being gained through new models and new advanced technology. These improvements are made in many parts of the machine including gearbox, drive units, power electronics, better control algorithms and data acquisition, and more importantly in the aerodynamic of the rotors that improved blade technology using lighter, stronger, and aerodynamically performing and efficient rotor blades. The new generation of advanced wind turbines include blades made from soft, flexible materials that change shapes in response to wind speed or aerodynamic loads. The technology is part of a trend making wind power almost as cheap as fossil fuels. For example, in 1991, the cost of a kilowatt hour from wind power cost 15 cents while now it has dropped to 6.5 cents per kilowatt hour [7].

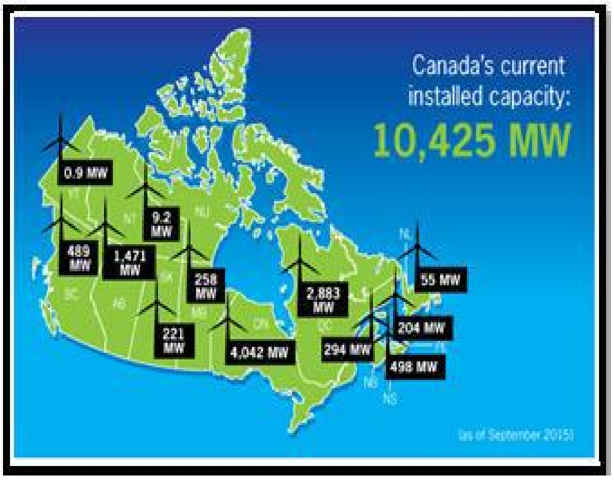

Fig. 1 Canada's current installed capacity [6]

III. Aerodynamic Models for VAWT

Modern wind turbines can basically be classified as either of vertical-axis (VAWT) design, such as the Darrieus model, or as horizontal-axis (HAWT) variety like the traditional farm wind pump, Fig. 2. In both cases, the turbine's rotating blades extract kinetic energy from the wind to generate electricity or pump water. Although the HAWT remains the main focus of all wind energy research and development, the vertical-axis wind turbine model offers an advantageous alternative due to its mechanical and structurally simplicity of harnessing the wind energy [1], [9]. The J.-A. Bombardier Aeronautical Chair at Ecole Polytechnique has developed computer codes to predict aerodynamic loads and performance of a Darrieus rotor. These models were based on the momentum theory where the rotor is replaced by an actuator disk and then the flow through the rotor is determined by equating the forces on the rotor blades to the time rate of change in momentum through the rotor. Other models include viscous effects, stochastic wind, and a fundamental study of the dynamic-stall phenomenon.

Fig. 2 VAWT and HAWT in Quebec [6]

A. Aerodynamic Codes Based on the DMS Model

Paraschivoiu [10], [11] developed an analytical model, the double-multiple stream tube model (DMS), that considers a multiple-stream tube system divided into two parts where the upwind and downwind components of the induced velocities at each level of the rotor are calculated by using the principle of two actuator disks in tandem, Fig 2.

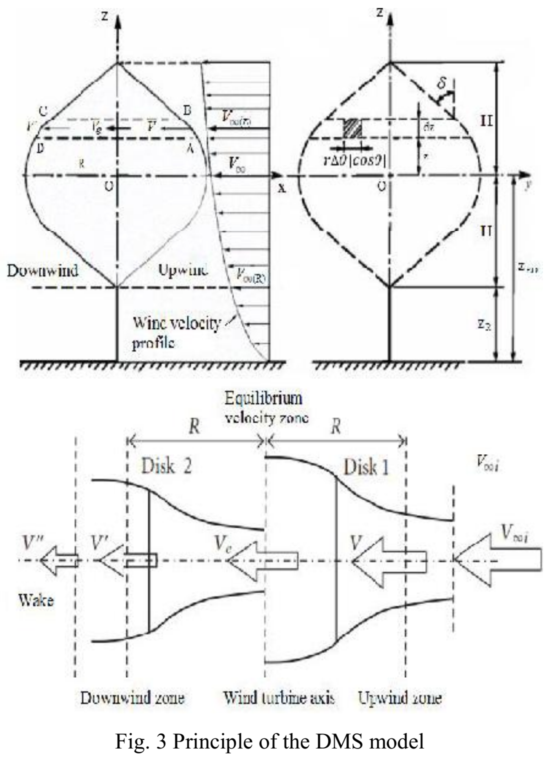

Fig. 3 Principle of the DMS model

For the upstream half-cycle of the rotor, the relative velocity and the local angle of attack as a function of the tips peed ratio "X" are given by:

$$W^2 = V^2[(X - s\quad)^2 + \cos^2\theta\quad s^2\delta] \tag{1}$$

$$\alpha = \arcsin\left[\frac{c}{\sqrt{(X-s\quad)^2+c\quad{}^2\theta\quad s^2\delta}}\right] \tag{2}$$

where $X = \frac{\omega}{V}$ and ω is the turbine rotational speed.

The non-dimensional normal and tangential forces as a function of the azimuthal angle θ are:

$$F_N\ (\theta) = \frac{c}{S}\int_{Z_R}^{Z_R+2H}\left(\frac{W}{V_\infty}\right)^2 C_N d \quad (3)$$

$$F_T(\theta) = \frac{c}{S}\int_{Z_R}^{Z_R+2H}\left(\frac{W}{V_\infty}\right)^2 \left(\frac{C_T}{c}\right) d \quad (4)$$

where c is the local airfoil chord and S is the plane area enclosed by the blade. The normal and tangential force coefficients of the blade section are given by

$$C_N = C_L c \quad + C_D s \quad (5)$$

$$C_T = C_L s \ \alpha - C_D c \quad (6)$$

The lift and drag coefficients C_L and C_D are computed by interpolating the available test data using both the local Reynolds number and the local angle of attack.

Three computer code variants based of the DMS model have been developed: CARDAA, CARDAAV and CARDAAX. CARDAA considers two constant interference factors in the induced velocities for each half-stream tube while CARDAAV code considers the variation of the interference factors as a function of the azimuthal angle on the upwind and downwind half of the rotor. In CARDAAX, the effect of the stream tube expansion is added to the code. Finally, CARDAAS 1D/3D includes a stochastic wind model incorporating the fluctuating nature of the wind. The velocity field of the wind is assumed to be a linear superposition of a mean and a fluctuating components. These codes have been constantly improved in order to produce an efficient software package appropriate for the needs of VAWT designers and have been widely used by many research centers such as Hydro-Quebec (Canada), Sandia National Laboratories (US), and many others [12]. A unique feature of the CARDAAV code, apart from the two actuator disks model, is that additional parameters options can be incorporated into the code, for example the influence of the blade geometry, the airfoil type, the rotating tower, the presence of struts, or the size of the spoiler. Among the principal operating parameters that are readily modifiable to meet the needs of a specific analysis are the wind speed, the rotation speed of the rotor, the local gravitational acceleration and the working fluid properties. Either constant rotation speed for different wind speeds or different rotation speeds for a constant wind speed can be considered when performing an analysis. A power law type variation of the wind speed (as a function of altitude) is taken into account during the computations.

B. Aerodynamic Code Based on Viscous Model

Aerodynamic codes based on the DMS model do not take the viscous effects into account, a computer code named 3DVF [13], [14] has been developed to analyses the Darrieus rotor in a steady incompressible laminar flow field by solving Navier-Stokes equations in a cylindrical coordinates using the finite volume method where the effect of the spinning blades is simulated by distributing source terms in the ring of control volumes that lie in the path of the turbine blades. The calculating method based on the control volume approach uses the widely known "SIMPLER" algorithm. Details of the governing equations with the numerical procedure are given in [15].

C. Dynamic Stall Models

Dynamic stall has a significant influence on the aerodynamic loads and performance of the wind turbine at low tip-speed ratios. It is an unsteady flow phenomenon which refers to the stalling behavior of an airfoil when the angle of attack is changing with time. Dynamic stall is characterized by dynamic delay of stall to angles significantly beyond the static stall angle as well as by massive recirculating regions moving downstream over the airfoil surface. When the Darrieus wind turbine operates at wind speed approaching its maximum, all its blades sections exceed the static stall angle, consequently the whole blade operates under dynamic stall conditions which causes structural fatigue, and even stall flutter leading to catastrophic failure limiting the performance of the turbine. In such conditions, the dynamic lift and drag characteristics present a hysteresis response which is completely different from the static coefficients. The objective of a dynamic-stall model is to propose a methodology to compute the dynamic characteristics from available experimental static coefficients.

To predict the aerodynamic performances and provide aerodynamic loading information to structural dynamic codes, four dynamic stall models are available in our aerodynamic code CARDAAV, three derived from Gormont's method [16], adaptation of [17], adaptation of [18], the modification of [19], and one derived from the indicial method [20].

The effects of dynamic stall are more complex during the turbine operation, in an experimental study [21] performed in a water channel at a tip speed ratio of 2.14, study shows the emission of a leading and trailing edge vortices interacting with the blade trajectory, Fig. 3. It has been suggested to apply the dynamic stall model only in regions of low turbulence as reported by [18].

Using TKFLOW the simulation of the computed flow structure around an airfoil in Darrieus motion based on Navier-Stokes solver in stream function-vorticity formulation has been developed [22]. Since 3-D simulation would be very expensive a 2-D simulation has been adopted. The code has the capability to predict the region where the dynamic stall may occur. Computational Fluid Dynamics (CFD) methods, based on the solution of the Navier-Stokes Equations, are the most accurate (qualitatively and quantitatively) in terms of flow analysis, but their major drawback is the very high computational cost (require large computational resources and very long time to provide converged solutions).

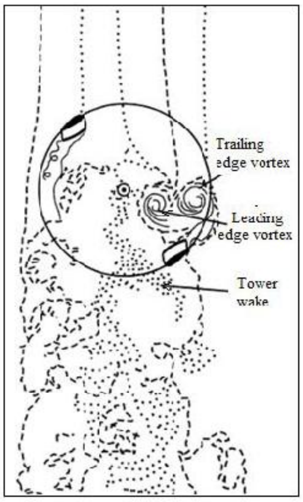

Fig. 4 Flow visualization in the dynamic stall condition for $\lambda = 2.14$

IV. VAWT Design Optimization

For the optimization of the Darrieus wind turbine given a set of constraints, the CARDAAV code has been coupled with a generic algorithm, GENIAL Code, developed by [23]. The variables considered in this optimization are the geometrical and operational parameters such as: height, aspect ratio, chord length, number of blades, airfoils, rotation speed, etc. The use of a genetic algorithm is not only appropriate to analyze a combination of these variables but also to be used for parametric studies since a large number of evaluations are possible due to the high performance of CARDAAV aerodynamic code in term of execution time.

Regarding the use of airfoil section types, the successful design of an efficient rotor can be obtained only when appropriate airfoil sections have been selected. Most VAWTs currently operating worldwide use blades of symmetrical NACA airfoil series. It has been proposed to use Natural Laminar Flow (NLF) airfoils to increase the efficiency of the VAWT [24]. NLF airfoils typically can maintain a laminar flow up to 50% chord through favorable pressure gradients, which results in a significant reduction of the airfoil drag.

A major concern for wind turbine developers is how their aerodynamic designs would fair in rated and extreme weather conditions in terms of structural viability and fatigue. In order to cater to these demands, much effort has been devoted towards the development of static and dynamic structural response of the VAWTs. Newly developed capabilities include a combined aero-structural design of the turbines with focus on structural dynamic response which has been successfully applied also for water turbines [25]. In this regards, Figs. 5-7, show the different steps in the structural dynamic response analysis of a simple 2-bladed H-Darrieus VAWT that include:

a) development of a 3D beam-element model for finite-element analysis (Fig. 5),
b) model analysis (Fig. 6), and
c) the translational and rotational displacement time history (Fig. 7).

The analysis helps identify critical response frequencies as well as help estimate turbine life expectancy under rated and extreme weather conditions.

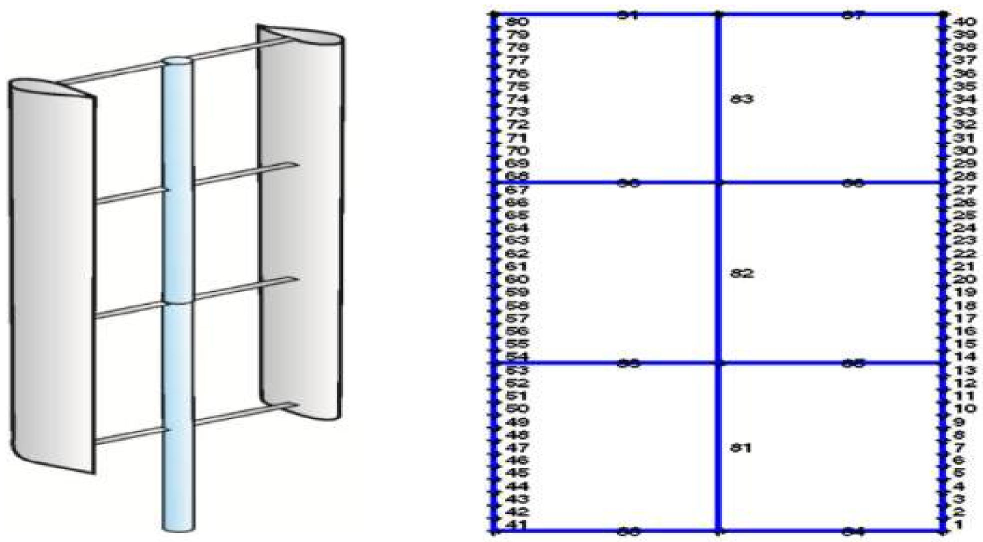

Fig. 5 The H-Darrrieus configuration and the corresponding 3D beam-element model

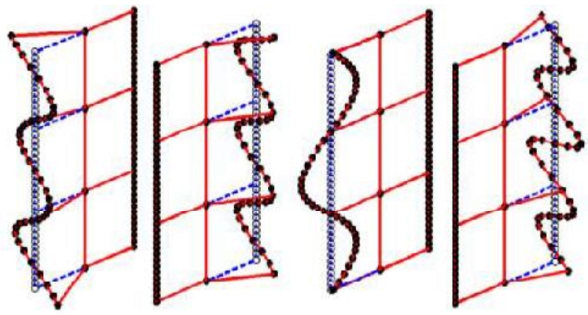

Fig. 6 Different mode shapes for the spinning H-Darrieus turbine

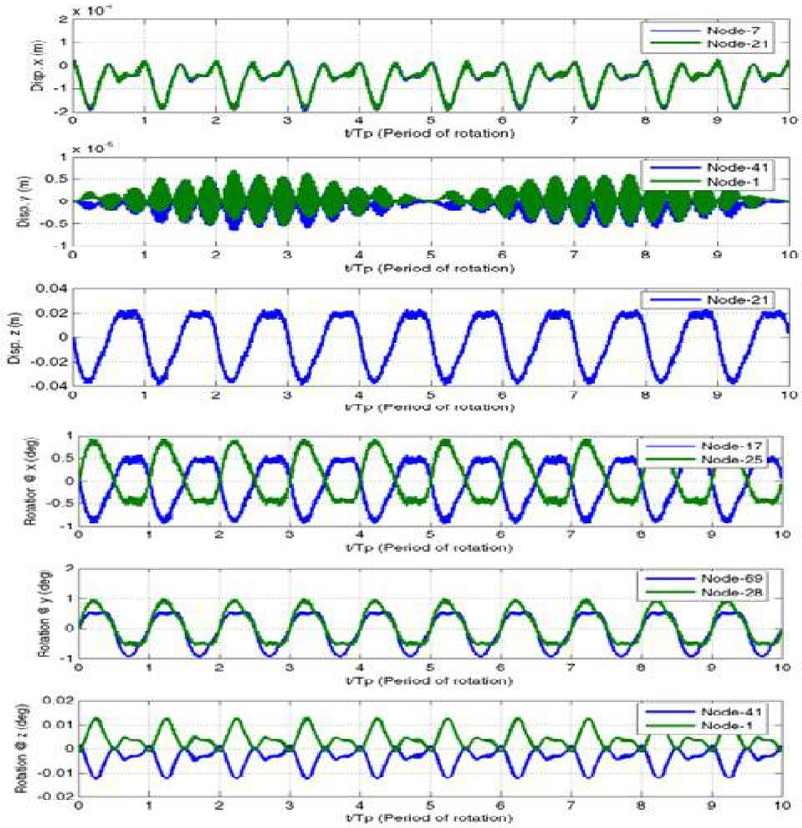

Fig. 7 Time history of maximum translational and rotational displacements of the nodes

V. Results and Discussion

The different capabilities discussed in previous sections make CARDAAV aerodynamic code a very attractive and efficient design and analysis tool. The performance prediction of Sandia 17-m wind turbine, Fig. 8, using CARDAA code was improved by considering the variable interference factors in CARDAAV code and by including stream tube expansion effects in CARDAAX code. We can see from the figure that CARDAA over predicts the power coefficient peak while CARDAAV and CARDAAX results are in good agreements compared to experimental data. Results were also compared to Strickland et *al.* vortex model (VDART3) [26]. The simulation of the dynamic stall hysteresis loop using 3DVF code with indicial model is given by Fig. 9. Compared to CARDAAV results, predictions in the upwind and downwind regions of the turbine are well compared to experimental data [27]. The performance predictions at 42.2 rpm using 3D viscous model it is also well predicted, Fig. 10. In Fig. 11 comparison of the normal force coefficients for the steady state and stochastic loads using CARDAAS 3D shows good agreement with experimental data. Fig. 12 shows the performance of Sandia-17 m machine at 42.2 rpm using the various implementations of the Gormont dynamic stall model where $A_{\_M}$ is an empirical constant used to correct C_l and C_d for dynamic stall effects [24]. Results are in good agreement with experimental data.

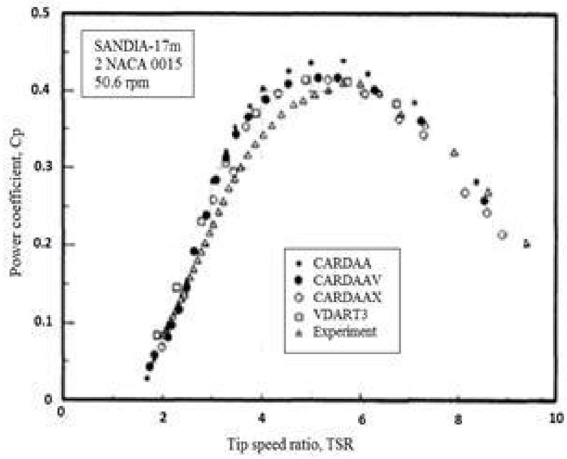

Fig. 8 Power coefficient as a function of the tip-speed ratio, DMS models, Vortex model, and experimental data

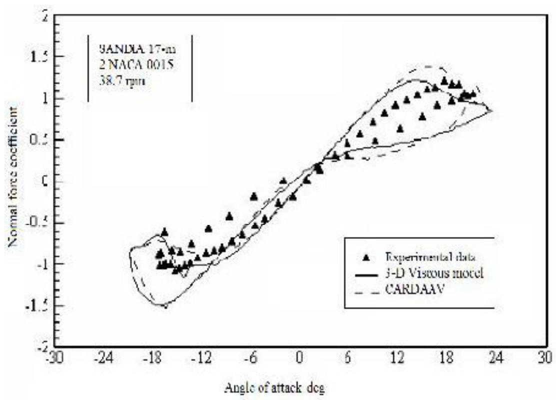

Fig. 9 Normal force coefficient vs. angle of attack at tip-speed ratio of 2.49

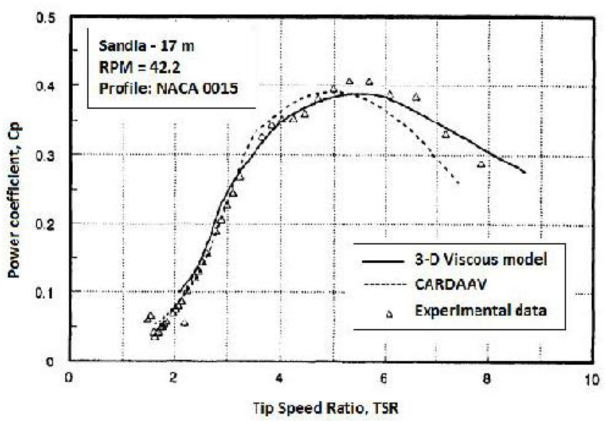

Fig. 10 Power coefficient as a function of TSR, comparison: 3-D viscous and models, CARDAAV, and experimental data

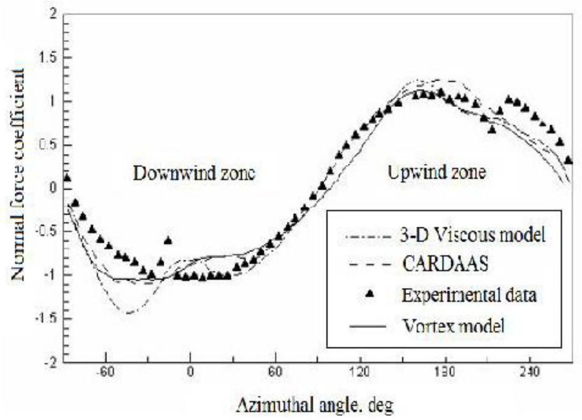

Fig. 11 Comparison of normal force coefficient at tip speed ratio of 2.86 and turbulence = (27%, 25%)

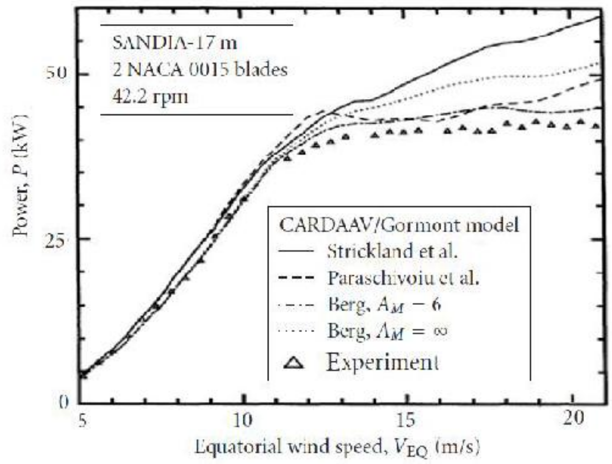

Fig. 12 Power coefficient with Gormont-model adaptations

VI. Conclusion

The Vertical Axis Wind Turbine (VAWT) offers a mechanically and structurally simple method of harnessing the energy of the wind. This simplicity, however, does not extend to the rotor aerodynamics. Aerodynamic loads and performance of the wind turbine depend on the flow field of the wind through the surface swept by the blades. The J. A. Bombardier Aeronautical Chair Group at Ecole Polytechnique de Montreal [28] has conducted many research on the development of computer codes for studying Darrieus rotor aerodynamics, today various aerodynamic code variants based on the double-multiple stream tube model, stochastic wind and viscous flow field, including dynamic stall, are available to designers [1]. Comparison of the analytical results with available experimental data have shown good agreement. The different codes developed represent valuable tools for simulating the flow field around the turbine and dynamic-stall phenomenon. CARDAAV proves to be an efficient and flexible software package, appropriate for the needs of VAWT designers. The capabilities that exist in the aerodynamic codes make CARDAAV a very attractive and efficient design and analysis tool. It computes the aerodynamic loads and rotor performance for VAWTs of any geometry at given operational conditions. It is also possible to couple CARDAAV with an optimization or structural analysis code in order to perform the optimized design of a VAWT.

ACKNOWLEDGMENT

The authors gratefully acknowledge the support of J.-Armand Bombardier Aeronautical Chair.

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