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Vertical-Axis Wind Turbines-The Current Status of an Old Technology*

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Abstract
Vertical-axis wind turbine technology is not well understood, even though the earliest wind machines rotated about a vertical axis. The operating environment of a vertical-axis wind turbine is quite complex, but detailed analysis capabilities have been developed and verified over the last 30 years. Although vertical-axis technology has not been widely commercialized, it exhibits both advantages and disadvantages compared to horizontal-axis technology, and in some applications, it appears to offer significant advantages.

Introduction
The earliest references to windmills in the European literature refer to machines similar to the one illustrated in Figure 1, which was used to grind grain in ancient Persia, near present-day Afghanistan. Sails of cloth or reed bundles attached to the vertically-mounted shaft caught the wind and turned the shaft and the attached grindstone. Windmills such as these were still in use in the same general area as recently as 30 years ago. There is also considerable evidence that the Chinese have used windmills for many hundreds of years in a configuration that we refer to today as a vertical-axis wind turbine, or VAWT. The earliest European reference to these machines dates back to 1279 AD.

A different configuration of windmill, one in which the sails rotated about a horizontal axis, first appeared in northern Europe around 1200 AD. Within 100 years, wind machines of this type, now referred to as horizontal-axis wind turbines, or HAWTs, had become a major source of mechanical energy throughout northern Europe. They remained so for over 500 years, before being displaced by the steam engine in many applications. Although they are no longer a major source of mechanical energy, wind machines have never disappeared entirely. Even today, they continue to be used for many tasks, especially in remote areas.

The use of wind energy to generate significant amounts of electricity appears to have been successfully demonstrated for the first time in 1888 by Charles Brush of Cleveland, Ohio, who built a 17-m diameter turbine to generate 12 kW of DC power. The next 45 years saw the development of aircraft propeller technology and the adaptation of that technology to wind turbines, producing turbines with only two or three blades of airfoil cross section and high rotation speeds. These new turbines were well suited to producing electricity, and many thousands of small wind-driven generators were built and sold to provide electricity to remote areas around the world.

Development of larger scale wind-powered generators began over 55 years ago, but not much progress was made until the Arab Oil Embargo of 1972 resulted in renewed interest in alternate sources of energy of all types. Progress in the past 24 years has been very dramatic. Today there

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are over 26,000 electricity-generating wind turbines operating worldwide, with an installed capacity of over 5,000 MW. Last year alone, the installed capacity increased by nearly 40%. The cost of wind-generated electricity has dropped from 25 cents per kilowatt hour in the early 1980s to as low as 5 cents per kilowatt hour today. Turbine availability (the portion of time the turbine is available to generate electricity) has risen from less than 50% to over 95% in the same time frame.

Virtually all of the wind turbines in use today are of the horizontal type; vertical-axis technology lay stagnant for many centuries before being re-discovered in this century. F. M. Darrieus developed and patented the concept of vertical-axis wind turbines with two or three slender blades of airfoil cross section about 1930. His patent covered machines with either straight or curved blades. The curved-bladed machine, illustrated by Figure 2, is now commonly referred to as a Darrieus turbine or rotor, while the most common configuration of a straight-bladed machine is now commonly referred to as an 'H' machine, due to the single horizontal arm supporting the blades. Apparently, little work was done on either type of machine until scientists at the National Research Council (NRC) of Canada began working on the Darrieus configuration in the late 1960s. That technology has seen extensive development in Canada (both at NRC and in the commercial sector) and in the United States (at Sandia National Laboratories and in the commercial sector) in the past 30 years. The United Kingdom spent considerable time and effort developing the technology for the 'H' turbine over a 15-year period before terminating its vertical-axis program in 1992, concluding that for sizes under 1 MW, that configuration was more expensive than a HAWT configuration (Milbarrow, 1995). These efforts have resulted in quite a good understanding of the operating environment and loads experienced by VAWTs, but they have not resulted in the widespread commercialization of VAWT technology.

This paper reviews the basic operating characteristics of Darrieus-type VAWTs and summarizes the current state of the art in VAWT technology and analysis tools.

The Basics of VAWT Operation

The operation of a VAWT depends on the vector addition of the blade rotational velocity and the freestream wind speed. Figure 3 illustrates a cross section of a VAWT blade rotating counterclockwise at a distance R from the center of rotation of the turbine. The effective wind acting on the turbine blade, $\vec{V}_e$, is the vector sum of the freestream wind speed, $\vec{V}_\infty$, and the blade rotational speed, $\vec{V}_t\left(=(R\omega)\vec{e}_t\right)$. This wind acts on the airfoil at an angle of attack, α, which depends on the freestream wind speed, the rotational speed of the blade, and the rotational or azimuthal position of the blade with respect to the freestream wind. A typical angle of attack variation with rotational position as a function of the tip-speed ratio, $\lambda_\infty\left(=R\omega/V_\infty\right)$, for a VAWT blade is shown in Figure 4. λ_∞=10 corresponds to a low wind speed ($V_\infty \approx 5$ mps for typical value of Rω=50 mps), while λ_∞=1.25 corresponds to a very high wind speed ($V_\infty \approx 40$ mps). At low wind speed (high λ_∞), the angle of attack variation is quite well approximated by a sine wave. As the wind speed increases, the tip-speed ratio decreases, and the angle of attack variation becomes increasingly skewed, as shown. For each revolution of the blade, α cycles from 0° to some maximum angle, through 0° to some minimum angle, and back to 0°.

The magnitude of both lift and drag depends on the magnitude of the wind speed, the angle of attack, α, and the performance characteristics of the airfoil. When α is large enough, the tangential component of lift will exceed the tangential component of drag, and the net aerodynamic torque will become positive. Since the angle of attack varies as the blade rotates, so does the blade torque, as shown in Figure 5, resulting in a fairly large cyclic torque oscillation with two peaks and two valleys each revolution. At low wind speeds (high λ_∞), the torque is positive for only part of the rotation and negative for the remainder, but as the wind speed increases (λ_∞ decreases), the entire torque curve becomes more positive and the blade begins to generate power. The torque oscillations can be reduced in size, but not completely eliminated, by placing two or three blades on a turbine. Although any VAWT rotor will generate a torque oscillation, that oscillation can be reduced dramatically with a drive line that is soft in torsion between the rotor and the transmission or generator.

Comparison of HAWTs and VAWTs

Figure 6 illustrates the principal features of HAWTs and VAWTs. While the two technologies contain many of the same components, there are also many differences. Some are obvious, but some are far more subtle.

VAWT blades are longer than HAWT blades for a given swept area, but they are attached to the tower at both ends. The blades experience highly cyclic aerodynamic loading, and dynamic stall effects become important at higher wind speeds. However, they experience only steady loading due to gravity and wind shear, and the loads are carried mainly in tension. Blades are usually constant cross section and fairly cheap to manufacture, but they may be long enough to require multiple joints on each blade. VAWTs accept wind from any direction and can be stall regulated, so they require no yaw controls and no pitch mechanism. Typically, the only active control is brakes on the rotor shaft, but those brakes have to stop a higher-inertia system. The VAWT is not self-starting, and typically uses the generator as a motor to spin the blades up to operating speed.

HAWT blades, on the other hand, are shorter than VAWT blades for a given swept area, but they are cantilevered from the hub, resulting in relatively higher loads at the hub. Rotor inertia is lower than for a VAWT of comparable size. The blades experience much less cyclic aerodynamic loading, but tower shadow or yaw error may cause dynamic stall effects to become important, even in moderate winds. Dynamic stall effects become important for either stall-controlled or pitch-controlled machines in higher winds. HAWT blades experience cyclic loading due to gravity and wind shear loading as they rotate, and they also experience gyroscopic loads due to yawing of the nacelle. Blades are usually twisted and tapered to achieve high efficiency, but this makes them more expensive to manufacture. They usually have joints only at the root. Power is limited by either stall regulation or pitching of the rotor blades. HAWTs require either a free-yaw mechanism or a yaw drive to align the rotor with the wind. They can use aerodynamic brakes and need smaller driveshaft brakes due to lower rotor inertia. Pitch-controlled HAWTs are self starting, but stall-controlled machines must utilize a motor to spin them up to operating speed.

VAWT drivetrains are located at ground level and can be enclosed for service in all kinds of weather. The only moving part above ground level is the rotor. HAWT drivetrains are located in the nacelle, on top of the tower, which can make service difficult in inclement weather, but the

HAWT tower can be extended to take advantage of higher winds due to positive vertical shear. VAWT blades are more difficult to access and inspect than HAWT blades.

VAWT foundations experience small overturning moments, due to the use of guy cables, but they must support both the turbine weight and the loading due to guy-cable tension, and the guy cables increase the amount of land needed for the turbine. HAWT foundations are smaller in size, but experience large overturning moments.

Numerous studies have compared the HAWT and VAWT technologies to determine which is superior. The results are inconclusive-while the cost of energy for a HAWT may be less than that of a VAWT at a site with high positive wind shear and a prevailing wind direction, the cost of energy for a VAWT may be less at a site with low or negative wind shear or no prevailing wind direction. In addition, there are not enough data available from actual machine operations to answer the question. FloWind Corporation in California is the only company operating significant numbers of VAWTs, and those machines were built over 10 years ago. Comparing production figures from them with production figures from newer horizontal-axis machines would not be a fair comparison, even if the HAWTs were operating in close proximity to the FloWind machines, which they are not. Even if the VAWTs do produce less energy per unit swept area, if they are cheaper to build, as claimed by FloWind (Milborrow, 1995), they may yield a lower cost of energy. Each technology has strengths and weaknesses, and neither one is a clear winner in all situations.

VAWT Analysis

Aerodynamic Analysis

The aerodynamic analysis of a wind turbine has two primary objectives: 1) to predict the aerodynamic performance of the turbine, and 2) to predict the wind loads that will act on the turbine. In general, the same models are used to accomplish both objectives.

The simplest aerodynamic models of a VAWT use streamtube theories. These models equate the rate of change in wind momentum in a stream tube to the time-averaged forces on the blades in that stream tube. Iteration is required to determine consistent velocities and forces, and two-dimensional airfoil lift and drag characteristics are used to determine the blade forces. Wind shear and local Reynolds number variations may be readily accounted for with these models. The various models represent the turbine as a single streamtube, multiple streamtubes, or as multiple streamtubes that distinguish between the upwind and downwind blades (the double-multiple streamtube models).

Multiple steamtube methods are extremely popular with wind turbine designers for three primary reasons: 1) they have been shown to accurately predict turbine performance for a wide variety of rotors and flow conditions, 2) they are simple to learn and use and are readily implemented on virtually any desktop computer, and 3) they run very quickly. However, they are time-averaged methods that ignore much of the fluid mechanics within the rotor, and thus cannot be expected to accurately predict unsteady effects or detailed loads.

Vortex methods are based upon some form of the vorticity equation and perform detailed calculations of the induced velocity field by determining the distribution of vorticity in the turbine wake. Vortex models can use either lifting line or lifting surface formulations for the blades with either free wake or fixed (or prescribed) wake models, although there are a number of variations of these models. The three dimensional, lifting surface, free wake formulation is the most physically realistic model, but no programs are currently available that will run such a model in a reasonable time, regardless of the type of computer being used. The problem with vortex codes is one of finding a balance between model simplification (and limitation) and computation time.

The local circulation model (LCM) is a hybrid between the momentum and vortex models. Similar to the streamtube models, the LCM utilizes a momentum balance between the force on the blade and the change in wind momentum as it passes through the rotor. The blade, however, is represented as a superposition of imaginary blades of different spans with elliptical circulation distributions. Local circulation models may be formulated to analyze unsteady flow, and are able to yield detailed flowfield velocity and blade-loads information. The LCM yields better answers than the momentum models, avoids the convergence problems of the vortex models, and, with an appropriate wake model, requires far less computer time than the vortex models. However, this model is not as easy to understand as the streamtube or vortex models, and it hasn't been widely used to this point.

All of the aerodynamic models in use today use airfoil section characteristic tables (lift and drag coefficients as functions of angle of attack and Reynolds number) to determine the blade loads and turbine performance. The airfoil section data are usually derived from two-dimensional, static wind tunnel tests or two-dimensional, static airfoil design codes. They are then modified with empirical, semi-empirical, or analytic methods and used to estimate blade loads under three-dimensional, dynamic conditions, including dynamic stall. The greatest difficulty in obtaining accurate predictions is the determination of the appropriate airfoil section characteristics for the operating environment.

Structural Dynamic Analysis

Darrieus turbine designs normally use relatively slender, high-aspect-ratio structural elements for the blades and supporting tower. The result is a very flexible, highly dynamic structure, with many natural modes of vibration that must be carefully analyzed to ensure the turbine is dynamically stable under all operating conditions. Typically, the guy cables and turbine support structure can be analyzed with conventional methods, but the tower and blades require a more refined analysis, usually performed with a special purpose structural analysis code.

The blades and tower can be modeled in the rotating coordinate frame with time-independent coefficients. The equations of motion are determined by the steady centrifugal and gravitational forces, the steady and oscillatory aerodynamic forces, and the Coriolis forces, together with the turbine physical properties. These equations of motion can be solved in the frequency domain, and the rotor frequency response to the oscillating aerodynamic loads may be determined. The rotor modes must be carefully examined to ensure that they will not be forced into resonance by the driving frequencies that occur at integer multiples of the rotational speed (the "per-rev" frequencies).

The VAWT blades must also be analyzed to ensure aeroelastic stability. In some cases, the aerodynamic loads may couple with the blades' elastic displacements to increase their motion, a potentially fatal condition known as flutter instability. In other cases, the aerodynamic loads may interact with the blades to decrease blade motion, a beneficial condition known as aerodynamic damping.

Fatigue Considerations

Wind turbines are fatigue-critical structures, subjected to combinations of wind, gravity, and gyroscopic loadings that are highly irregular in nature. At rotation rates of 30 to 60 rpm, the blades of a turbine typically must withstand at least 10^9 cycles during a 30-year lifetime-100 to 1000 times more than a typical transport aircraft is designed to withstand. The VAWT does experience higher cyclic aerodynamic loads than a HAWT, due to its aerodynamic environment. However, once a VAWT has been designed to withstand those cyclic loads, it is relatively immune to the turbulent wind and other effects that adversely effect HAWT fatigue life.

Turbulent Wind Effects

The wind is stochastic in nature, with significant short-term variations in both direction and velocity. In addition, as turbines become larger, the relative size of an atmospheric gust or eddy becomes smaller than the size of the turbine, and the effect of a stochastic wind becomes greater. Analysis of the effect of these fluctuating wind loads on the response of the turbine shows an increase in the broad-band response, accompanied by a decrease in the magnitude of the per-rev responses. This increase in broad-band response can result in significant excitation of turbine vibration modes that are close to a per-rev frequency, but that are not excited by a uniform wind.

Additional information and references on VAWT aerodynamics and structural dynamics may be found in Touryan, Strickland, and Berg (1987) and Wilson (1994).

34-m Test Bed

The 34-m Test Bed, shown in Figure 2, is a research-oriented VAWT located at the US Department of Agriculture Agricultural Research Service facility in Bushland, Texas. Sandia National Laboratories designed and built this machine to perform research in structural dynamics, aerodynamics, fatigue, and controls. The two-bladed rotor is 34 meters in diameter with a height-to-diameter ratio of 1.25 and a swept area of 955 m^2. This continuously-variable-speed machine has an operating range of 28 to 38 rpm (although it can actually be operated down to 5 rpm), with a rated power of 500 kW at a rotation speed of 37.5 rpm in mean winds of 12.5 m/s (28 mph). Further details on the Test Bed may be found in Berg (1985), Berg and Ashwill (1986), and Ashwill and Veers (1990).

The Test Bed blades are unique in that they are tailored both structurally and aerodynamically to minimize stresses and maximize energy capture. The root sections (near the tower) are 1.22-m chord NACA 0021 profiles. The equatorial sections are curved 0.91-m chord SNL laminar flow 0018/50 profiles, and the transition sections (between the root and equatorial sections) are curved 1.07-m SNL 0018/50 profiles. Figure 7 is a schematic of the airfoil shapes used in the blades. The transitions from one chord length to another were smoothed with fiberglass, but not fully faired to minimize adverse effects on turbine performance. Additional information on the blade design may be found in Berg, Klimas, and Stephenson, (1990).

After the turbine was fully assembled, but prior to operation of the turbine, we performed a modal test on the stationary rotor. Accelerometers were temporarily attached to the blades, tower, and cables, and frequency response functions were measured using both step relaxation and wind excitations. These measurements were used to determine the turbine mode shapes, their frequencies of vibration, and their damping values. The mode shape and vibration frequency data were then used to validate the turbine finite element model we had developed during the design of the turbine.

Table I compares the first 8 measured modal frequencies with those predicted analytically. The mode number and shape are listed in the first two columns, while columns three and four list the measured modal frequencies and the analytical values, respectively. All predicted values are within 3% of the measurements, except for the first blade edgewise mode, which is just over 5% low.

Modal frequencies change with turbine rotational speed, and accurate prediction of these changes is essential to the successful design of a VAWT. In Figure 8, the measured variations with rpm of several modal frequencies are compared with the frequencies predicted by the NASTRAN-based FEVD code. The mode labels are as defined for Table I. The per-rev driving frequencies are also included in the figure; the noted 3P crossings of the 1BE and 1TI modes are possible resonance conditions. Again, the agreement is excellent.

The aerodynamic performance of the Test Bed was predicted with a double-multiple streamtube code (DMST) that accounts for local Reynolds number effects and incorporates a dynamic stall model, but does not model the effect of the step changes in chord. Figure 9 compares the measured aerodynamic performance data with those predictions. The agreement between measurement and prediction at moderate to high wind speeds is very good, with the power regulation in the high-wind regime worthy of particular notice. This is due to the stall characteristics designed into the SNL 18/50 airfoil, and this regulation was one of the key objectives of the blade design effort.

The predicted performance does not agree as well at low wind speeds. We feel this is due both to the non-faired step changes in chord and airfoil sections, and to the inherent inaccuracies at low winds of the DMST code, which does not include streamtube spreading effects.

An excellent summary of the work performed on the Test Bed through early 1990 may be found in Veers (1990). Additional experimental results may be found in Ashwill (1991).

Summary

The earliest wind machines rotated about vertical shafts, but after the appearance of horizontal-axis machines in the 13th century, the vertical-axis machines were virtually ignored until this century. In the last 30 years, the vertical-axis technology has advanced to a relatively mature state through efforts in Canada, the United States, and the United Kingdom.

While HAWTs and VAWTs share many common elements, they also differ in many ways, with each technology having both advantages and disadvantages. They are comparable in performance, and each type has a clear advantage in certain siting scenarios.

The vertical-axis wind turbine environment is a very dynamic one, with the blades experiencing large magnitude cyclic loading, even when the incident wind is steady. Quite complex and detailed aerodynamic and structural dynamic codes are required to accurately model the machine. While room remains for improvement, comparison of the predicted and measured aerodynamic and structural dynamic performance for the 34-m Test Bed has shown that existing codes are quite accurate.

In spite of these facts, VAWT technology is not widely commercialized today, but not because it has been shown to be inferior to HAWT technology. Rather, it appears to be because the VAWT technology is much different from HAWT technology, and relatively few companies have made the investment required to truly understand and objectively evaluate the VAWT. Given the fact that neither HAWT nor VAWT is clearly technically superior, the final choice between the two technologies may well be made on the basis of non-technical and market-driven issues such as turbine-caused avian mortality, perceived visual impact, noise, and customer preference.

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Mode Number	Mode Shape*	Modal Test	Analytical	Deviation
1,2	1FA/1FS	1.06	1.05	1.0%
3	1Pr	1.52	1.56	2.6%
4	1BE	1.81	1.72	5.2%
5	2FA	2.06	2.07	0.5%
6	2FS	2.16	2.14	1.0%
7	1TI	2.50	2.46	1.6%
8	1TO	2.61	2.58	1.2%

*Mode Shape Abbreviation Key:
1FA = First Flatwise Antisymmetric
1FS = First Flatwise Symmetric
1Pr = First Propeller
1BE = First Blade Edgewise
2FA = Second Flatwise Antisymmetric
2FS = Second Flatwise Symmetric
1TI = First Tower In-Plane
1TO = First Tower Out-of-Plane

Table I. 34-m Test Bed Parked Modal Frequencies (Hz) - Test and Analysis

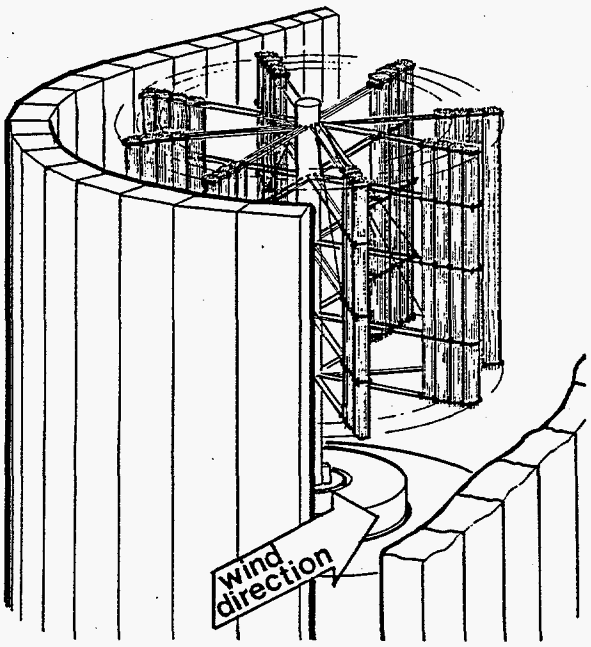


Figure 1. Sketch of Ancient Persian Windmill

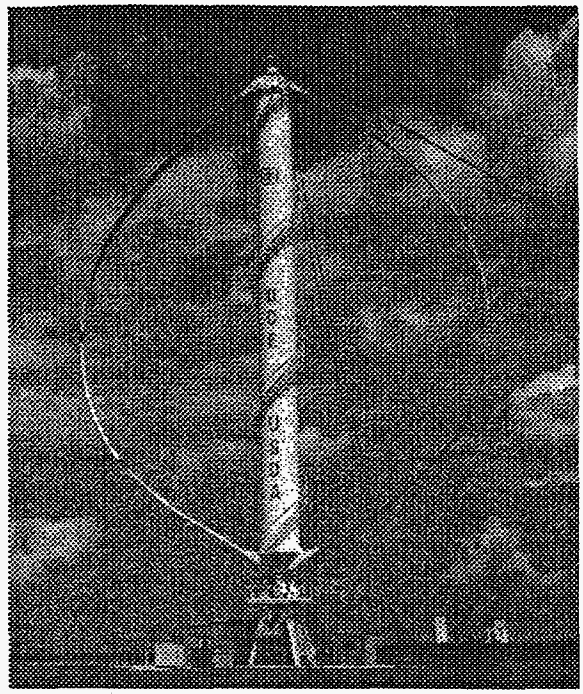


Figure 2. 34-meter Test Bed at Bushland, Texas

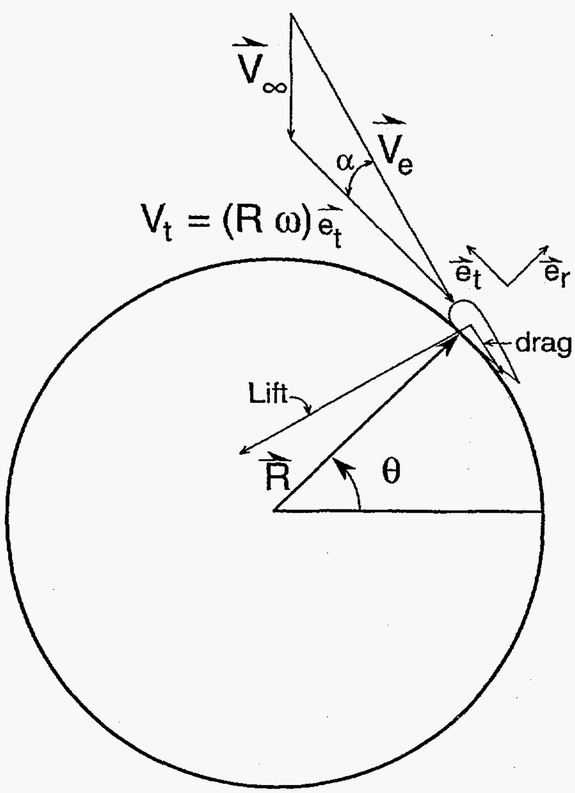


Figure 3. VAWT Blade Velocities and Forces at λ_∞=2

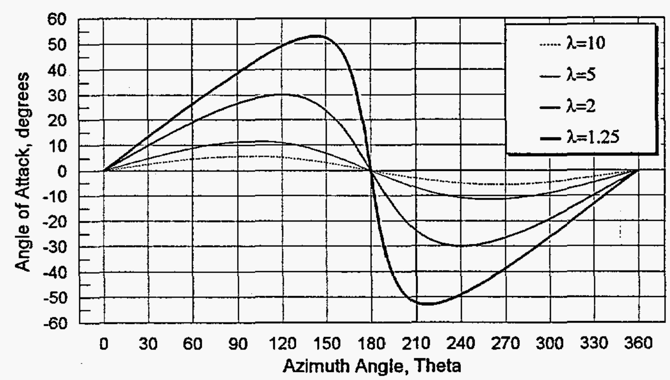


Figure 4. Cyclic Angle of Attack Variation for VAWT Blade

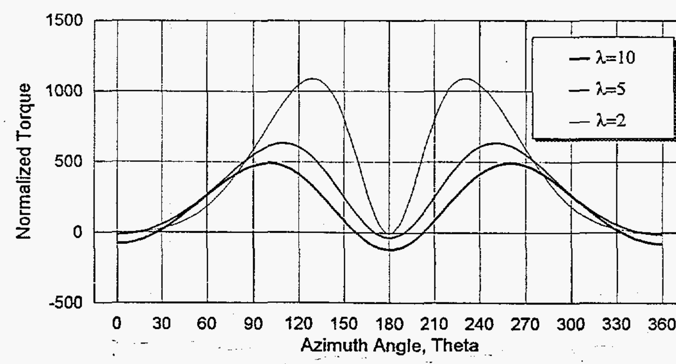


Figure 5. Cyclic Torque Variation for Single VAWT Blade (Neglecting Stall)

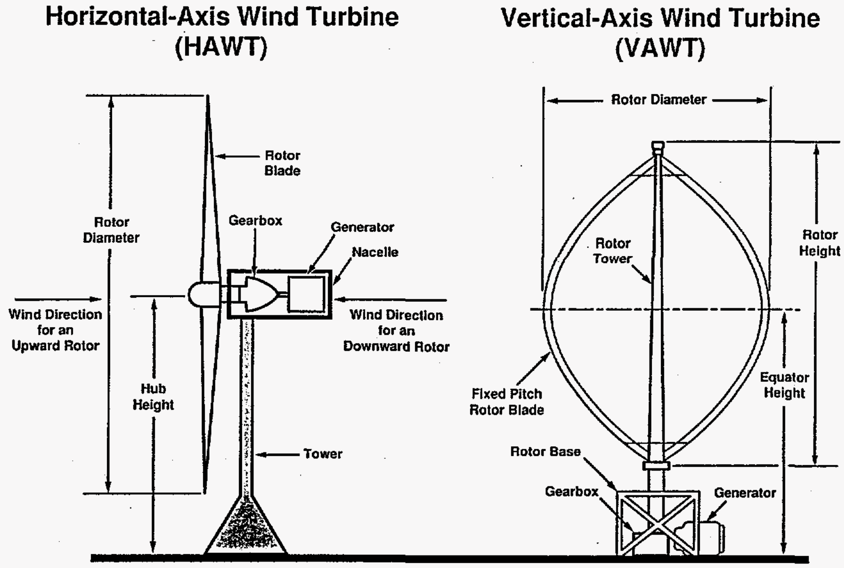


Figure 6. Comparison of HAWT and VAWT Configurations

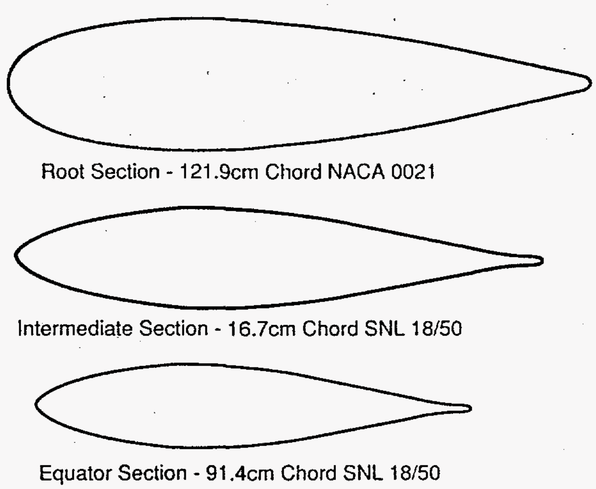


Figure 7. 34-m Test Bed Blade Airfoil Sections

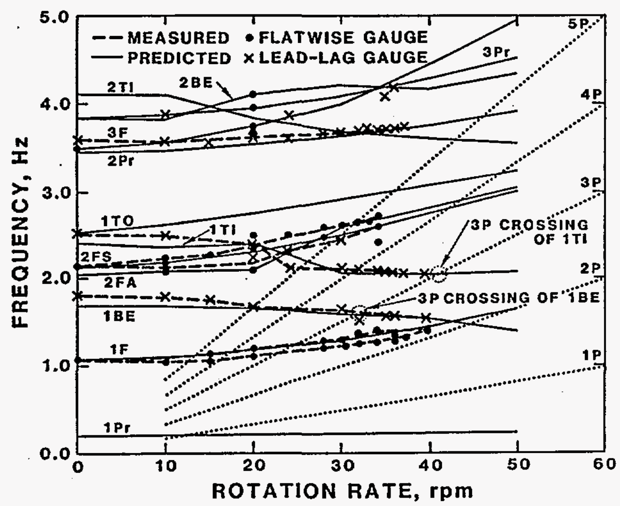
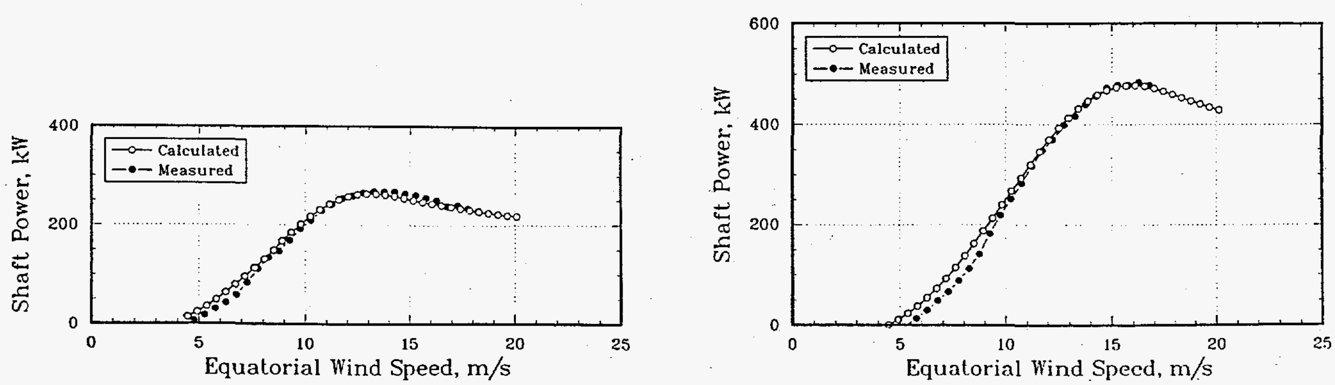


Figure 8. Test Bed Frequencies of Vibration as Functions of Rotational Speed



a. 28 rpm

b. 34 rpm

Figure 9. Test Bed Aerodynamic Performance