

Compliant blades for wind turbines

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This paper details an aeroelastic study of compliant blades used in the passive power control of horizontal-axis wind turbines. By designing the blades using fibre-reinforced composite materials, coupling between bending and torsion can be incorporated. The present work investigates the capability of a 50 kW constant speed wind turbine to automatically shed power in gusts by feathering the blades, i.e. twisting them towards the relative wind vector thus reducing the angle of attack, whilst bending away from the wind.

Although the design of compliant or flexible blades is rather more complex than rigid blades, it has the advantage of reducing the aerodynamic loads at their source, and consequently this reduces the loads which need to be carried by the power train and the tower. Wind turbine designers have experienced some difficulty developing active controllers to pitch blades fast enough to control the power generation, and so in windy gusty conditions such as in hilly New Zealand terrain, one would expect the power output of fixed speed pitch controlled wind turbines to vary rather more than desired. Compliant blades may offer a more effective means of power control, and of reducing fatigue damage.

This numerical study demonstrated that it was difficult to achieve constant power output with compliant blades for a fixed-speed wind turbine because a large amount of twist is required. When a gust arrives at a blade the relative wind vector is rotated forwards, thus increasing the angle of attack, and hence the lift coefficient. In order to reduce the power, the blade feather angle had to be larger than this gust-induced increased angle of attack. This would typically be several degrees, and meant that induced blade pitch angles need to be at least 15° to be effective.

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1. Introduction

The development of wind turbines has made a significant contribution to human achievement and technological advancement throughout history. With an ever increasing demand for limited energy resources, and global concern about pollution and environmental damage arising from fossil fuels, wind turbines may begin to assert an ever increasing role during the next century and beyond.

Recent advances in technology and performance have resulted in current wind turbine designs being increasingly efficient, cost effective, and reliable. The popular size of machines has moved from the small-medium range, 50–100 kW, to much larger 200 kW to 1 MW systems. In the period from the mid 1970s to the mid 1980s, the average power (kWh) per swept area (m²) increased approximately 40% (Spera, 1994). The installed costs have decreased on average by 83% since the mid 1970's. Performance improvements can be expected in the future, especially in the areas of blade construction and durability, control systems, materials and weight. A greater understanding of the fatigue characteristics of blade materials and the effect of wind conditions such as turbulence on the rotor and tower, will no doubt improve future designs.

New Zealand's location across the prevailing westerly winds associated with the 'Roaring Forties' provides a plentiful wind resource. The current utilisation of this

resource is insignificant, with only a handful of machines rated above 50 kW in operation throughout the country. The recent installation of seven Enercon E-40 wind turbines at the Hau Nui site near Wellington is the first commercial wind farm in the country, with a rated output of 3.5 MW. Van Lieshout (1993) produced various cost estimates relating to the set-up of wind-farms in New Zealand. The initial capital cost would be in the region of NZ\$2,000/kW, and the operation and maintenance cost between 2–5% of the capital cost per annum. The cost to the consumer could be as low as 8c/kWh if sites with average wind-speeds 10–11 m/s are used, and the capacity factor is up around the 35% mark. It was also suggested that future costs could fall to as low as 5c/kWh for exceptional sites. Further information on the cost of wind farm electricity can be found in Collecutt(1994) and Biggar (1995).

A major problem influencing the design and operation of wind turbines is fatigue. The lifetimes of most components are gradually reduced by the high number of revolutions that occur at relatively low stress magnitudes. Turbine blades are the components which exhibit the largest proportion of fatigue failure (50%), and the centrifugal and gravity loads are primarily responsible (Eggleston and Stoddard, 1987). Other contributions to fatigue damage arise from, wind shear, turbulence, tower shadow and interference from upwind turbines. The affect that each

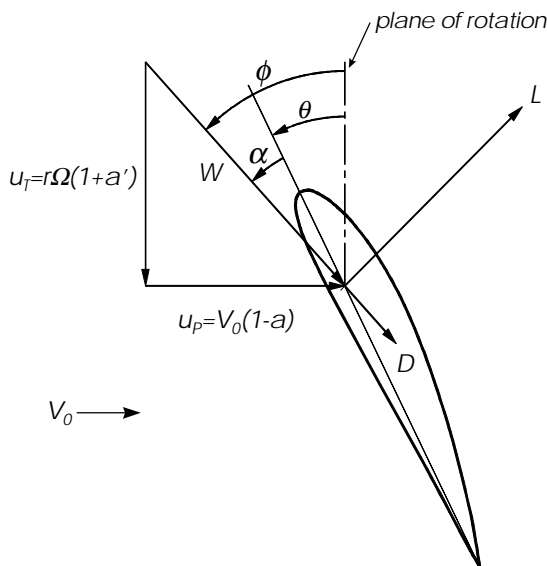


FIGURE 1. Blade element force velocity diagram.

of these factors has on the rotor is difficult to determine, and much research is being conducted to gain an improved understanding, such as the work described by Noda (1997).

2. Wind turbine design theory

The first and most fundamental aerodynamic model developed for horizontal axis wind turbines, was the actuator disk theory proposed by Rankine in 1895. This highly idealised model treats the turbine rotor as a non-rotating homogeneous disc that removes energy available in the wind, and converts it into useful mechanical energy. Using momentum theory, considering the pressure drop across the actuator, and by applying Bernoulli's equation upstream and downstream of the disc it can be shown that the maximum possible power coefficient $C_{p,max}$ is 0.593. This value is called the Betz limit, and enables the maximum amount of power that a wind turbine can theoretically produce to be determined.

This idealised flow theorem was further developed by Glauert [1935], who treated the rotor as a rotating actuator disk, and summed individual effects through a number of annulus stream-tubes. At this stage the effects of wake rotation had also been incorporated into the analysis to give a more accurate estimation of the power output. Glauert's optimum actuator disk theory prompted the conception of *Blade Element Theory*, which further increased accuracy by integrating all properties over radial increments of the blades.

A section of a blade at radius r is illustrated in Fig. 1, with the associated velocities, forces and angles shown. The relative wind vector at radius r , denoted by W , is the resultant of an axial component u_p , and a rotational component u_r . The rotational component is the sum of the velocity due to the blades motion, $r\Omega$, and the swirl velocity of the air, $r\Omega a'$. The axial velocity u_p , is reduced by a

component $V_0 a$, due to the wake effect or retardation imposed by the blades, where V_0 is the upstream undisturbed wind speed. The a' and a terms represent the rotational and axial interference factors respectively. The angle of attack is denoted by α , the pitch of the blade by ϕ , and the angle of the relative wind to the plane of rotation, by θ . The resultant lift and drag forces are represented by L and D , and directed perpendicular and parallel to the relative wind as shown.

Designing wind turbine blades using strip theory or related blade element theories requires knowledge of the characteristics and behaviour of airfoil sections. This information is presented in the form of data which is usually obtained from wind tunnel tests on 2-D sections. In the past, wind turbine designers have relied on airfoil sections and data intended for aircraft use. The *NACA 230XX* series, *NACA 44XX* series, and the *NACA 63-2XX* series airfoils are primarily for aircraft use, but have all been used extensively in the design of HAWTs. The *NACA 63-2XX* series has since proven to provide the best overall performance, and are almost insensitive to surface fouling. The increase in efficiency of modern wind turbine blades is a direct result of independent research into new sections specifically tailored for wind turbine blades. It is important to remember that much of a turbine blade operates in the stalled region where the angle of attack is large, and low Reynolds number flows are experienced. Aircraft wings typically operate at lower angles of attack, and in extremely high Reynolds number flow regimes.

3. Composite material wind turbine blades

Modern wind turbine blades are commonly constructed from some form of composite material. A composite material is formed from two or more discrete component materials, which in combined form possess different, ideally improved properties than exhibited individually. The most commonly used types of composite material in the wind turbine industry are glass fibre-reinforced plastics (GRP). GRP dominates the market because it provides the necessary properties at a low cost. The important characteristics of GRP are good mechanical properties, good corrosion resistance, high temperature tolerance, ease of manufacture, and favourable cost. More importantly, composite materials enable structures to be designed to provide significant advantages such as weight reduction, over traditional engineering materials, whilst maintaining the required levels of performance and reliability.

By laying up the individual plies at certain orientations, the laminates can be designed to provide the desired strength and stiffness characteristics required for specific applications. Furthermore, the material anisotropy observed in some laminate configurations can be exploited to induce coupling between different deformation modes. For example, bend-twist coupling results in twisting of a structure when a pure bending load is applied. Stretching-twisting coupling can occur when a tensile load is applied, and the object deforms both axially and torsionally about some reference axis. This behaviour is influenced

both by the material characteristics of the laminate and geometric properties of the structure to which it is assigned.

Ironically, in the past these cross-coupling effects have posed serious difficulties to designers, who have attempted to eliminate these undesirable couplings from their materials. However, some industries are beginning to capitalise on these responses, such as the aeronautical community, where the performance of wings may be improved by the use of materials exhibiting bend-twist, and tension-shear couplings. The use of fibre reinforced composite blades enables a number of possible passive aerodynamic control options to be investigated. The three options considered in this study rely on coupled deformation effects of the composite materials to obtain the necessary twist or *pitch* for power control.

Traditionally, the majority of composite material structures are constructed with symmetrical laminates. A symmetrical laminate is one that is mirrored about its mid-plane. An important characteristic of all symmetric laminates is that coupling between the membrane and bending modes is effectively zero. Fortunately symmetric laminates are capable of inducing bend-twist coupled deformation, whereas to utilise the tension-twist coupling effect, non-symmetric laminates must be used. Having to consider the membrane-bending stiffness coupling terms not only increases the complexity of the design process, but also increases the risk of introducing effects that are difficult for designers to detect and account for.

4. Wind turbine loads model and simulation

The development of software to calculate the loads on a turbine blade and the overall performance was necessary for the static and dynamic FEM modelling of the blades, and aided the understanding of the theory and design methodology. The analytical code and associated graphical user interface was developed using the mathematical modelling package Matlab™, using its vast library of pre-defined operations, and its flexible high level code. The software, although crude, was intended to provide the necessary data for the subsequent blade modelling in this project, and not as a complete design or analysis package.

A number of forces and moments are experienced by a typical HAWT blade during normal operation. The relative magnitudes of these loads, and the impact on the blades make some more critical than others. The loads that were identified as being the most significant for subsequent analysis and design purposes in decreasing order of importance for a small (50 kW) wind turbine were:

- Aerodynamic forces and moments in both the chordwise and flapwise directions.
- Gravity force and moment in the chordwise, flapwise and axial directions.
- Centrifugal forces and moments in the flapwise and axial directions.
- Pitching moments about the aerodynamic centre due to the lift force and the blade self weight.

The gyroscopic loads were ignored, based on the assumption that the rotor yaw rate would be sufficiently low as to cause negligible effects.

5. Requirements for passive power control by coupled bend-twist blade pitch

Although passive power control of wind turbine rotors achieved by exploiting the cross coupling characteristics of anisotropic fibre reinforced composite materials has exhibited some potential (Karaolis et al., 1991) the extent of its effectiveness to actual designs requires further investigation. This section presents the required operating conditions necessary for the successful application of a blade feathering control method. These requirements are illustrated by the analysis of a turbine rotor whose blades are twisted by various amounts and then the power output calculated for a range of wind speeds.

The specifications of the blade design used for this investigation are presented in Table 1. Rotor and generator efficiencies were incorporated in the design so that the applied loads reflected realistic rather than ideal values. The generator and rotor were each assigned an efficiency of 0.9, giving the turbine an overall efficiency of 0.81. Therefore in order to generate 50 kW of useful power the rotor must be directed to produce around 62 kW to allow for the system losses.

TABLE 1. Specifications of base blade design.

Rated power:	50 kW	Rated wind speed:	12.0 m/s
Rotor diameter:	16.0 m	Profiled Blade length:	7.0 m
Root chord:	0.8 m	Tip chord:	0.30 m
Root pitch angle:	+14.0°	Tip pitch angle:	0°
Rotor speed:	62.0 RPM	Tip-speed ratio:	4.33
NACA airfoil:	4415	Average Reynolds no.	1.5×10^6

Figure 2 displays a family of power curves for the simulation model 50 kW HAWT operating under ideal conditions between cut-in and cut-out speeds. The solid curve represents the response of fixed pitch blades (the base design). The other curves (e.g. the diamonds denoting -15 degrees of twist) have a linear twist distribution, 0 at the root to the specified value at the tip, superimposed on the base design twist distribution. The angle of attack is thus reduced as the radius increases, simulating a possible feathered blade twist distribution.

Using these data, a plot of the ideal twist distributions required for above-rated wind speeds and constant power output of this rotor, can be generated in terms of the necessary tip pitch angle, as shown in Fig. 3. For example the “passive feathering” line in Fig. 3 was generated by reading off the wind speeds in Fig. 2 corresponding to the fixed power of 50 kW for each of the twist angles. It is obvious from Fig. 3 that large magnitudes of pitch are required for successful feathering at the wind speeds above rated.

For comparison the corresponding curve for pitch towards stall is shown and indicates that significantly lower magnitudes are required for above-rated wind speeds. The pitch angle gradient for above-rated wind speeds is simi-

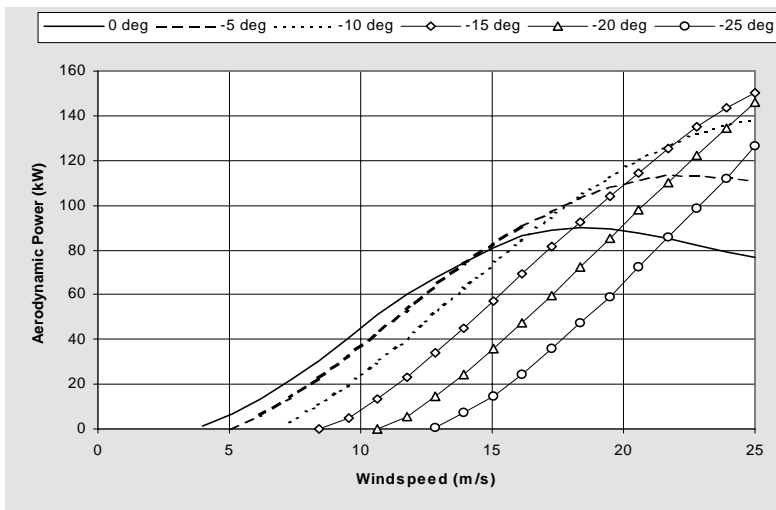


FIGURE 2. Ideal bend-twist pitch control simulation.

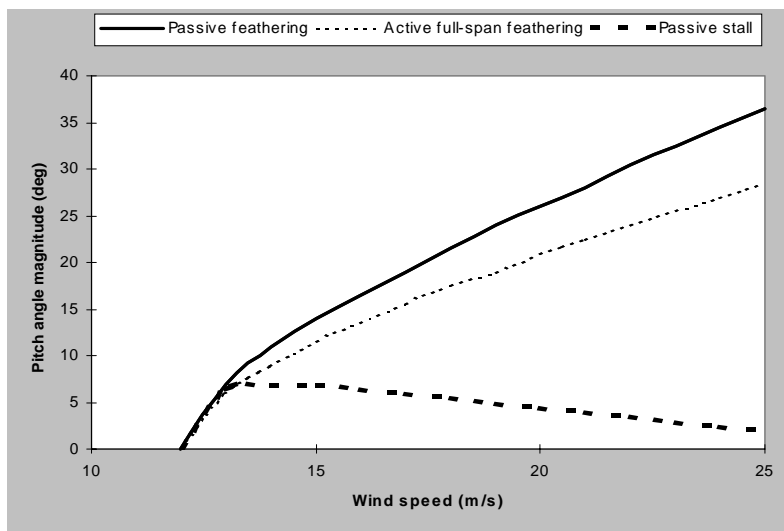


FIGURE 3. Simulated pitch requirements for constant power output.

lar to feathering initially, but then changes sign resulting in smaller angles as the wind speed increases. At the cut-out speed of 25 m/s, the necessary pitch angle is only 2 degrees for the stall case, about 18 times less than the feathering pitch magnitude. The large pitch magnitudes required for feathering are characteristic of fixed speed HAWTS such as the Vestas V27-225 kW machine which is designed to vary the blade pitch angle up to 30 degrees at the tip in order to maintain the rated power level (Petersen, 1990).

The “active full-span feathering” line in Fig. 3 shows the required twist angles when the whole blade is twisted through the same angle. Thus the required angles are less than for “passive feathering” line where the imposed twist distribution is linear and the tip is twisted but the root is not twisted at all.

6. Aeroelastic modelling of blades

Aeroelasticity refers to the response characteristics of a flexible structure when coupled with aerodynamic loading, and is primarily associated with the design and per-

formance optimisation of aircraft. The term *aeroelastic tailoring* is commonly used to describe the design and optimisation process of structures that are constructed of laminated composite materials. These structures are used to achieve aerodynamic performance benefits by controlled structural deformation. The aeroelastic tailoring of wind turbine blades using the cross-coupling characteristics inherent in some laminated composites relies on the structure being both the control system sensor and actuator. The response behaviour is defined by the blade’s geometric structure and material properties. A finite element method (FEM) approach was used to model the aeroelastic behaviour of a wind turbine blade, and this was performed using the commercial packages *Lusas*, *Patran* and *Nastran*.

The main purpose of aeroelastic analysis is to obtain information describing the control, stability and strength characteristics of a lifting body or structure. Modelling the aeroelastic behaviour of a wind turbine blade required a method of coupling the aerodynamic load evaluation system with the structural response system. Such an analysis system is diagrammatically represented in Fig. 4.

It is generally accepted that higher mean annual wind speeds are likely to be experienced at potential sites in New Zealand, than at most American or European sites. This claim is supported by a study of the comparative operating conditions for HAWT generators in New

Zealand and wind farms in Altamont Pass, California, where a total capacity of almost 1700 MW has been installed since 1981. The annual mean wind speed was found to be almost 4 m/s higher for the former (Van Lieshout, 1991) and as a result, most commercially available wind turbines are not optimally suited for the more adverse and seasonal New Zealand conditions. Research has shown that the higher wind speeds are likely to inflict greater magnitudes of fatigue damage per cycle, and therefore turbine blades primarily designed for European and American conditions should exhibit shorter lifetimes (Noda, 1997).

The following points were considered during the design process for flexible blades:

- The high strength, low modulus properties of GRP results in blades with higher thickness to chord ratios than for other materials.
- Thin-walled hollow sections are typically used to provide minimal weight blades for a given stiffness, but foam cores or internal struts are usually necessary to

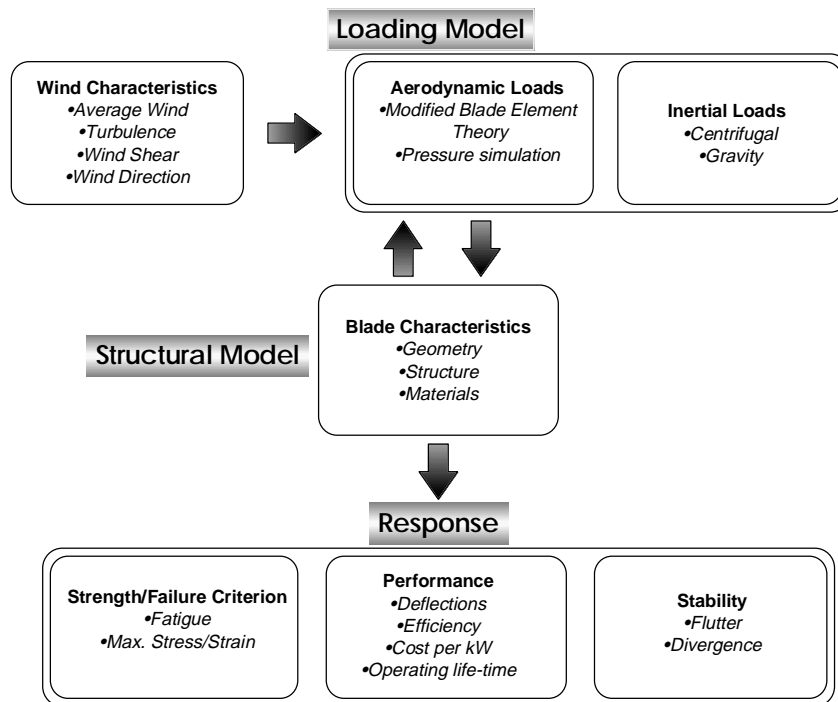


FIGURE 4. Aeroelastic model analysis system.

prevent local buckling, especially for low stiffness blades.

- Skin fibre-reinforced composite laminates for conventional *stiff* blades incorporate a combination of unidirectional plies to support radial loads and provide sufficient bending stiffness, and 45° plies to restrict shear and torsion.
- An iterative process is typically used to arrive at the optimum ply stacking sequences that satisfy the desired stiffness and strength requirements.
- A current practice for composite wind turbine blade design is to limit the axial strains in the skins to 0.002 or 0.2%. This figure corresponds to the conservative value of the linear limit observed for typical glass reinforced polyester laminates (Mayer, 1996). The linear limit is defined as the point at which the stress-strain values begin to fall significantly below the linear tensile modulus line.

The same rotor-blade aerodynamic design was used for this analysis as for the study in Section 5 (see Table 1). The rotor-blade design was based on a rated power of 50 kW for the HAWT. It was assumed that the site mean wind speed was 8 m/s at a height of 10m, and the rated wind speed was taken as 1.5 times (Collecutt, 1994, Johnson 1985) the mean wind speed, i.e. 12 m/s. The fixed rotational speed was specified as 6.5 rad/s or 62.1 RPM.

The line with squares in Fig. 5 displays the power output curve for the composite rotor blades. They have been designed with an optimum composite lay-up to achieve maximum

twist in the feather direction (to reduce the angle of attack of the blades). The tip twist and average deflection for this configuration were 4.8° and 0.42 m respectively. Results for stiff (zero twist) blades are shown by the full line. The effect of having the blades twist towards stall (to increase the angle of attack) was also investigated by simply reversing the sign of the twist obtained for the feathered blades, and recalculating the power. Previous analyses had shown that this approach for the stall calculation would not introduce significant errors.

The results presented in Fig. 5 show that the sensitivity of the turbine performance to relatively small magnitudes of induced twist is significant. The effect of feathering is to amplify the blade loads, and hence the power output, to almost double the rated power at above rated speeds. Thus reducing the blade angle of attack by a smaller amount than that required would result in undesirable power surges

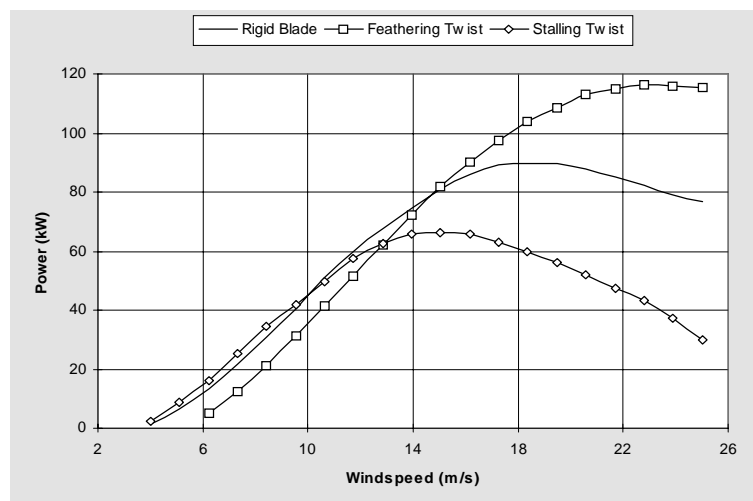


Figure 5. Effect of blade twist on turbine performance.

during gusts or high wind speeds. This behaviour is potentially unstable and analogous to torsional divergence of aircraft wings where the more the wing twists the greater the twisting moment becomes, twisting it even further. The stall case behaves more ideally so that the power reaches a limit close to the rated value, and continues to gradually decrease as the wind speed increases. However, stall control using rigid bladed rotors is more effective because of the recovery and maintenance of the rated power level after stalling.

7. Conclusions

The numerical analysis of the bend-twist material cross coupling option indicated that for blade feathering, very large angles of pitch are required. The required distributions increase non-linearly from the root to tip, with maximum values at the tip reaching angles between 30°–40° for the simulation model.

A significantly lesser pitch demand is displayed by the pitching to stall option, and the angles are more likely to be achieved by the bend-twist configured blades. However unlike the feathering option the required pitch angles decrease with increasing wind speed as the blade becomes more stalled

To obtain the levels of bending deflection for power reduction requires blades that are as lightweight as possible to minimise the restoring effect of the centrifugal loads. The levels of axial strain experienced will be far greater than the typical guidelines used in the design of GRP blades, and are likely to exceed the elastic limit for GRP

The structural non-linear finite element analysis of rotating flexible blades was accomplished successfully using the commercial F.E packages LUSAS and PATRAN/NASTRAN. The convenience of using the commercial packages is restricted by the limitations and inflexible nature associated with the software. Steady state dynamic analysis was performed using the 50 kW simulation model, and the results obtained were very satisfactory.

The maximum twist rate obtained during the study was for a hollow blade model. This rate was 1.25°/m length based on a 0.136 m per metre flapwise deflection rate. The levels of induced twist were insufficient for power control by feathering, and the required levels of pitch are not attained during high winds or gusts. However pitching to stall by passive means is likely to maintain the power below the rated level at high wind speeds but decreases the power to such low levels that the capacity factor for the machine becomes too low to make it economical.

8. Acknowledgements

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