Three Pitch Control Systems for Vertical Axis Wind Turbines Compared

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ABSTRACT

The desirable performance attributes of a vertical axis wind turbine (VAWT) include high starting torque, high peak efficiency, broad operating range and a reasonable insensitivity to the parameters that define its operation. The theoretical performances of three variable pitch mechanisms for VAWT are compared. Cycloturbines use cam devices or gears to impose a sinusoidal pitch regime. In the mass-stabilised system, pitch is determined by the interplay of two opposing moments on the blades. These two mechanisms are compared with "Aero-pitch", a hypothetical pitch control system in which stabilising moments are related to the blade relative velocity.

NOMENCLATURE

Symbol	Unit	Description
A	m^2	Airfoil plan area
c	m	Blade chord length
C_d		Airfoil drag coefficient
C_l		Airfoil lift coefficient
C_m		Airfoil quarter chord pitching moment coefficient
C_p		Turbine performance coefficient
C_{ploss}		Parasitic loss coefficient
C_q		Turbine torque coefficient
F_r^*		Non-dimensional blade radial force
F_t^*		Non-dimensional blade tangential thrust
J	$kg\ m^2$	Blade polar moment of inertia
K_{in}	kg	Aero-pitch parameter opposing pitching of trailing edge inwards
K_{out}	kg	Aero-pitch parameter opposing pitching of trailing edge outwards
N		Number of blades
M_a	N m	Pitching moment on blade
M_{in}	N m	Stabiliser moment opposing pitching of the trailing edge inwards
M_{out}	N m	Stabiliser moment opposing pitching of the trailing edge outwards
M_p	N m	Nett moment causing pitching of blade
m_s	kg	Stabiliser mass
R	m	Turbine radius
U	$m\ s^{-1}$	Ambient wind velocity
Y	$m\ s^{-1}$	Local wind velocity at the blade
W	$m\ s^{-1}$	Blade relative velocity
X_{in}	% blade chord	Moment arm opposing pitching of trailing edge inwards
X_{out}	% blade chord	Moment arm opposing pitching of trailing edge outwards
X_p	% blade chord	Direct distance from pivot point to blade quarter chord
α	rad	Blade angle of attack for zero pitch

β	rad	Blade angle of attack
γ	rad	Blade pitch angle
γ_{off}	rad	Blade offset pitch angle
γ_{amp}	rad	Blade pitch angle amplitude
γ_{in}	rad	Maximum permitted blade pitch amplitude of trailing edge inwards
γ_{out}	rad	Maximum permitted blade pitch amplitude of trailing edge outwards
γ	rad s^{-1}	Blade pitch angle velocity
γ	rad s^{-2}	Blade pitch angle acceleration
λ		Tipspeed ratio
ρ	kg m^{-3}	Air density
σ		Turbine solidity = Nc/R
θ	rad	Blade azimuth angle
Ω	rad s^{-1}	Turbine angular velocity

INTRODUCTION

Previous Attempts at Improving Self-starting

Some fixed pitch configurations of the straight blade VAWT will self-start under zero-load conditions[1,2], however none produce enough starting torque to drive positive displacement pumps or air compressors directly, i.e. without a clutch.

Early attempts at improving the self-starting of VAWT concentrated on optimising configurations of static geometric parameters. Turbine solidity, blade camber and thickness, blade offset pitch angle, and blade lean forward (or yaw) angle have been examined with the expectation that combinations of all or some of these parameters will substantially increase desirable characteristics. More recently, blades with trailing edge extensions have been studied. From these investigations a number of general qualitative conclusions can be drawn:

- High solidities tend to provide some starting torque but with lower peak efficiency and narrower operating range[2,3].

- Thicker blade profiles seem to contribute to slight increases in starting torque. Peak efficiencies are attained at higher tipspeed ratios, and there seems to be little or no effect on operating range[2,3,4].

- A judicious choice of blade camber can increase starting torque, but reductions in peak efficiency and narrower operating ranges have been observed[1,2,5,6]. Small trailing edge extensions seem to further improve the starting torque with little further degradation of peak performance or operating range[6].

- Offset pitch angle can increase starting torque, however peak efficiencies seem to occur at lower tipspeed ratios[7].

- Blade yaw angle can affect the blade stall angle and should improve starting torque[1].

Despite some of the individual performance gains, there seems to be nothing in the literature that suggests that combinations of these static geometric parameters would allow consistent starting under load, high peak efficiency, and a wide operating range.

VARIABLE PITCH

The performance of a straight blade VAWT can theoretically be greatly improved by causing – or allowing – the blades to pitch so as to avoid stall and maintain favourable angles of attack. The present paper extends the investigations of (2), (8) and (9) and compares the performance of three pitch control systems.

Sinusoidal Forced Pitch Variation

The Pinson cycloturbine, which incorporates a cam or gears to actuate blades, has been tested and found to increase starting torque and peak performance[10-16].

Vandenberghe and Dick[12,13] found that there were some performance gains in using (at least) a first order harmonic system. Further harmonics were dismissed as not justifying the complexity of the necessary mechanism. In the present paper a first order device is considered. The blade pitch angle for any azimuth angle is defined to be

$$\gamma=\gamma_{\text{off}}+\gamma_{\text{amp}}\sin\theta \tag{1}$$

Thus the system can be considered as an initial blade offset angle plus a sinusoidal component proportional to the pitch amplitude.

Self-acting Stabilised Pitch Control

A fundamentally different approach to pitch control is the use of "self-acting" devices in which, rather than forcing the blades to pitch according to some predetermined pattern, they are allowed to pitch under the action of aerodynamic forces so as to reduce the angle of attack and hence the tendency for blades to stall at low tipspeed ratios[2].

Kirke and Lazauskas[2,8,9] showed that one particular self-acting system could be modelled by considering the interplay of two opposing moments on the VAWT blade. With minor modifications the performance of other stabilised, self-acting pitching mechanisms can be estimated.

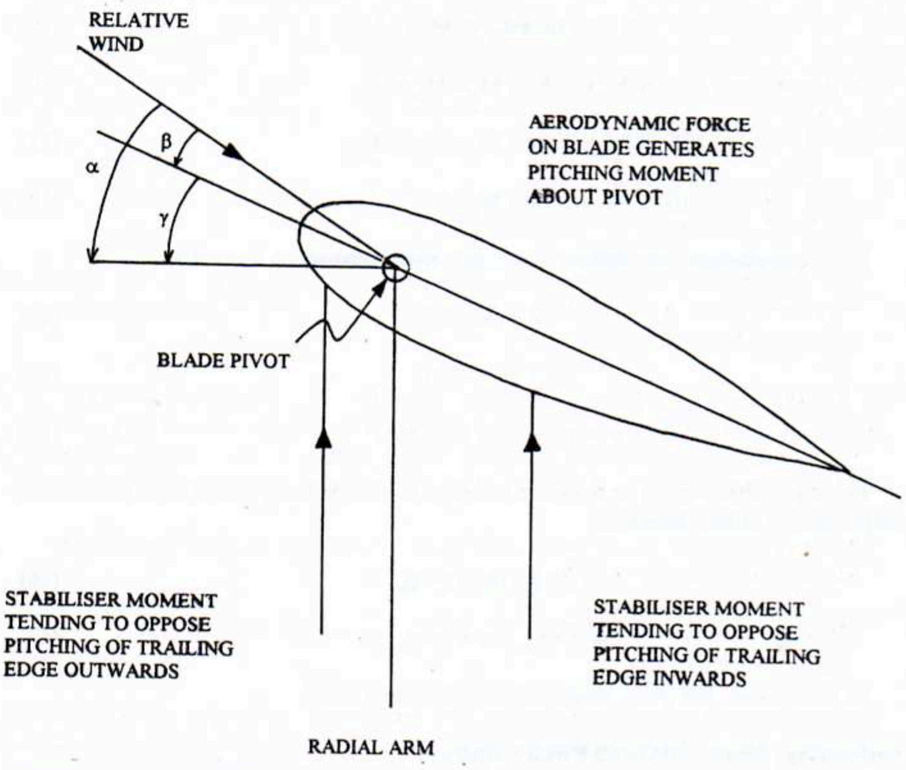

Figure 1. Schematic representation of a stabilised self-acting pitch control system.

Figure 1 shows a schematic representation of an idealised, stabilised, self-acting pitch control system. Pitching moments generated by aerodynamic forces on the blades tend to reduce the angle of attack. Opposing this tendency to pitch in either direction are stabilising moments which tend to maintain each blade at zero pitch.

As the turbine rotates, lift, drag and pitching moment all act to change the angle of attack, β. The pitching moment on the blade, by definition tending to decrease $|\beta|$, is given by

$$M_a = 1/2\rho AW^2[X_p(C_{l\beta}\cos\beta + C_{d\beta}\sin\beta) - cC_{m\beta}] \qquad (2)$$

where X_p is the direct distance from the pivot point to the aerodynamic centre. (As an approximation, the aerodynamic centre is taken as the blade quarter chord.)

Angles of attack, blade relative velocity and non-dimensional force coefficients are calculated using the following formulae:

$$\beta = \alpha - \gamma \qquad (3)$$

$$\alpha = \tan^{-1}[\sin\theta / (R\Omega/V + \cos\theta)] \qquad (4)$$

$$W = V[(R\Omega/V + \cos\theta)^2 + \sin^2\theta]^{1/2} \qquad (5)$$

$$F_t{}^* = (C_{L\beta}\sin\alpha - C_{D\beta}\cos\alpha)(W/U)^2 \qquad (6)$$

$$F_r{}^* = = (C_{L\beta}\cos\alpha - C_{D\beta}\sin\alpha)(W/U)^2 \qquad (7)$$

The tendency to pitch so as to reduce $|\beta|$ is opposed by moments M_{in} and M_{out} which depend on – or define – the type of pitching mechanism. The calculation of the nett moment tending to pivot the blade, M_p, is best appreciated through the relations:

$$\text{if } \gamma<0 \text{ then } M_p = M_a+M_{in} \qquad (8)$$

$$\text{if } \gamma>0 \text{ then } M_p = M_a+M_{out} \qquad (9)$$

$$\text{if } \gamma=0 \text{ then (i) if } M_a<0 \text{ then } M_p=M_a+M_{in} \qquad (10)$$

$$\text{(ii) if } M_a>0 \text{ then } M_p=M_a+M_{out} \qquad (11)$$

$$\text{(iii) if } M_a=0 \text{ then } M_p=0 \qquad (12)$$

Pitch parameters now follow from the usual Newtonian formulae:

$$\ddot{\gamma} = M_p/J \qquad (13)$$

$$\dot{\gamma} = \dot{\gamma}_0 + \ddot{\gamma}\Delta t \qquad (14)$$

$$\gamma = \gamma_0 + \dot{\gamma}\Delta t + 1/2\ddot{\gamma}\Delta t^2 \qquad (15)$$

Finally, a check must be made on whether the blade has pitched to its maximum amplitude in either direction:

$$\text{if } \gamma>\gamma_{in} \text{ then } \gamma=\gamma_{in} \qquad (16)$$

$$\text{if } \gamma>\gamma_{out} \text{ then } \gamma=\gamma_{out} \qquad (17)$$

In both cases, the pitch angle velocity drops to zero[2].

Self-acting, Mass-stabilised Pitch Control

The preceding mathematical formulation has been used[2,8] to investigate the performance of a self-acting, mass-stabilised pitching system where the stabiliser moments tending to oppose pitching are proportional to the square of the turbine speed of rotation.

$$M_{in} = M_s X_{in}\Omega^2 R \qquad (18)$$

$$M_{out} = M_s X_{out}\Omega^2 R \qquad (19)$$

"Aero-pitch"

The author is currently examining self-acting pitch control systems in which stabiliser moments are proportional to the square of the blade relative wind velocity, i.e.

$$M_{in} = K_{in}W^2 \tag{20}$$

$$M_{out} = K_{out}W^2 \tag{21}$$

where K_{in} and K_{out} are constants (with units of mass).

These devices can be considered as aerodynamic pitch control devices in the same sense that the mass-stabilised system can be considered as a mechanical system. For this reason, the term "aero-pitch" seems appropriate.

MATHEMATICAL MODELLING

Double Disk Multiple Streamtube Model

To predict turbine performance the extended double disk multiple streamtube model described in (8) is used. This includes flow curvature effects and streamtube expansion, and incorporates a modified Boeing-Vertol dynamic stall model. Reynolds number and stall effects are included through interpolation of two-dimensional static aerodynamic coefficient tables.

Assumptions and VAWT Dimensions

Results are based on a three blade VAWT with blade chord length $c=0.400$ m and radius $R=3.0$ m. This yields a turbine solidity $\sigma=0.4$.

For both self-acting pitch control systems, the blade polar moment of inertia $J=0.442$ kg m^2. In addition for the mass-stabilised system, the stabiliser mass $m_s=1.25$ kg. Except where indicated an ambient wind velocity of 10.0 ms^{-1} is used.

For comparison, results are based on blades of infinite aspect ratio. Mast wake, wind shear and tip losses are ignored. Also ignored are mechanical losses unique to each system, e.g. pivot point friction, and possible parasitic losses due to the control mechanisms. In real VAWTs these losses might well reduce the output advantage of one system over another.

Airfoil Data

All lift, drag and pitching moment coefficients were taken from (17) and corrections were made for obvious inconsistencies. Although this reference contains data for Reynolds numbers as low as 10,000 a minimum Reynolds number of 80,000 was used, as lift coefficient data for lower Reynolds numbers seemed unusual and atypical.

RESULTS

Sinusoidal Pitch Variation

Figures 2(a) and 2(b) show the effect on the power coefficient of varying the blade offset angle, γ_{off}, and the pitch amplitude angle, γ_{amp}, for tipspeed ratios of 2.0 and 3.0.

There seems to be a local maximum for $\gamma_{off}=6.0$ degrees, $\gamma_{amp}=3.0$ degrees. Consideration of equation 1 indicates that the resulting pitch angle, γ, is positive for all azimuth angles. This is unusual and unexpected as it suggests that the pitch angle has the wrong sign on the downwind side of the turbine. Vandenberghe and Dick[13] reported a similar anomaly in trying to derive an optimum pitch control law for the second order sinusoidal pitch control system:

> *At the downwind side, the second order harmonic pitch angle has the wrong sign.*

At a tipspeed ratio of 2.0, blades are stalled for much of the time. Relatively large offset and/or amplitude angles improve overall C_p by reducing the time spent in the post-stall region. At a tipspeed ratio of 3.0, blades are stalled for less time than at lower tipspeed ratios and thus smaller offset and amplitude angles can be used to avert stall and improve C_p.

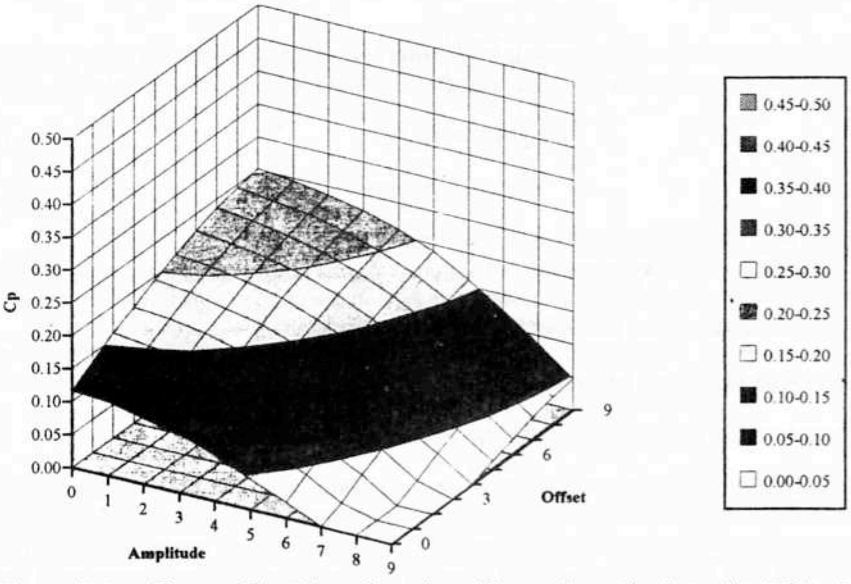

Figure 2(a). Pinson: The effect of varying offset and amplitude angles; TSR=2.0.

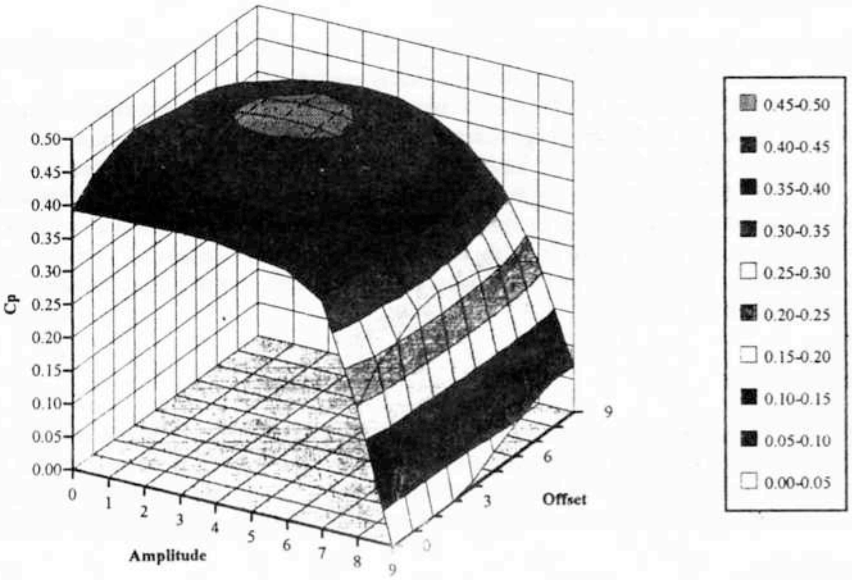

Figure 2(b). Pinson: The effect of varying offset and amplitude angles; TSR=3.0.

Mass-stabilised Pitch Control

Figures 3(a) and 3(b) show the effect on the power coefficient of varying the maximum pitch amplitude of the trailing edge inwards, γ_{in}, and the stabiliser arm opposing pitching of the trailing edge inwards, X_{in}. In both cases, the maximum pitch amplitude of the trailing edge outwards, γ_{out}, is held constant at zero, i.e. there is no pitching of the trailing edge outwards. Similar graphs (not included here) were produced for the case where the blade trailing edge is allowed to pitch outwards but not inwards. This corresponds (roughly) to allowing pitching on the downwind side but not on the upwind side. The figures are similar to those presented here but the performance gains are less. The case where blades are allowed to pitch in either direction is considered below in the "optimised performance" section.

At a tipspeed ratio of 2.0 a relatively large amplitude and a long stabiliser moment arm seem to give the best C_p. Allowing the blade to pitch through a large amplitude tends to reduce the time spent by the blade in the post-stall region as long as the stabiliser arm is correctly specified. If the stabiliser arm is too long the blade does not

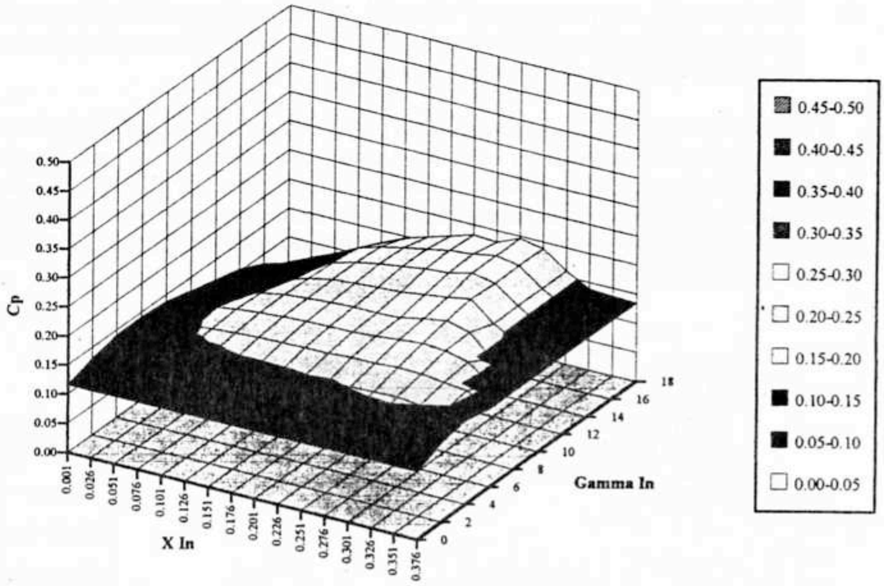

Figure 3(a). Mass-stabilised: The effect of varying X ILn and Gamma In; TSR=2.0.

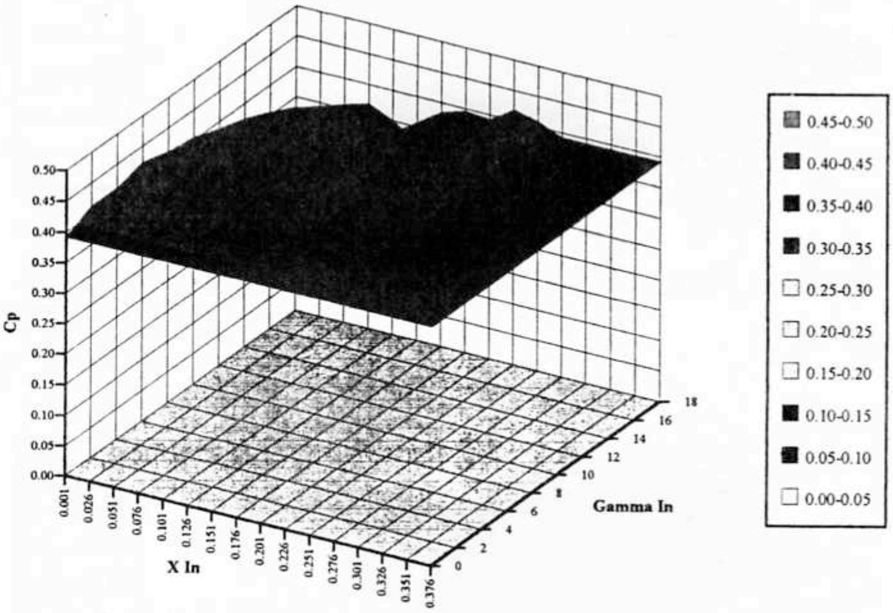

Figure 3(b). Mass-stabilised: The effect of varying X ILn and Gamma In; TSR=3.0.

pitch enough - if too small, the blade tends to overpitch. In both cases performance is reduced.

At a tipspeed ratio of 3.0 there are three notable features:

1. For a stabiliser arm of 0.226 chord, performance is nearly independent of maximum pitch amplitude. However, a small error in specifying the stabiliser arms leads to performance reductions: in other words, the configuration is relatively sensitive to one of the parameters governing its operation.

2. For a maximum pitch amplitude of approximately 3.0 degrees, performance is nearly independent of the length of the stabiliser arm for $0<X_{in}<0.226$. When X_{in} is greater than 0.226, the stabiliser moment is too large to allow the blade to pitch.

3. Maximum C_p seems to occur when $X_{in}=0.076$ and $\gamma_{in}=10.0$ degrees and obviously this configuration is less sensitive to the two parameters than the configurations which lead to the two ridges.

These figures clearly illustrate the difficulty in optimising self-acting pitch control systems. Starting values must be carefully chosen otherwise "blind" optimisation routines will return unstable solutions. An objective function is difficult to define since it largely depends on load characteristics. For these reasons it may be preferable to optimise the integrals of torque and power coefficients with respect to some limited range of tipspeed ratios[8].

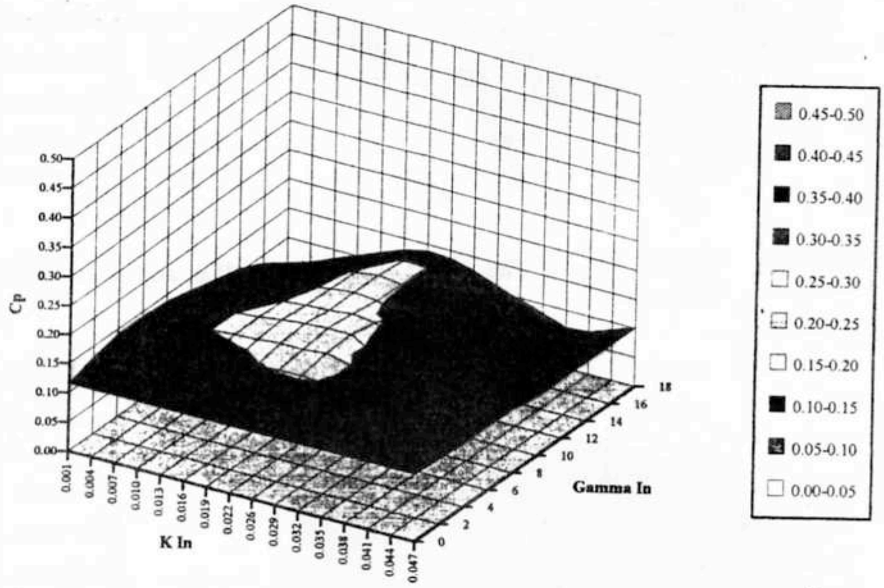

Figure 4(a). Aero-pitch: The effect of varying K In and Gamma In; TSR=2.0.

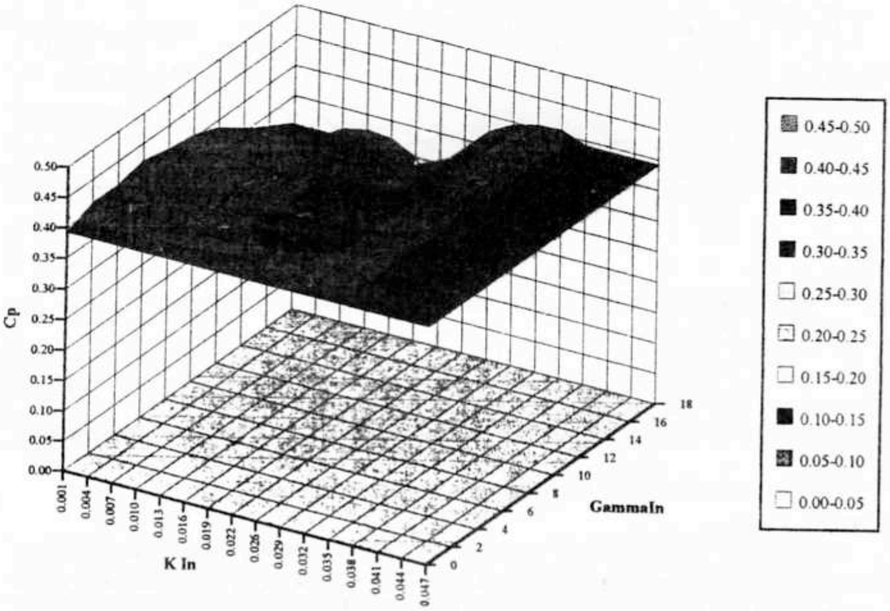

Figure 4(b). Aero-pitch: The effect of varying K In and Gamma In; TSR=3.0.

Aero-pitch

Figures 4(a) and 4(b) show the effect on the power coefficient of varying the maximum pitch amplitude of the trailing edge inwards, γ_{in}, and the aero-pitch stabiliser

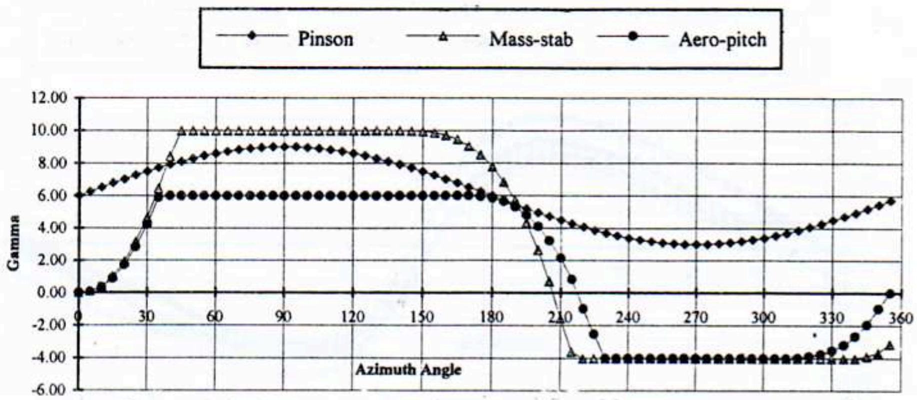

Figure 5(a). Pitch angles for various pitch systems; TSR=2.0.

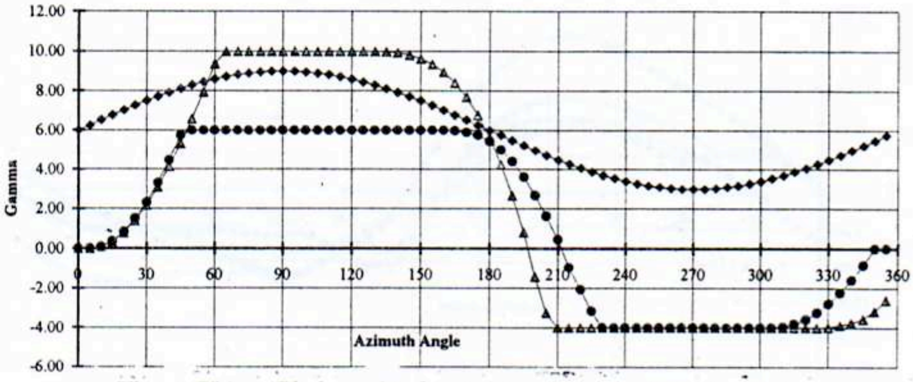

Figure 5(b). Pitch angles for various pitch systems; TSR=3.0.

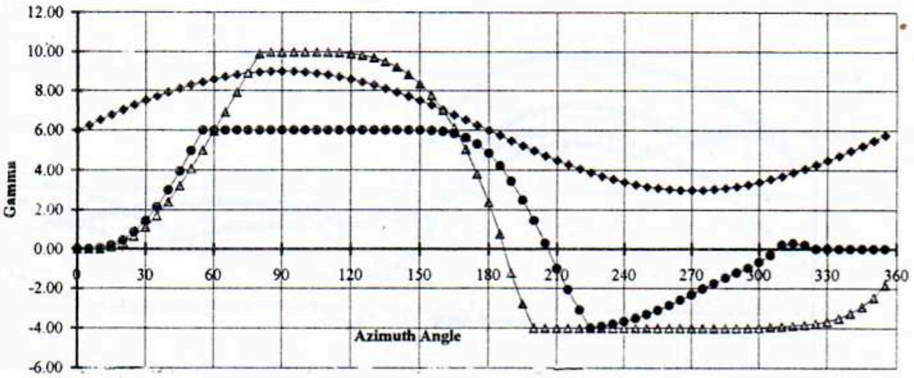

Figure 5(c). Pitch angles for various pitch systems; TSR=4.0.

parameter opposing pitching of the trailing edge inwards, K_{in}. In both figures, the maximum pitch amplitude of the trailing edge outwards, γ_{out}, is held constant at zero, i.e. there is no pitching of the trailing edge outwards.

The figures for the aero-pitch control system are similar to the mass-stabilised system and similar comments can be made regarding the general features.

Optimised Performance

As a first attempt to optimise the performance of each system, parameters apparently producing the maximum C_p at a tipspeed ratio of 3.0 were selected. The values used for each mechanism are summarised as follows:

Pitch System	Parameters			
Pinson	$\gamma_{off}=6.0$,	$\gamma_{amp}=3.0$		
Mass-stabilised	$\gamma_{in}=10.0$,	$\gamma_{out}=-4.0$,	$X_{in}=0.076$,	$X_{out}=-0.020$
Aero-pitch	$\gamma_{in}6.0$,	$\gamma_{out}=-4.0$,	$K_{in}=0.007$,	$K_{out}=-0.013$

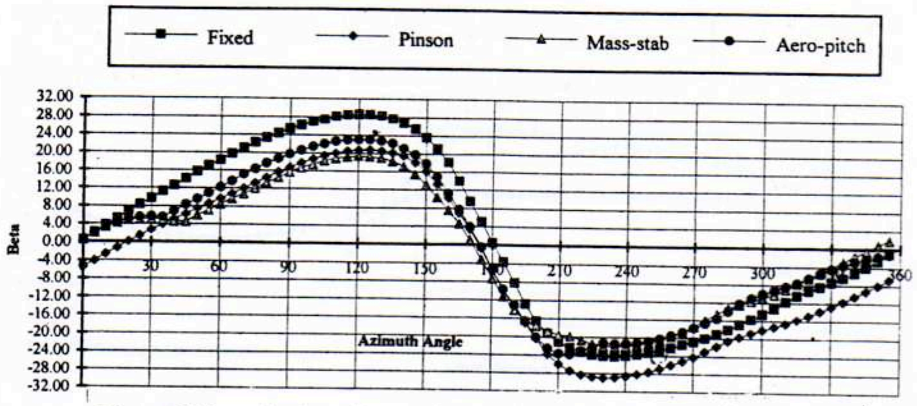

Figure 6(a). Angles of attack for various pitch systems; TSR=2.0.

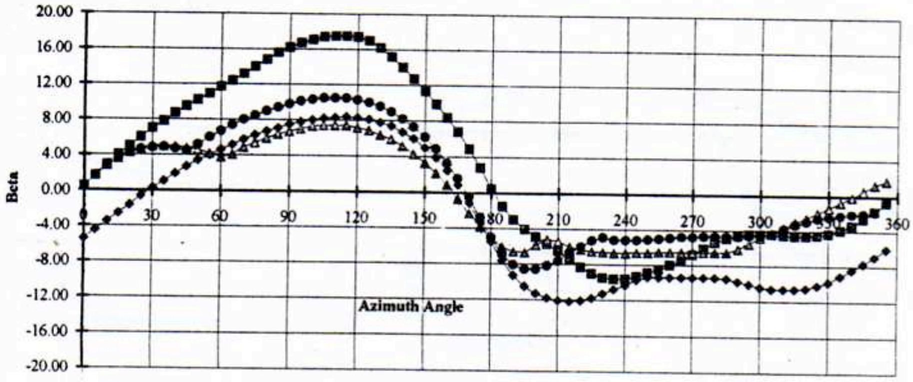

Figure 6(b). Angles of attack for various pitch systems; TSR=3.0.

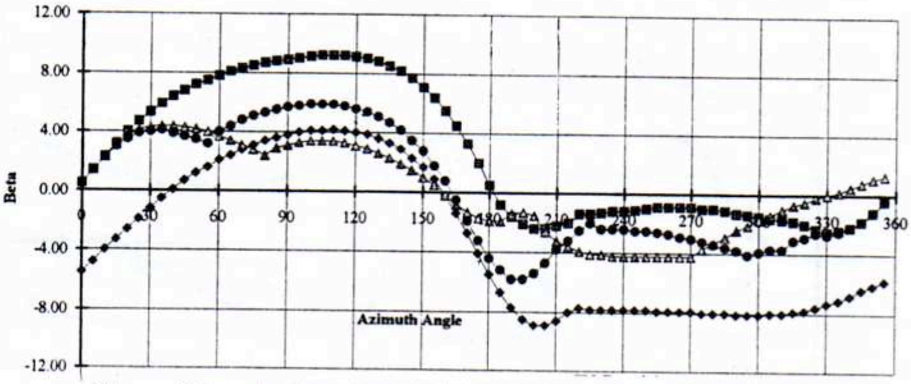

Figure 6(c). Angles of attack for various pitch systems; TSR=4.0.

Figures 5(a)-(c) compare blade pitch angles for the various "optimised" pitching systems at tipspeed ratios of 2.0, 3.0 and 4.0. The sinusoidal system has the same pitch angle regime for all tipspeed ratios.

The plots for the self-acting systems are very similar. Pitch angle increases in a parabolic fashion to the respective maximum allowable amplitudes. When the blade reaches the relevant amplitude maximum the blade pitch angle velocity instantly drops to zero. Aerodynamic forces keep the blade in this position for most of the upwind pass. Eventually, the aerodynamic pitching moment on the blade, M_a, decreases sharply and inertial forces predominate – the blade then begins to pitch outwards until it reaches the (trailing edge outwards) maximum permitted amplitude. When inertial forces again predominate, the blade begins to pitch inwards again.

The azimuth angle at which a blade reaches its amplitude limit, and the duration for which it remains at that pitch angle, varies with the tipspeed ratio. In general, the higher the tipspeed ratio the greater the azimuth angle at which a blade reaches the amplitude limit, and the shorter the duration it remains at this pitch angle. This is as expected – at high tipspeed ratios inertial forces are greater than at low tipspeed ratios.

Figures 6(a)-(c) compare angles of attack for the "optimised" systems at tipspeed ratios of 2.0, 3.0 and 4.0. At a tipspeed ratio of 2.0 blades are stalled for some of the time.

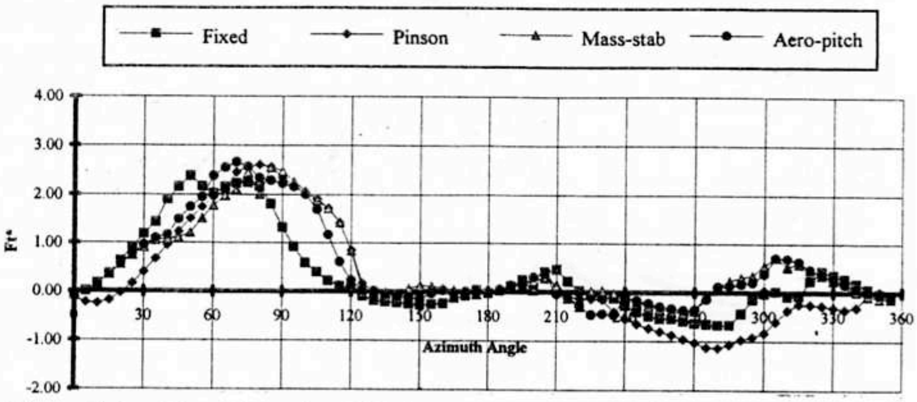

Figure 7(a). Non-dimensional blade tangential thrust for various pitch systems; TSR=2.0.

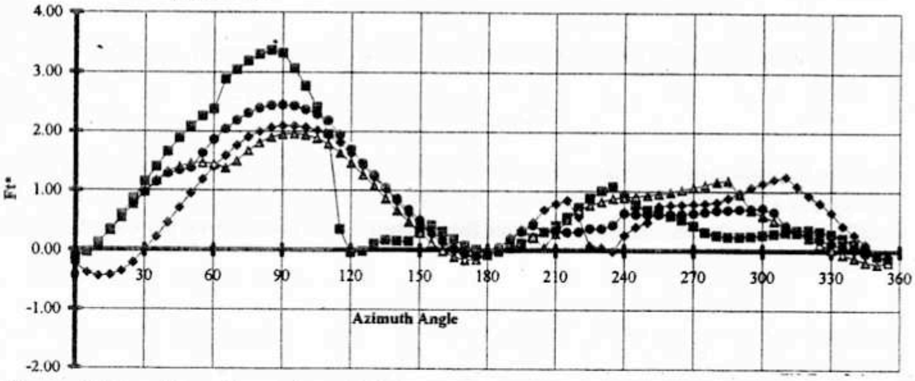

Figure 7(b). Non-dimensional blade tangential thrust for various pitch systems; TSR=3.0.

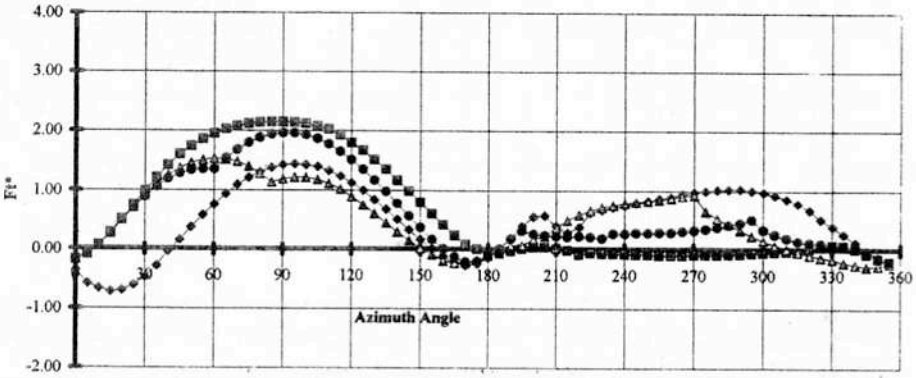

Figure 7(c). Non-dimensional blade tangential thrust for various pitch systems; TSR=4.0.

At tipspeed ratios of 3.0 and 4.0 the self-acting systems keep blades below the stall angle for all azimuth angles. For the sinusoidal system blades are stalled for some azimuth angles. However, as discussed before, there are anomalies with the parameters chosen.

Figures 7(a)-(c) compare the non-dimensional tangential force for the "optimised" systems at tipspeed ratios 2.0, 3.0 and 4.0. In general, improvements are most noticeable on the downwind side of the turbine.

Figure 8 compares turbine performance coefficients for the "optimised" pitch con-

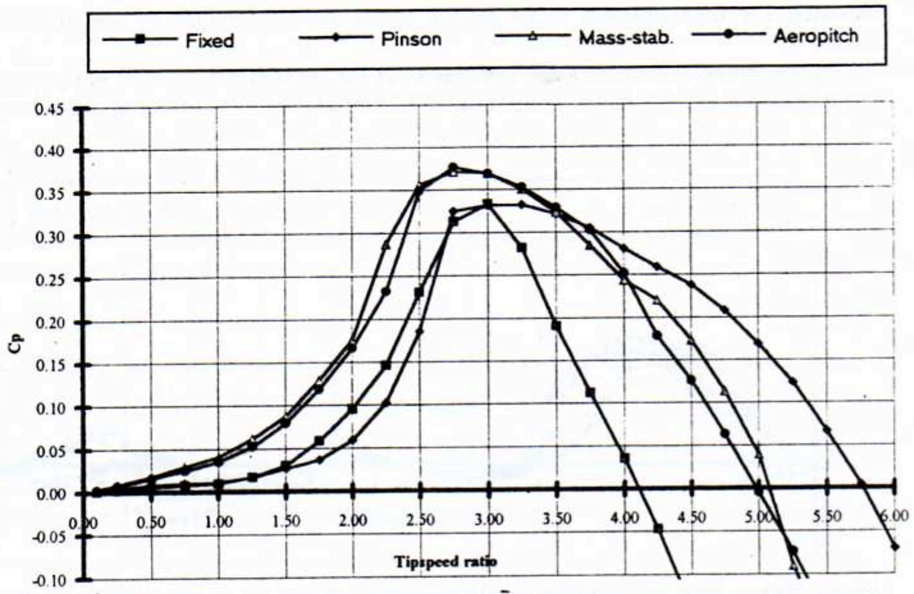

Figure 8. Turbine performance coefficients for various pitch systems - parasitic losses included.

trol systems. Parasitic losses are calculated using the formula:

$$C_{p_{loss}} = 0.002\,\lambda^3 \tag{22}$$

where the figure of 0.002 is an assumed parasitic drag factor which incorporates strut drag and allows for other "real effects". Obviously, different pitching systems will have different loss characteristics, however this formula was considered as reasonable for comparative purposes.

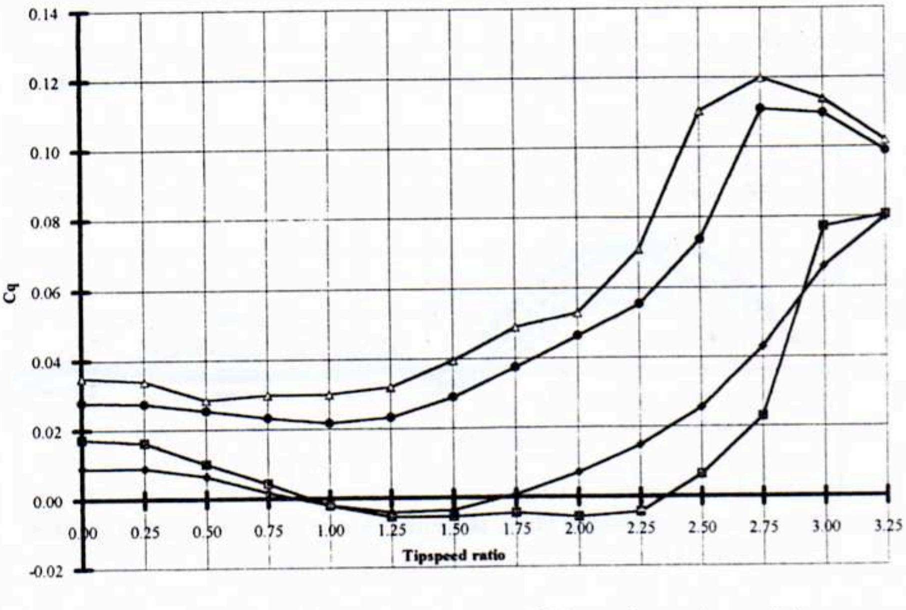

Figure 9. Low speed turbine torque coefficients for various pitch systems - parasitic losses included.

Figure 9 compares low speed torque coefficients for the "optimised" systems. For this graph, an ambient wind speed of 4.0 ms^{-1} was used, and equation 22 used to estimate parasitic losses. This figure shows that the two self-acting systems would self-start at a wind speed of 4.0 ms^{-1} but that the fixed pitch and sinusoidal pitch systems would not.

CONCLUSION

The performance of variable pitch VAWT is a complex function of many variables and the optimum geometry will depend ultimately on load characteristics. The pitch control systems examined in this paper can all be configured to produce better starting torque, a broader operating range and greater efficiency than fixed pitch VAWT. While self-acting pitch control systems seem to produce better low speed torque than the forced pitch device, further work is necessary to assess their performance under real conditions.

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ERRATA

The author of the above paper has pointed out some errors in the paper by Dr. Kirke and himself, published in Volume 16 No. 1:-

Performance Optimisation of a Self-acting Variable Pitch Vertical Axis Wind Turbine

Page 13: In equations (1) and (2), C_{Nu} and C_{Nd} should be C_{Ru} and C_{Rd}

Page 14: The second equation should be labelled (6), not (5), and should read

$$C_T = C_{L\beta}\sin\alpha - C_{D\beta}\cos\alpha$$

The Editor apologises for having let these errors through.