Comparison of various control strategies for a two-bladed wind turbine

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SYNOPSIS Control stategies for a typical 300kW two-bladed full-span HAWT are considered. A conventional PI controller provides the baseline, and is compared with (i) a linear controller designed using classical loop-shaping, (ii) a novel nonlinear controller based on a strategy of tracking the the optimum open-loop cross-over frequency as closely as possible as wind-speed rises, and (iii) a simplified version of this nonlinear controller.

1. INTRODUCTION

Many medium-scale constant-speed HAWT's are regulated by continuous adjustment of the pitch angle of either the full-span of the blades, or an outer region at the tips. The purpose of this paper is to compare the performance achieved by using various control strategies. It is important that fair comparisons are made, and to this end each controller studied is required to have similar stability margins and to operate within the same actuator restrictions. The objectives for the control system are discussed elsewhere (1)(2)(3). A typical 300 kW two-bladed full-span configuration is considered, since it is known (4) that this presents a more demanding control problem than alternative configurations. Although the wind turbine is fictitious, it is representative of this configuration.

The actuator characteristics, especially the limits on its torque, are the main restriction on the performance that can be achieved by a controller. In the case of a wind turbine, as wind speed rises a linear controller places less demand on the actuator since the sensitivity of the aerodynamic torque to pitch changes increases faster than the sensitivity to wind speed changes. Hence, for a fixed controller, while the actuator may be worked to its full capacity at low wind speeds, it may not be used as fully at higher wind speeds. However, it is at these higher wind speeds that the loads are highest, and therefore controller performance is most critical. Theoretical studies (4)(5)(6) indicate that there is an advantage in using this spare actuator capacity as the wind speed rises; and that there exists an optimum level of activity for the controler at each wind speed. Whether the optimum cross-over frequency can actually be achieved at any particular wind speed depends on the capabilities of the actuator.

A conventional PI controller provides the baseline for making comparisons, and three alternative controllers are judged against it. These are (i) a linear controller designed using a classical loop-shaping methodology (1)(2), (ii) a nonlinear controller based on a strategy of tracking the optimum cross-over frequency as wind speed varies, and (iii) a simplified version of this nonlinear controller.

2. CONTROLLER SPECIFICATIONS

In order to provide a fair comparison between the various controllers studied, all are designed to meet the following requirements:

(i) Gain margin of at least 10 dB.

(ii) Phase margin of approximately 60 degrees.

(iii) Pitch acceleration standard deviation no more than approximately 10 deg/s^2.

As the wind speed increases, the gain of the plant increases since the rate of change of aerodynamic torque with pitch angle increases. If not catered for, the cross-over frequency of the open-loop system would increase and the accompanying change in phase in the region of the cross-over frequency would seriously reduce the stability margins. To counter this, it is standard practice for wind turbine controllers to include a nonlinear gain to compensate for the variation with wind speed in the sensitivity of aerodynamic torque to pitch change (see e.g. (1)). The representation of the aerodynamics is subject to considerable uncertainty and the gain of the controller is incapable of always being scheduled to match the varying windspeed. Consequently, good gain and phase margins are required to achieve adequate stability margins. If these are not achieved the system must sometimes destabilise, although not necessarily become unstable, when the wind turbine would experience large load fluctuations. Requirement (iii) represents a practical limitation imposed by the blade servo system. Attention is restricted to continuous-time controller implementations. In previous work (7), the application of linear controllers designed using a classical loop-shaping methodology (1)(2) to a commerical design of two-bladed wind turbine has been investigated. While the controller complexity was severely restricted by limitations in the digital control hardware, and the full potential of the design methodology could therefore not be realised, the generic simulation methodology was thoroughly validated for the two-bladed case. It is used in the present work to estimate the performance of a nonlinear controller for a fictitious machine which corresponds to configuration 3 in (5).

3. PI & LINEAR CLASSICAL CONTROLLERS

Controllers with the following transfer functions were used.

PI Controller $0.961 \times 10^{-3}(1+10.504/s)$

(gain margin 10 dB, phase margin 76.14 degrees, cross-over frequency 1.58 r/s)

Linear Classical Controller

$$871.229 \frac{(s+1.6)^2(s^2+7.243s+38.637)}{s(s+0.3)(s+3.7)(s+20)(s+50)}$$

$$\times \frac{(s^2+1.5s+104.04)(s^2+6s+416.16)}{(s^2+11s+104.04)(s^2+10s+416.16)(s^2+65.8s+2209)}$$

(gain margin 10 dB, phase margin 56.14 degrees, cross-over frequency 1.826 r/s)

These are similar to previous controllers used with a commercial two-bladed design of wind turbine (2). The classical controller is denoted controller M1D.

4. NONLINEAR CONTROLLERS

The objective is to design a controller whose level of activity varies with wind speed so as to be near optimal, within the limitations allowed by the actuator. A measure of the controller level of activity is the cross-over frequency of the open-loop system; that is, the frequency at which its gain is 0 dB. Since the cross-over frequency is to vary with wind speed, the controller must also vary with wind speed to cater for the accompanying changes in phase in the region of the cross-over frequency. In practice, a measurement of wind speed is unavailable, indeed there is no such thing as "the windspeed" experienced by the wind turbine. Simple scheduling is therefore not appropriate and the wind speed must be inferred from the plant dynamics, in this case via the pitch demand. If the controller is operating correctly, the demanded pitch angle is a good indicator of wind speed. This approach is in widespread use for varying the nonlinear gain noted in Section Two, which is used to compensate for variations in the aerodynamic torque sensitivity. Using an internal state of the system, such as the pitch demand, to change the controller as wind speed varies must be treated with some caution. It introduces an additional feedback loop, thereby changing the dynamics of the system by its very presence. The design task is to develop a varying controller which induces the required open-loop dynamics at any wind speed, despite the presence of the additional feedback loop. The result is a nonlinear controller.

A series of linear controllers is designed for various wind speeds using classical loop-shaping design techniques. Some care was taken to minimise the differences between these controllers so that interpolation between them could be carried out as smoothly as possible. The continuous family of controllers thereby generated is :

$$g \frac{(s^2+7.59s+68.06)}{(s^2+as+b)} \frac{(s+1.7)(s+1.8)(s^2+3s+416.16)}{s(s+0.3)(s+3.75)(s^2+8s+416.16)}$$

$$\times \frac{2209\,(s^2+2s+104.04)(s^2+7.243s+38.637)}{(s^2+11s+104.04)(s+100)(s+30)(s^2+65.8s+2209)}$$

where,

$$a=-0.033047p^2 + 0.75064p + 3.3749$$

$$b= 2.6002p + 58.040$$

$$g= (0.13779p + 0.29784)\ 68.06/b$$

and p is the pitch angle demanded by the controller, in degrees.

This family of linear controllers has the following features.

- Low frequency shaping to improve disturbance rejection.
- Notches at 2P and 4P to reduce actuator activity and prevent the enhancement of the loads induced by these spectral peaks
- High frequency roll-off to reduce actuator activity.

Upper and lower bounds are placed on a, b and g,. When p is less than 3.84 degrees a, b and g are held at their 3.84 degree values. Similarly, when p is greater than 20.59 degrees a, b and g are held at their 20.59 degree values. It can be seen that these controller transfer functions are the same except for a varying gain and a pair of varying poles. The gain and phase margins of these controllers as p is varied are as follows:

p (deg)	gain margin (dB)	phase margin (deg)	cross-over freq (r/s)
3.84 (12 m/s)	13.74	55.23	1.36
11.14 (16 m/s)	10.03	55.89	2.51
16.21 (20 m/s)	10.00	55.62	2.85
20.59 (24 m/s)	10.79	55.64	3.25

The optimum cross-over frequencies to minimise the standard deviation of the power output are approximately1.5 r/s, 2.25 r/s, and 4 r/s at 12 m/s, 16 m/s, and 23 m/s respectively for this configuration of wind turbine (4)(5)(6). While at 24 m/s the optimum cross-over frequency of around 4 r/s is not achieved due to the physical limitations of the actuator, the minima is broad and the cross-over frequency of 3.25 r/s is near optimal. The dependance of performance on the controller cross-over frequency is illustrated in figure 1, on which the minima can be clearly seen.

The gain margin of the 12 m/s controller is rather higher than 10 dB. Since there is always a trade-off between performance and robustness, this controller will not achieve the best performance possible at low wind speeds. This choice of controller is necessary, however, if the variation between the transfer functions of the controllers is to be restricted to the values of a, b and g.

A nonlinear controller, denoted M3C, is obtained by continuously varying the controllers with pitch demand. As an alternative, a simpler arrangement is to use a dual-mode controller, where at low wind speeds one linear controller is used, and at some point a switch is made to a second linear controller for use in higher wind speeds. It is to be expected that this will lead to some degradation in performance, the level depending on the characteristics of the aerodynamic torque variation with wind speed, and on the switching point used. A suitable compromise, denoted DM1D, was found to be the use of classical controller M1D at low wind speeds, switching to the 24 m/s M3C controller at rated wind speeds above 20 m/s (that is 16.21 degrees pitch demand).

5. CONTROLLER COMPARISONS

The performance of the various controllers was investigated using a well validated simulation model. Simulations were run over a range of wind speeds and turbulence levels to reproduce the real machine conditions noted in (7), and to predict performance at higher wind speeds. Four mean wind speeds of 12, 16, 20 and 24 m/s were used at three nominal turbulence levels of 10, 15 and 20 %. The simulations were run for 260 seconds, giving four one minute periods of data. The nominal turbulence level only applies over a long time period, and the range of turbulence levels for the 1 minute samples was 6 - 26 %. These runs produced only 48 data points to cover the whole operational range of the machine, but this approach has nevertheless been found to be sufficient to indicate the comparative performance between controllers (7).

Power time histories with the PI, M1D and M3C controllers are presented in figure 2 for a mean wind speed of 24 m/s and 20% turbulence intensity. Although this is a fairly extreme wind condition, it is not unrealistic, and serves to highlight the marked differences in performance between the controllers. The conventional classical controller M1D when compared to the PI controller can clearly be seen to reduce both the peak power level and the time spent at higher power levels, consequently reducing drive-train loads. The power series for the nonlinear controller M3C and the dual-mode controller DM1D are very similar and therefore only that for M3C is shown. It can be seen that a significant improvement is obtained in turn over the linear controller M1D.

Probability distributions of the power time histories are given in figure 3 at a mean wind speed of 24 m/s and 10% and 20% turbulence intensity. A large reduction in the time spent at high power levels is evident with the nonlinear and dual-mode controllers. For example, the percentage of time that the power level exceeds 400 kW for the various controllers is as follows.

	10% Turbulence	20% Turbulence
PI	5.53%	18.82%
M1D	2.09%	14.04%
M3C	0.58%	5.09%
DM1D	0.66%	6.19%

For comparison, the percentage of time exceeding 450 kW at 20% turbulence is as follows.

PI	8.60%
M1D	4.02%
M3C	0.64%
DM1D	0.62%

Linear fits are made to the power maxima from the 1 minute samples with turbulence in the range 8-18% , corresponding to the wind regime experienced in (7), and also to samples with turbulence in the range 13-26% (figure 4), corresponding to a slightly more severe situation. The equations of these fits are as follows.

Turb-ulence	Controller	Fit	Standard Deviation
	PI	7.65*wind+288.82	18.96
8-18%	M1D	6.86*wind+296.44	19.99
	M3C	4.71*wind+326.01	11.78
	DM1D	4.90*wind+321.06	11.88
	PI	11.67*wind+240.37	29.02
13-26%	M1D	8.49*wind+280.05	20.02
	M3C	5.11*wind+330.49	14.52
	DM1D	5.79*wind+317.17	16.62

The lines at three times the standard deviation of the residues have been found to be a reliable guide to the peak transient loads which the drive-train would experience (7). The PI controller's maxima increase at the fastest rate, followed by the linear classical controller and finally the dual-mode and nonlinear controllers, which have around half the rate of increase of the PI controller, and much lower standard deviations, corresponding to a tighter bunching of the maximums.

The pitch acceleration standard deviations for the 1 minute samples with turbulence in the range 8-18% are shown in figure 5. The PI controller works the actuator least, and has the lowest standard deviation, while the conventional classical controller has a slightly higher level of activity. The standard deviation in both these cases falls as the wind speed rises, due to the increase in the sensitivity of the aerodynamic torque to pitch changes. In contrast, the standard deviation for the nonlinear controller M3C remains roughly constant as wind speed rises, exploiting the extra actuator capacity available at higher wind speed, as intended. The pitch acceleration demanded by the dual-mode controller is similar to that of the nonlinear controller M3C, but with a slight downward trend at higher wind speeds as might be expected.

6. CONCLUSIONS

To conclude, in extensive simulations using a well validated model, both a continuously varying nonlinear controller and a simpler dual-mode controller are found to give significant performance improvements over a PI controller and a linear classical controller. In particular, both the peak power, and the time spent at high power levels are greatly reduced, with a consequent reduction in drive-train loads. This improvement is obtained by exploiting the actuator capability that is left unused at higher wind speeds by linear time-invariant controllers.

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Figure 1 - Predicted variance of power output vs open-loop cross-over frequency and wind speed (6)

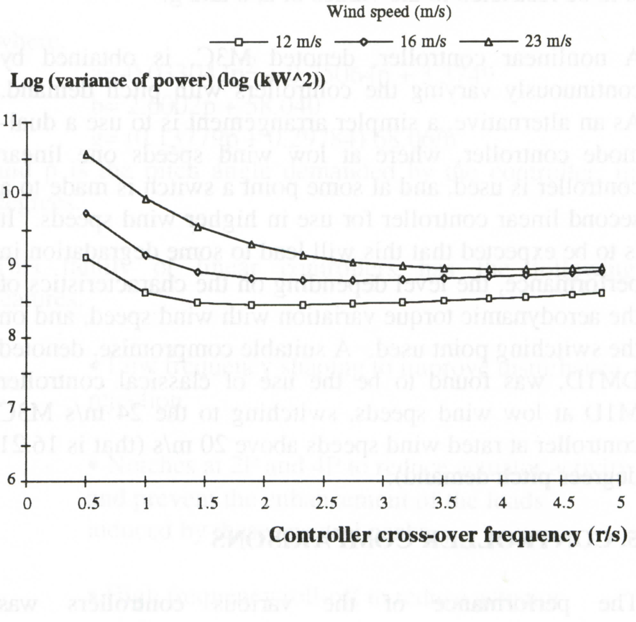
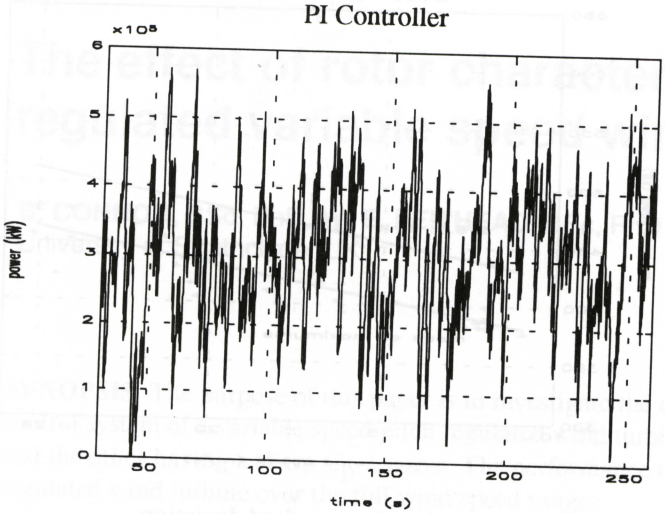
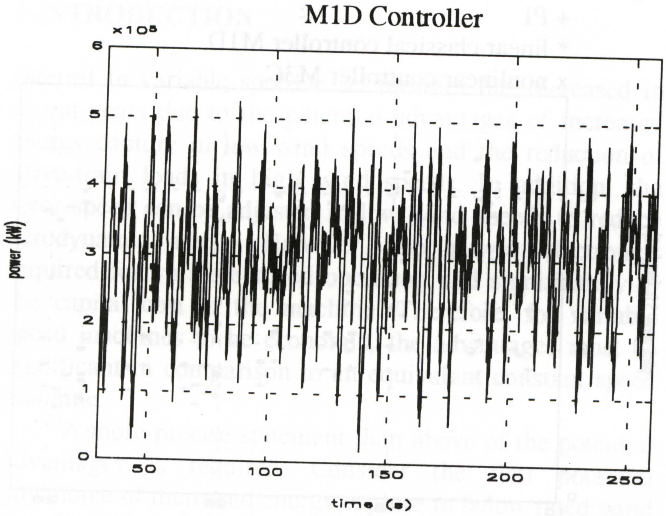


Figure 2 Power time histories for mean wind of 24 m/s, 20% turbulence intensity (TI).

PI Controller



M1D Controller



M3C Controller

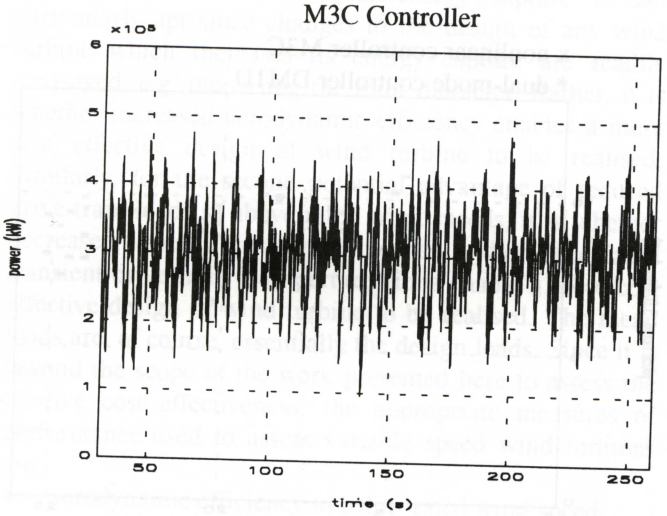
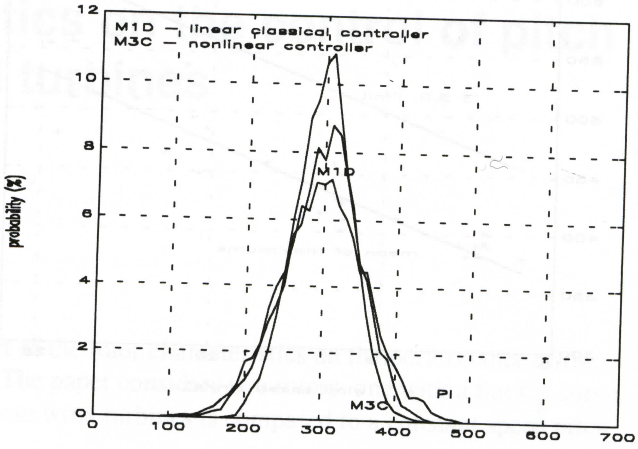
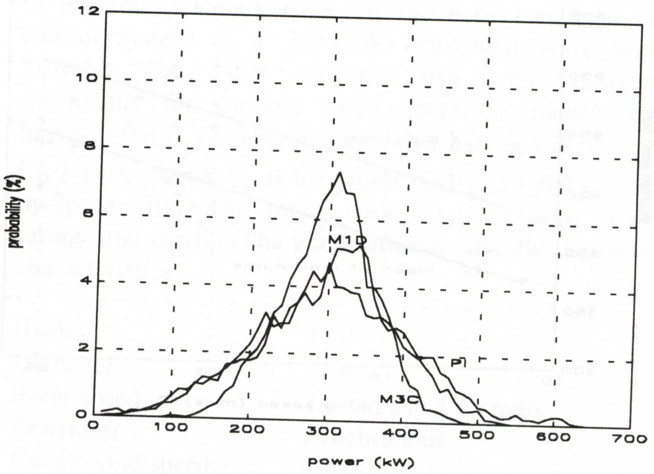


Figure 3 Probability. distribution of power,24 m/s 10% TI



20% TI



20% TI

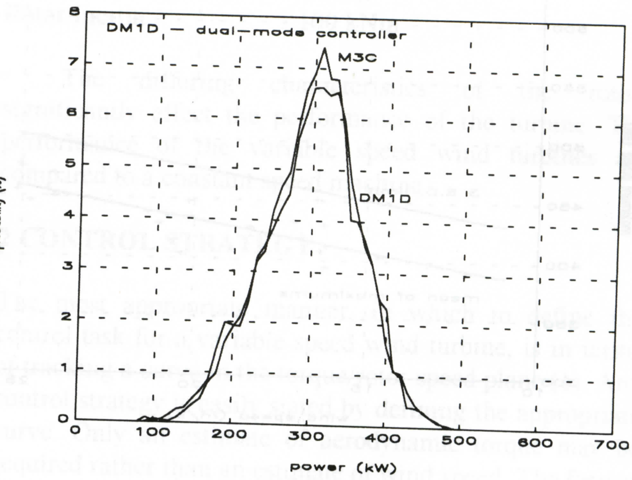
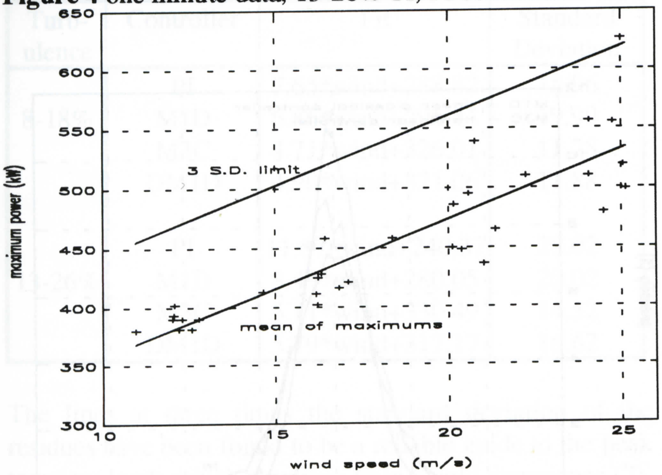
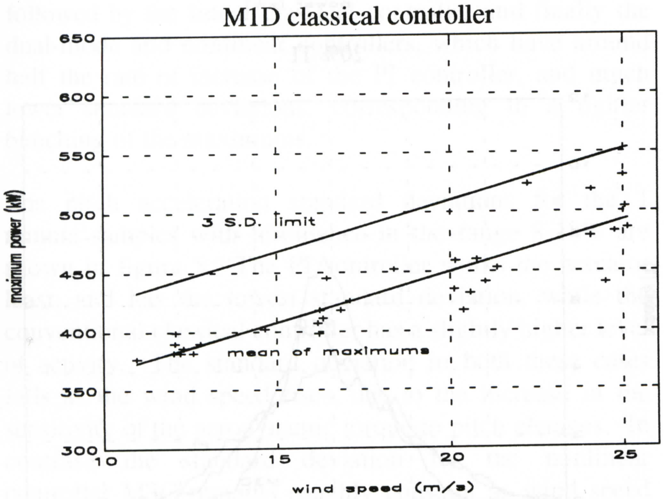


Figure 4 one minute data, 13-26% TI, PI controller



M1D classical controller



M3C nonlinear controller

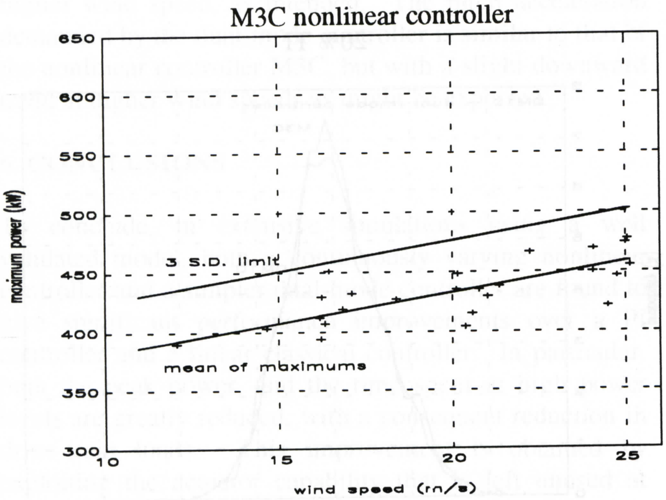


Figure 4 (cont)

DM1D dual-mode controller

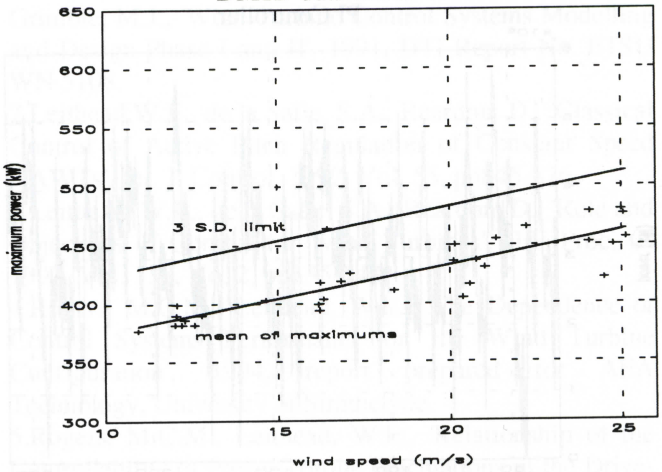
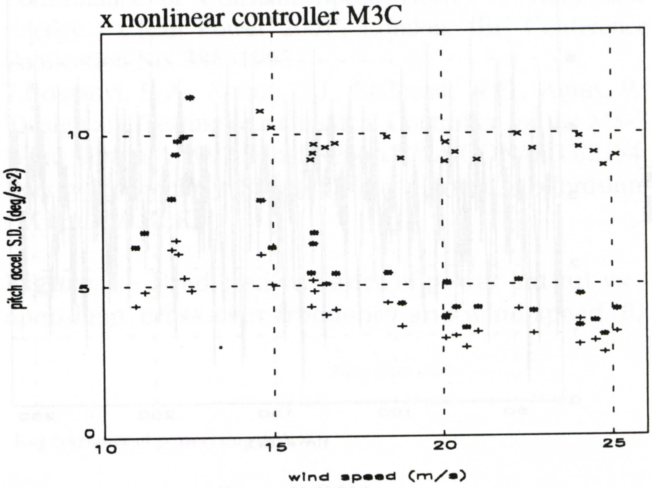


Figure 5 Pitch acceleration standard deviation
+ PI
* linear classical controller M1D
x nonlinear controller M3C



x nonlinear controller M3C
* dual-mode controller DM1D