SOME ALTERNATIVE DYNAMIC DESIGN CONFIGURATIONS FOR LARGE HORIZONTAL AXIS WECS

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Abstract

The present US development effort toward large horizontal axis WECS concentrates on the configuration with two rigid blades with collective pitch variation and a yaw gear drive. Alternative configurations without yaw gear drive are considered where the rotor is either self-centering or where the yaw angle is controlled by blade cyclic pitch inputs. A preliminary evaluation of the dynamic characteristics for these alternative design configurations is presented.

List of Symbols

a	lift slope
c	blade chord at .7R station
$\bar{C}_M$	$= M/\rho\pi R^3(\Omega R)^2 a\sigma$ yaw moment coefficient
$\bar{C}_{M\dot{\chi}}$	$= \partial\bar{C}_M/\partial\dot{\chi}$ partial derivative with respect to $\dot{\chi}$
$\bar{C}_{M\mu}$	$= \partial\bar{C}_M/\partial\mu$ partial derivative with respect to μ
I_N	nacelle moment of inertia about yaw axis
I_b	blade moment of inertia about rotor center
I_R	average rotor moment of inertia about yaw axis, 2 blades: $I_R = I_b$, 3 blades $I_R = (3/2)I_b$

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List of Symbols (cont')

M	yawing moment
N	number of blades per rotor
P	non-dimensional blade natural flap frequency when rotating, frequency unit Ω
R	rotor radius
T	$= \Omega R/V$ tip speed ratio
t	non-dimensional time, unit $1/\Omega$
V	wind velocity
γ	$= \rho c a R^4/I_b$ blade Lock number
θ_o	collective pitch
θ_c	cyclic pitch
μ	$= V\chi/\Omega R$ non-dimensional velocity in rotor plane from yaw angle χ (small χ assumed)
ρ	air density
σ	$= Nc/\pi R$ rotor solidity ratio
χ	yaw angle, defined in Fig. 8
Ω	angular rotor speed

Introduction

The MOD-0 wind turbine has initially experienced dynamic difficulties with the yaw gear drive that had to be considerably stiffened by adopting a dual drive system (reference 1). The yaw gear system stiffness requirements will be even harder to satisfy for larger WECS. It thus seems appropriate to look into some alternative dynamic design configurations that are less demanding of the yaw gear drive or that can possibly do without this drive. A very cursory examination of the economic potential of wind electric power shows that even relatively small first cost or maintenance cost savings may mushroom into billions of dollars. If wind power captures 10% of the future yearly US investments in electric power plants we will have investments in WECS in the order of 2 billion dollars per year or 20 billion dollars per decade. Before embarking on such a large capital program we better make sure that we have not overlooked alternative WECS designs with possibly lower initial and/or life cycle costs. A very rough outline of some such alternatives will be given here.

Eight Pairs of Alternatives

Table 1 shows 8 pairs of alternatives for horizontal axis WECS configurations. The first five are conventional classifications and are listed for example in reference 2. Another important alternative - two or more blades per rotor - is not included in Table 1 since we will mainly discuss here two-bladed wind turbines. Mast and nacelle dynamic loads and vibrations can be reduced by adopting more than 2 blades and, in the long run, the selection of a 3 or 4 bladed wind turbine may pay off despite the greater first cost. In rotor craft, 2-bladed rotors are limited to smaller sizes and all large helicopters are 3 or more bladed. There are, however reasons for this preference that may not apply to wind turbines.

The alternatives 6 to 8 are unconventional. Cyclic pitch is today a standard requirement for rotorcraft and in the following we will discuss its potential application to wind turbines. Gearless yawing is of course a feature of most small WECS that have an upwind rotor and a vane downwind of the mast. For large systems the vane size would become rather awkward and vanes have been replaced by yaw gears. What is meant here in Table 1 is vaneless <u>and</u> gearless yawing. This can be achieved either by a downwind turbine that has self-centering characteristics, called here rotor self-yawing, or by cyclic pitch controlled yawing. The first feature was tested by Saab-Scania on their 75 KW wind turbine, see reference 3. It was also suggested by Boeing-Vertol, see reference 4.

A recent interesting study is concerned with the first 3 pairs of alternatives in Table 1, see reference 2. For the case of 2 rigid blades with variable collective pitch 3 combinations of the alternatives 1 to 3 were looked at:

1. rotor downwind, rotor axis tilted 12°, blades radial
2. rotor downwind, rotor axis level, blades coned 12°
3. rotor upwind, rotor axis tilted 12°, blades radial

Loads for blade root bending, hub bending and hub torque in selected load cases have been determined for a 200 ft diameter wind turbine. The first two configurations have about the same hub bending moments and torques, while the third configuration shows largely reduced hub loads, particularly in the hub torque. The reason is the mast wind shadow for the downwind configuration assumed to reduce the inflow velocity by 22% over 30° azimuth angle, see reference 1 for a substantiation of these assumptions.

The alternative 4, hinged or rigid blades, is treated for a 2 bladed wind turbine in reference 5. A teetering hinge entirely relieves the nacelle of gyroscopic and aerodynamic hub moments, though the effects on the blades are less pronounced, since they receive a large portion of their bending moments both flapwise and chordwise from gravity, the more so, the larger the turbine. Thus the main effect of a teetering hinge is to alleviate nacelle and mast loads and vibrations. In particular, the yaw gear drive is relieved of loads when a teetering hinge is adopted. Thus the overall weight and cost of the system may well be smaller with teetering hinge than without. The rather successful Allgaier-Hütter wind turbine that operated between 1958 and 1967 in Stötten, F.R. Germany, had a teetering hinge that allowed ± 7° teetering, limited by elastic stops. The unconventional pairs of alternatives 6 to 8 are the main topic of this paper.

Five Alternative Configurations

Table 2 shows for the 8 alternatives of Table 1 the columns 1 or 2 applicable to 3 actual large WECS and to 2 configurations without yaw gear drive. The 3 actual large WECS began to operate in 1940, 1958 and 1975 and they have in most respects the same features. Differences exist only with respect to alternatives 2 and 4; level or tilted rotor axis, hinged or rigid blades. Actually there is a difference not shown in Table 2, since the Smith-Putnam wind turbine had a hinge for each blade, while the Allgaier-Hütter turbine had only one teetering hinge.

The two rigid blade configurations without yaw gear drive in the 4th and 5th row of Table 2 are first; a self-yawing rotor, located downwind of the mast, with variable collective pitch and fixed or possibly variable cyclic pitch, second; a rotor that is yawed by cyclic pitch inputs, located either downwind or upwind of the mast with fixed or possibly variable collective pitch. The selection of rigid blades is believed to be necessary for wind turbines without yaw gear drive, otherwise the centering capability for the first configuration or the cyclic pitch effectiveness for the second configuration would be inadequate. One principle reason for having a teetering hinge - load alleviation for the yaw gear drive - does not apply any way to self-yawing turbines. An auxiliary yaw gear drive for the initial start-up period may be used as in the Saab-Scania 75 KW wind turbine, reference 3, though proper yawing by natural rotor moments appears to be possible and may be preferable.

Self-Yawing

Before knowing that Saab-Scania had built and begun testing a self-yawing wind turbine, a preliminary study was made at Washington University to determine both analytically and with a small wind tunnel model the self-yawing characteristics of a wind milling rotor. The analysis was made with the method of reference 6, which assumes the blades to be rigid in bending and flexibly hinged at the rotor center. This assumption usually gives good approximations for the aerodynamic blade root bending moments. The blades were assumed to be of constant chord and untwisted, as were those of the wind tunnel model. The analysis is of the linear type, omitting blade stall or large angle effects and omitting effects of non-uniform or dynamic inflow. The nacelle inertia moment is negligible as compared to gyroscopic or aerodynamic rotor moments. Also the forces in the plane of the rotor have a moment about the yaw axis that is negligible as compared to the rotor hub moments. These assumptions made for the analysis are valid for the MOD-0 turbine (see for example reference 7) and also for the wind tunnel model.

Under the foregoing assumptions the pitching and hub moment coefficients depend only on two rotor parameters; the non-dimensional blade Lock number $\gamma = a\rho cR^4/I_b$ (which relates the airloads to the blade inertia), and the non-dimensional flapping frequency P. The moment coefficients depend further on two operational parameters; the blade pitch setting Θ and the non-dimensional velocity in the rotor plane when yawed by the angle χ assumed to be small

$$\mu = V\chi/\Omega R \qquad (1)$$

One can show that rotor self-yawing is governed by the first order differential equation

$$\dot{\chi}\ \bar{c}_{M\dot{\chi}} + (\chi V/\Omega R)\bar{C}_{M\mu} = 0 \tag{2}$$

If we have initially a yaw angle χ_o, this equation gives an exponential decay to $\chi = 0$ with a time constant

$$\tau = (\bar{C}_{M\dot{\chi}}/\bar{C}_{M\mu})\Omega R/V \tag{3}$$

The derivative $\bar{C}_{M\dot{\chi}}$ is independent of blade setting, while $\bar{C}_{M\mu}$ increases with the average angle of attack of the blade. For typical operating conditions the time constant is 10 to 30 turbine revolution periods. During start-up at low $\Omega R/V$ the time constant is much shorter.

The theory briefly outlined here was used to determine for a given yaw angle the reduction of the hub moment at the instant when the yaw restraint is released. The yawing moment then goes to zero, but the pitching moment is not zero. The total hub moment reduction factor depends only on γ and P as shown in Fig. 1. It is seen that in the region of P = 2.5 typical of a configuration like MOD-0 (reference 7) the hub moment reduction factor is about .6. When P is reduced to a value of about 1.4, the hub moment reduction factor is below .2.

The reduction in hub moment or blade root bending from self-yawing is even more impressive for a system described in reference 4 from which Fig. 2 is taken. The much larger hub moment reduction despite very stiff blades with P > 2.5 is obtained by feeding the hub pitching moment into a cyclic pitch control system, apparently in a way related to that developed by Lockheed for their Advanced Mechanical Control System (AMCS), see reference 8. Such feedback system is effective in canceling hub-moments for rigid blades, and its application looks promising for large self-yawing wind turbines with 2 rigid blades. As stated in reference 4, the feedback system not only reduces blade root moments to almost zero but also removes a yaw position instability that was encountered beyond the operating condition characterized in Fig. 2 by the trough of the cantilever system curve at 37 mph wind velocity. One must keep in mind, however, that the nacelle angular acceleration moment must give rise in a two bladed rotor to a vibratory hub moment with an amplitude equal to the angular acceleration moment. This is the reason why the vibratory blade root moment for self-yawing is not quite zero, except where the cantilever system produces zero restoring moment, see Fig. 2 at V = 37 mph. Fig. 2 is the result of a computation. The system has not as yet been tried even in a wind tunnel model.

When discussing reference 4 with its author the following facts were learned that are not evident from the reference: First, the curves shown in Fig. 2 are vibration amplitudes, consisting mainly of the first harmonics. If these first harmonics were plotted instead, the curves beyond 37 mph would cross the horizontal axis and be negative at higher wind speed. The explanation is that with decreasing collective pitch angle to keep the rotor speed constant at increasing wind speed, a reverse inflow pattern develops in the blade tip region that is responsible for the yaw position instability. Second, the blade coning angle was assumed to be zero when computing the conditions of Fig. 2. With increasing coning angle the trough in the cantilever system curve and the associated onset of instability will move to higher wind speeds.

At Washington University a small two bladed auto-rotating self-yawing wind tunnel model has been tested as shown in Fig. 3. The rotor diameter is 400 mm, the test section is square with 610 mm sides. The rigid blades are attached by flexures to the hub. The blades are untwisted and have a constant chord of 25 mm. The blade flap frequency without rotation is 13 cps, the blade Lock number is 4.5. The rotor has a high blade solidity ratio of .08. The "nacelle", consisting of a massive shaft of 20 mm diameter and a pulley at the bottom, has in relation to the blades more yaw inertia than the MOD-0 nacelle.

The "nacelle" could be deflected in yaw by hand using the pulley below the lower wall of the wind tunnel test section. When yawed about 20 to 30 degrees, the pulley was released and the nacelle moved to its equilibrium position that in all cases except one was close to the alignment position of rotor and tunnel axis. The time to center agreed roughly with Eq. (2). The rotor speed was measured with a stroboscope, the tunnel speed with a pitot static probe. The blade pitch angle Θ_0 could only be varied in between runs. $\Theta_0 = 90°$ corresponds to the feathered position of the blades, $\Theta_0 = 0$ to their in-plane position. As Θ_0 is lowered the rotor speed at a given tunnel speed picks up and the non-dimensional flap frequency P becomes lower.

Fig. 4 shows the test results as plots of Θ_0 and $\Omega R/V$ vs. P. Two tunnel speeds are shown; 4.6 and 8.2 m/s. The unstable condition, where the rotor would not center but rather go to a 40° yawed position, occurred for the higher tunnel speed, however not at the highest $\Omega R/V$. Above the critical $\Omega R/V$ the rotor centered again. The unstable condition probably occurs in a range of collective pitch angles rather than for a specific angle which was missed because only rather large steps in collective pitch were made.

The instability occurred only at the higher tunnel speed, not at the lower tunnel speed with equal Θ_o and $\Omega R/V$. The likely explanation of this phenomenon is the difference in coning angle between aerodynamically similar conditions. As the tunnel speed is lowered together with the rotor speed, the blades become relatively stiffer as indicated by the higher non-dimensional flap frequency P. The negative increment of coning angle in the reversed tip flow region is now smaller and the rotor centers at exactly the same Θ_o and $\Omega R/V$ that lead to non-centering at the higher tunnel speed. If this explanation is correct, a higher P-value and or pre-coning should eliminate the non centering region for 8.2 m/s tunnel speed. It appears that Saab-Scania have as yet not encountered a non-centering region despite operation up to 35 mph wind velocity.

Tests were also conducted with the stopped rotor. When the feathered blades were horizontal the nacelle did not show a centering tendency beyond ± 70° from the center position. However, when the feathered blades were inclined by about 20° from horizontal, centering occurred from every yawed position except for a small dead range at 180° yaw angle. Thus it may not be necessary to have an auxiliary yaw gear drive for start-up of the wind turbine, if the blades are parked in a position that is inclined somewhat from horizontal.

In summary, it can be said of the self-yawing configuration that it looks promising from the point of view of avoiding for rigid blades a heavy yaw gear drive together with its control system. Without cyclic pitch inputs the vibratory hub moments are reduced somewhat but are still quite high for a 2 bladed rotor of the MOD-0 type. Cyclic pitch inputs can be used to reduce the vibratory hub moments to near zero. The question then is, whether or not a teetering hinge in combination with a light yaw gear drive is not a simpler and cheaper solution to the problem of alleviating the vibratory hub moments of the rigid blades. The regions of centering instability can probably be removed by blade preconing, they can also be removed by cyclic pitch feedback. The development of such a feedback system can be a demanding and time consuming task judging from the experience at Lockheed. The ultimate success is, however, beyond a doubt.

Yawing by Cyclic Pitch Control

While in the previous section cyclic pitch was considered as an auxiliary input from a feedback system, we will now discuss the possibility of cyclic pitch as the main yaw control mechanism for a large wind turbine. All previously discussed configurations are based on propeller technology and require a variation of the collective pitch angle over a range of approximately 90°. In contrast, cyclic pitch control for yawing is based on helicopter rotor technology. Cyclic pitch application allows the rotor to be rapidly positioned at any desired yaw angle without encountering large hub moments.

One may question the wisdom of utilizing helicopter technology for wind turbines with their much longer expected life times. Actually the number of lifetime load cycles for a large wind turbine is not much different from that for a helicopter. For example, a 4-bladed helicopter rotor with 300 rpm rotor speed and 10,000 hours operational life has the same number of main load cycles as a large 2-bladed wind turbine with 30 rpm and 200,000 hours operational life, namely 720 million. Thus the dynamic design considerations for rotorcraft and for large wind turbines should not be different, and much of the dynamic design experience gained in 40 years of rotorcraft design should be applicable to large wind turbines.

Helicopter type blade pitch controls require no gears as found in propeller hubs but merely blade pitch arms, rotating axial links and a mechanism to transmit the rotating control loads to non-rotating actuators. This mechanism avoids the rotating hydraulic seals which have a tendency to leak. In helicopters collective and cyclic pitch ranges are usually about 12°, which is more than enough to operate a wind turbine.

Fig. 5 shows the collective pitch Θ_0 versus tip speed ratio $T = \Omega R/V$ at rated rotor speed of the MOD-0 wind turbine for the entire power range from zero to rated power. These curves have been transcribed as well as possible from data in references 9 and 10. The range of collective pitch required between syndronization wind speed and cut-off wind speed is from zero to less than 10°. The remaining range up to 90° is merely used for parking the turbine in the feathered position. A cyclic pitch controlled turbine would be parked edgewise to the wind as is done for most small WECS. A position close to edgewise could also be used for start-up and shut down similar to the autogiros of the twenties that used to taxi around the airport to start the wind milling rotor. Since the large WECS are to deliver power into a net, start-up with net power is also convenient same as for the non-self starting vertical axis large WECS.

A particularly simple cyclic control system is possible if the wind turbine is designed for fixed collective pitch operation. Fig. 6 shows one of many examples for such a system as a schematic planview of the shaft S, the power take-off P and the cyclic pitch control system, when the blades B are in a horizontal position. A rotating flexure F allows sideways motions parallel to the blade axes but it is stiff in the plane perpendicular to these axes. At the aft end of the flexure and connected to it by a bearing is a non-rotating lug L that can be horizontally displaced by a rod R with the help of an also non-rotating linear actuator A that can respond to signals representing errors in either yaw angle, rpm, or torque or power. The sideways displacement of the rod R causes a cyclic pitch change of the blades. The mechanism is very simple and rugged both compared to the conventional helicopter pitch controls and to the pitch controls employed in the first three WECS listed in Table 2. There are no gears in the hub and no bearings that are axially loaded, since the centrifugal force of the 2 blades B is balanced, so that the bearings which connect the blades with the shaft experience mainly radial forces. The cyclic blade rotations are quite small, at most about ± 6°, so that bearings can be of the elastomeric type without any gliding or rolling surfaces. The control actuator is non-rotating thus avoiding the difficulties of rotating hydraulic seals.

In some large WECS an emergency feathering system is employed in case of failure of the primary pitch change system. One can question the wisdom of such an added complication. In rotorcraft it is customary to use for the blade pitch variation single hydraulic actuators with dual pistons driven by two independent hydraulic circuits. The same arrangement would seem to be appropriate also for WECS. If the oil pressure is one system drops below a critical point the WECS would be shut down with the help of the second hydraulic system. Fig. 6 shows only one cyclic pitch control for yaw. For rotor pitching a second cyclic pitch control could be used in order to keep the hub moment in rotor pitch small. It is also possible that a second cyclic pitch control may be unnecessary if the yaw control is properly phased.

For a fixed collective pitch rotor the question is how to protect one self against over speeding or over torquing. When cyclic pitch is used for yawing this can readily be achieved by turning the rotor out of the wind. Fig. 7 shows a computed yaw rate response to a unit cyclic pitch input assuming a blade Lock number of $\gamma = 8$, a blade flap frequency of $P = 1.5$, and a ratio of nacelle over rotor inertia of $I_N/I_R = 1.7$ which applies to the MOD-0, except that γ and P are actually higher, leading to even faster rates of yaw and lower time constants. The first curve from the left represents the time lag from nacelle inertia, if the rotor were to respond instantaneously to a cyclic pitch input. The second curve includes the delay from rotor dynamics. The curves were computed with the method of reference 11.

The asymptotic yaw rate is .73°/time unit per degree of cyclic pitch input. The time constant is about 1.7 time units. For the MOD-0 with 40 rpm the time unit is $1.5/2\pi$ = .24 seconds. Assuming 6° cyclic pitch range, one would obtain for the MOD-0 case an asymptotic yaw rate of $.73 \cdot 6/.24$ = 18° per second, with a time lag of about .4 seconds. This must be compared to the one or two degrees per second yaw rate usually assumed for the gear drive of large WECS. The high rate of yaw from cyclic pitch does not cause high hub moments since the gyroscopic moments are balanced by aerodynamic moments. A hub moment is required in order to accelerate the nacelle, and in a two-bladed rotor it will cause 2 per rev. vibratory amplitudes of the same magnitude. One can easily compute that these hub moments will be moderate.

At 18° per second a complete turning out of the wind of the rotor by 90° would take 5 seconds, which is even shorter than the 8 seconds for emergency feathering of the MOD-0. The preceding estimates ignore the centering moment expressed by the second term of the left hand side of Eq. 2. This centering moment is, however, small as compared to the power of a cyclic pitch control system with 6° cyclic pitch amplitude.

Fig. 8 shows in the same form as Fig. 6 the relations between tip speed ratio T (or MPH for MOD-0) and yaw angle χ for rated rotor speed and a range of power between zero and rated power. The definition of χ is given in the graph. The rotor plane is perpendicular to the wind direction for $\chi = 0$, and edgewise to the wind direction for $\chi = 90°$. The graphs have been estimated from reference 12. One should realize how similar the curves of Fig. 8 are to those of Fig. 5.

In reference 13, Fig. 8d a condition of the MOD-0 system is described where the nacelle wind velocity varied from a mean of 25 mph by ± 5 mph and where the nacelle yaw angle varied by ± 10°, both with a period of about 8 seconds. This condition caused for the then MOD-0 configuration substantial over-loading of various components. From Fig. 8 it is seen that at most ± 20° yaw angle variation would compensate for the variable wind velocity and wind direction if rated power were to be kept constant. With 18° per second of maximum yaw rate, such a compensation should be achievable with only a small variation in power or torque.

For operation of the WECS as part of a large electric network one might select a procedure indicated in Fig. 8 by the heavy lines with the arrows. After start-up, the cyclic pitch control would be operated by the rotor speed error. Synchronization would occur at near zero power and about 40° yaw angle. After synchronization the cyclic pitch control would be operated by the yaw angle, which could be either zero or more than zero as shown in Fig. 8. The latter setting has the advantage of obtaining a less steep slope of the yaw angle vs. wind speed curve for rated power.

After the wind speed for rated power is reached, cyclic pitch control would be operated by the signal representing the torque error from rated torque. At cut-off wind speed the load would be disconnected and the cyclic pitch control would revert again to operation by the signal representing rotor speed error, possibly from less than rated rotor speed. The rotor could be kept turning up to the highest wind speeds and turbulence without encountering dangerous loads.

Rotor speed control by cyclic pitch has been used in the McDonnell-Army XV-1 convertaplane and tested on the ground and in the air during hundreds of hours down to tip speed ratios of one, see reference 14. The system was simple, rugged and very well behaved. The speed governor was a fifty dollar commercial product. The rotor speed error was very small even in gusty weather and during maneuvers of the rotorcraft. There is no doubt that automatic rotor speed and torque control by cyclic pitch is feasible for WECS and should represent no more than the usual development problems for a new application of a tested system.

Though both upwind and downwind rotor location could be used with cyclic pitch control for yaw, it is likely that the downwind location would prove more attractive because of its more compact design. The mast wind shadow problem will be largely alleviated since first harmonic blade moments are cancelled by the cyclic pitch inputs, though higher harmonics from mast wind shadow will persist. For parking, start-up, and shut-down, provisions must be made to allow positioning of the wind turbine at a yaw angle of 90° or less when non rotating. Preferably this should be achieved by proper aerodynamic shaping of the nacelle, possibly using a small drag plate opposite to the rotor to balance the rotor drag. The blades themselves for all but horizontal positioning produce a weather-vaning effect that tends to keep the rotor at 90° yaw angle. The rotor brake would probably be designed to stop the blades in an azimuth position favorable for start-up. If positioning of the rotor for start-up by natural wind effects should prove to be too cumbersome, an auxiliary low torque yaw drive and/or start-up with net or storage power could be used.

A major advantage of the WECS previously described is that the blades are never exposed to flatwise gravitational bending moments. These moments lead even for non-rotating helicopter blades to critical stresses. For the much larger diameters of wind turbines, these flatwise gravitational moments are even more significant and have led to blade designs with very thick root sections and very high flapwise natural blade frequencies. With non-feathering wind turbine blades, whether they are fixed in collective pitch or have a small collective pitch range of about 10° for speed and torque control (Fig. 5), gravitational loads are essentially edgewise to the blades, which thus can be built with much thinner root sections. Substantial reductions in blade weight and cost and improvements in aerodynamic performance can be expected when adopting a non-feathering system.

In summary, the use of cyclic pitch control for yawing large WECS with rigid blades looks promising. Collective pitch variation could either be completely eliminated or limited to a small range of about 10°. In either case the blades will be much lighter and aerodynamically better, since flatwise gravitational loads remain small. The rotor need not be stopped at winds above cut-off velocity but could be kept in autorotation at constant rotor speed without high blade loads. The principle of rpm or torque control by cyclic pitch has been successfully tested on a rotorcraft, so that the transfer of this technology to WECS will involve no major problems or uncertainties.

Conclusion

The rigid propeller technology presently pursued for the large WECS program appears to the writer as a step in the wrong direction. Lifting rotor technology appears to promise superior, simpler and cheaper solutions probably by a wide margin. Published arguments like those in reference 15 in favor of the rigid propeller solution are quite unconvincing and also contain errors of fact. The gist of these arguments are that by adopting systems that were designed 20 and 40 years ago by very small groups of engineers, a low risk of failure is achieved. This is a poor argument for laying the technical foundations of a possible multi billion dollar industry. We should try to find the best solution on the basis of present know-how and present related technologies. This takes careful comparative studies and a fresh look at the overall problem before making quantum jumps in WECS size. It is hoped that the preceding comments will lead to such a fresh look. The best solution may not be among the alternatives discussed here.

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Notes to paper by Kurt H. Hohenemser

1. Since writing the preceding paper the author learned from Professor D. E. Cromack that the University of Massachusetts 25 KW self-yawing wind turbine has been tested up to about 40 mph wind velocity without encountering the instability reported here for the wind tunnel model. The turbine has 3 blades with substantial built-in coning angle, which is probably the reason why it is self-centering up to at least 40 mph. The Grumman Windstream II turbine is also self-yawing, has 2 blades, but according to Mr. Stoddard has not been fully tested at high wind velocity.

2. As Mr. Doman pointed out to the author, the description of Fig. 2 contains an error. The vibratory blade root bending moment shown for the floating nacelle does not include the nacelle angular acceleration. Rather, the moment shown in Fig. 2 occurs when the nacelle is yawed by 20 degrees with the help of a cyclic pitch control system that trims first harmonic flatwise blade moments to zero. The moment contains only higher harmonics. When accelerating the nacelle first harmonic blade bending moments will occur.

DISCUSSION

Q. Your slide showed instability a function of blade pitch. Do you know if you experienced blade stall at this condition?

A. I doubt it that blade stall was involved. The instability did not occur with the same blade pitch and the same tip speed ratio at lower wind speed, when the blade angle of attack was the same.

TABLE 1. - EIGHT PAIRS OF ALTERNATIVES

		1	2
1	ROTOR	UPWIND	DOWNWIND
2	ROTOR AXIS	LEVEL	TILTED
3	BLADE AXES	CONED	RADIAL
4	BLADES	HINGED	RIGID
5	COLLECTIVE PITCH	VARIABLE	FIXED
6	CYCLIC PITCH	VARIABLE	FIXED
7	YAWING	GEAR	GEARLESS
8	GEARLESS YAWING BY	SELF-YAWING	CYCLIC PITCH

TABLE 2. - FIVE CONFIGURATIONS

	1	2	3	4	5	6	7	8
SMITH-PUTNAM 1940	2	2	1	1	1	2	1	-
ALLGAIER-HUTTER 1958	2	2	1	1	1	2	1	-
NASA 1975	2	1	1	2	1	2	1	-
SELF-YAWING	2	-	-	2	1	1 or 2	2	1
CYCLIC PITCH YAWING	1 or 2	-	-	2	1 or 2	1	2	2

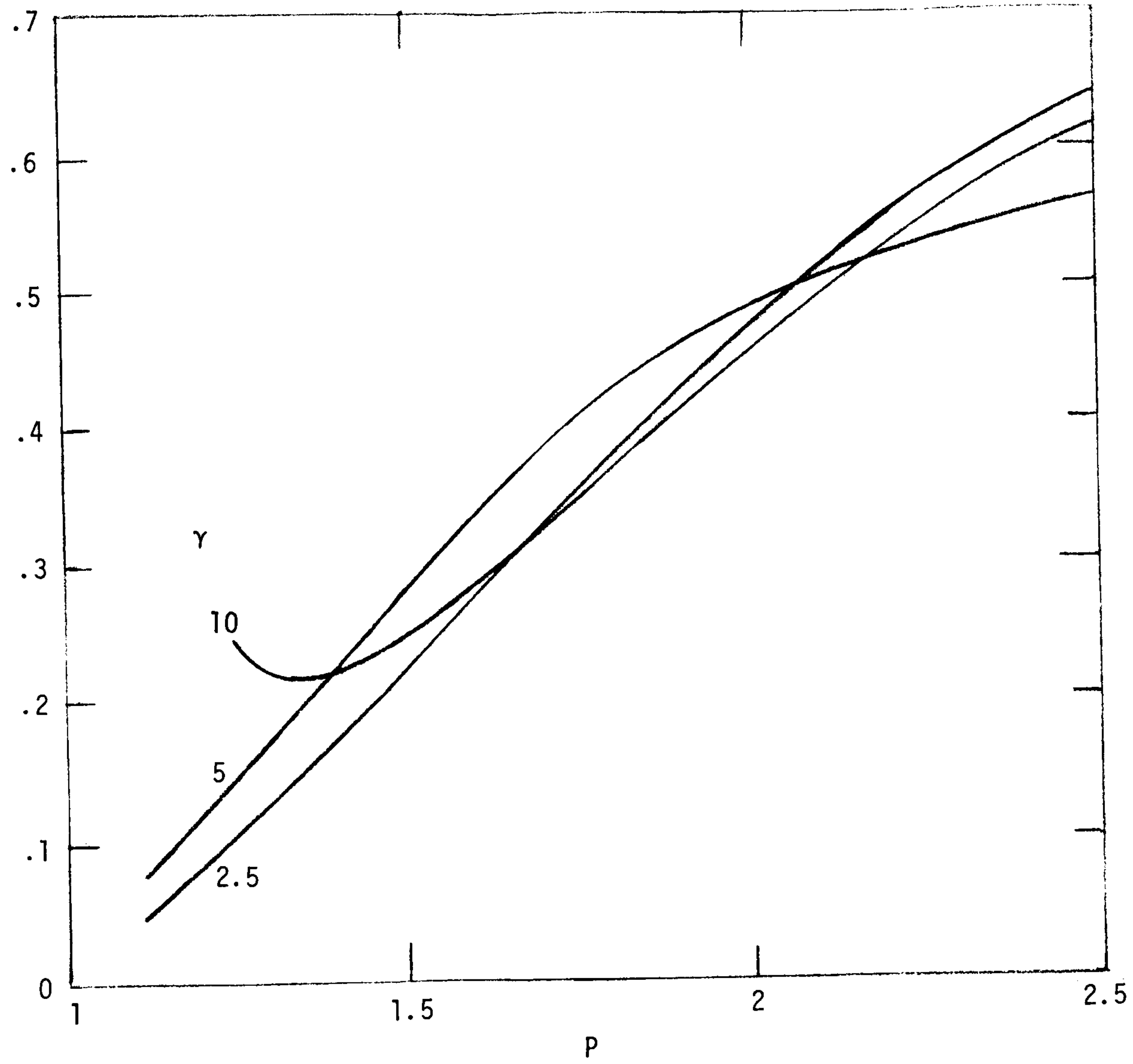

Figure 1. - Hub moment reduction factor from gearless yaw control versus nondimensional flap frequency P.

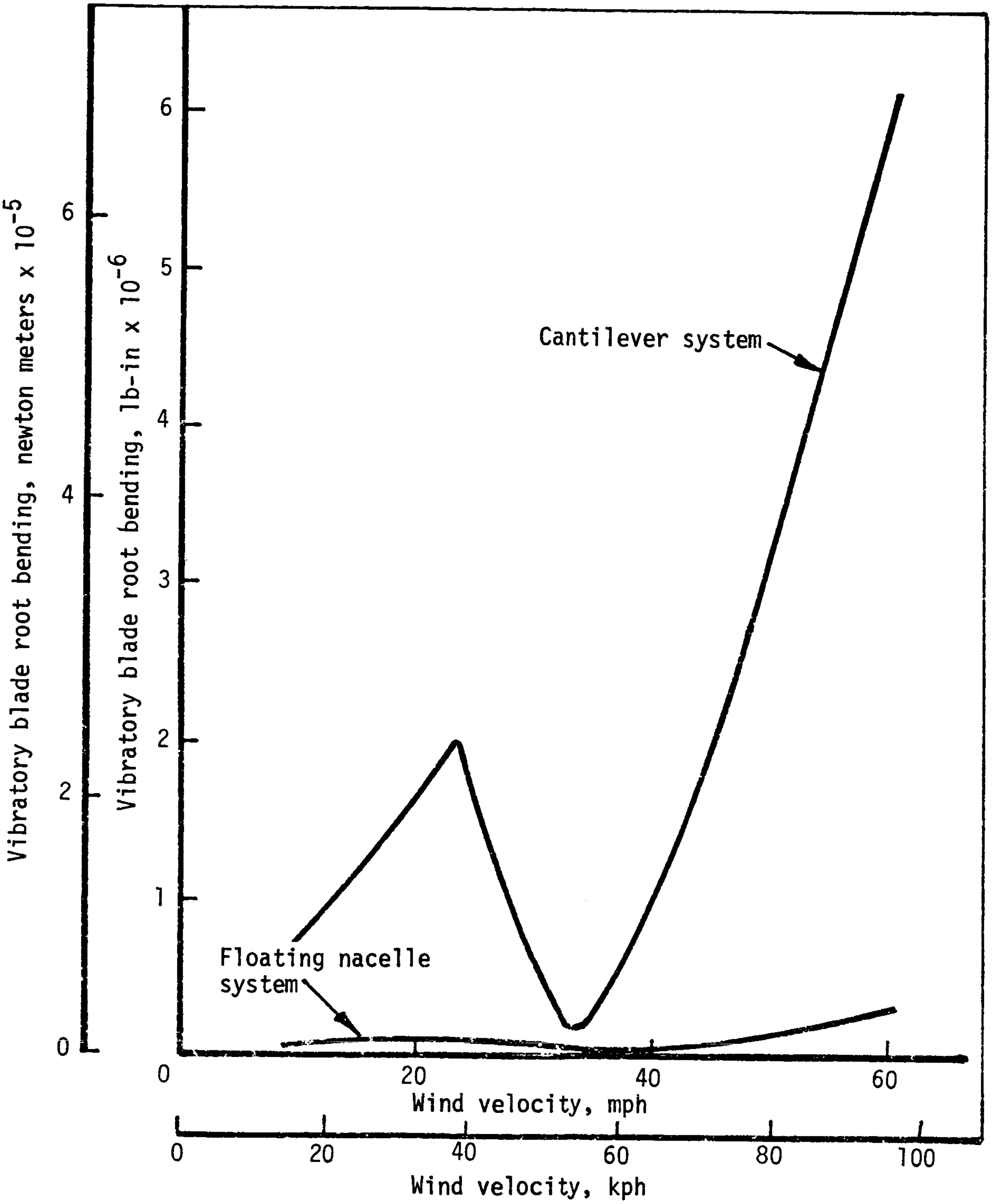

Figure 2. - Vibratory blade root moment versus wind velocity for two systems at 20° yaw angle.

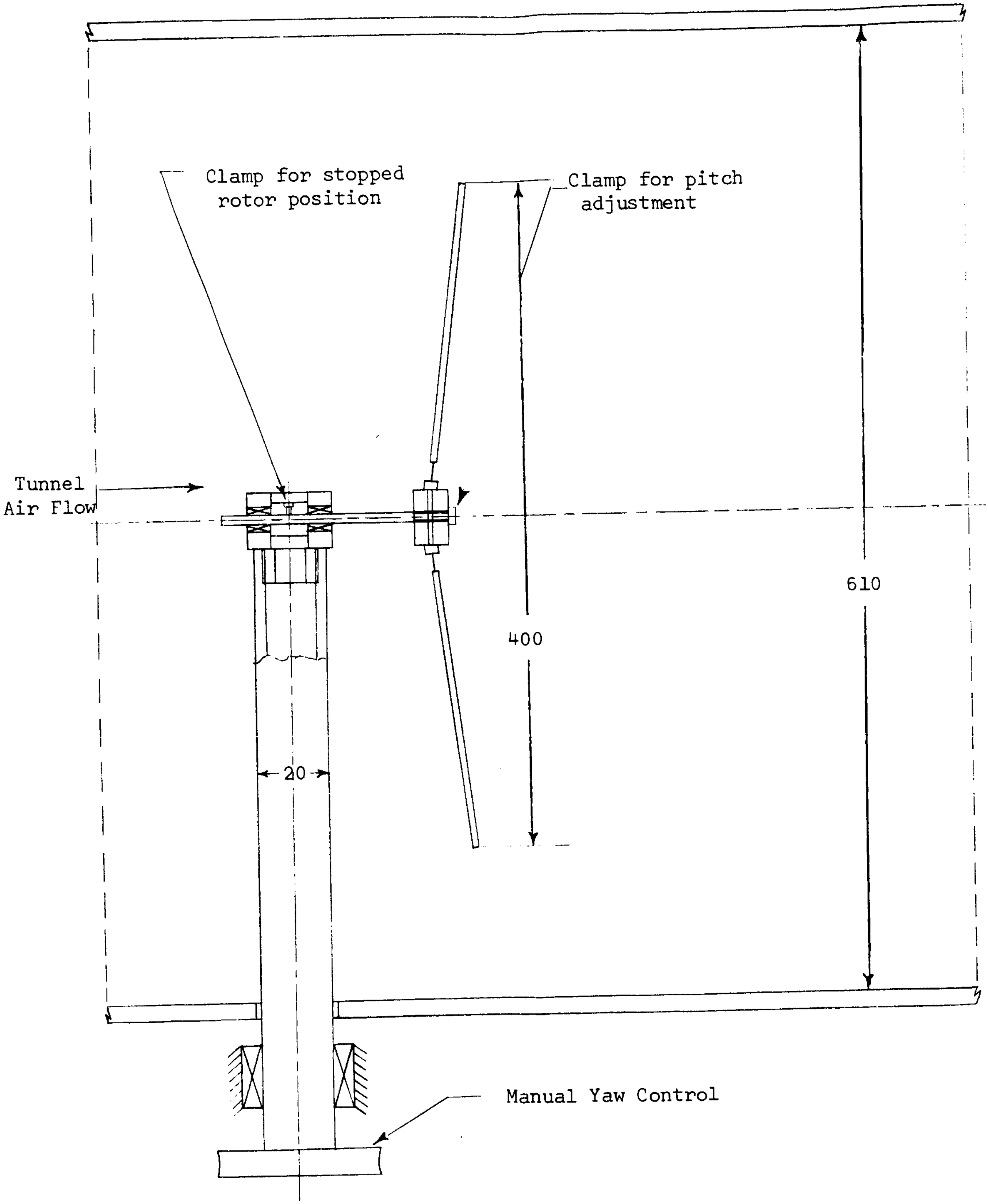

Figure 3. - Schematic side view of self-yawing, windmilling model rotor in wind tunnel.

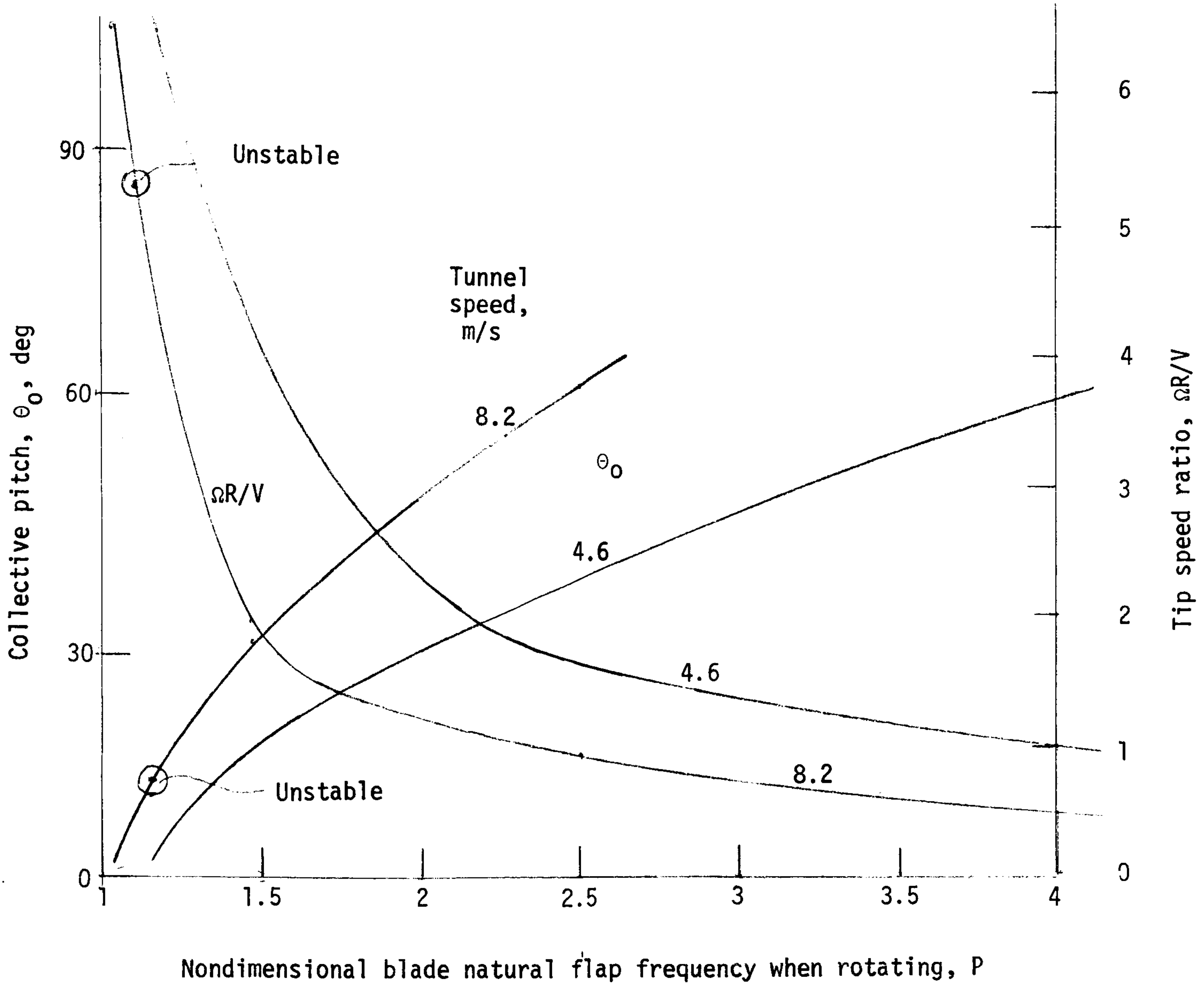

Figure 4. - Blade pitch setting Θ_o and tip speed ratio $\Omega R/V$ versus nondimensional blade flapping frequency P when rotating.

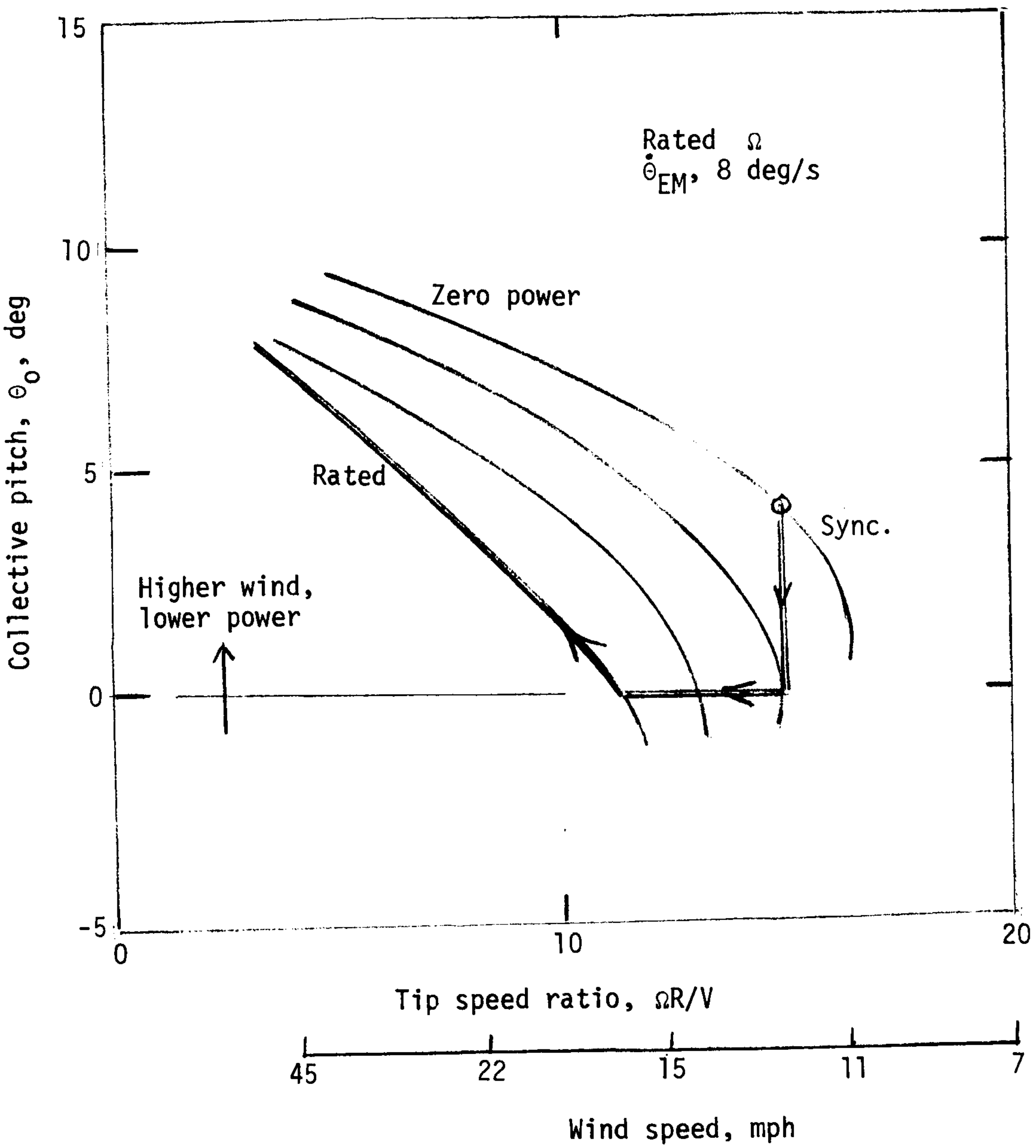

Figure 5. - Collective blade pitch angle Θ_o versus tip speed ratio $T = \Omega R/V$ (or mph) at various power settings for rated tip speed. (MOD-0.)

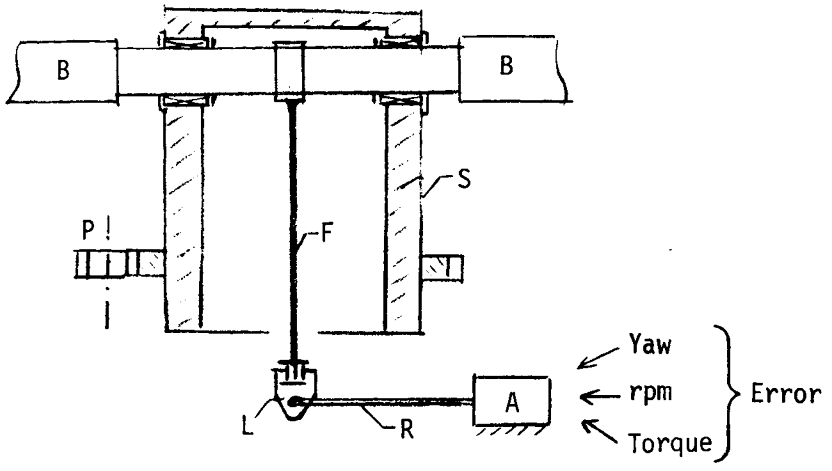

Figure 6. - Schematic of a possible cyclic pitch control system for fixed collective-pitch rotors.

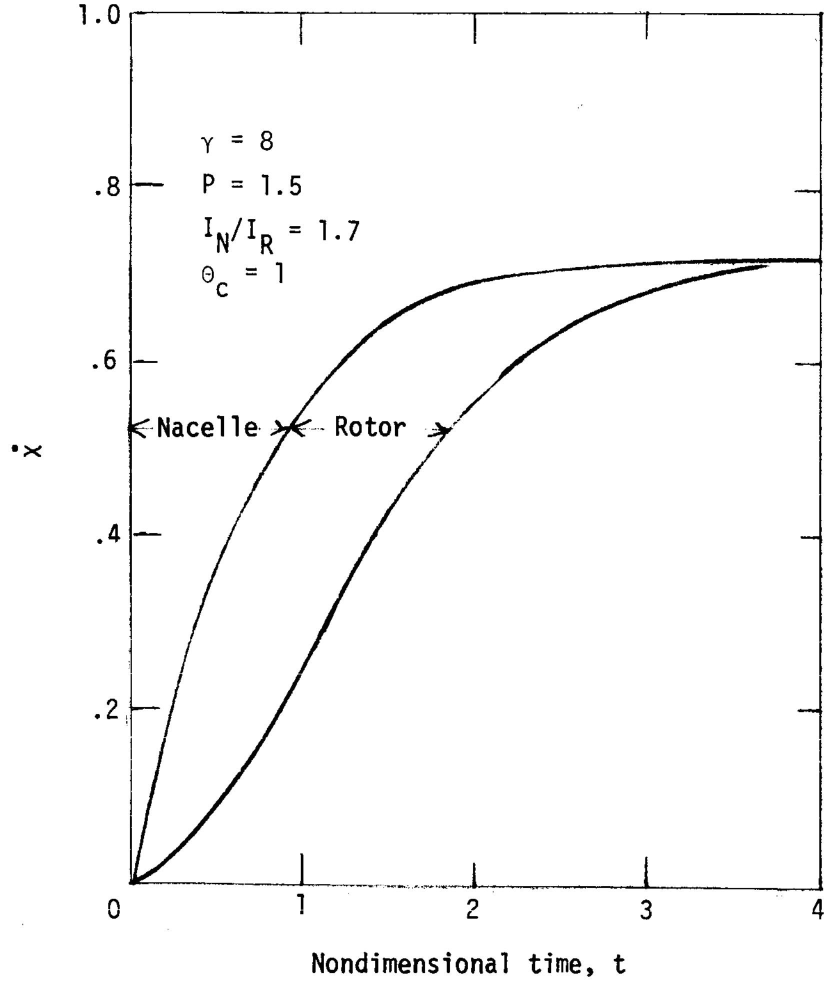

Figure 7. - Buildup of yaw rate $\dot{\chi}$ versus nondimensional time t after unit step cyclic pitch input.

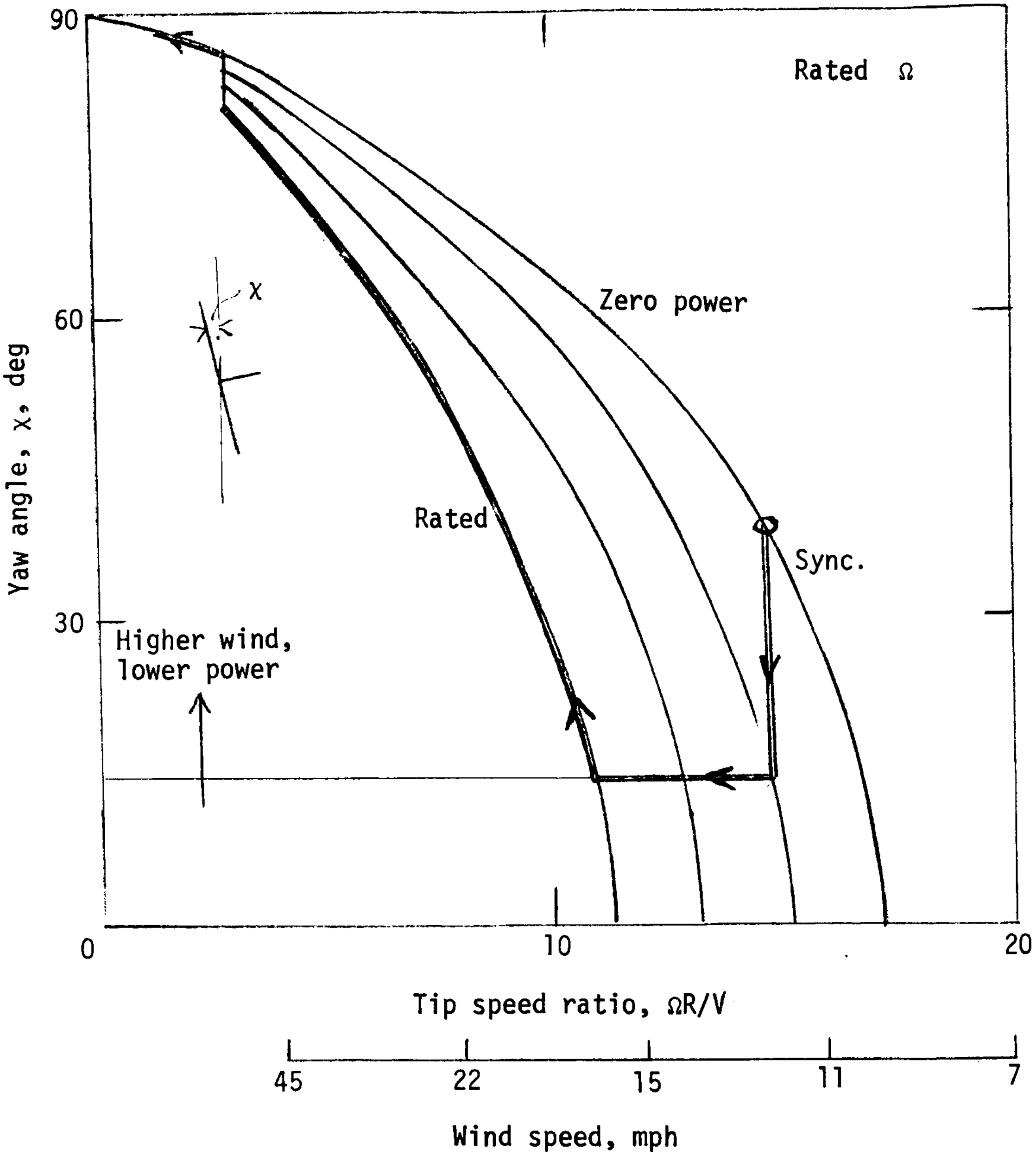

Figure 8. - Yaw angle χ versus tip speed ratio T = ΩR/V at various power settings for rated tip speed (mph scale for MOD-0).