

ROTOR DYNAMIC CONSIDERATIONS FOR LARGE
WIND POWER GENERATOR SYSTEMS

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Practical large-scale wind power generating systems must be competitive in terms of energy cost. Low available wind energy per unit area demands efficient aerodynamic design, a location with high mean wind velocity, and proper integration with established power grids. Also essential for low initial and operating costs are reliable, lightweight, mechanically simple designs requiring a minimum of maintenance. To a large extent, these qualities depend on the dynamic loads and vibratory stresses of the rotor/tower structure that, for very large wind turbines, will probably constitute the ultimate design constraints.

In many respects the dynamic properties of large wind turbines will be similar to helicopter rotors where cost, reliability, vibration, etc., are also of primary importance. Although some differences exist, much of today's helicopter rotor technology is applicable to the design of wind power systems. Based partly on this experience, the following comments are offered to provide some understanding of the dynamic properties of large wind turbines and suggest some possible design concepts.

DETERMINATION OF VIBRATORY LOADS

Vibratory loads and stresses result from unsteady aerodynamic, inertial, and gravitational forces which act on the rotor/tower structure. If this structure is ideally rigid, vibratory loads and stresses can be easily determined from known applied forces. For real flexible structures, elastic deformations contribute additional aerodynamic and dynamic forces, and the determination of vibratory stresses is considerably more difficult. If exciting forces occur at frequencies near the natural frequencies of the structure, resonance may seriously amplify dynamic loads.

Principal Structural Deformations

The elastic deformations of the rotor blades and tower structure are shown schematically in figure 1. In this example the blades are

shown cantilevered to the rotor hub, but similar deformations occur for articulated (hinged) blades. Structural deformations include flap and lead-lag bending of the blade perpendicular and parallel to the plane of rotation, respectively, blade torsion or elastic twist, vertical and horizontal bending of the rotor shaft (not shown in fig. 1), and bending and torsion of the tower structure. The importance of these elastic deformations will be dependent on the degree of flexibility of the rotor/tower structure.

Rotor Blade Frequencies

The vibratory loads and stresses of a rotor system depend to a large extent on the natural frequencies of the structure. Some understanding of the dynamics of a single rotor blade can be obtained from the linear bending-torsion equations (ref. 1) that determine the rotating natural frequencies.

$$\text{Flap:} \quad -(\underline{T_w'}) + EI_y w'''' + m\ddot{w} = L_z$$

$$\text{Lead-lag:} \quad -(\underline{T_v'})' + EI_z v'''' + m(\ddot{v} - \Omega^2 v) = L_y$$

$$\text{Torsion:} \quad -GJ\phi'' - k_A^2 (T\phi')' + mk_m^2 \ddot{\phi} + m\Omega^2 \left[k_{m_2}^2 - k_{m_1}^2 \right] \phi = M_\phi$$

where $T' = -m\Omega^2 x$.

Flap and lead-lag deflections are given by w and v , respectively, and torsional deflection by ϕ (See fig. 1.) The effects of centrifugal tension and stiffening due to rotational velocity Ω are underlined. The remaining terms are due to bending stiffness (EI) or torsional rigidity (GJ) and inertial forces due to blade mass m . The forces and moment L_z , L_y , and M_ϕ applied to the blade are caused by aerodynamic, inertial, and gravitational forces. When these applied forces are not retained, the homogeneous equations define the blade natural frequencies and mode shapes. Rotor-blade frequencies are typically displayed in dimensionless form as a function of the normalized rotor speed. A typical example is sketched in figure 2. The frequencies and rotor speed are normalized by the nominal or rated operating speed Ω_0 . The frequencies correspond to the fundamental and higher modes of bending and torsional deformations and they increase with rotor speed because of centrifugal stiffening. Also shown on this plot are frequencies of the applied blade forces which occur at integer multiple harmonics of the rotor speed (such as one per revolution, twice per revolution, ..., or, $1P$, $2P$, ..., for short). These applied forces will exist whenever the rotor blade is not uniformly loaded around the azimuth, for example, nonaxial wind components, gravity forces, rotor disk tilt, or shaft precession. Generally, the applied forces diminish with increasing harmonic number.

The significance of this figure is that resonance and severe vibratory stresses may occur when a blade natural frequency is close to the frequency of an applied force. Therefore, the rotor blade must be designed to avoid such resonances to achieve low fatigue stresses and long life. One difficulty is that during operation below rated speed, or with

ungoverned wind turbines, it is virtually impossible to avoid a resonance at some speed. This may preclude operation at that speed if severe vibratory stresses result.

DYNAMICS OF LARGE ROTORS

The importance of flexibility for vibratory loads and stresses depends partly on the degree of flexibility of the structure. Therefore, the proper questions in discussing wind turbines are:

- (1) what parameter best characterizes blade flexibility, and
- (2) how does this parameter vary as a function of rotor size?

Perhaps the most appropriate parameter is the dimensionless fundamental blade natural frequency, which depends on the ratio of blade bending stiffness to centrifugal forces $\bar{\omega} \equiv \omega/\Omega \sim \sqrt{EI/M\Omega^2 R^4}$.

This parameter establishes the condition for dynamic similarity for a wide variety of rotor blades having large differences in size, stiffness, mass, and rotational speed. It does not, however, account for gravitational forces. The blade natural frequencies are also a good measure of the importance of flexibility on dynamic loads. For very high stiffness or frequency, only low-energy, higher integer harmonic forces will be available to cause resonant vibratory stresses. The low frequency forces will then act on the structure much as static loads. Lowering the blade stiffness and frequencies will tend to relieve high "static" loads but will increase the importance of dynamic response.

It is interesting to compare expected wind turbine blade fundamental flap and lead-lag frequencies with conventional rotor and propeller blade frequencies as shown in figure 3. The conventional fully articulated rotor has very low fundamental frequencies because of the blade hinges. The teetering helicopter rotor with a single hinge has a low flap frequency and a moderately high lead-lag frequency. Other systems include the cantilevered hingeless helicopter rotors and conventional propellers which are relatively stiff. Structural information for large wind turbines are nonexistent and therefore only estimated frequency values can be shown. The lead-lag bending frequency is assumed relatively high in view of the typical low operating speeds of wind turbines, and the need to stiffen large rotor blades against gravitational stresses. Three possible wind turbine configurations are shown:

- (1) a teetering or coning hinge design to relieve aerodynamic thrust and hub moments,
- (2) a hingeless design to relieve blade root stresses with elastic flap bending, and
- (3) a stiff design to withstand aerodynamic loads directly.

These fundamental frequency values must be more precisely known before it will be possible to accurately compare the dynamic load characteristics of large wind turbines with other types of rotor systems.

Scaling Effects for Large Rotors

Sizing trends for wind turbine properties may be deduced from dimensional analysis considerations. For purposes of comparison, a constant level of aerodynamic efficiency at a given wind speed is assumed which in turn constrains the blade tip speed $R\Omega$ to a constant value. For geometrically similar construction then, the rotor parameters will vary with size, or radius R , in the following manner:

Parameter	Proportional to -
Rotor speed	R^{-1}
Blade mass	R^3
Centrifugal force	R^2
Solidity	R^0
Power	R^2
Thrust	R^2
Centrifugal stress	R^0
Aerodynamic stress	R^0
Gravitational stress	R
Dimensional natural frequencies	R^0

These relationships show that the important aerodynamic and centrifugal stresses are independent of rotor size, but that gravity stresses increase in proportion to the radius. The dimensionless natural frequencies remain constant, however, which means that dynamic response and resonant characteristics will not be influenced by rotor size. Interestingly, the power output increases with the square of the radius but blade weight increases with the cube. This is an example of the "square-cube law" that will eventually limit wind turbine size because of diminished power to weight ratio. This factor as well as aerodynamic efficiency trade-offs will alter the ground rules of geometric similarity and constant tip speed as a basis for establishing trends for dynamic properties of large rotors. For example, power losses due to aerodynamic profile drag can be reduced by increasing the rotor solidity and reducing tip speed, but only at the expense of increased blade weight and cost. Improvements in airfoil lift/drag ratio will permit reduced solidity and higher tip speeds. Increased tip speeds would be advantageous for reducing the capacity of the speed-increaser gear needed to step-up the low rotor shaft speed to the electrical generator speed. Although these trade-offs are complex, it will probably be necessary to sacrifice some aerodynamic efficiency to reduce blade size and weight of large wind turbines. Therefore, thinner blades operating at higher tip speeds will tend to reduce the dimensionless natural frequencies and so increase dynamic response and the effects of flexibility for large rotors. And, inevitably, gravitational stresses will be important for large wind turbines.

ROTOR CONFIGURATIONS

The choice of a specific rotor configuration can strongly influence

the mechanical complexity, vibratory stresses, reliability, and maintenance cost of wind turbines. Therefore, the attributes of different rotor concepts must be carefully weighed. Important configuration properties include the number of blades, blade to hub articulation, pitch control mechanisms, etc. Before discussing the dynamic characteristics of several rotor systems, the various forces contributing to blade vibratory stresses will be described.

Rotor Blade Forces

These include aerodynamic, inertial, and gravity forces. The major aerodynamic loads are generated by the unsteady nonuniform wind environment. The mean axial wind component generates thrust forces which deflect the blades equally downwind (coning). Gradients in axial velocity (the vertical gradient of the ground boundary layer for instance) produce a tilting of the rotor disk with respect to the shaft. Velocity components perpendicular to the rotor axis also produce disk tilting as well as higher harmonic loadings. Nonuniformities in velocity peculiar to the wind turbine location, the tower wake, and atmospheric turbulence will produce important unsteady loads. Additional unsteady loads, though probably small, will be induced by the rotor wake vorticity that itself results from unsteady blade loadings. Inertial blade loads include centrifugal tension due to rotation, lead-lag, and flapping loads due to Coriolis forces arising from blade oscillations, and gyroscopic forces due to precession of the rotor shaft to maintain alignment with the wind velocity vector. The primary lead-lag Coriolis loads result from tilting of the rotor disk (flapping deflections). Finally, gravity loads may produce significant lead-lag bending stresses for large rotors as noted above.

Hub Configurations

The importance of minimizing cost by reducing mechanical complexity favors the use of a minimum number of blades and the elimination of unnecessary articulation (blade attachment hinges) at the hub. Usually, however, some articulation is required to reduce blade stresses, due to aerodynamic loads, and blade flapping motion. Several types of rotor hubs found on helicopters are shown in figure 4. The simplest two-bladed teetering rotor is typical of current helicopters and allows simple flapping freedom (disk tilting) to relieve LP aerodynamic loads. The teetering hub does not provide individual blade flapping (coning) to relieve thrust forces due to wind gusts. The coning hub relieves these forces with an additional hinge, but these hinges must support the full centrifugal force load as well as the lead-lag bending moments. A hub configuration found on helicopters with three or more blades eliminates individual blade flapping hinges by attaching the blades to a gimbaled hub. This would not provide coning freedom for a wind turbine, but it does provide relief for inertial lead-lag bending moments. The common fully articulated helicopter rotor hub provides nearly complete relief for the major blade loads by using individual flap and lead-lag hinges for each rotor blade. However, this system is complex and, again, the hinges must carry the full centrifugal load of the blade. The last configuration shown in figure 4 is the hingeless rotor system in which

hinges are replaced by flexible spars that deflect elastically to relieve applied loads. Because flap bending moments are transmitted to the shaft, two bladed hingeless rotors would not be practical unless the tower structure could withstand $2P$ vibratory hub moments due to rotor disk tilting. With three or more blades, only steady hub moments due to disk tilting are transmitted to the shaft. Although hinged rotor hubs are currently in wide use, the hingeless rotor has definite advantages in terms of reduced complexity and improved reliability; and with continued development it is gaining acceptance for helicopter applications. Suitability of the hingeless rotor for wind turbines remains to be established and would require detail design and feasibility studies aimed particularly at reducing vibratory loads and stresses. Especially attractive is the use of molded composite materials to reduce fabrication costs and optimize the blade structural properties.

Each of the rotor hubs in figure 4 requires additional bearings to permit blade pitch changes for regulating power and feathering the rotor in extreme wind conditions. A possible extension of the hingeless rotor concept might permit the elimination of the pitch change bearing for maximum simplicity. A conceptual sketch in figure 5 shows the flexible cantilevered spar with bending flexibility to relieve stresses and with torsional flexibility accommodating blade pitch changes. This twisting may not be sufficient to fully feather the blade, however, and alternate means for dealing with extreme wind velocities might be necessary.

AEROELASTIC STABILITY

Practical rotor systems, including both helicopter rotors and wind turbines, must avoid aeroelastic instabilities. These may stem from several different but related physical mechanisms. Perhaps the best known is classical bending torsion flutter encountered on fixed-wing aircraft. This type of flutter occurs when relatively high-frequency unsteady aerodynamic forces couple with the elastic flap bending and torsion of the rotor blade to produce negatively damped oscillations. This is generally precluded by proper mass balance. Another type of instability, although less well known, can occur for cantilever (hingeless) rotor blade configurations. This type of instability involves both flap and lead-lag elastic bending as well as torsional deformations. It is primarily due to the strong structural coupling between bending and torsion that is characteristic of cantilevered rotor blades and can be avoided by proper tailoring of the bending and torsional stiffness distributions. A typical example of stability boundaries for a helicopter rotor of this type operating in hovering flight is shown in figure 6. These boundaries show that instability will be encountered above a certain pitch angle θ for configurations having various dimensionless torsional ω_ϕ and lead-lag ω_v natural frequencies. This figure, taken from reference 1, is only indirectly representative of specific wind turbine configurations. But it does indicate that aeroelastic stability should be considered in the design of large rotor systems.

CONCLUSIONS

Successful large, reliable, low-maintenance wind turbines must be designed with full consideration for minimizing dynamic response to aerodynamic, inertial, and gravitational forces. Much of existing helicopter rotor technology is applicable to this problem. Compared with helicopter rotors, large wind turbines are likely to be relatively less flexible with higher dimensionless natural frequencies. For very large wind turbines, low power output per unit weight and stresses due to gravitational forces will be limiting factors. The need to reduce rotor complexity to a minimum favors the use of cantilevered (hingeless) rotor configurations where stresses are relieved by elastic deformations.

REFERENCES

1. Hodges, D. H. and Ormiston, R. A.: Stability of Elastic Bending and Torsion of Uniform Cantilevered Rotor Blades in Hover. Paper No. 73-405, AIAA, Mar. 1973.

DISCUSSION

Q: You say a helicopter rotor is apparently designed for much higher frequency?

A: Yes. You couldn't take a helicopter rotor and turn it sideways and have an efficient wind turbine. In principle there are many similarities, but in terms of detail characteristics there are many differences.

Q: I have one question and one comment. You did not in your presentation state the difference of material. Materials have natural frequencies. The natural frequency is divided by the density. Perhaps this will be used to evaluate rotors. Did you investigate this?

A: Well, we haven't done any work on that, but I have made that point in my written comments. There is a tremendous potential for using glass fiber components or epoxies or whatever kind of molding materials, to tailor not only the aerodynamic configuration but the structural characteristics as well. This is extremely important in terms of aeroelastic characteristics, the blade frequency, vibration, and so forth. It's a tremendous potential for a rotor, any type of rotor. And it makes for much simpler construction. I think the work that Professor Hutter has done is a good example of that, and from what I've seen it looks a very good way to go.

The hingeless rotor I mentioned has no bearings or hinges, is made with composite materials and, is quite simple. They are nothing like typical rotors that we have nowadays.

COMMENT: There are problems of vibration, that would increase beyond limits we have so far heard on the tests. Therefore, I see that vibration would be most serious in the development of some windmills. It would be very difficult to erect these machines because a vertical rotor can't have downhanging rotors.

A: I think you are referring to gravitational loads under static conditions? Yes, that's going to be a problem. You don't have to go too much higher in size before just the static deflections get to be a problem.

In helicopter rotors, the plane of the rotor is normal to the gravity field so the blades all drop evenly. The rotor can start up and gain centrifugal stiffening, and the blades can be made much more flexible. But for wind turbines, they have to start vertically. It could be a real problem.

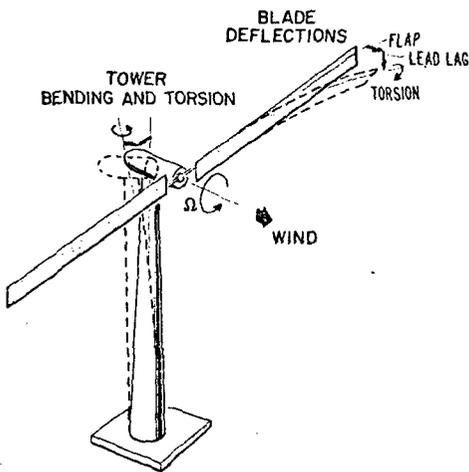


Fig. 1 - Elastic deformations of rotor/tower structure.

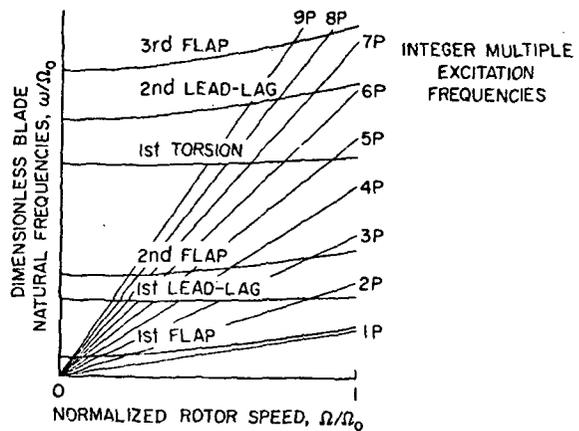


Fig. 2 - Variation of rotor blade natural frequencies and excitation frequencies with rotor speed.

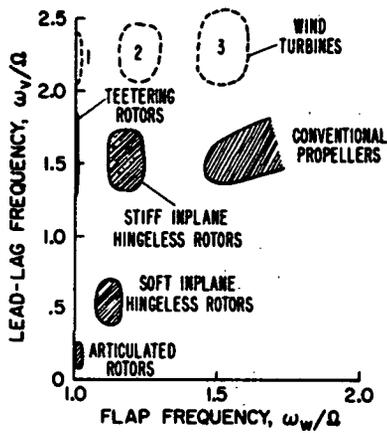


Fig. 3 - Comparison of rotor systems according to dimensionless bending frequencies.

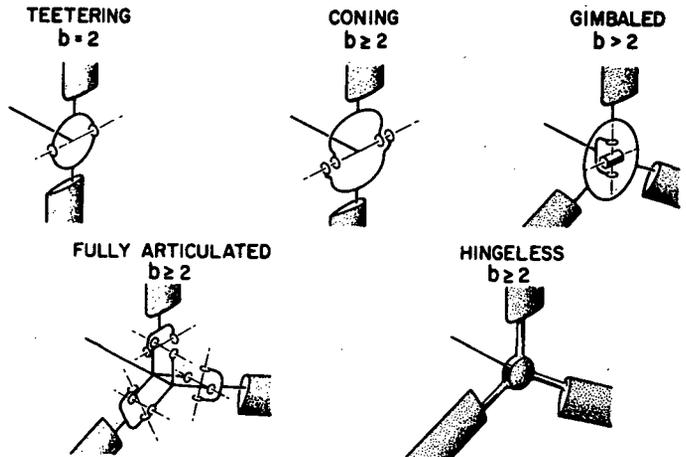


Fig. 4 - Typical rotor hub configurations.

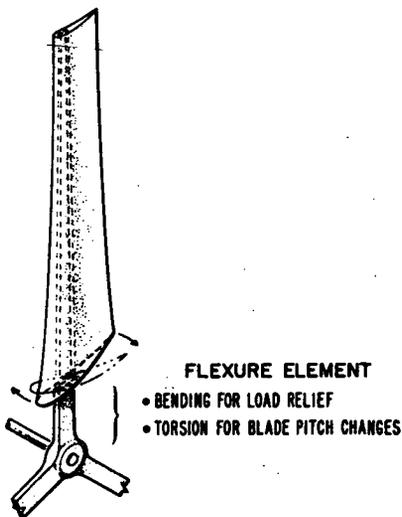


Fig. 5 - A hingeless rotor concept of simplified design.

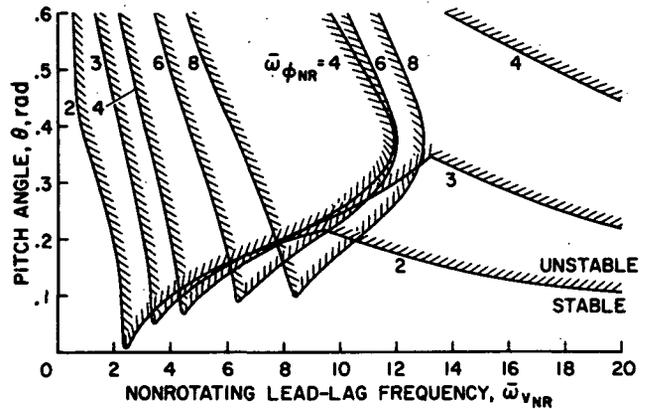


Fig. 6 - Aeroelastic stability of hingeless helicopter rotor blades in hover.