SYSTEM CONFIGURATION IMPROVEMENT

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The design of a wind turbine generator is a very complex process because of the many (and often conflicting) choices and considerations involved. As a consequence, the determination of a superior system can best be achieved from intensive studies and probings that reflect the truly pertinent governing factors. This paper presents a discussion of such a process in terms of word charts and associated figures.

Factors involved in the choice of the system configuration are listed below. It has been found that choices among the many configuration options can be based strictly upon the resulting cost of energy results. Choices made on that basis also lead to reduced analytical complexity, less hardware complexity and reduced program risk. It was also found that many seemingly minor details turn out to have important impacts that are seen only after design, performance and cost-finding have been thoroughly probed.

The final result of these processes was the identification of a currently superior system, as indicated in the chart. The ensuing charts will examine the considerations that lead to this determination.

THE CHOICE OF CONFIGURATION

- **All Choices Can Be Made on Cost of Energy Basis**
- **The Impact of Dynamics Configuration Can Be Large**
- **There Are No Analytical Problems**
- **Intensive Study of Capital Cost and Energy Capture Impacts Are Required**
- **Design and Cost-Finding Refinement Can Change Early Judgements**

- **Present View of Superior System**
  - **— Two-Bladed, Teetered, Gravity-Balanced, Downwind Rotor**
  - **— Yaw Free with Δ_3 to Correct Heading Trim**
  - **— Soft, Tall Tower**
  - **— Softened and Damped Drive**
  - **— Full Span, Active Pitch Control**
  - **— Actuators in Rotating System**

Systems studies by Hamilton have spanned a wide array of concepts and dynamics design philosophies. We have kept pushing configuration improvement in all promising directions, rather than stop upon merely substantiating that a concept is feasible or satisfactory. At the same time, the behavior of unsatisfactory systems has been intensively studied to gain an understanding of cause and effect aspects and to build confidence in our computer codes.

Analysis in a time domain is of greatest engineering value because it displays both transient and steady state loads and stability conditions. System behavior can be studied, modified, and improved. Our F-762 program has had the benefit of validation during full-scale helicopter flight and wind tunnel tests and also for wind tunnel tests of scale model wind turbines. Although F-762 is still evolving in its detail features, it has become established as a very adequate and reliable design tool. It can handle wind turbine configurations that are much more difficult than those we are finding to be superior.

The dynamics of wind turbine generator systems exerts a large impact on the cost of energy for the system. Dynamics considerations can decrease capital costs and increase energy capture. System dynamics is also the key factor in the quest for unlimited fatigue life and increased utilization.

The major basic configuration options that were considered in the system dynamics trade-offs, and the resultant selected configuration, are listed below.

BASIC CONFIGURATION TRADE-OFFS IN SYSTEMS DYNAMICS

Stiff Vs. Soft Structural Design

Trimmed Vs. Untrimmed Vibratory Airloads

Configurations Examined:
- **Rigid Rotor on Stiff Tower with Stiff Drive System — First Generation**
- **Rigid Rotor on Soft Tower**
- **Cyclic Pitch Rotor on Stiff Tower**
- **Teetered Rotor on Stiff Tower**
- **Teetered Rotor on Soft Tower**
- **Soft Drive System with Torsional Damping**

Selected Configurations:
- **Teetered Rotor on Soft Tower**
- **Soft Drive System with Torsional Damping**

Why:
- **Large Reductions in Operating Loads**
- **Makes Soft Tower Feasible**
- **Simplifies Rigorous Analysis**
- **Soft Drive System Keeps System on Line**

One of the earliest design considerations is the form of the blade articulation. The chart below lists the three options studied, with resultant major advantages and disadvantages for each case.

The choice of a teetered (two-bladed) rotor configuration has large advantages and no significant disadvantages. When combined with a slender, soft tower and with soft drive system concepts, the teetered rotor presents such low vibratory load levels that there is no remaining reason for choosing an upwind rotor location. Unlike either hingeless or individually flap-hinged configurations, the teetered system can be so balanced that it achieves full, maximum energy capture when operating in a shear gradient.

For free-yaw operation the teeter hinge can be modified to correct a heading trim error that would sacrifice energy capture performance. The subject trim error is characteristic of all three blade articulation concepts when operating in a shear gradient.

FORM OF BLADE ARTICULATION

- **Hingeless**
  - **— Very Costly Vibratory Loads**
  - **— Yaw Rate and Yaw Angle Are Limited**
  - **— Cannot Be Positioned for Maximum Energy Capture**
- **Individual Flap Hinge**
  - **— Free of Flatwise Root Bending Loads**
  - **— No yaw Rate or Yaw Angle Limits**
  - **— Loss of Energy Capture Due to Excess Coning**
  - **— Inevitable Gravity Induced 2P Vibration**
  - **— Inevitable Gravity Induced Power Loss**
- **Teeter Hinge**
  - **— Free of Odd Integer Flatwise Root Bending**
  - **— No Yaw Rate or Yaw Angle Limits**
  - **— Coning Can Be Restrained**
  - **— Can Be Gravity Balanced**
  - **— Will Trim Itself for Maximum Energy Capture**

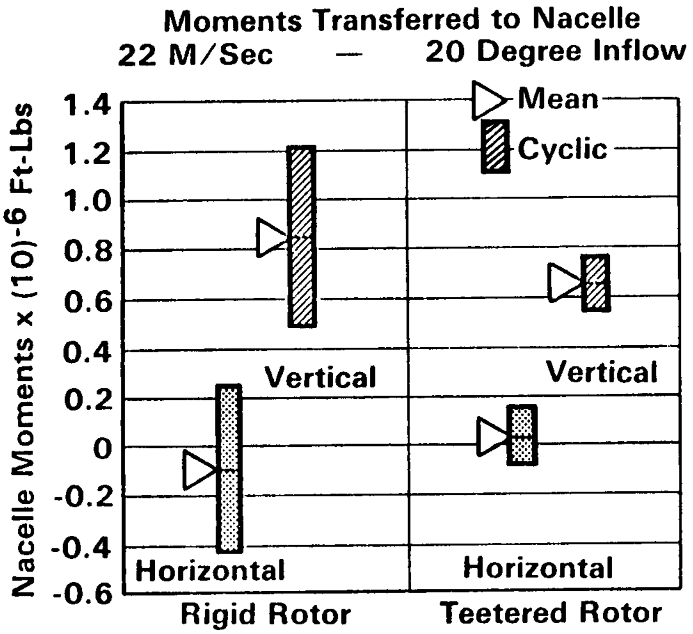
Reduction of system vibratory loads is the cumulative result of numerous choices available to the designer. As indicated previously, the form of blade articulation is a major factor.

The plot below shows the reductions of nacelle shaking moments that can be obtained from merely introducing a teeter hinge at the apex of the rotor cone. For this location, the residual vibratory moments are significant and of a two-per-rev frequency.

However, by placing the teeter hinge on the rotor center of gravity, these two-per-rev moments are reduced substantially to zero. Surprisingly, when the rotor is thus balanced, the energy capture also improves.

With the final balanced rotor, the only vibratory loads reaching the nacelle are small two-per-rev thrusts that exert only ±0.02 g on the nacelle. Tower vibratory stresses drop to only 2% of steady, thus eliminating fatigue as a design problem.

NACELLE AND TOWER LOADS REDUCTION



A second major design choice is the stiffness of the drive system and tower. Some major considerations regarding stiffness are listed in the chart below.

After thorough system dynamic study, it becomes apparent that there are very few aspects of wind turbine design that benefit from high stiffness. Stiffness is only essential and valuable to protect the blades against resonant first mode bending response to gravity loads. The choice of low stiffness design concepts directly attenuates the vibratory structural loads and improves the quality of the power delivered.

Low stiffness requires detailed attention to matters of system stability. However, solutions are found to be simple and straightforward.

SOFT VERSUS STIFF DESIGN CONCEPTS

- **Where Stiffness is Useful**
  - **First Edgewise Blade Mode to Preclude Gravity Resonance**
  - **First Flatwise Blade Mode to Resist Coning and to Avoid Gravity Resonance if Blade is Fully Feathered**
- **Where Stiffness is Detrimental**
  - **In Drive System It Precludes Benefits of Uncoupling the Rotor Inertia**
  - **In Tower It Moves Coupled Frequencies Up to Create Resonance Problems**
  - **In Blade Modes Above First It Inhibits Damping and Increases Bending Moments**
- **Stability Aspects**
  - **Modal Stiffness May Be Tailored to Assure Stability But High Stiffness Per Se is Not Required**
- **The Value of Low Stiffness**
  - **Reduced Vibratory Loads**
  - **Steady Power Output**
  - **Reduced Weight**

The major considerations involved in the question of fixed or variable pitch for the rotor are delineated in the chart below. Variable pitch can be either part span or full span.

Choice of partial span fixed pitch is of interest and feasible from the standpoint of system dynamics and of rotor aerodynamic performance. However, system studies to date indicate that partial span pitch leads to tower costs that tend to inhibit tower height increase. This in turn leads to poor COE performance in an environment that has a significant shear gradient.

Thus it appears that full-span pitch control will usually deliver best system COE performance.

FIXED VERSUS VARIABLE PITCH

- **Value of Fixed Pitch**
  - **Simplicity in the Rotor**
  - **First Flatwise Blade Frequency Can Be Reduced**

- **Obstacles to Achievement**
  - **Starting and Overspeed Control Not Provided**
  - **Energy Capture is Reduced in Synchronous Systems**
  - **Machine Comes Closer to Stall**
  - **Hurricane Loads Become Greater Problem**
  - **Higher Thrust Loads Lead to Limited Tower Height**

- **Prospective Compromise**
  - **Partial Span Control Can Remove First Flatwise Frequency Problem**
  - **Energy Capture Suffers Directly**
  - **Tower Height Compromise Also Loses Energy Capture**
  - **No Problem with Outboard Actuator Mass**

The question of degree of yaw control is addressed in the table below. The two options considered are active yaw control or complete yaw freedom.

Provided the system is given stable and correct heading trim characteristics when operating downwind, there appears to be no reason to adopt an active yaw control. The trim correction can be provided in teetered or individually flap-hinged configurations. Hingeless systems cannot be given the necessary stable heading trim behavior without adding complex corrective devices.

YAW CONTROL VS. YAW FREEDOM

- **Value of Yaw Control**
  - **Needed Only if Rotor is Upwind**
  - **Useful for Service Orientation**
- **Disadvantages**
  - **Consumes Parasite Power**
  - **Depends Upon Heading Sensors**
  - **Adds Capital and Maintenance Costs**
  - **Introduces Tower-Coupled Yaw Modes**
- **Essentials of Yaw Free Operation**
  - **Downwind Rotor**
  - **Stability**
  - **Inherently Correct Heading Trim**
  - **Feathered for Pre-Start**
  - **Vertical Parking**

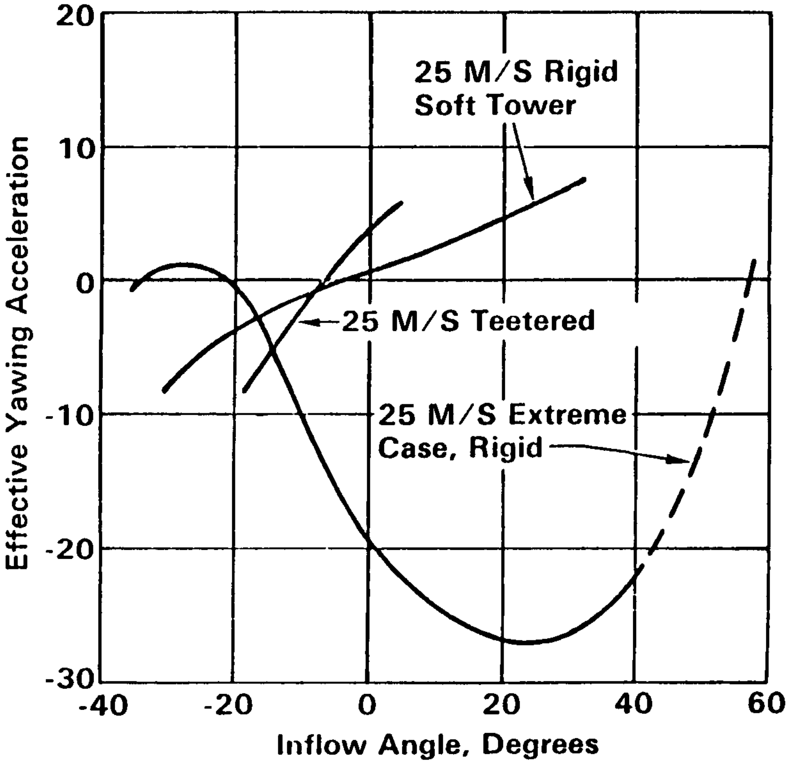
The characteristics of free yaw systems for several rotor configurations are shown in the plot below. Teetered and hingeless rotor are compared.

Both adverse yaw trim and heading instability are characteristic of hingeless free-yaw systems. As seen in the lower curve, a hingeless system under the influence of a torque limiting pitch control (well above rated power) has two stable trim positions - one at 35° left and another at 55° right yaw. An unstable equilibrium also exists at 22° left. This totally unsatisfactory trim behavior is accompanied by large vibratory loads build-up in the right yaw sector.

By contrast, the teetered rotor displays a highly stable behavior.

Also plotted is the surprising behavior of the rigid rotor when mounted on a very soft tower. Tower elastic deflection provides a teeter hinge effect and stabilizes the yaw behavior! The cost, however, is high vibratory loads in both rotor and tower.

HEADING TRIM AND STABILITY FOR FREE YAW SYSTEMS



The control of static and transient thrusts is discussed in the chart below. Static and transient thrusts have their impact on cost of energy through tower costs that inhibit tower height.

A softening of the tower has benefits analogous to a softening of the drive, in that system inertia is uncoupled to better absorb impulsive loads. As with the drive system, damping is needed to control transients. This is well provided in most modes by the inherently large aerodynamic damping forces that come from axial (thrustwise) motions of the rotor disk. Furthermore, torque control system design must also give attention to the thrustwise system modes and their responses to pitch change.

CONTROL OF STATIC AND TRANSIENT THRUSTS

- **Impact**
  - **Capital Cost of Tower Can Be Reduced**
  - **Blade and Hub Fatigue Life Are Enhanced**
  - **Tower Height Can Increase Energy Capture**
- **Feasibility**
  - **Benefit is Inherent with Torque Control**
  - **Applies Also to Stand-Alone Machines Because of Gearbox Cost Limits**
  - **Control Must Be Tailored to Avoid Adverse Effects in First Flatwise Blade Mode**
- **Related Issues**
  - **Rotor Thrust Damping is Large and Helpful**
  - **Tower Softness is Helpful**
  - **Stall As Thrust Limiter is Applicable Only to Synchronous Machines**
  - **Result, Fixed Pitch Constant Velocity Ratio Probably Uneconomic**

Good system damping is highly desirable. Considerations involved in system damping are listed in the table below.

It is found that systems that apply low stiffness design concepts are easily provided with good damping in all the pertinent modes. This in turn means that a given system can be run satisfactorily at various rotational speeds. Attention to achieving this capability can pay off in freedom to change operating speed with changes of site conditions.

ASSURANCE OF GOOD SYSTEM DAMPING

- **Impact**
  - **Ability to Run On or Across Rotor Resonant Frequencies**
  - **Rapid Decay of Tower Bending Transients**
  - **Rapid Damping of Torque Transients**
- **Feasibility**
  - **Flatwise Blade Modes Are Well Damped**
  - **Tower Bending Modes Are Well Damped**
  - **Damper on Gearbox Gets the Even-Integer Edgewise Blade Modes**
  - **With Soft Tower the Rotor Thrust Damping Gets Most of the Odd-Integer Edgewise Blade Modes**
  - **Damping Around the Yaw Bearing Can Get the Remaining Odd-Integer Blade Modes**
- **Related Issues**
  - **Ability to Adjust Operation to Various Average Wind Velocities**
  - **Ability to Run at Variable Speed Under Non-Synchronous Loads**
  - **Control System Design Requirements Are Eased**

The attainment of unlimited fatigue life is an important objective for system design. The factors involved in this quest are presented in the chart below.

Virtually all of our dynamic configuration improvement choices have contributed to reducing vibratory loads and to easing the fatigue design task. Concurrently we have found that high wind, turbulent conditions can be accommodated without protective cutoff that would cost any significant energy capture. The choices that enable these gains have also been found to simplify the structure, eliminate subsystems, reduce weight and enhance energy capture.

ATTAIN UNLIMITED FATIGUE LIFE

- **Objectives**
  - **Avoid Premature Retirement**
  - **Reduce Maintenance and Inspection**
  - **Accomplish without Increased Capital Cost**
- **Approach**
  - **Reduce Applied Vibratory Loads**
  - **Reduce Dynamic Response**
- **Methods**
  - **Eliminate First Harmonic Airloads with Teeter Hinge or Cyclic Pitch**
  - **Uncouple Blade from Fixed System**
    - **a) For Flatwise Bending — Teeter Hinge**
    - **b) For Torque-Torsionally Soft Shaft**
  - **Provide Multi-Modal Damping**
    - **a) Gear Case Damper**
    - **b) Nacelle Yaw Damper**
  - **Provide Fast Pitch Control**

CONCLUSION

We have found that there is a large payoff from intensive effort to improve the system dynamics configuration. To apply the results most effectively, however, the design must evolve under constant and thorough scrutiny of the cost of energy impact of each choice.

DISCUSSION

Q. In conjunction with the rpm sweep from 25 to 85 rpm which passed through all of the resonances, what was the chordwise natural frequency at the high rpm?

A. I don't recall a specific number, but the natural frequency remained well above one-per-rev. That model was run in an overspeed condition while searching for coupled mode instabilities on the soft tower. They were found around 150 rpm. The gravity edgewise resonance was well above 80 rpm. Also, we were very interested in whether yaw motion damping would be needed in the system. The conclusion, to our surprise, was that it wasn't.

Q. Did you evaluate the possibility of having perhaps a selection of two or three frequencies as would be obtained from a gearbox or drive type of arrangement, instead of going with continuous variable tip speeds?

A. That point is included in the study, but not very vigorously. We at Hamilton Standard are waiting now for the results of an electrical system study. My personal opinion at the present time is that it will be just as economical to have an electrical torque control which can hold a constant velocity ratio as any other way.

Q. Would it be preferable for the blade to be on the stiff and lightweight side?

A. As a previous comment pointed out, the blade has to be stiff enough edgewise to avoid the one-per-rev gravity resonance. It is not an important problem in the flatwise direction.