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SELF-REGULATING COMPOSITE BEARINGLESS WIND TURBINE

Executive Summary, June 3, 1975—June 2, 1976

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Work Performed Under Contract No. E(11-1)-2614

United Technologies Research Center
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Self-regulating Composite
Bearingless Wind Turbine

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SUMMARY

An investigation was conducted into the feasibility of applying the Composite Bearingless Rotor (CBR) concept to wind turbines. The CBR was developed for helicopter application in an attempt to reduce the high costs, weight, and complexity of current helicopter designs. The CBR blade is comprised of a conventional blade construction over the outboard span, but inboard is made up simply from a finite length (about 15% of the radius) of unidirectional composite material. This member, called the flexbeam, replaces the hinges and bearings normally located at the blade root and provides the necessary flatwise and edgewise stiffness, but due to the unidirectional fiber alignment, has low torsional stiffness. Blade pitch control is achieved by applying a moment at the outboard end of the flexbeam and elastically twisting it.

The study also examined several innovative self-regulating concepts made possible by the specialized properties of the CBR hingeless rotor. These concepts included a self-starting mechanism which is self contained and requires no external actuators or sensors. This device allows the turbine to accelerate from zero rpm and adjusts the blade pitch automatically as wind speed varies. A wind alignment capability resulting from the inherent dynamic response characteristics of the blades, provides a system in which the turbine axis continuously aligns itself to the wind without the need for external controls. The objective of achieving a fully self-regulating system is to reduce or eliminate the costs associated with maintenance of pitch and yaw controls and the power required to operate them.

The work described in the final report was conducted under contract with ERDA and consisted of the design and fabrication of a dynamically scaled wind turbine model, the wind tunnel testing of this model, and the evaluation of several control concepts in an attempt to achieve a self-regulating system. Such a system was achieved and experimentally demonstrated in the wind tunnel. Operating characteristics at wind speeds exceeding 30 mph were investigated and simulated start ups and wind direction changes were successfully executed. The test encompassed all normal wind conditions anticipated for a full-scale system, and the rotor showed high stability, and during transient motions, displayed favorable damping characteristics. Blade stresses were measured during the test and under all conditions tested, the stress levels were well below allowable limits.

INTRODUCTION

Much of the work in recent years in the field of wind energy conversion systems has been related to investigations of total system concepts and the general energy producing capability of rotors designed around current state-of-the-art aerodynamics. The general theme which one obtains from recent reports is that wind energy systems must be developed, installed, and operated at costs that are competitive with alternate forms of energy conversion. To achieve this, all high cost aspects of such systems must be identified and dealt with as efficiently as possible before proceeding to full-scale development. Significant progress can be made in this regard in the area of the principle component of a wind energy conversion system -- the rotor itself.

A major activity in rotary wing research in recent years has been directed at the task of reducing costs. Progress has been made to achieve lower costs through the application of new rotor concepts, improved manufacturing and construction techniques, and the use of advanced composite materials. The experience gained in these areas can now be applied to other rotor or propeller systems, such as wind energy conversion systems, to achieve improvements in life cycle costs over that which would be expected for systems based on technology of a few years ago. In addition to cost reductions available through general advancements in rotary wing state-of-the-art, potential improvements specifically related to wind energy conversion systems become apparent. These are related to the control of such systems to maximize efficiency over the full range of operating conditions, which requires control of rotor axis alignment, rotational speed, and blade pitch. Further controls are desirable to guard against blade or tower failures resulting from gusts and excessive wind velocities. The objective of this study is to show that most of these controls can be achieved automatically (aerodynamically or mechanically) without the need for exotic sensing mechanisms or energy absorbing subsystems which would increase costs and reduce reliability. The specific rotor system studied is the Composite Bearingless Rotor (CBR), which has been under development at the United Technologies Research Center (UTRC) and the Sikorsky Aircraft Division for eight years. Full-scale main and tail rotors have been fabricated and tested during the past two years and 30 percent reductions in weight have been achieved and cost reductions up to 30 percent have been projected for production designs. The Sikorsky UTTAS aircraft employs a CBR tail rotor and experience to date indicates a 50 percent reduction in maintenance over conventional tail rotors. The Composite Bearingless Rotor particularly lends itself to innovative concepts in automatic control by virtue of its unique aeroelastic characteristics. The purpose of this research program was to experimentally examine the CBR as a wind turbine and several mechanisms designed to achieve a self-starting and self-regulating system.

EXPERIMENTAL PROGRAM

Model Design

Before a dynamically scale model could be designed, a typical full-scale wind turbine had to be selected so that its stiffness characteristics could be realistically scaled. The design selected was similar to the 125ft Mod 0 turbine constructed by NASA. The important nondimensional frequency and mass parameters were maintained for the model design to ensure that the response characteristics would be equivalent. Full scale tip speeds and wind speeds were retained; however, gravity effects could not be accurately simulated.

In keeping with the size restrictions of the low speed wind tunnel scheduled for this experiment, the model diameter was set at 4.5 ft. Four blades were used and consisted of a carbon/epoxy spar and inboard "flexbeam" with the aerodynamic portion constructed of balsa wood. Tip speeds up to 300 ft/sec were anticipated.

Model Tests

The model tests consisted of four basic control configurations: 1) fixed pitch without pitch-flap coupling, 2) fixed pitch with pitch-flap coupling, 3) control pendulum fixed to the outboard end of the flexbeam, and 4) control pendulum supported at the hub.

The fixed pitch configurations produce performance and stress results typical of conventional designs and were tested primarily to obtain baseline data. The blade supported pendulum configuration resulted in a low torsional frequency, approximately equal to the rotational frequency, and therefore was easily excited by once-per-revolution excitation such as that produced by the tower wake. The tests of this configuration indicated questionable stability and therefore were discontinued. The final configuration, the hub mounted pendulum, achieved the self starting and self regulating features desired, and it is only this configuration, which will be discussed in this executive summary report.

A photograph of the model and support tower is presented in Fig. 1. A close up of the hub area depicting the details of the pendulum control mechanism is shown in Fig. 2. The weights shown are mounted so as to form a pendulum with a natural frequency of approximately 1.5 times the rotational frequency. The flexbeam torsion spring and the spring due to pendulum flapping are continuously in equilibrium via the steel connector strap. The connector can flex to absorb the changes in distance between the pendulum and the end of the flexbeam due to coning angle and rpm. When the pendulum is mounted statically on the downwind side of the turbine disc, as shown in Fig. 2, a negative sign for $d\theta/d\Omega$ results, producing

an rpm-governor type mechanism. With the pendulum located at the upstream side of the turbine disk, a positive $d\theta/d\Omega$, or self starting configuration is obtained. The effects of both types of coupling on the performance of the wind turbine are shown in Fig. 3. In the rpm-governor configuration of the pendulum, the tip speed variations with wind speed are less, as expected, than those for a fixed pitch condition. In contrast, the tip speed for the self-starting configuration increases more rapidly with wind speed. Figure 4 shows the time history of the self-starting configuration at a wind speed of 25.8 mph where the static pitch angle was set at -31° . The turbine is initially yawed -90° . It is then released at $t = 0$, and initially the turbine weathervanes to the downwind position in a second order fashion. The tip speed then increases, and after about two seconds the pitch angle, under the action of the pendulum motion, begins to increase. This causes the continued acceleration through the start up. The torsional stresses change proportionally with the pitch angle. The edgewise and flatwise stresses show, at 14 seconds after release, a slight amplification at 6P which is caused by the coalescence of the 1st edgewise and the 2nd flatwise natural frequencies. However the amplification is relatively mild and is quickly passed through.

The capability of the turbine in the self-starting configuration to respond to sudden wind direction changes is shown in Fig. 5. The turbine, rotating at its high rotational speed equilibrium is released from a preset yaw angle. In a first order fashion the turbine tends to realign with the wind. The initial flatwise stress amplitude is due to the large helicopter type cyclic input because of the initial yaw angle. The results demonstrate that the CBR wind turbine in its self-starting configuration is self-aligning to the wind, self regulating in rpm by means of automatic pitch changes, and has low vibratory stress levels during normal maneuvers of start up and alignment.

CONCLUSIONS

The conclusions set forth below were arrived at as a direct result of the model test program conducted under this contract. Since the model was dynamically scaled it is expected that the conclusions are applicable as well to full-scale designs. However some variations in the full-scale characteristics might be expected as a result of the Reynolds number and Froude number difference, but the conclusions reached should generally be applicable. Reference to normal wind speeds means speeds up to approximately 30 mph.

1. The Composite Bearingless Rotor (CBR) can be used in conjunction with a hub-mounted pendulum to produce a self-regulating stable wind turbine. Self regulating is defined as self starting with an automatic pitch-RPM schedule to provide efficient power output at all reasonable wind speeds.
2. Wind turbines having hingeless blades of conventional stiffness, and free to yaw, have inherent dynamic moments which tend to maintain alignment of the turbine axis with the wind.
3. The CBR wind turbine in its self regulating configuration operates well below stress allowables for normal wind speeds. This characteristic is independent of wind direction, initial yaw position, and initial rpm, and encompasses transient as well as steady operation.
4. For a free yawing wind turbine designed for operating downstream of the support tower, the rotor drag when nonrotating is normally sufficient to align the turbine to the wind for any initial wind direction.
5. The equilibrium yaw position for a free yawing wind turbine operating downstream of its support tower is skewed from the downwind position. This is due to unloading of the downward blade caused by the reduction in wind velocity behind the tower.
6. The CBR wind turbine with fixed pitch performs as a conventional wind turbine.
7. Blade stress levels are well below allowables when fully feathered and nonrotating at windspeeds up to 60 mph.
8. A CBR wind turbine with a self regulating pitch control comprised of a pendulum fixed to the blade which produces a torsional frequency near the rotor speed (1P), is unstable.

RECOMMENDATIONS

The initial objective of the research program described herein was to determine a wind turbine configuration which demonstrated the potential for significant improvements in cost effectiveness over conventional designs. This particular study concentrated on the rotor itself and methods by which its initial and operating costs could be reduced. The study has shown that significant improvements could be expected by application of the Composite Bearingless Rotor (CBR), already established for helicopter applications as a simple low cost concept, and utilizing its specialized aeroelastics to evolve a completely self regulating system. Such a system has been experimentally demonstrated using a small dynamically scaled model. An important milestone has been reached, however additional research is recommended before substantial investments are made in full-scale hardware.

Two particular areas related to the operation of the rotor itself are: 1) the performance and self regulating characteristics when operating in a more realistic Reynold's number environment, and 2) the self aligning and self-regulating characteristics when coupled with a dynamically realistic tower. Design studies should also be conducted for a moderate size full-scale prototype, and that plans be established for an extended demonstration of the complete wind turbine system employing the CBR self-regulating concept.

FIGURE 1 : PERSPECTIVE VIEW OF MODEL
WIND TURBINE AND TOWER

FIGURE 2 : CONFIGURATION WITH HUB-MOUNTED PENDULUM

FIGURE 3: PERFORMANCE OF HUB-MOUNTED PENDULUM CONFIGURATION

FIGURE 4 : TIME HISTORY OF STARTUP IN SELF-STARTING CONFIGURATION.

$V_{WIND} = 20 \text{ MPH}$ $\Omega R = 282 \text{ FPS}$

FIGURE 5 : RESPONSE OF WIND TURBINE TO SIMULATED ABRUPT WIND CHANGE.

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