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Development of Methodology for Horizontal Axis Wind Turbine Dynamic Analysis

Summary Report

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Massachusetts Institute of Technology

September 1982

for
U.S. DEPARTMENT OF ENERGY
Conservation and Renewable Energy
Division of Photovoltaic Energy Technology

NOTICE

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Summary Report

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INTRODUCTION

The present report briefly summarizes the work done at the Massachusetts Institute of Technology under NASA Grant NSG-3303, "Development of a Methodology for Horizontal Axis Wind Turbine Dynamic Analysis". The work took place over a period of three years. The NASA Technical Officer was David C. Janetzke, and the principal investigator was Professor John Dugundji of the Department of Aeronautics and Astronautics at M.I.T. Two graduate and one undergraduate student participated in this work.

The stated purpose of this grant was,

(a) To develop state-of-the-art design tools for horizontal axis wind turbine dynamics.

(b) To review existing codings and analytical techniques to establish the state-of-the-art.

(c) To develop simple auxilliary design models for structural dynamic loads and stability behavior of horizontal axis wind turbines.

To accomplish some of the above purposes and ends, the work on this grant covered the below listed areas.

1.   Review of the MOSTAS Computer Program

A study and review was made of the MOSTAS computer code for horizontal axis wind turbines. The techniques and methods used in its analyses were examined in some detail. Some impressions of its strengths and weaknesses, and some recommendations for its application, modification and further

development were made. Additionally, some basic techniques used in general wind turbine stability and response analyses for systems with constant and periodic coefficients were reviewed and summarized concisely. A report on this work was written by Dugundji and Wendell, Ref. 1.

2. Analysis Methods for Rotating Systems with Periodic Coefficients

A study and review was made of various analysis methods for determining the dynamic stability and forced response of rotating wind turbine systems with periodic coefficients. Floquet methods, multiblade coordinates and harmonic balance methods, rotating coordinates, and perturbation methods were all reviewed and described in a concise succinct fashion. This work resulted from the previous study of the MOSTAS Computer Program, and appeared in the Appendices of Ref. 1. A preliminary version of this work was given at the 2nd DOE/NASA Wind Turbine Dynamics Workshop, Cleveland, Ohio, Feb. 24-26, 1981 by Dugundji and Wendell and was published in the conference proceedings, Ref. 2. A revised and ammended version by Dugundji and Wendell has been submitted for publication in the AIAA Journal, Ref. 3.

3. State-of-the-Art Review of Structural Dynamics Analysis Tools for
Large Wind Turbines

The principal investigator of this grant participated along with three others, namely, R.W. Thresher, K.H. Hohenemser, and W.C. Walton, Jr., in a state-of-the-art review on structural dynamics analysis tools for design of large wind turbines. This was based on personal impressions and information gathered at the 2nd DOE/NASA Wind Turbine Dynamics Workshop, Cleveland, Ohio, Feb. 24-26, 1981. The above dynamics workshop was attended, and a memorandum

was written reviewing the meeting and attempting to describe the current
state-of-the-art in wind turbine aerodynamics, structural dynamics, acoustics,
and electrical and control systems. The author's contribution to this review,
along with those of the three other reviewers is given in Ref. 4.

4. Yaw Characteristics of a Rotating Rotor

Some experiments were made on the fixed yaw moments and on the free yaw
characteristics of a 2 foot (.610 m) diameter rotor with varying amounts of
precone, spinning in a wind tunnel. Yaw moments were measured for both upwind
and downwind configurations. Also, the rotor was set free and the free yaw
behavior was examined. It was found that at high rotation speeds, the rotors
were stable in yaw and lined up with the wind, while at low rotation speeds,
the rotors were unstable and would yaw out of the wind. This prevented the
turbine from spinning up, unless it was locked into the wind. A report on
these experiments has been written by Bundas and Dugundji, Ref. 5. These
simple experiments could provide useful data for checking out theoretical
calculations for yaw characteristics of wind turbine rotors.

5. Finite Element Models for Rotors

A finite element program has been set up for obtaining the static
quiescent position, bending moments, vibration moments, aeroelastic stability,
and dynamic response of a rotating blade on a fixed hub. The analysis allowed
for flatwise bending, chordwise bending, and torsion of a twisted blade, and
included aerodynamic forces, pitch link stiffness, and root attachment details.
This finite element analysis parallels in some details the analyses given by
Friedmann and Straub, Reb. 6, and Sivaneri and Chopra, Ref. 7. Additionally,

the finite element analysis has been extended to allow for small vibrations of a blade which is bent into an initially curved shape (i.e., large, swept back propeller blades). This finite element work formed an M.S. thesis by Kamoulakos, and appears as Ref. 8.

6.   Simple Models for Aeroelastic Stability of Wind Turbines with Fixed Hub

This work presents a systematic derivation of an equivalent hinge model to study the flap-lag-torsion aeroelastic stability of an isolated blade. Equations of motion, aerodynamic forces, and an ordering scheme for higher order terms were derived, then a parametric study of the resulting equations was made to identify regions of possible aeroelastic stability. Comparisons of the equivalent hinge model with a generalized coordinate, modal model showed generally good agreement. This work formed part of a Ph.D. thesis by Wendell, and appears as the first part of Ref. 9.

7.   Simple Models for Stability and Response of Wind Turbines on Flexible Towers

This work included formulation of a general 11 degree of freedom rotor-tower system for a two-bladed rotor, and includes blade flapwise bending for each blade, blade chordwise bending for each blade, teetering motion of the rotor, three translations of the hub point, and three rotations of the hub point (pitch, yaw, and torsional motion of the shaft). Aerodynamic loads were obtained using quasi-steady strip theory and included wind shear and crossflow. Additionally, a systematic harmonic balance solution method was developed for the resulting system of second order equations with periodic coefficients.

The method applies not only to steady state response calculations, but to stability and transient response analysis as well.

The solution techniques above were applied to a simple 3 degree of freedom rotor-tower model which includes nacelle yawing, nacelle pitching, and rotor teetering. Transient response time histories were calculated and compared to a similar model by Janetzke and Kaza, Ref. 10. Agreement between the two was good, especially considering how few harmonics were used. Finally, a stability study was presented which examined the effects of support stiffness, support damping, inflow angle, and preconing. This rotor-tower work forms part of a Ph.D. thesis by Wendell, and appears as the second part of Ref. 9.

CONCLUDING REMARKS

It is hoped that the preceding investigations have contributed to better general knowledge and understanding of horizontal axis wind turbine analysis and behavior, needed for preliminary design of such turbines. The principal investigator wishes to acknowledge the helpful guidance and advice of Professor R.H. Miller of M.I.T. on this grant. Also Professor M. Martinez-Sanchez participated in various discussions.

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16 Abstract

This report briefly summarizes the work done at the Massachusetts Institute of Technology under NASA Grant NSG-3303. The 3-year effort included:
(1) Review of the MOSTAS computer programs for dynamic analysis of horizontal axis wind turbines
(2) Review of various analysis methods for rotating systems with periodic coefficients
(3) Review of structural dynamics analysis tools for large wind turbine
(4) Experiments for yaw characteristics of a rotating rotor
(5) Development of a finite element model for rotors
(6) Development of simple models for aeroelastic
(7) Development of simple models for stability and response of wind turbines on flexible towers

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