EXPERIENCE ON THE USE OF MOSTAB-HFW COMPUTER CODE FOR HORIZONTAL-AXIS WIND TURBINES

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ABSTRACT

Experience gained from the dynamic analysis of horizontal axis turbine rotors based on the use of the MOSTAB-HFW computer code is described. Three topics are covered, dealing with the frequencies of a rotating beam, the use of the fundamental mode of a uniform cantilever beam, and the analysis of resonance dwell. Immensely high peak loads were generated by the code for resonance dwell, indicating further need for including structural damping and for transient analysis capability. The effect of structural damping, newly incorporated in the code, is finally described.

INTRODUCTION

The MOSTAB-HFW computer code was developed by Paragon Pacific under support from NASA Lewis Research Center for the dynamic analysis of horizontal-axis wind turbine rotors. Experience on the use of the code is described in this paper. Three topics are covered.

FREQUENCIES OF ROTATING BEAM

The first topic deals with the frequencies of a rotating beam, which are needed as input to the MOSTAB-HFW code. Based on the numerical results of Yntema (Ref. 1), a simple expression has been derived relating the frequency of a rotating beam to that of the same beam without rotation. For wind turbine blades with commonly used dimensions, the expression is very convenient and accurate enough for preliminary design and analysis purposes. The derivation is presented below.

Yntema (Ref. 1) has given the frequency of a rotating beam by the equation

$$\omega_{Rn}^2 = \omega_{NRn}^2 + (K_{0n} + K_{1n}e)\,\Omega^2$$

where ω_{Rn} and ω_{NRn} are frequencies of the beam with and without rotation, respectively, K_{0n} and K_{1n} are dimensionless coefficients, the subscript n denotes the mode, e is the ratio between the offset and the beam length, and Ω the rotation speed. This equation is quite general and applicable to nonuniform beams with a large variety of mass and stiffness distributions. For linear mass and stiffness distributions Yntema calculated K_{0n} and K_{1n} for the first three modes of hinged and cantilever beams. The linear distributions vary from a beam with constant-mass and/or constant-stiffness to a beam whose mass and/or stiffness diminishes all the way down to zero at one end of the beam.

Yntema's results for K_{01} and K_{11} for the fundamental modes of cantilever beams deserve special attention, because these modes play an important role in the dynamics of wind turbine blades and are needed in the MOSTAB-HFW code. Such results are given in his Figs. 15 and 16.

It is noteworthy that, for the wide range of linear mass and stiffness distributions these coefficients lie within limited ranges:

$$1.17 < K_{01} < 1.26, \quad 1.57 < K_{11} < 1.93$$

Thus, K_{01} already lies within a very narrow band. Although K_{11} does not, we note that the offset ratio e is seldom greater than 0.1 for wind turbines. Hence, by assuming a maximum value of $e = 0.1$, we have

$$0.157 < K_{11}e < 0.193$$

and, for $e \leq 0.1$

$$1.17 < (K_{01} + K_{11}e) < 1.45$$

This interesting result shows that $(K_{01} + K_{11}e)$ has only a limited variation for $e \leq 0.1$. Within 11 per cent accuracy we propose to take simply

$$(K_{01} + K_{11}e) = 1.31 \text{ for } e \leq 0.1$$

The fundamental frequency of a rotating cantilever beam is then given by

$$\omega_{R1}^2 = \omega_{NR1}^2 + 1.31\,\Omega^2$$

For some blades analyzed by the use of this equation, the accuracy on ω_{R1} has been found to be within 1 per cent.

USE OF FUNDAMENTAL CANTILEVER MODE

The next topic is associated with the natural modes of vibration of the blade which are also needed as input to the MOSTAB-HFW code. Although the code can accommodate coupled modes including flapwise and chordwise bending together with twisting of the blade, the use of the fundamental mode of a uniform cantilever beam for both flapwise and chordwise bending has been found to be satisfactory for quick calculation of the dynamic loads. This is essentially to apply the classical

Rayleign procedure in structural dynamics to the computer computation.

The use of the fundamental cantilever mode simplifies the execution of the MOSTAB-HFW code greatly. The mode is well known and can be entered as input once for all, regardless of the values of the associated bending frequencies. The advantage of this is obvious, particularly during preliminary design and analysis of the rotor blade, when many changes may be needed.

The use of the fundamental cantilever mode in the code has been compared with the use of coupled modes in sample calculations. Differences between the resulting blade peak and cyclic loads ranged from 8 per cent for the twisting moment to 23 per cent for the flapwise bending moment. These are considered satisfactory, since the loads generated by the MOSTAB-HFW code can deviate from the test data by as much as 25 per cent, as reported by Spera (Ref. 2).

RESONANCE DWELL

The third topic in this paper deals with resonance dwell. This is when the ratio between a natural frequency of the blade and the rotor speed is an integer. Such a situation is naturally to be avoided in the design for the normal operation of a wind turbine. However, it cannot be avoided during a transient operation such as start-up, shut-down, or emergency shut-down, when the rotor speed varies and passes through resonances with the blade. Resonance dwell represents the limiting case of constant rotor speed or zero rotor acceleration and can be handled by the MOSTAB-HFW code, although the code does not treat the general transient case with a non-zero acceleration.

The importance of accommodating transient operations in the design of wind turbines cannot be overemphasized. Dynamic loads on the blades of the MOD-0A wind turbines were measured during actual transient operations and found to be four to five times the loads during normal operation (Ref. 3). High transient loads have also been reported by Dugundji (Ref. 4), who tested a small wind turbine model in a wind tunnel at MIT.

It had been hoped that, in the dynamic analysis of a wind turbine, results of trim analysis during resonance dwell based on the use of the MOSTAB-HFW code would shed some light on what might happen when the rotor speed was varying and passing through a resonance. Unfortunately, the peak loads generated by the code for resonance dwell turned out to be too high to be realistic. For instance, in one case of resonance dwell the code generated a maximum flapwise bending moment in the blade 36 per cent higher than that for normal operating speed, a maximum chordwise bending moment more than 5 times higher, and a maximum shaft torque more than 16 times higher.

The very high loads for resonance dwell given by the MOSTAB-HFW code were due to lack of structural damping in the code. The results reflect the extreme sensitivity of the structurally undamped dynamic system as treated by the original code. They point to the need for including structural damping and for transient analysis capability.

EFFECT OF STRUCTURAL DAMPING

In view of its apparent importance, structural damping was recently incorporated in the MOSTAB-HFW code by Paragon Pacific, in addition to the already present aerodynamic damping. The same case of resonance dwell mentioned before was analyzed again by means of the code, only now with 2 per cent of critical damping added for both the flapwise and chordwise bending modes. The maximum flapwise and chordwise bending moments in the blade and maximum shaft torque were found to be 69, 18, and 12 per cent, respectively, of their previous level for zero structural damping. The load reduction was, therefore, drastic.

REFERENCES

1. Robert T. Yntema, Simplified Procedures and Charts for the Rapid Estimation of Bending Frequencies of Rotating Beams, NACA Technical Note 3459, June 1955.

2. David A. Spera, Comparison of Computer Codes for Calculating Dynamic Loads in Wind Turbines, NASA TM-73773, September 1977.

3. Project Information Release No. 158, Wind Energy Project Office, NASA Lewis Research Center, 1980.

4. J. Dugundji, E. E. Larrabee, and P. H. Bauer, Experimental Investigation of a Horizontal Axis Wind Turbine, Wind Energy Conversion, Vol. V, ASRL TR-184-11, Aeroelastic and Structures Research Laboratory, Department of Aeronautics and Astronautics, MIT, 1978.

QUESTIONS AND ANSWERS

Y.Y. Yu

From: G. Beaulieu

Q: Does your constant K values consider the reducing stiffness of the cantilever blade? If not, your resonant frequencies will be shifted.

A: *The values of K_{on} and K_{ln} given by Yntema cover a large variety of linear stiffness (as well as mass) distributions. The final approximate frequency equation in the paper therefore applies to cantilever blades with such stiffness variations.*

From: T. Currin

Q: After rough approximations of input, is using a large code, i.e., MOSTAB, justified?

A: *The use of approximate frequencies and mode shapes as indicated in this paper saves time for preparing input during the early stage of design when a number of configurations may be considered and many changes needed. When the design is narrowed down, such approximations are replaced by more accurate values while many other inputs to the code remain the same. The use of the code at an early stage therefore does not add much to the analysis work.*

From: Jack Landgrebe

Q: Does your sensitivity demonstration indicate that you can get any answer with different dampings and what answers do you believe?

A: *Data on structural damping of wind turbine blades are lacking because little attention has been paid to such damping. When it is better known, the transient loads can be estimated more accurately.*

From: W.C. Walton

Q: 1) Should results be compared with "normal operating loads" or with design loads?

2) Please explain the term fixed axis.

A: *1) The transient loads are compared with normal operating loads because both must be taken care of as far as structural strength is concerned, although their fatigue effects are different due to the different numbers of cycles during the life of the wind turbine.*

2) The MOSTAB-HFW code assumes a rotor with a fixed axis in space. In other words, the rotor is assumed to be uncoupled from the other components of the wind turbine system. In contrast, the MOSTAS code considers the interaction between the rotor and the other components.

From: Anonymous

Q: How was damping incorporated into MOSTAB and what is required for <u>input data</u> to take this into account?

A: *Modal damping was introduced for each mode in the form of a viscous damping term. Damping ratio (percentage of critical damping) is assigned to each mode as input.*

From: Jack Hoffman

Q: Why did the flap loads go up with damping?

A: *The flapwise bending moment did not go up. With 2 percent damping, the moment was 69 percent of its value for zero damping.*