Determination of Wind Turbine Blade Flapwise Bending Dynamics

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Abstract

Damages related to flapwise bending of wind turbine blades is a very common type of failure experienced by small wind turbines in Thailand. Turbine blade structural designs and hub connections are usually capable of withstanding steady high speed wind. However, when it comes to unsteady flows, especially strong gusts, the wind turbine blade structural integrity is often vulnerable. Had the wind turbine experience a steady rise of wind speed, the local angle of attack at every blade element would have been kept relatively low due to the increasing rotor rotation speed at high wind speed. However, the gusts usually happen so quickly that the rotation speed is incompatible to the approaching wind resulting in exceedingly large local angle of attack which, in turn, causes large drag forces and bending moment in the flow direction. The resulting deflection may be catastrophic. This research work aims to study the flapwise bending dynamics of a wind turbine blade by assessing the blade flapwise equation of motion. The analysis focuses on Hopf bifurcation determination (instability analysis) with respect to changes in governing parameters, in this case, wind velocity and the blade structural stiffness. The calculation procedures and example results may be used by blade designers in material selection, connection type selection and establish the wind turbine safe operational envelope.

***Keywords**: Wind turbine blade, flapwise bending, Hopf bifurcation, stability analysis.*

Nomenclature

β = Flapping angle (radians)

γ = Lock number

ψ = Azimuth angle (radians)

$\bar{V}_0$ = Non-dimensional cross flow

$\bar{q}$ = Non-dimensional yaw rate term

$\bar{d}$ = Normalized yaw moment arm

K = Flapping inertial natural frequency

B = Gravity term

A_3 = Axisymmetric flow term

K_{vs} = Vertical wind shear constant

$\bar{U}$ = Normalized wind velocity

ε = offset term

I_b = mass moment of inertia of a single blade

Ω = rotor rotational speed

K_β = flapping spring constant

1. Introduction

Wind energy is undeniably an integral part of Thailand and the world foreseeable future energy roadmap. Since 2000, the global wind power capacity has been steadily increasing and in 2007 alone, the annual installed capacity reached 20GW bringing the global total capacity to nearly 80GW. Nearly half of the new installations are based in the United States [1]. According to Electricity Generating Authority of Thailand (EGAT) Power Development Plan 2004, Thailand will have installed 68.25MW of wind power by 2015. This figure seems dwarfed when compared to the installation scale in other countries but considering the installation costs of these projects, the amount of capital required proves to be significant [2]. This is a common situation for a country beginning to adopt wind energy such as Thailand where there are shortages of trained personnel, technical expertise and infrastructure. Hence, this research work will directly benefit the country wind energy sector by delivering a wind turbine blade stability analysis method which is fundamental to wind turbine design.

Wind turbines are constantly exposed to possible damages caused by forces of nature such as monsoon storms, lighting strikes, hail, gusts, etc. Preventive measures are usually included in the design process so that wind turbines can operate safely. It is worth noting that this research will only focus on three-bladed HAWTs. Strong horizontal gust occurrences are difficult to predict and they can cause serious damages to wind turbines. Most modern three-bladed multi-megawatt wind turbines employ a safety system which shuts down the turbine operation when the wind speed exceeds a certain value for a period of time, normally referred to as the cut-out wind speed. This is typically accomplished by deliberately pitching the turbine blade up into stall regime or yawing the wind turbine away from the wind direction. This safety system is only applicable in the case of strong continuous wind. However, gusts happen very quickly and last only a few seconds, but they are enough to cause large impulsive aerodynamic loads on the blades that can result in blade destruction. Flapwise bending type damage is a very common gust related problem. Figure 1 illustrates the degree-of-freedoms of a wind turbine, including flapwise direction. An example of wind turbine flapwise bending damage is shown in figure 2. It shows a deformed metal bracket used for supporting the 2-metre span blades of a 4.5kW wind turbine. Several other units have also been damaged in this fashion during operation.

Wind turbine aeroelastic stability has already been studied in details by many, for instance [3, 4]. A major flaw in a large number of research works in this area is in the accuracy of aerodynamic loading calculation. The local angle of attack on the blade element of the blade is a variable due to the changing azimuth angle, the rotor angular velocity (tip speed ratio), the tower shadow, the atmospheric boundary layer, the wake of other turbines, and the turbulence intensity. These factors cause the local angle of attack to be a time-variable and the steady

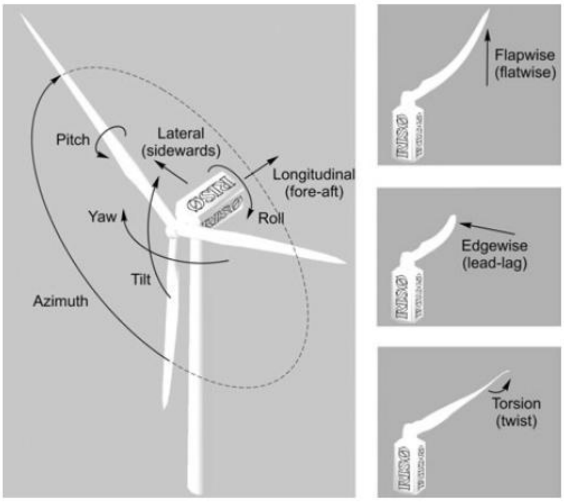


Fig. 1 Terminology for degree-of-freedom of wind turbines [6]

Fig. 2 Photograph of a damaged turbine blade bracket caused by large flapwise bending moment during a horizontal gust (taken at the wind farm on Koh Larn, Chonburi in June 2009)

(static) aerodynamic approach is inappropriate [5]. Unsteady aerodynamic computation is much more complex as it must accurately model the effects of time-delay, trailing-edge and leading-edge flow separations, and most importantly shed vortices. Many modern Computational Fluid Dynamics (CFD) packages are able to handle these requirements but at a significant computation cost, therefore it is common to find steady state CFD computations are used in wind turbine applications especially in three-dimensional flow domain [7].

Dynamic stall models provide an alternative, computationally cheaper, method for calculating aerodynamic loads under unsteady conditions. Aerodynamic loads are calculated using the time history of the angle of attack and a system of ordinary differential equations (ODEs) or algebraic equations. Examples of well-known dynamic stall models are the Boeing model [8], the ONERA model [9], the Leishman-Beddoes model [10, 11] and, most recently, the Larsen model [12]. These models will be assessed and selected for use in this research according to their reliability, simplicity, accuracy and compatibility with the structural model.

This work will, however, only attempt to determine the dynamic stability characteristic of the wind turbine using a linear aerodynamic model as the authors have only begun the first phase of the investigation. The final outcome of this research will be advancement in understanding the flapping dynamics of the wind turbine blade which can be extended into other blade degree-of-freedom in the future. Although the aeroelastic analysis of the wind turbine blade may not be as accurate as ones properly performed by CFD, it requires only a fraction of computational cost, hence making it highly desirable at conceptual design stage. To conclude, the product of this research will serve as a powerful design tool for wind turbine manufacturers.

2. Methodology

2.1 Wind turbine blade flapwise bending equation of motion

The equation of motion which govern the dynamics of each wind turbine blade is taken from reference [13]. The equation represents a simplified aeroelastic system in the flapwise direction where elastic blade bending is modeled as a rigid body rotation about a hinge with a rotation spring. It is given by

$$\beta'' + \frac{\gamma}{8}\left[1 - \frac{4}{3}\cos(\psi)\left(\overline{V}_0 + \overline{q}\overline{d}\right)\right]\beta' + \left[K + 2B\cos(\psi) + \frac{\gamma}{6}\overline{V}_0\sin(\psi)\right]\beta$$

$$= \frac{\gamma A}{2} - \frac{\gamma\overline{q}}{8}\sin(\psi) - \left\{2\overline{q} + \frac{\gamma}{2}\left[A_3\left(\overline{V}_0 + \overline{q}\overline{d}\right) + \left(\frac{K_{vs}\overline{U}}{4}\right)\right]\right\}\cos(\psi)$$

Eq. (1)

where β denotes the flapping angle. Other terms are fully defined at length in reference [13]. The equation is written in the form of a second order ordinary differential equation (ODE) with β'' and β'. The primes denote derivatives with respect to azimuth, ψ.

Equation 1 consists of damping, stiffness and forcing terms which represent all physical aspects of the loadings that a wind turbine blade experiences, ie. aerodynamic loading, gravitational force, yaw motion, wind shear, spring stiffness and inertial terms. A linearised aerodynamics model is used here in order to maintain the level of simplicity, ie. the local aerodynamic forces are functions of the instantaneous angle of attack and flow unsteadiness due to the blade motion is ignored.

2.2 Stability analysis and bifurcation

The wind turbine blade flapwise stability can be assessed by studying its motion with respect to certain system parameters. The magnitude of flapping motion in a real wind turbine largely depends on the structural stiffness of the blade. Hence, this stiffness term in the simplified model presented here is governed by the parameter K in equation 1. It represents the flapping inertial natural frequency, which is given by

$$K = 1 + \varepsilon + K_\beta / I_b\Omega^2 \qquad \text{Eq. (2)}$$

This study will focus on the significance of the variation of wind velocity and the effects on the flapping stability of the blade due to flapping spring constant, K_β.

2.3 Numerical integration algorithm

The second order ODE must be transformed into a system of first order ODEs before it can be successfully numerically integrated. We selected the Runge-Kutta-Fehlberg 4th order with adaptive time step algorithm to solve the system of equations. It is a robust explicit algorithm which is suitable for a nonlinear system such as the one presented here. This algorithm is available as a package in MATLAB.

3. Results and discussion

3.1 Dynamical responses of flapping motion in time domain

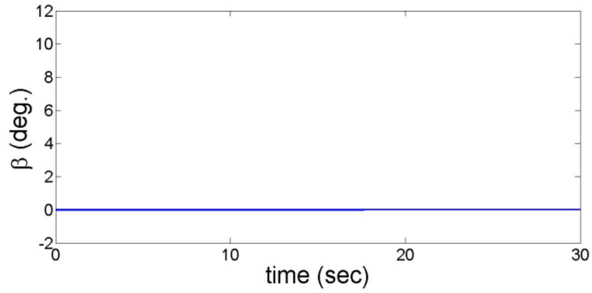
Equation 1 has been integrated using the numerical solver using a set of parameters which are appropriate for a generic 1.5 MW wind turbine. These include blade physical parameters, atmospheric parameters under a typical operation environment. The parameters and the variables which are allowed to vary in order to study its effects are the flapping spring constant, K_β and wind velocity, *U*, respectively. The figures below show the time histories of the blade flapping angle β which are defined K_β = 10x10^6 Nm/rad at four different values of *U*.

The time histories presented in figure 3.1(a) show that a system with low value of wind velocity, the wind turbine blade flaps with a small different of maximum and minimum flapping angle which is said to have been attracted to a fixed point. As the value of wind velocity increases, it becomes a large divergence with a uniform frequency and amplitude as indicated by the sinusoidal plot. It can be said that the system steady state is a limit cycle oscillation (LCO) type in figure 3(d).

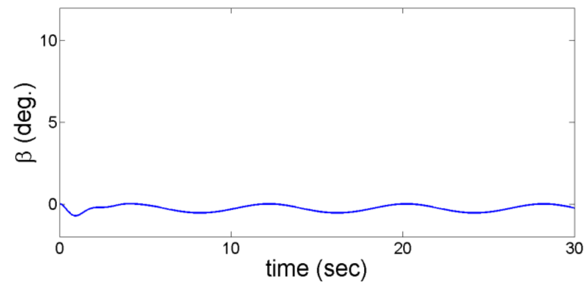
3.2 Bifurcation and stability analysis

The series of results presented in figure 3.1 may be easily summarised on a bifurcation diagram as shown in figure 3.2(a). The calculation is repeated over a range of values of wind velocity and only the loci of maxima and minima flapping angle are plotted.

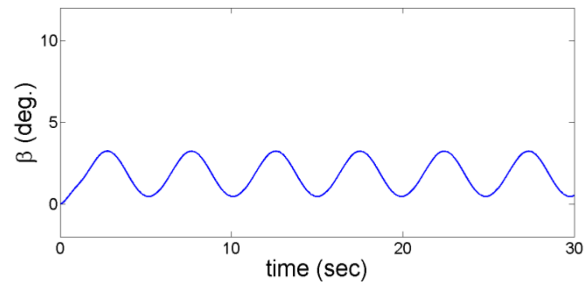
Note that the result presented in figure 3.2(a) has been calculated using a same set of structural parameters from those used to produce figure 3.1, hence they possess the same dynamical behavior. In this application, the Hopf bifurcation seems to occur at $U = 3$ m/s. The loci of maxima and minima begin to diverge at this point. Figures 3.2(b) and 3.2(c) show bifurcation diagrams with the stiffness values of



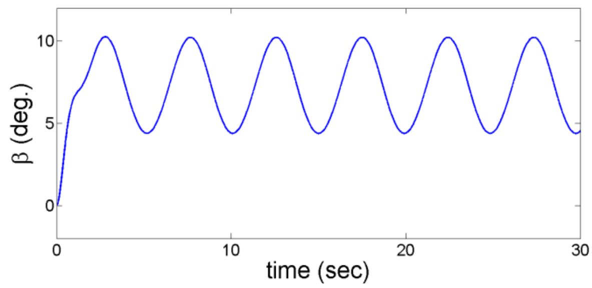
(a) wind velocity = 1 (m/s)



(b) wind velocity = 5 (m/s)



(c) wind velocity = 15 (m/s)



(d) wind velocity = 30 (m/s)

Figs. 3.1 Time histories of blade flapping angle at defined K_β = 10 x10^6 Nm/rad showing flap behaviours due to wind velocity from a fixed point to a limit cycle oscillation as the wind velocity increases.

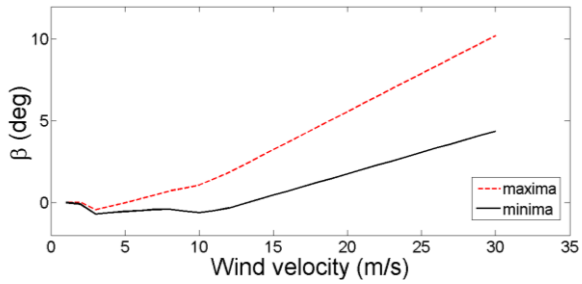
50×10^6 *Nm/rad* and 170×10^6 *Nm/rad*, respectively. The position of the Hopf bifurcation has changed to $U = 8$ m/s and $U = 15$ m/s, respectively.

The flapping angle oscillation magnitude decreases with an increase in spring stiffness as demonstrated in figure 3.2. The system becomes stable if the flapping angle oscillation magnitude is small or it can be said that the system tends to be attracted to a fixed point as the stiffness increases. Blade flapping effectively reduces the blade life span as it affects the fatigue life or, in an extreme case, a structural catastrophic failure. The maximum bending angle which the wind turbine blade can withstand before failure occurs will depend on the design and internal structural construction of the turbine blade itself.

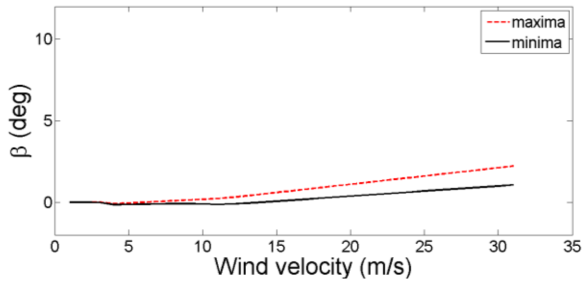
Figure 3.3 shows the operation limit of blade for two allowable deflection standards, *R/300* and *R/180*, where R is the blade length. The lines represent Hopf bifurcation boundaries. In this case, we assume that the allowable deflection standards mark the difference between stable and limit cycle oscillation steady state. These lines divide the space into different regions with different values of maximum flapping angle oscillation amplitudes. This plot is useful to blade construction engineers as it provides a guideline to the minimum stiffness requirement.

4. Conclusion

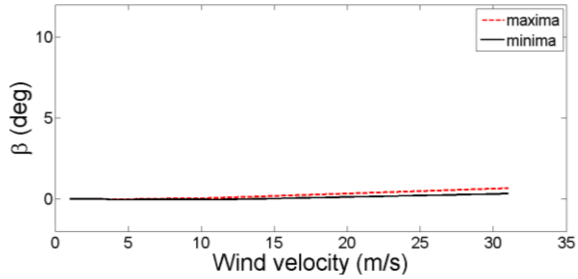
The paper has demonstrated a computationally cheap way to determine the wind turbine blade flapwise dynamics and its stability boundary with respect to changes in system parameters. The method needs more structural modeling



(a) $K_\beta = 10 \times 10^6\ N\,m\,/rad$



(b) $K_\beta = 50 \times 10^6\ N\,m\,/rad$



(c) $K_\beta = 170 \times 10^6\ N\,m\,/rad$

Figs. 3.2 Bifurcation plot show the increase of different of maximum and minimum flapping angle at each flapping stiffness which depend on the increasing of wind velocity.

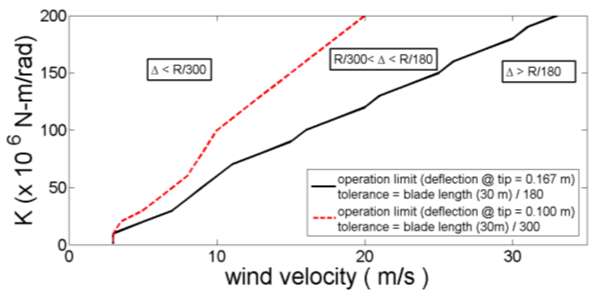


Fig. 3.3 Diagram of bifurcation boundaries which shows regions of different values of maximum oscillation amplitudes with variation in wind velocity and flapping spring stiffness. Δ denotes steady state oscillation amplitude.

refinement and additional modules such as unsteady aerodynamics, instantaneous local angle of attacks and three-dimensional effects near the blade tips. From preliminary results shown here, it seems that the numerical integration algorithm can capture the nonlinear behaviour of the system and the stability can be clearly assessed.

5. Acknowledgments

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