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Flapwise non-linear dynamics of wind turbine blades with both external and internal resonances

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ABSTRACT

An investigation on the non-linear aeroelastic behavior of a wind turbine blade with both external and internal resonances is presented. The external resonance is a primary resonance that appears at the first flapwise mode; it can cause severe damage to blade. The internal resonance happens at the first two flapwise modes; it can enhance the energy transfer between two modes, and change blade dynamics in primary resonance. Three aspects including blade behavior in pure primary resonance (abbr. PPR; only considering external resonance), blade behavior in combination resonance (abbr. CR; including both external and internal resonances), and the influence of internal resonance (i.e. modal interaction) on external resonance are examined. A simple Bernoulli–Euler beam model, in which geometric non-linearity and unsteady aerodynamic force are considered, is used to describe the flapwise motion of blade. The perturbation method is applied to the infinite-degree-of-freedom discrete system, which is obtained from the original continuous system via Galerkin's method, to get dynamic responses. Amplitude–frequency curves of resonance modes in CR and PPR are derived, and the stability of the steady state motion of blade is judged. The strongest modal interaction between two resonance modes is taken into account, and then effects of modal interaction, excitation amplitude, damping and non-linearity on non-linear vibration properties of blade are analyzed. Also, influences of three designing parameters (inflow ratio, setting angle and coning angle) and two detuning on the non-linear behavior of blade are discussed for a concrete downwind turbine.

1. Introduction

Aeroelasticity (the coupling of aerodynamics and structural dynamics) is a key problem in wind turbine technology [1]. Researches of the aeroelasticity of blades are mainly on three aspects: stall-induced vibrations for stall-turbines [2–4], classical flutter for pitch-regulated turbines [5,6], and aeroelastic structure analysis [7,8]. In previous studies, lots of aeroelastic codes were established based on linear structural models of blades [9,10]. With growing capacity of turbine generators, large deformations often appear due to the increasing size and flexibility of blades. The roles of non-linearities get more and more outstanding in aeroelasticity [10]. Experimental tests have validated that non-linear effects can bring out phenomena unexpected from linear theories [11]. However, investigations on non-linear aeroelasticity are still scarce; these works are mainly on subjects of parametric resonance [12], internal resonance [10,13–15], sup-harmonic and sub-harmonic resonances [16,17], and non-linear aeroelastic stability [18,19]. As an external resonance, primary resonance is a crucial case which should be avoided or controlled. However, non-linear dynamics and instability of blades in primary resonance have not been studied. The present work focuses on this subject.

The frequency ratio $\omega_1/\omega_2 \approx 1/3$ of the first two flapwise bending modes is often met for many types of blades (e.g. XF-series blades produced in XF Turbine Co., Ltd in China). So 1:3 internal resonance leads to the energy transfer between two modes via modal coupling in cubic non-linearities. Modal interactions (either internal resonance or non-resonant coupling) among multi-modes of physical systems have been examined widely, e.g. [20–33]. Especially, the energy transfer properties of modal coupling have been used to suppress vibrations of mechanical systems, e.g. [34–39]. However, previous researches on modal interactions of physical systems with both internal and external resonances mainly focus on sub- or super-harmonic responses excited by external resonance. Little is done about the concrete effect of internal resonance on external resonance.

In this paper the non-linear behavior of a blade that is subjected to both external and 1:3 internal resonances is studied.

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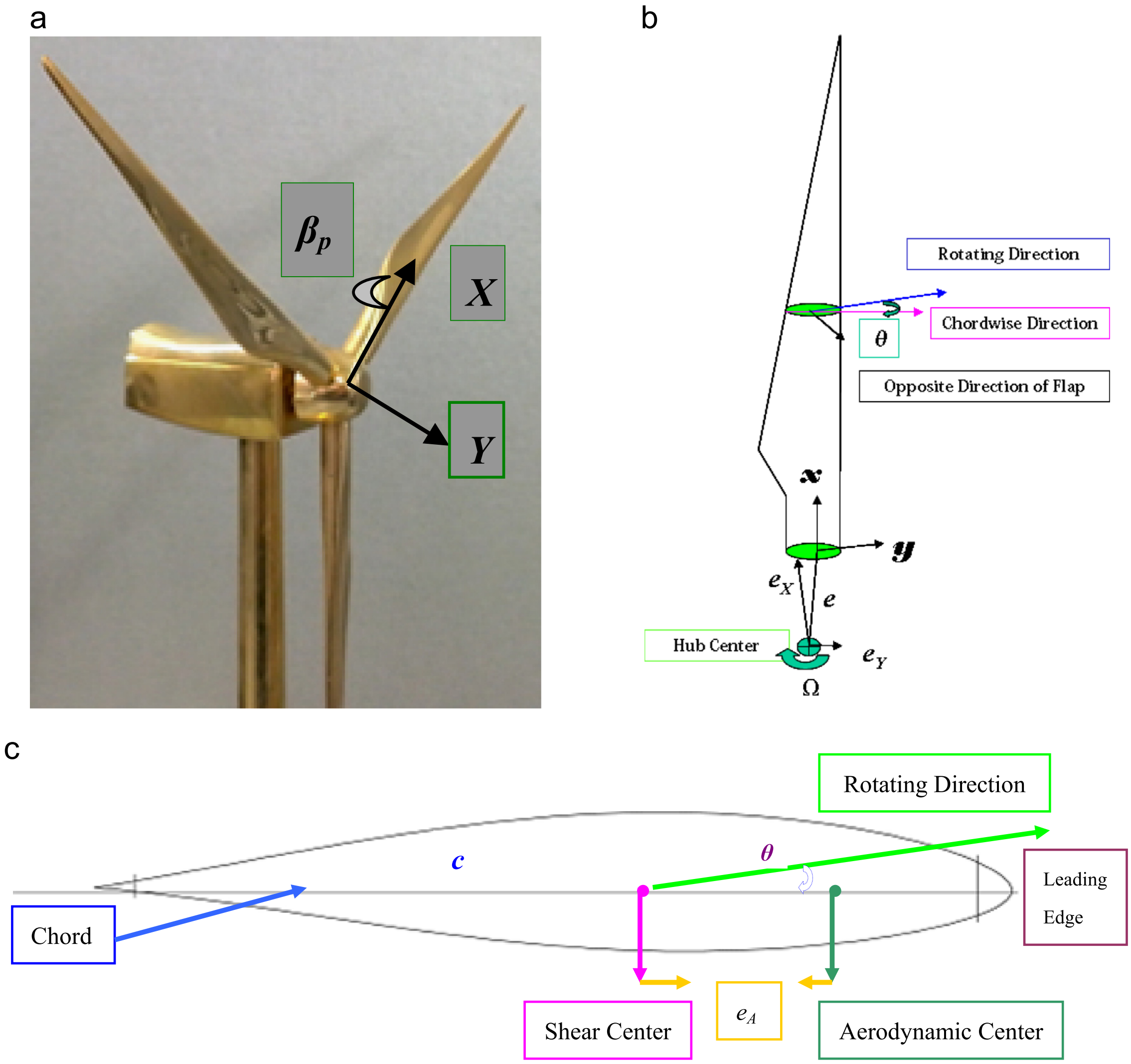

Fig. 1. Schematic diagrams of (a) wind turbine, (b) blade and (c) blade section.

The external resonance is a primary resonance happening at the first flapwise mode. The 1:3 internal resonance appears at the first two flapwise modes. In order to study the influence of internal resonance on external resonance, non-linear aeroelastic dynamics of blade in combination resonance (abbr. CR; include both external and internal resonance) and pure primary resonance (abbr. PPR; only consider external resonance) are solved by applying the method of multiple scales [40] separately. From the visual angle of generality, effects of external excitation, damping and non-linearity on non-linear behaviors of blade in CR and PPR are analyzed. The influence of internal resonance on primary resonance is discussed. These results can also be used to suppress vibrations of physical systems in primary resonance by using internal resonance strategy. By adopting a concrete downwind turbine, the influences of designing parameters (inflow ratio, setting angle and coning angle) and detuning on resonant responses are examined.

2. Governing equations

Considering an isolated blade bolted to rigid hub (see Fig. 1), two right-hand Cartesian coordinate systems are introduced to interpret blade geometry. (xyz) is a body coordinate system that is attached to blade root such that the x-axis corresponds to the undeformed elastic axis, the y-axis is along the rotating direction. (XYZ) is a global coordinate system with origin at the center of mass of the hub such that the Z-axis is along the spin axis which rotates with a constant angular speed Ω (we assume blade rotates about the hub clockwise when one faces it), and the Y-axis is parallel to the y-axis all the time. The flapwise motion of blade is the bend that is perpendicular to the plane of rotation.

Many types of physical models for rotating blades are proposed in previous works, e.g. rigid body with hinge springs [12], beam model [6,10,13,14,17], plate and shell model [42,43]. In view of the high aspect ratio of large wind turbine blade, the Euler–Bernoulli beam theory is adopted to describe the flapwise motion of blade. The mechanical model established in Ref. [17] is used here, while the dynamic deformation of axial motion is ignored since it is very small (its influence is tiny). There are four popular aerodynamic models (blade element momentum (briefly, BEM) model, lifting panel and vortex model, actuator line model, computational fluid dynamics (briefly, CFD) model) for wind turbines, where the BEM model is the most widely used code [9]. Unsteady aerodynamic force (for shear inflow, see Fig. 2) based on the BEM model that is given in [44] is applied in the model. The governing equation is given as

$$(EIw'')'' - (N_p w')' - m\Omega^2(\sin^2\theta + \cos^2\theta\,\sin^2\beta_p)w$$
$$-(\rho a c/2)\Omega^2[c/2 + (c/4)\cos\theta - e_A - e_Y]xw'$$