Journal of Wind Engineering & Industrial Aerodynamics 175 (2018) 169–178

Contents lists available at ScienceDirect

Journal of Wind Engineering & Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia

Ultimate and fatigue load mitigation by an inertial-driven passive flap, using a geometrically exact multibody formulation

Pierluigi Montinari [b], Federico Gualdoni [b], Alessandro Croce [b], Carlo L. Bottasso [a,b,*]

[a] Wind Energy Institute, Technische Universität München, D-85748 Garching b. München, Germany
[b] Department of Aerospace Science and Technology, Politecnico di Milano, 20156 Milano, Italy

ARTICLE INFO

Keywords:
Wind turbine
Load mitigation
Passive flap
Aeroservoelasticity
Wind turbine control

ABSTRACT

The paper characterizes the performance of a passive flap concept when applied to a modern very large conceptual wind turbine. The passive flap responds automatically to blade and/or tower vibrations, inducing a change of camber that opposes dynamic loads on the wind turbine. This is obtained in a purely passive manner, without the need for actuators or sensors.

The present study is based on a detailed, geometrically exact multibody formulation of the device, which is able to capture all kinematic and structural dynamic effects of this inertia-driven device. The present modeling of the passive device improves on previous studies conducted with simplified models.

Results show a significant ability in the reduction of both fatigue and ultimate loads, including the case of flap-specific fault scenarios. Solutions for limiting losses in energy yield caused by non-null average flap rotations in the partial load region are also investigated. The present analysis motivates further studies aimed at reaping the benefits of load alleviation enabled by the passive flap, for example by designing a new enlarged rotor at similar key loads on the rest of the machine.

1. Introduction and motivation

Wind energy has grown dramatically in the last fifteen years, to the point that it has become today the world principal source of renewable energy. Among many significant technological improvements that have enabled the success of wind energy, one aspect that clearly stands out is the continuous growth of the size of wind turbines. This growth trend is driven by at least two factors. Firstly, larger wind turbines capture more wind because of the greater area swept by their blades and because of their taller towers, leading to improved capacity factors. Second, all the rest being the same, installing and operating a smaller number of large machines implies significant advantages in logistics, grid connection, and operation & maintenance with respect to operating a larger number of small machines. This implies consequent benefits on the cost of energy (CoE). Clearly, optimal sizes for onshore and offshore applications may be very different, and also strongly depend on various local conditions.

In the future, the design of even bigger machines will most probably have to be enabled by suitable load mitigation technologies. In fact, the simple upscaling of existing solutions will not be economically and technically viable, due to the cubic law of growth: weight (and hence cost) grows cubically with size, implying an about ten-fold increase when doubling the dimensions of a wind turbine. The present study falls within this general topic, and in particular it considers the assessment of the performance of a passive flap concept for the alleviation of ultimate and fatigue loads, when applied to a modern very large conceptual wind turbine.

The mitigation of loads can be obtained by different means. Full-blade span solutions involve the response of the entire blade. Individual pitch control (IPC) is a full-span active solution that has been studied extensively in the literature and that is now seeing an ever increasing acceptance by industry. Bend-twist coupling (BTC) is a full-span passive solution, which is not yet routinely adopted although it is being actively investigated (Bottasso et al., 2013; Bortolotti et al., 2017). However, although often very effective, any full-span solution is inherently somewhat limited in bandwidth, due to the inertia and non-local response of the blade.

On the other hand, distributed solutions locally affect the airloads by the use of pitchable tips/flaps/tabs (Andersen et al., 2010; Bergami and Poulsen, 2015; Bernhammer et al., 2016; Bottasso et al., 2016a, b; Chow and van Dam, 2007). The local nature of such solutions allows for a higher bandwidth in space and time, which may potentially result in an improved load mitigation effectiveness. In the case of actively controlled

---

* Corresponding author. Wind Energy Institute, Technische Universität München, D-85748 Garching b. München, Germany.
E-mail address: carlo.bottasso@tum.de (C.L. Bottasso).

https://doi.org/10.1016/j.jweia.2018.01.038
Received 30 October 2017; Received in revised form 25 January 2018; Accepted 27 January 2018

Notation

c	Sectional chord
k	Stiffness
m	Mass
t	Time
C_H	Hinge moment coefficient
J	Moment of inertia
V	Wind speed
α	Angle of attack
β	Blade pitch
δ	Flap deflection
τ	Gear ratio
Ω	Rotor angular speed
$(\cdot)^{NC}$	Non-circulatory term
$(\cdot)_{/*}$	Partial derivative, $\partial\cdot/\partial*$
$\dot{(\cdot)}$	Derivative wrt time, $\mathrm{d}\cdot/\mathrm{d}t$
ADC	Actuator duty cycle
AEP	Annual energy production
BEM	Blade element momentum
BTC	Bend twist coupling
CoE	Cost of energy
DEL	Damage equivalent load
DLC	Dynamic load case
EOG	Extreme operating gust
IPC	Individual pitch control
NTM	Normal turbulence model
NWP	Normal wind profile

devices, the required moving parts, actuators and sensors will invariably increase the complexity of the rotor, which might in turn affect not only the cost of manufacturing, but also the cost of operation & maintenance and the availability of the machine, with possible consequent negative effects on the CoE. Therefore, deploying in the field a wind turbine with active distributed devices still posses some not fully solved challenges. As an alternative, passive devices –not requiring actuators and sensors– might be more appealing, if they can deliver significant load mitigation benefits at a greater simplicity.

An inertial-driven passive flap concept was proposed by Bottasso et al. (2016a) and Croce et al. (2016). The concept was further expanded to accommodate also the implementation by a passive tip in Bottasso et al. (2016b), albeit using a different physical phenomenon to drive the response of the device (see also Croce et al. (2016)). In the passive flap solution, the flap center of gravity is moved in front of the hinge line by the use of an offset mass. This way, flapwise accelerations of the blade excite a response of the flap that, by changing the airfoil camber, tend to oppose the acceleration itself, thereby attenuating dynamic blade loads. The flap is also aerodynamically balanced, in the sense that it is designed in order not to respond to the deliberate changes in angle of attack imposed by the wind turbine control system. Multiple load cases were considered in Bottasso et al. (2016a) through a loose coupling procedure between a state-of-the-art aeroservoelastic simulator and a typical section model. The preliminary analysis of that paper indicated a very promising performance of the novel device, which however had to be verified by a more sophisticated analysis.

It is the goal of the present paper to perform a complete aeroservoelastic analysis of the system, using a detailed multibody model of a wind turbine equipped with passive flaps. The multibody formulation is based on an exact fully nonlinear formulation of the geometry, kinematics and dynamics of the system, based on three dimensional rotation theory. The only linear assumption is in the beam model, which assumes a linear proportionality of internal stress resultants on sectional strains through a possibly fully populated stiffness matrix, something that is perfectly valid in the present context. However, all effects due the three dimensional relative motion of the system rigid and flexible bodies and their connecting mechanical joints is rendered exactly. The mathematical model is hence capable of capturing the exact structural dynamics of the system without approximations, except for vanishingly small numerical effects. This is particularly important in the case of the passive flap, because the inertial forces that drive its motion (including gravity, which acts as a disturbance) depend in a complicated manner on the exact geometry of the system, including its deformation. The model is coupled with an unsteady aerodynamic model of the flap, together with a blade-element momentum (BEM) model of the rotor wake. The passive flap concept is applied to the conceptual INNWIND.EU 10 MW wind turbine (INNWIND.EU, 2017).

A second objective of the paper is the study of the possible impact of the proposed passive flap on the power capture of the rotor. In fact, non-null average flap rotations may reduce the rotor efficiency. If this happens in the partial load region, then energy yield may be affected. Two solutions are investigated: a simple constant preload, and a more sophisticated rotor-speed-varying preload implemented through a screw joint, inspired by the work of Bottasso et al. (2016b). In fact, differently from what was found in Bottasso et al. (2016a), the more sophisticated mathematical model used in the present investigation shows that the inertial coupling effects induced by precone/prebend of the blade and up-tilt of the rotor axis make it difficult to obtain small flap rotations without restraining it at the hinge. A detailed explanation of the phenomenon is provided in section 2. Results obtained in the present study indicate that modest average flap rotations, and hence modest losses in annual energy production (AEP), can be achieved by the simplest of the two solutions.

There are few alternatives to the passive flap concept presented in the literature. A different passive device is described by Lambie et al. (2011), where a passive camber control concept is investigated using a 2D aeroelastic typical section. A variation of airfoil camber is obtained by exploiting the chordwise aerodynamic load distribution, which changes as a function of angle of attack, while the original shape is restored by the use of a spring/damper system. A significant decrease of load fluctuations is shown by simplified load cases. However, this device will not only respond to undesirable changes of angle of attack due to blade vibrations, but also to the deliberate changes caused by the full-span pitching of the active control system that is responsible for the normal and emergency operation of the machine. In addition, the flexible airfoil camber will also change with the operating condition. This might impact the energy yield in the partial load regime, where the rotor should operate at maximum efficiency. A more recent analysis is reported in Marten et al. (2015), where a nonlinear lifting line free vortex wake model is employed to assess the performance of the passive device on a multi-megawatt wind turbine. Results indicate a reduction of the standard deviation of blade root bending moments, although a single simulation was considered and the energy yield was not analyzed.

The present paper is organized according to the following plan. At first, the working principle of the passive flap concept is reviewed, together with the structural dynamics and aerodynamic models used for the simulation of the wind turbine equipped with the flap. The sizing of the device is discussed next. Turbulent wind simulations are performed with the goal of identifying an optimal choice of flap parameters. To limit the effects of non-null average flap rotations on rotor efficiency, which may impact energy yield, the two solutions of constant and rotor-speed-varying preload are investigated. After having sized the device, a more complete assessment of its overall performance is studied, including its effects on AEP, fatigue and ultimate loads at a few critical verification