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Load mitigation for wind turbines by a passive aeroelastic device

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ABSTRACT

This paper conducts a preliminary investigation of a novel passive concept for the mitigation of loads on wind turbines. The device, which can be implemented as a flap or a pitching blade tip, moves passively in response to blade vibrations, opposing them, thereby yielding an attenuation of loads. In comparison to active load mitigation devices, such as active flaps, this solution has the advantage of not requiring sensors nor actuators, resulting in a particularly simple implementation, with potential benefits in manufacturing and maintenance costs, as well as in reliability and availability.

The paper first describes the novel passive device, here implemented by means of a flap, highlighting its main characteristics. A proof of concept of the new idea is then given by a simulation study conducted with the combination of a sectional model of the flap and an aeroservoelastic multibody model of the rest of the machine. Results, obtained for a 10 MW wind turbine, indicate the ability of the passive flap in attenuating blade vibrations in a significant frequency range, which in turn yield a reduced fatigue damage to the structure without noticeable effects in terms of power production and ultimate loads.

1. Introduction and motivation

In recent years, a desire to increase wind turbine dimensions while escaping the cubic law of growth has spurred an ever increasing attention to techniques for load alleviation. In fact, the mitigation of both ultimate and fatigue loads may translate into lighter weight or reduced use of high performance materials, or it can even be exploited by designing larger rotors that capture more energy.

In principle, load alleviation can be achieved by active or by passive techniques. Active solutions include full span blade pitch, as well as active flaps, tabs or other flow control devices. While full span active pitch is a standard solution on virtually all modern horizontal axis wind turbines, it has a limited bandwidth both in space and time as it can only react to relatively large and slow turbulent eddies in the flow. To address these limits, active local devices may offer a substantial bandwidth increase with a faster and more localized response, which however comes at the cost of additional complexity. In fact, the presence of sensors, actuators and moving parts may significantly increase manufacturing, maintenance and repair costs, and may reduce availability. It is not yet clear to what extent these contrasting effects may actually provide a final effective benefit in terms of the Cost of Energy (CoE).

On the other hand, passive load alleviation techniques typically do not necessitate of sensors or actuators, resulting in simpler implementations that may have a reduced or even negligible impact on maintenance, repair and availability. Bend-twist coupling (BTC), which may be obtained by the use of anisotropic materials and/or blade sweep, is very effective from this point of view because there are not only no sensors and actuators, but also no moving parts. However, similarly to blade pitch, BTC involves a full span response that may only react to large and slow wind fluctuations.

As for the active case, even for the passive solution a higher bandwidth can be achieved by using local devices, as first studied in the fixed and rotary wing literature. One of the first examples of gust-alleviating passive flaps can be found in Doney and Shufflebarger (1940). That study developed an experimental setup for investigating in a wind tunnel the effects of a long-period dynamically overbalanced flap on a fixed wing aircraft. Results indicated a reduction of accelerations due to gusts, which was however accompanied by a decrease in stability of the vehicle. For rotorcraft applications, an analytical investigation of various aeroelastic devices appended to rotor blades is reported by Bielawa (1984). Among different solutions, a passive trailing edge tab concept is considered in that work using a simplified analysis. That study highlighted the crucial importance of tuning, since the tab motion must be phased in a correct manner to reduce the blade harmonic loads that induce vibrations to the mast. Although

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Nomenclature

a	non-dimensional distance between elastic axis and section mid chord
b	section semi-chord
c	section chord
c_h, c_θ, c_δ	plunge, torsion and flap damping coefficients
e	distance between flap hinge and mid chord
h	plunge deflection
k	stiffness
k_0, k_Ω	constant stiffness and centrifugal stiffening coefficient
k_h, k_θ, k_δ	plunge, torsion and flap stiffness coefficients
l	distance between flap hinge and airfoil trailing edge
m	mass
q	dynamic pressure
s	complex number frequency
s'	reduced frequency
t	time
C_H	hinge moment coefficient
C_L	lift coefficient
C_M	pitch moment coefficient
J	inertia
U	flow speed
V	wind speed
$\boldsymbol{u}$	input vector
$\boldsymbol{x}$	state vector
$\boldsymbol{A}$	state matrix
$\boldsymbol{A}^{AE}$	aerodynamic matrix
$\boldsymbol{B}$	input matrix
$\boldsymbol{C}$	damping matrix
$\boldsymbol{K}$	stiffness matrix
$\boldsymbol{M}$	mass matrix
$\mathcal{C}$	Theodorsen function
α	angle of attack
β	blade pitch
δ	flap deflection
ϕ	Wagner function
ψ	Küssner function
ρ	air density
τ	non-dimensional time
θ	torsional rotation
Ω	rotor angular speed
$(\cdot)^C$	circulatory term
$(\cdot)^G$	turbulent fluctuation term
$(\cdot)^{AS}$	aeroelastic term
$(\cdot)^{NC}$	non-circulatory term
$(\cdot)_r$	rated quantity
$(\cdot)_S$	structural term
$(\cdot)_{QS}$	quasi-stationary term
$(\cdot)_{/*}$	partial derivative, $\partial \cdot / \partial_*$
$\dot{(\cdot)}$	derivative w.r.t. time, $\mathrm{d} \cdot / \mathrm{d}t$
$\mathrm{T}_{/*}$	Theodorsen coefficients
AEP	annual energy production
BEM	blade element momentum
BTC	bend-twist coupling
CoE	cost of energy
DEL	damage equivalent load
DLC	dynamic load case
FEM	finite element method
HAWT	horizontal axis wind turbine
LQR	linear quadratic regulator
LTI	linear time invariant
NTM	normal turbulence model
RWT	reference wind turbine

results appeared to be promising, the device seemed to be counter-productive when examined more carefully with its overall effects. Another passive rotorcraft appended device, similar to the passive flap, is the free tip rotor, as reported by Stroub (1982). In this solution, the blade is modified in its outer part to embed a free pitching tip. This device smooths the airload distribution in the blade tip region as the blade travels azimuthally over the rotor disk. Passive control strategies are applied to modulate the torsional moment applied to the free-tip. Different solutions are shown by Young (1986), which also reports sketches of the various design concepts.

Although these studies did show the general ability of passive devices of decreasing loads, these advantages are typically offset by an increase of weight, to the point that passive solutions do not seem nowadays to be commonly employed in aeronautical applications. The situation appears to be somewhat different in the wind energy field. In fact here, although weight is certainly a concern, the key design figure of merit is the CoE, a quantity that captures the effects of all aspects of the design of a machine over its entire lifetime. For a given load reduction achievable by two devices, the one that might actually bring a benefit to the CoE is the one that is less expensive to manufacture but also, and often more importantly, that is less costly to maintain and that ensures a greater availability. These aspects might be even more important for offshore operations, or in general in remote and difficult to reach locations, where simplicity and robustness might be particularly desirable features.

A first application in wind energy of a passive distributed system for load alleviation is analyzed by Lambie et al. (2011). A passive camber control concept is investigated, considering 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 the angle of attack, while the original shape is restored by the use of a spring and damper. Three simplified load cases are evaluated, showing a significant decrease of load fluctuations. This device will however not only respond to undesired 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 operation of the machine. In this sense, this passive device will work against the wind turbine active controller, something that casts some doubts on the actual final benefits of this particular solution. Passive load alleviation can also be achieved by structural morphing, as reported by Arrieta et al. (2012). A bi-stable specimen is designed in that work, by tailoring using an orthotropic material. When the applied load exceeds a threshold value, the structure switches from the reference state to a second statically stable one that generates less lift. This process does not require moving parts, but the main drawback is that an active component is needed to restore the original shape (see also Arrieta et al., 2014).

The passive concept proposed in this work merges the advantages of high bandwidth distributed control with the reliability of a passive device. In a nutshell, the main idea is to use one or more flaps at suitable locations along the blade span. Such flaps are conceived so as to move in response to blade vibrations in order to oppose them. This is obtained by offsetting a mass with respect to the flap hinge, so that when the blade accelerates in one direction the flap is automatically deflected in the other, resulting in a change of camber that opposes blade motion.