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Modelling of a tuned liquid multi-column damper. Application to floating wind turbine for improved robustness against wave incidence

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ABSTRACT

In this paper, the coupling of a float with a tuned liquid multi-column damper (TLMCD), a novel structural damping device inspired by the classical tuned liquid column damper (TLCD), is modelled using Lagrangian mechanics. We detail the tuning of the design parameters for each considered variant of the TLMCD, and compare each of them against a layout of multiple TLCDs. The results show that the proposed TLMCD is superior to multiple TLCDs for this application as it is more robust against wave incidence and it creates significantly less parasitic oscillations.

1. Introduction

Wind power is the second fastest growing source of renewable electricity (National Renewable Energy Laboratory, 2012) in terms of installed power. The construction of offshore wind farms is growing worldwide. In Europe, offshore wind energy is expected to grow to 23.5 GW by 2020, tripling the installed capacity in 2015 (Ernst and Young, 2015). The major causes of this recent trend are the strength and regularity of wind far from the shore, which should allow for the easy mass production of electricity. To generate offshore wind energy, two types of technologies have been considered: fixed-bottom wind turbines (foundations fixed into the seabed) and floating wind turbines (FWTs). The fixed-bottom offshore wind turbine technology is too costly for use in water deeper than 60 m (Musial et al., 2006). This disqualifies them from use in most seas. FWTs are a tempting alternative. One advantage is that FWTs are not as dependent on seabed conditions for installation and can be moved to a harbour for maintenance. The main drawback of FWTs is their sensitivity to surrounding water waves that increase the mechanical load on the wind turbine (Jonkman, 2007), hence reducing the lifespan of its mechanical parts. This sensitivity can be mitigated by increasing the mass and size of the mechanical structure. However, this leads to a prohibitive rise in the cost per kWh.

Previous studies have proposed compensating for tower fore-aft oscillations using collective and individual blade pitch control to modify the wind thrust forces (Jonkman, 2007; Namik, 2012; Christiansen et al., 2013). This solution has the advantage of requiring no structural modification, but delivers limited performance. The tower movements are still many times superior to those observed on onshore wind turbines. Instead of using aerodynamic forces, it is tempting to consider using hydrodynamic forces. In naval engineering, considerable attention has been paid to ship roll damping (since the advent of steamboats). However, most solutions involve the use of the speed of the ship relative to the water to generate lift to control the roll (Perez and Blanke, 2012) and, for this reason, are not easily transferable to our problem.

In addition to naval engineering, civil engineering has been a great contributor to such approaches, as skyscrapers are highly sensitive to wind gusts and earthquakes. This general field (*structural control*) is beyond the scope of this paper, and the reader can refer to (Saeed et al., 2013) for an overview. To improve the response of massive structures to external disturbances, attached moving masses, such as tuned mass dampers (TMD), can be employed. Among the most economical and efficient solutions is the tuned liquid column damper (TLCD), also known as the anti-roll tank or the U-tank. As originally proposed by Frahm (Frahm, 1911; Moaleji and Greig, 2007) to limit ship roll, it is a U-shaped tube on a plane orthogonal to the ship's roll axis, and is generally filled with water. The liquid inside the TLCD oscillates due to the movement of the structure and liquid's energy is dissipated through a restriction located in the horizontal section. The TLCD is usually chosen to damp the natural frequency of the structure. While TLCD systems have been modelled in the past by, for instance, (Chang and Hsu, 1998; Gao et al., 1997), it remains an active field of research (Di Matteo et al., 2014). A considerable amount of relevant research has been conducted over the

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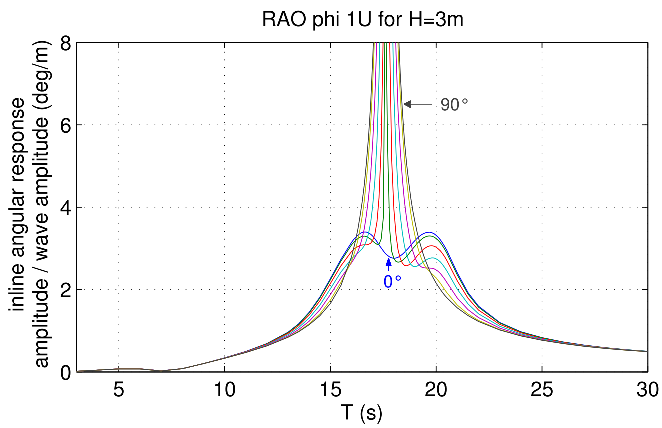

Fig. 1. RAO of the float damped by a single TLCD for different incident angles.

last two decades on civil engineering applications, where most of the work has focused on determining the optimal design of passive TLCDs, such as (Gao et al., 1997; Wu et al., 2009; Yalla and Kareem, 2000).

Several studies have shown that the structural control of floating wind turbines using active (Lackner and Rotea, 2011; Namik et al., 2013) or passive (Stewart and Lackner, 2013; Si et al., 2014) TMDs can substantially reduce the load on the wind turbine. Other studies (Coudurier et al., 2015; Luo et al., 2011; Shadman and Akbarpour, 2012) have shown that the passive and semi-active TLCDs are an interesting alternative.

In this paper, we consider the damping of an offshore platform subject to waves of various angles of incidence. Such a system behaves as a six-DOF periodically oscillating rigid body. We try to minimize the roll and pitch oscillations by means of a TLCD, and neglect aerodynamic forces. Due to the mooring system, we cannot easily change the orientation of the float to adapt to the wave incidence. In the past, we studied the disturbance rejection capabilities of a TLCD aligned with the wave incidence (Coudurier et al., 2015). As shown in Fig. 1, the damping provided by the TLCD is not robust against a change in the wave incidence.

This work is partly based on (Holden and Fossen, 2012). However, unlike the ships considered there, the float we consider has isotropic properties, meaning that its roll and pitch motions have the same characteristics. Here we go a step further introducing three multidirectional damping devices based on the concept of the TLCD. Their dynamics and their robustness against wave incidence are investigated.

2. Description of the system

The floater considered was the MIT/NREL Shallow Drafted Barge and the wind turbine was an NREL 5 MW; both are described in Tables 2 and 3.

Table 1
Nomenclature.

$\mathscr{R}_n$	Earth-fixed frame
$\mathscr{R}_b$	Barge-fixed frame
$R(\Theta) \in \mathbb{R}^{3\times3}$	Rotation matrix from $\mathscr{R}_b$ to $\mathscr{R}_n$ so that $\forall r \in \mathbb{R}^3$, $r^n = Rr^b$
$x^n = [x, y, z]^\top \in \mathbb{R}^3$	Position of the centre of gravity of barge in $\mathscr{R}_n$
$\Theta = [\varphi, \theta, \psi]^\top \in \mathbb{R}^3$	Euler triple associated with R
$v^b \in \mathbb{R}^3$	Speed of *CoG*, the centre of gravity of the float
$\omega^b \in \mathbb{R}^3$	Rotational speed of $\mathscr{R}_b$ with respect to $\mathscr{R}_n$
nc	Number of variables needed to describe the liquid speed in the TLCD/TLMCD
$w \in \mathbb{R}^{nc}$	Vector describing the position of the liquid in the TLMCD
$w_i \in \mathbb{R}$	position of the liquid in the i^{th} element
$q = [x^{n\top}, \Theta^\top, w^\top]^\top \in \mathbb{R}^{6+nc}$	System's generalized positions
$\nu = [v^{n\top}, \omega^{b\top}, \dot{w}^\top]^\top \in \mathbb{R}^{6+nc}$	System's speeds
$G(\Theta) \in \mathbb{R}^{3\times3}$	Matrix relating $\dot{\Theta}$ and ω^b so that $\omega^b = G\dot{\Theta}$

(continued on next column)

Table 1 (*continued*)

$\mathscr{P}(\Theta) \in \mathbb{R}^{6+nc\times6+nc}$	Matrix relating $\dot{q}$ and ν so that $\nu = \mathscr{P}\dot{q}$
$S(\cdot) \in \mathbb{R}^{3\times3}$ $S^2(\cdot) = S(\cdot)^\top S(\cdot)$	Skew symmetric matrix representing the cross-product in $\mathbb{R}^3$, with $S(x)y = x \times y$.
A_v and $A_h \in \mathbb{R}$	Cross-sections of the vertical and horizontal tubes of the tank
$\nu \in \mathbb{R}$	Cross-section ratio defined as $\nu \triangleq \frac{A_v}{A_h}$
$\sigma_i \in \mathbb{R}$	Curvilinear abscissa describing the geometry of the i^{th} element
$\varsigma_i, \varsigma_{pi}, \varsigma_{si} \in \mathbb{R}$	Abscissa of the free surfaces in the i^{th} element
$\alpha_i \in \mathbb{R}$	orientation angle of the i^{th} element
$r^b(\sigma) = [x_t^b, y_t^b(\sigma), z_t^b(\sigma)]^\top \in \mathbb{R}^3$	Function describing the centreline of the damper
$A(\sigma) > 0 \in \mathbb{R}$	Cross-section of the tank at abscissa σ
L_v and $L_h \in \mathbb{R}$	Length of the vertical and horizontal tubes of the TLCD
$e \in \mathbb{R}$	Distance between *CoG* and the horizontal tubes
$\rho \in \mathbb{R}$	Liquid density
$\eta \in \mathbb{R}^{nc}$	Vector of the head-loss coefficients of the restrictions
$M_s = M_s^\top \in \mathbb{R}^{6\times6}$	Mass matrix of the float
$m_t \in \mathbb{R}$	Total mass of the liquid in the damping system
$Q_{hydro} \in \mathbb{R}^6$	Generalized force due to the barge/waves interactions
$Q_{res} \in \mathbb{R}^{nc}$	Generalized force due to the restrictions in the TLMCD
$F_h \in \mathbb{R}^N$	Force generated by the fluid flow through the restrictions
$\beta \in \mathbb{R}$	Wave incidence angle

The barge and the wind turbine are modelled as a single rigid body, referred to as “the float” in this paper. Deformations in the wind turbine are neglected as its resonant period is inferior to the period of the monochromatic waves we consider here – ranging from 3 s to 30 s. The float is studied with all six degrees of freedom. To avoid any bias in the study, we do not consider the interaction between the rotor and the wind because the damping induced is dependent on the controller chosen for

Table 2
Summary of MIT/NREL barge properties, from (Jonkman, 2007).

Diameter, Height	36 m, 9.5 m
Draft, Freeboard	5 m, 4.5 m
Water Displacement	5089 m^3
Mass, Including Ballast	4,519,150 kg
CM Location below SWL	3.88238 m
Roll Inertia about CM	390,147,000 kg m^2
Pitch Inertia about CM	390,147,000 kg m^2
Yaw Inertia about CM	750,866,000 kg m^2
Anchor (Water) Depth	200 m
Separation between Opposing Anchors	436 m
Unstretched Line Length	279.3 m
Neutral Line Length Resting on Seabed	0 m
Line Diameter	0.127 m
Line Mass Density	116 kg/m
Line Extensional Stiffness	1,500,000,000 N

Table 3
Gross properties chosen for the NREL 5-MW baseline wind turbine, from (Jonkman, 2007).

Rating	5 MW
Rotor Orientation, Configuration	Upwind, 3 Blades
Control Variable Speed	Collective Pitch
Drivetrain High Speed	Multiple-Stage Gearbox
Rotor, Hub Diameter	126 m, 3 m
Hub Height	90 m
Cut-In, Rated, Cut-Out Wind Speed	3 m/s, 11.4 m/s, 25 m/s
Cut-In, Rated Rotor Speed	6.9 rpm, 12.1 rpm
Rated Tip Speed	80 m/s
Overhang, Shaft Tilt, Precone	5 m, 5°, 2.5°
Rotor Mass	110,000 kg
Nacelle Mass	240,000 kg
Tower Mass	347,460 kg
Coordinate Location of Overall CM	(-0.2 m, 0.0 m, 64.0 m)