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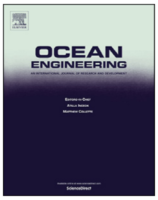

Modelling of a hydrokinetic energy converter for flow-induced vibration based on experimental data

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ABSTRACT

The VIVACE Converter is a novel and highly efficient renewable energy device in Marine Hydrokinetic (MHK) energy. The operational principle of the converter is to immerse a slender body with bluff cross-section in a flow and extract energy from the transverse oscillations induced by the unsteady von Kármán vortex street. In general, the Converter consists of one or more mass–spring–damper oscillators subjected to non-linear hydrodynamic forces. These forces are strongly influenced by variations of the inflow velocity, damping, stiffness and mass ratio, which in turn influence the harnessed power and efficiency of the Converter. For a reliable model of the hydrodynamic forces, experimental and numerical research plays a key role in the study of the hydrodynamic characteristics of the Converter. This study focuses on modelling the harnessed power and efficiency of the Converter based on a surrogate model methodology, in vortex-induced vibration (VIV) and galloping region. To avoid excessive experimentation or computational inaccuracy, the surrogate model is constructed from a Radial Basis Function (RBF) network by using experimental data of equal-interval harnessing damping-ratio and stiffness in a specified design domain. The harnessed power at different flow velocities is computed by the present model and is found to be consistent with experimental results. Optimization is performed to obtain the maximum harnessed power and efficiency and the corresponding harnessed damping-ratio and stiffness distributions in both the VIV and galloping regions. The method introduced in this study provides a novel tool for numerical modelling of oscillators in flow-induced vibrations, which can be used in engineering applications such as optimization of MHK energy converters.

1. Introduction

Renewable energy devices are attracting increasing attention in an industrial context. Energy generated by waves, tides, open-ocean currents, rivers, ocean thermal gradients and salinity gradients is typically referred to as Marine Renewable Energy (MRE). Within MRE, Marine Hydrokinetic (MHK) energy refers to wave, tidal, current and river energy. Horizontal hydrokinetic energy refers to MHK energy generated by horizontal currents due to tides, ocean currents, or rivers. Since 2005, a focus area of the Marine Renewable Energy Laboratory (MRELab) (Bernitsas et al., 2006; Bernitsas, 2016) at the University of Michigan is the basic hydrodynamics of enhancing Fluid-Induced Vibration (FIV) in the form of Vortex-Induced Vibrations (VIV) and galloping in order to convert horizontal hydrokinetic energy into mechanical and subsequently electrical energy.

In 2011, a reliable virtual spring–damper (V_{ck}) system (Lee et al., 2011) was built to replace the physical dampers and springs of the VIVACE converter by a servo-motor and controller. V_{ck} was further improved by Sun et al., (2015). The hydrodynamic force is not included in the control loop, thus avoiding bias. On the other hand, the system identification process – particularly for damping - is very elaborate requiring careful modelling and repeated testing as well as verification with well-calibrated springs and predetermined damping. Turbulence stimulation was added to cylinders in the form of narrow sand strips named passive turbulence control (PTC) (Bernitsas and Raghavan, 2011). A *PTC-to-FIM Map* has been developed to enable selection of the

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flow-induced vibration of a cylinder with PTC (Park et al., 2013a, 2013b). Thus, the VIV range of synchronization and the galloping range can be placed back-to-back resulting in a response amplitude operator with high response starting at the onset of VIV and having no-end as the flow velocity increases. A Converter designed that way is very robust is the sense of being able to respond with high amplitude ratio (Amplitude/Diameter, A/D) in an open-ended range of velocities in VIV or galloping (Bernitsas, 2016).

A rigid cylinder on end-springs, in a transverse flow, can be excited in one or two degrees of freedom Flow Induced Vibrations (FIV). Starting from zero flow velocity and increasing it gradually, when the vortex-shedding frequency is sufficiently close to the oscillator's natural frequency, lock-in is initiated, and the self-excited oscillations of the cylinder occur. Galloping, also used by the VIVACE Converter, is another type of instability of slender structures with bluff cross-sections that occurs due to geometric or flow asymmetry when certain flow velocity is reached (Blevins, 1990; Chang et al., 2011). The underlying hydrodynamic mechanisms are different. VIV is based on alternating vortex shedding, in which interaction between its two shear layers is essential, extends over a finite velocity range, and is self-limiting in amplitude. Galloping initiates at a critical absolute velocity and does not stop with increasing velocity. The galloping generation mechanism interrupts the interaction between the shear layers on the two sides of the cylinder. Typically, galloping initiates at velocities higher than the upper velocity limit of VIV. By properly designing a Converter the two phenomena can be brought close together and overlap. A transition region may exist, between VIV and galloping, where both mechanisms coexist. In such a case, the response amplitude operator of the Converter initiates near its natural frequency and does not end resulting in higher and higher response with increasing velocity (Bernitsas, 2016).

The harnessed power and efficiency are the main assessment criteria in the conceptual design of green energy devices. Lower harnessed power and efficiency are typical of renewable energy technologies. From a mathematical perspective, the Converter can be viewed as a linear mass–spring–damper dynamical system under non-linear excitation. In the VIV range it is under lock-in and in the galloping range in instability. Others interpret VIV as linear resonance of variable added-mass over the range of synchronization. Experimental research indicates that the harnessed power and efficiency are related to the values of mechanical parameters (Lee and Bernitsas, 2011; Bernitsas, 2016). In particular, the harnessed power and efficiency are functions of the damping ratio and stiffness and, of course, variation in flow velocity (Sun et al., 2015). Meanwhile, there is still a lack of theoretical models for the hydrodynamic lift force (Zdravkovich, 1997, 2002; Blevins, 1990; Shigehiko et al., 2008; Foulhous and Bernitsas, 1993). Research related to the harnessed power and efficiency is limited to experiments and computational fluid dynamic (CFD) simulations (Wu et al, 2011; Ding et al., 2013, 2015). In the MRELab, we conduct experiments, CFD simulations, broad field-of-view laser visualization, mathematical modelling and data processing. Experiments are the most reliable of course. CFD results need to be compared to experiments. The experimental setup with the channel, the controllers, the virtual oscillators based on elaborate system identification took several years to develop; but now that all have been developed and thoroughly tested hundreds of experiments are conducted in a matter of hours rather than months as both the spring stiffness and damping function (linear or multiple nonlinear forms, Ma et al. 2016) and values can be changed on the run with no need for change and calibration of physical components.(See Figs. A1-A4)

Surrogate models, also known as meta-models, were initially developed as surrogates of expensive simulation processes to improve the overall experimental efforts and costs or computational efficiency (Wang and Shan, 2007). Using surrogate models in place of high-fidelity engineering simulations or experiments can help reduce design cycle times and cost by enabling rapid analysis of alternative designs. They can also be used as an efficient replacement of software to predict quantities that cannot be measured directly.

Different surrogate modelling techniques have recently been introduced into areas such as ocean engineering design (Song et al., 2011; Sultan et al., 2013; Mahfouz, 2007; Guarize et al., 2007) and aerodynamic engineering design (Matias et al., 2016; Sommerwerket al., 2008). Popular methods for creating surrogate models include polynomial functions (particularly for linear and quadratic models) (Myers and Montgomery, 1995), radial basis function (RBF) networks (Buhmann, 2003) and Kriging interpolation (Zhang et al., 2015; Cresssie, 1988). In addition, ensembles of surrogate models are proposed to improve the predictive capabilities of the global approximation modelling (Viana et al., 2013; Müller and Shoemaker, 2014).

Proper meta-model determination is dependent on the nature of the engineering problems, as well as on the available experimental and numerical data. The difficulty within the surrogate modelling lies in the construction of a reliable emulator using as few samples as possible. For this reason, conducting a comparative analysis of the surrogate models built using the proper methods is of great importance.

In this work, surrogate-based modelling is performed to implement a single-cylinder VIVACE design based on experimental data. The harnessed damping ratio and stiffness are treated as the basic design variables. The surrogate models representing the relationship between the design variables and the hydrodynamic lift force, harnessed power or efficiency are constructed by using both the Kriging method and RBF networks, based on the processes of equal-interval sampling. In view of the validation of comparison between the Kriging and RBF methods, RBF networks are finally decided upon as the black-box tool for modelling a MHK energy Converter (VIVACE).

A selective sampling point is chosen to verify the forecasting ability of the surrogate modelling on the harnessed power developed in this paper. Then, hybrid optimization based on RBF modelling is performed using the multi-objective particle-swarm optimizer (MOPSO) (Yang et al., 2009). The physical mode of the Converter is presented in Section 2; the mathematical model for harnessed power and efficiency are presented in Section 3; surrogate numerical modelling of the converter is established in Section 4. The case study is presented in Section 5. Conclusions are drawn at the end.

2. Physical model

2.1. Experimental facility: LTFSW channel

All tests were conducted in the Low-Turbulence Free-Surface Water (LTFSW) Channel in the MRELab of the University of Michigan (Fig. 1). The LTFSW channel recirculates 10,000 gallons (37,854 lt) of fresh water at speeds of up to 1.5 m/s using an impeller powered by a 20-hp

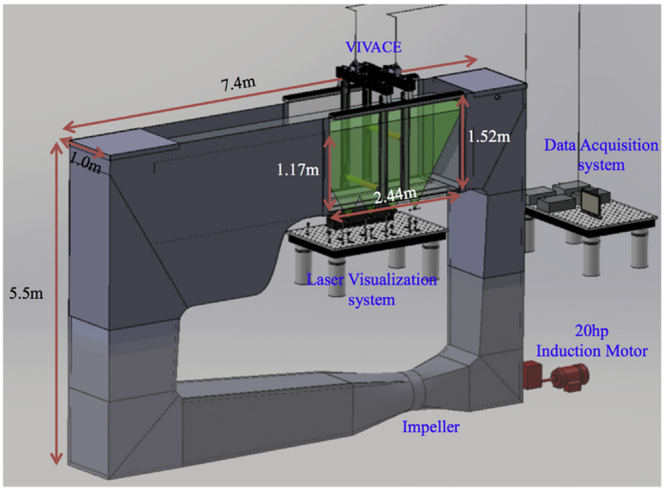

Fig. 1. Schematic of the LTFSW channel and the *Vck* system.