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Disturbance-adaptive stochastic optimal control of energy harvesters, with application to ocean wave energy conversion☆

J.T. Scruggs*, R. Nie

Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, MI 48109-2125, USA

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ABSTRACT

This paper proposes a technique for optimizing the power generated from stationary stochastic vibratory disturbances, using a resonant energy harvester. Although the theory is general, the target application of the paper concerns ocean wave energy harvesting. The control technique involves the use of a causal discrete-time feedback algorithm to dynamically optimize the power extracted from the waves. The theory assumes that the input impedance of the harvester is known precisely, but that *a priori* models are unavailable for the characterization of the stochastic behavior of the incident waves as well as the transfer functions characterizing their hydrodynamic excitation of the system. For these assumptions, we develop an adaptive control technique, which adapts the feedback law at each time step based on updated estimates for the stochastic disturbance model, obtained through a subspace-based system identification algorithm. The technique is demonstrated on a simulation example pertaining to a cylindrical surface-floating wave energy converter in heave.

1. Introduction

It has long been recognized that control theory can be used to optimize the power generated by ocean wave energy converters (Evans, 1981; Falcão, 2010; Falnes, 2002; Ringwood, Baceli & Fusco, 2014; Salter, Taylor & Caldwell, 2002). The determination of the optimal controller for a wave energy converter (WEC) system is predicated on knowledge of its dynamic behavior, as well as a characterization of the sea state to which it is to be subjected. For WECs with linear dynamic models, control designs typically presume harmonic waves, and are designed according to the same network-theoretic impedance-matching principles used in the design and operation of antenna arrays and waveguides (Falnes, 1980). This design technique results in a feedback law between the voltage (or, equivalently, velocity) and the collocated current (or, equivalently, force) of the WEC system, which optimizes power absorption.

However, true sea states are stochastic, with standardized power spectra (such as Pierson–Moskowitz or JONSWAP spectra (Faltinsen, 1990) which exhibit significant available energy over a nontrivial band of frequencies. For such cases, controllers optimized via impedance matching theory must impose a feedback law which is the Hermitian adjoint (i.e., complex-conjugate transpose) of the driving-point admittance matrix for the WEC, at all frequencies (Nebel, 1992). Such controllers are always anticausal, and thus require some anticipatory technique in which present decisions are made with future wave information.

This can be accomplished with model predictive control (MPC) techniques (Bacelli, Gilloteaux & Ringwood, 2009; Cretel, Lightbody, Thomas & Lewis, 2011; Li & Belmont, 2014). Such techniques make use of deployable, up-wave free surface elevation sensors to construct a forecast for future wave excitation forces on the WEC. With this forecast, the optimal control trajectory of the WEC system can then be determined in an anticipatory manner, and can be periodically updated as forecasts are improved. If nonlinear dynamics and constraints require to be taken into account, the MPC techniques can facilitate this via the use of standard Hamilton–Jacobi optimal control techniques (Hals, Falnes & Moan, 2011b; Richter, Magaña, Sawodny & Brekken, 2013). Although MPC techniques are quite powerful, they generally presume complete and precise knowledge of the system model (including the mapping from the free surface elevation to the resultant excitation forces on the WEC), and that the excitation forces can be predicted accurately over some receding horizon (Fusco & Ringwood, 2010). The methodology also assumes that the system state (including the dynamic states of the surrounding fluid) can be observed in real time with sufficient accuracy.

In applications where it is desirable to limit the real-time measurements to phenomena in close proximity to the WEC, controllers can alternatively be optimized subject to the constraint of causality. Over the years, a great many causal controllers have been proposed.

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* Corresponding author.

E-mail addresses: jscruggs@umich.edu (J.T. Scruggs), nie@umich.edu (R. Nie).

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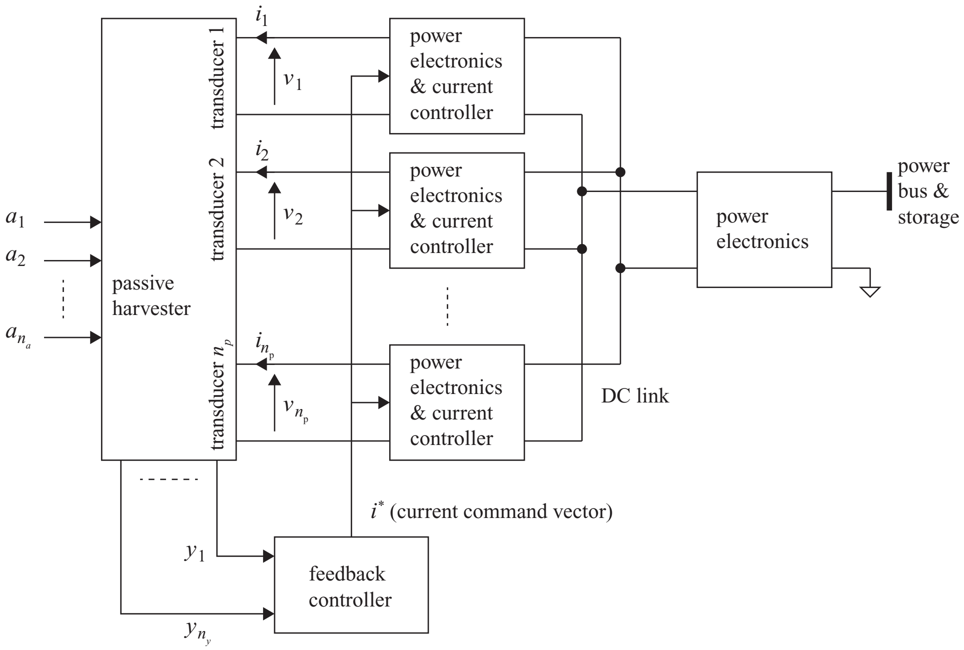

Fig. 1. Diagram of a general energy harvesting system.

(See, for example, Hals, Falnes and Moan (2011a) and Fusco and Ringwood (2011), and the references therein). It was recently shown by Scruggs, Lattanzio, Taflanidis and Cassidy (2013) that under the assumptions of linear dynamics, a stationary stochastic sea state, and unconstrained power controllability, the optimal causal WEC control problem is a special case of the classical Linear Quadratic Gaussian (LQG) control problem. The optimal causal controller has a number of features (besides, of course, causality) that differentiate it from the optimal anticausal controller. Most importantly, while the optimal anticausal controller does not depend on the power spectrum of the sea state, the optimal causal controller does. The reason for this is that the optimal causal controller, operating without the benefit of precise knowledge of future excitations to the system, contains an internal model for the excitation force dynamics. In effect, this internal model can be viewed as providing an optimally-estimated forecast of future excitation forces, based on past data.

In most realistic applications of control to wave energy conversion, it is straight-forward to identify a model for the controllable response of the system (i.e., the mapping from the control force, or current, to the feedback measurements), because both the inputs and output measurements are readily available, and because the control input may be used to probe the system. However, there will be uncertainty about the nature of the wave excitation; both in terms of the power spectrum and propagatory direction of the free surface elevation, as well as the mapping between the free surface elevation and the resultant excitation forces. Causal controllers that are optimized under an assumed disturbance model, which is markedly different from the true disturbance, may perform quite poorly – so much so that they may exhibit negative average power generation. It is therefore essential that causal controllers be capable of accommodating disturbance model uncertainties, either through robust control techniques, adaptation, or some combination of both.

In this paper, we consider the design of controllers that are disturbance-adaptive; i.e., which presume a precise *a priori* model for the controllable response of the system, but for which no *a priori* knowledge is assumed for the hydrodynamic excitation other than that it is a stochastic process. This approach falls into a class of adaptive control techniques sometimes called *adaptive regulation*, to imply the situation in which the plant model is assumed to be known, but the controller must be made to adapt to unknown or variable disturbance characteristics (Landau, Lozano, M'Saad & Karimi, 2011). The approach taken in this paper accomplishes adaptation indirectly; i.e., by identifying a stochastic model for the disturbance, and then re-optimizing the feedback law under the assumption of certainty-equivalence.

1.1. Scope of the paper

For the majority of the paper, we develop the theory for general vibration energy harvesting systems (i.e., not for wave energy applications, specifically), as shown in Fig. 1. In this diagram, the "passive harvester" is a generic mechanical assemblage (such as a WEC) which is driven to vibrate by an external vibratory disturbance (such as a wave). We assume that within the passive harvester are embedded n_p generic "transducers," the ports of which allow energy to flow to and from the harvester. (In the literature on wave energy, these transducers are generally called power take-off systems.) Vectors i and $v \in \mathbb{R}^{n_p}$ are the colocated current and voltage vectors for the transducers, $a \in \mathbb{R}^{n_a}$ is a vector of disturbances, and $y \in \mathbb{R}^{n_y}$ is the vector of feedback outputs. Components of y may include information about the response states of the harvester, as well as information about disturbance a. Components of a may include exogenous disturbances to the system, as well as measurement noise. The feedback controller maps y into a vector i^* of desired current commands for each transducer. Each component of i^* is then sent to a localized power electronic controller, which is assumed to facilitate high-bandwidth current tracking, resulting in the assumption that from the point of view of the harvester dynamics, $i^*(t) \approx i(t)$.

With the high-bandwidth current tracking assumption, the system in Fig. 1 is approximately equivalent to the block diagram in Fig. 2. In this context, the optimal energy harvesting control design problem is to determine the feedback law that maximizes the generated power from the harvester; i.e., the time-averaged value of $-i^T v$. For some technologies, such as hydraulic power take-off systems for WECs, it makes more sense to think about control of mechanical colocated quantities instead of electrical quantities. In such circumstances the theory here may still be applied, by taking i to be the force (or torque) vector of the power take-off devices, and v as the

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