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Experimental Investigation of Hydrodynamic Response of an Ocean Uranium Extraction Machine Attached to a Floating Wind Turbine

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With conventional sources of uranium forecasted to be depleted within a century, developing methods to cost-effectively harvest uranium from seawater, which is estimated to contain 1,000 times more uranium than land does, is crucial to the continued viability of nuclear power generation. Studies have shown that coupling a uranium harvester system with an existing offshore structure, such as a floating wind turbine (FWT), could greatly reduce the cost of harvesting uranium from seawater as it eliminates the need for dedicated moorings and increases the overall energy-gathering ability of the offshore wind farm. This paper explores the hydrodynamic effects of adding a uranium harvester to an offshore FWT. The experimentally determined hydrodynamic responses of two designs of a symbiotic machine for ocean uranium extraction (SMORE) are compared with that of an unmodified FWT. Both SMORE designs utilize adsorbent filament that is enclosed in a hard permeable shell to decouple the mechanical and chemical requirements of the device. It was found that neither SMORE design significantly shifted the resonant peaks of the FWT.

INTRODUCTION

With global conventional terrestrial reserves of uranium (estimated at 7.6 million tonnes) expected to be depleted in a little over a century (OECD, 2016), it is anticipated that future uranium supplies will come from lower-quality sites, resulting in higher extraction costs and even greater environmental impact. Fortunately, approximately 4.5 billion tonnes of uranium exist in the world's oceans (Tamada, 2009) in concentrations of approximately 3 ppb (Oguma et al., 2011). The most promising method of recovering uranium from seawater is using chelating polymers (Kim et al., 2013). In this method, chelating polymers are deployed in seawater and remain submerged until the amount of captured uranium approaches the adsorption capacity. The polymer is then run through an elution bath to strip off uranium and other metal ions. The polymer may be immersed several times in elution baths before it needs to be regenerated by an alkali wash to free its functional groups, allowing for the reuse of the polymer. The output from the elution process undergoes purification and precipitation typical for mined uranium to produce yellowcake.

Initial concepts for offshore systems for the extraction of uranium from seawater utilized an adsorbent that is deployed and moored for extended periods of time, brought back to shore for the elution process, and redeployed afterward. These stand-alone, intermittent operation systems have significant practical and economic deployment challenges (Seko et al., 2003), and to date none of these systems have become economically viable. Specifically, detailed economic analysis by Schneider and Sachde (2013) found that a major cost driver of seawater uranium extraction is the mooring and recovery of the adsorbent. The Symbiotic Machine for Ocean Uranium Extraction (SMORE) described in this paper utilizes the structure of an offshore floating wind turbine (FWT) to provide the mooring and structural support for an autonomous, offshore uranium-harvesting platform. SMORE reduces the mooring and deployment costs of seawater uranium production by continuously passing the adsorbent from the ocean through an elution process and then returning the polymer to the ocean. The integration of a uranium harvesting system with an FWT is pursued because the systems can then share structural support and moorings, which reduces their cost compared to stand-alone systems (Byers et al., 2016).

SMORE is sized to recover 1.2 tonnes of uranium from seawater per year, enough annual fuel for 5 MW worth of nuclear power (Haji and Slocum, 2016), and is designed to work with the National Renewable Energy Laboratory (NREL) 5 MW wind turbine mounted on the OC3 Hywind floating spar (Jonkman et al., 2009; Jonkman, 2010). Thus, approximately 200 FWTs would also provide enough yellowcake to manufacture fuel for a 1 GW nuclear power plant. It is important to ensure that the incorporation of the uranium harvester by the FWT will not adversely affect the dynamics of the FWT, which could result in reduced power output by the turbine, increased material requirements for the turbine, or changes in the turbine's operation and maintenance. FWT motion complicates rotor aerodynamics and control, which generally decreases FWT efficiency, and increases FWT structural stresses (Sebastian and Lackner, 2013; Tran and Kim, 2015; Jonkman and Matha, 2009; Kluger et al., 2017). This paper experimentally investigates the hydrodynamic responses of full-scale SMORE designs and compares the responses to that of an unmodified NREL 5 MW OC3 Hywind FWT.

THEORY

The hydrodynamics of the FWT are considered in head-on incident waves of amplitude A and frequency ω, which result in heave, X_3, and coupled surge, X_1, and pitch, X_5, degrees of freedom (DOF) taken about the still water line (SWL), as shown in Fig. 1. The linear equations of motion of the system are given by

$$(\mathbf{M}+\mathbf{A})\ddot{\xi}+\mathbf{B}\dot{\xi}+\mathbf{C}\xi=\mathbf{X}(t) \tag{1}$$

where $\mathbf{M}$ is the mass matrix, $\mathbf{A}$ is the added mass coefficient matrix, $\mathbf{B}$ is the linear damping coefficient matrix, $\mathbf{C}$ is the restor-

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