Quasi real-time and continuous non-stationary strain estimation in bottom-fixed offshore structures by multimetric data fusion

Rajendra P.Palanisamy[1a], Byung-Jin Jung[2,3b], Sung-Han Sim[1c], and Jin-Hak Yi*[2,3]

[1]*School of Urban and Environmental Engineering, Ulsan National Institute of Science and Technology (UNIST), Republic of Korea*
[2]*Ocean Science and Technology School, Korea Maritime and Ocean University, Republic of Korea*
[3]*Coastal Development Research Center, Korea Institute of Ocean Science and Technology, Busan, Republic of Korea*

(Received keep as blank , Revised keep as blank ,Accepted keep as blank)9pt

Abstract. Offshore structures are generally exposed to harsh environments such as strong tidal currents and wind loadings. Monitoring the structural soundness and integrity of offshore structures is crucial to prevent catastrophic collapses and to prolong their lifetime; however, it is intrinsically challenging because of the difficulties in accessing the critical structural members that are located under water for installing and repairing sensors and data acquisition systems. Virtual sensing technologies have the potential to alleviate such difficulties by estimating the unmeasured structural responses at the desired locations using other measured responses. Despite the usefulness of virtual sensing, its performance and applicability to the structural health monitoring of offshore structures have not been fully studied to date. This study investigates the use of virtual sensing of offshore structures. A Kalman filter based virtual sensing algorithm is developed to estimate responses at the location of interest. Further, this algorithm performs a multi-sensor data fusion to improve the estimation accuracy under non-stationary tidal loading. Numerical analysis and laboratory experiments are conducted to verify the performance of the virtual sensing strategy using a bottom-fixed offshore structural model. Numerical and experimental results show that the unmeasured responses can be reasonably recovered from the measured responses.

Keywords: strain estimation; multimetric data fusion; Kalman filter; buffer; nonstationary responses; offshore structures

1. Introduction

Bottom-fixed offshore structures such as monopiles, tripods, jackets, and gravity-based structures have been widely utilized for the purpose of extracting oil and gas and supporting metrological towers and multipurpose ocean science platforms, and their applications are expanded for supporting ocean energy facilities (OEFs) including offshore wind turbines and tidal stream turbines. Indeed, in recent years, the number of bottom-fixed offshore structures has been increasing rapidly with the increase in the large-scale offshore wind farms (EWEA, 2015). Because these offshore structures are generally built in harsh environments, strong winds and tidal currents can cause structural degradation (fatigue and corrosion) that leads to catastrophic failure. In addition, the quasi-periodic excitation forces due to the rotating devices including rotors, main shafts, and generators can be a source of fatigue (BMT report, 2013; Ren and Zhou, 2014; and Yeter et al., 2015). Being prone to the structural failures due to various external excitations, these offshore structures for

*Corresponding author, Ph.D.Principal research scientist, Professor, E-mail: yijh@kiost.ac.kr
[a]Ms., Student
[b]Ms., Student
[c]PhD.,Professor

*Note: Copied from the manuscript submitted to "Smart Structures and Systems, An International Journal" for the purpose of presentation at ACEM18/Structures18.

OEFs are carefully maintained to prevent catastrophic collapses and to prolong their lifetime.

Structural health monitoring (SHM) provides an effective means of maintaining the offshore structures appropriately to assess the present status as well as the remaining lifetime. SHM is typically performed by collecting the response data measured from a limited number of accessible locations using sensors such as accelerometers and strain gauges. In the monitoring of the offshore structures of OEFs, most of the fatigue-sensitive spots and critical members are located in regions that are inaccessible for direct measurements (e.g., at the mudline several ten meters below the water level). Thus, the sensor installation at important regions deep inside the water can be quite challenging.

Recently, virtual sensing approaches are being actively developed for offshore wind turbines to indirectly obtain the responses at the unmeasured locations by using the measured responses such as acceleration and strain (Paust, 2015; Iliopoulos et al., 2015; and Ren and Zhou, 2014). The virtual sensing technologies can be classified as data-driven techniques, such as the neural network-based methods, and model-driven techniques, such as Kalman filtering (Kalman, 1960) with finite element (FE) models.

The model-based virtual sensing technology has been intensively studied for estimating the unmeasured responses from a limited set of response data based on the Kalman filter (Van der Male and Lourens, 2014; Papadimitriou et al., 2010; Park et al., 2013; Park et al., 2014; Cho et al., 2014; and Jo and Spencer, 2014) and modal decomposition and expansion (Iliopoulos et al., 2014). Joint input-response estimation techniques are developed to improve the accuracy of estimation (Lijun et al., 2016; Maes et al., 2015; and Lourens et al., 2012). Iliopoulos et al. (2014) proposed response estimation techniques using a modal decomposition and expansion algorithm and validated the performance of their method using the measurement data obtained from a monitoring campaign on an offshore Vestas V90 3 MW wind turbine mounted on a monopile foundation. Further, similar algorithms with data fusion techniques are used in reference-free displacement estimation (Cho et al., 2016) and the estimation of a flexibility matrix (Sim, 2016). Van der Male and Lourens (2014) proposed a strategy to monitor the accumulated fatigue damage in real time by employing a joint input-state estimation algorithm. Measuring the operational vibrations at appropriate locations enables the estimation of strain responses at the unmeasured locations. The estimation algorithm is applied to a wind turbine mounted on a lattice support structure for which the response estimates of the lattice members are based on the measurements obtained only from the turbine tower. Most of these studies are limited to zero mean responses, and their algorithm is verified only using numerically simulated responses. Some recent experimental results have been reported by Maes et al (2016) and Iliopoulos et al (2017).

This study investigates a near real-time virtual sensing strategy based on Kalman filtering associated with an FE model tailored to the offshore structures under non-zero mean stochastic external loads. A multimetric data fusion technique is incorporated to overcome the difficulties related to the non-zero mean static response estimation. This technique is implemented by the fusion of different sensors such as strain gauges and accelerometers for low and high-frequency regions. The bottom-fixed offshore structures of OEFs consists of broad spectrum of strain responses because of the thrust force as well as the dynamic excitations due to the turbulent effect and the periodic operational loads due to the rotors. Therefore, extracting accurate responses from homogeneous sensor networks using either acceleration or strain is quite challenging. Thus, a multi-sensor network is more appropriate to estimate broad spectrum responses.

The proposed method includes a buffering technique, which reduces the computation time significantly in contrast to any other estimation techniques. Thus, this estimation technique can be easily implemented in wireless and mobile sensing technologies (Lee and Kim, 2016). The proposed method is verified numerically and experimentally using a four-legged portal frame in a circulating water channel.

2. Formulation

Monitoring the offshore structures under water is unique in that the sensor installation and maintenance associated with the data acquisition systems are quite challenging because critical structural members are often inaccessible.