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Phased Array Ultrasonic Testing of Offshore Wind Bolted Flange Connections

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Abstract

Offshore wind will play a key role in the majority of countries' plans to accelerate towards NetZero and low-carbon energy transitions. Using fasteners (bolts and nuts) as a joining strategy is a common practice in various sections of the Offshore Wind Turbines (OWT) which needs regular Non-Destructive Testing (NDT). For example, the bolted connection between the monopile and the transition piece is under an immense stress concentration, which can result in loosening and even failure of the connection. The current procedure to test the bolts involves fixed permanent strain gauges and/or ultrasonic methods (using single-element transducers) to ensure the specific preload is maintained during the wind turbine operation. In the case of using the strain gauge, the challenge is the number of bolts used in turbines in a wind farm, which can result in thousands of required strain gauges, and then as a usual practice, only a very limited number of bolts can only be monitored.

The ultrasonic stress measurement technology is based on the acoustoelasticity theory, the relationship between the acoustic wave velocity and material stress, and the change in the ultrasonic Time of Flight (ToF) corresponded to the change in the length of the bolt due to the tightening axial force. This process will then rely on the calibration procedure including measurement of the acoustoelastic coefficient and also the ToF in the free-stress bolt. In the traditional ultrasonic method, the operator uses single-element transducers and assumes any difference between the ToF of a bolt in service and the calibration bolt corresponds to the stress (pre-load) change. While this assumption can be true for a brand-new bolt, similar to what is used in the lab for calibration, it will ignore corrosion, defects, ageing, creep, strain-hardening, fatigue and other material changes during the service life. In this paper, the Phased Array Ultrasonic Testing (PAUT) system will be used instead of the single-element approach. The advantage of the PAUT system over the single-element transducer is the possibility of (I) defect detection and (II) stress measurement, simultaneously. Combining the defect detection and stress measurement is critical, otherwise, the ultrasonic stress measurement and calibration procedure will be influenced by the possible defects. Using the PAUT and an array instead of a single-element transducer, will allow the detection of the possible defects in some of the specific acoustic paths used for the ToF measurement and then use alternative acoustic paths for the stress measurement. Furthermore, advanced post-processing algorithms like Total Focusing Method (TFM) can allow the possibility of focusing on more threads which are usually critical points of concern in the safety-critical bolts. It should also be noted that the bolt material used for offshore applications is usually marine-grade high-alloy steel and/or stainless steel which can result in a poor Signal-to-Noise Ratio (SNR) corresponding to the austenitic microstructure and large grain noise. In this paper, Phase Coherence Imaging (PCI) was used to improve the SNR value in the PAUT bolt testing. PCI is an amplitude-free synthetic beamforming method, which considers the phase dispersion at each discrete image point. This allows incoherent noises resulting from side lobes, grating lobes, reverberations and grain noise to be reduced.

The experimental setup included an M20 bolt tested by a 10 MHz 32-element array (Olympus, USA) and FIToolbox phased array controller (Diagnostic Sonar, UK). A washer-shaped load cell (BoltSafe, Netherlands)

was used to verify the ultrasonic stress measurement results. The PAUT stress measurement system could successfully detect the ToF variations caused by the bolt's stress change recorded by the load cell. For defect detection, two Side-Drilled Holes (SDH) were produced between the threads to quantify the scanning image and SNR. The Full Matrix Capturing (FMC) was then imported into a Matlab-programmed TFM and PCI code. The application of these advanced post-processing algorithms resulted in a clearer scanning image, improved SNR value and detection of the SDHs with a lower gain.