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Experimental validation of an active heave compensation system: Estimation, prediction and control

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ABSTRACT

This work presents a comprehensive active heave compensation (AHC) approach proposing estimation, prediction and control methods. The estimation concept covers the estimation of the attitude using sensor fusion as well as the estimation of heave which is obtained by applying adaptive filtering methods. Moreover, a prediction approach based on a Levinson recursive least squares (RLS) algorithm is proposed. The actuation concept consists of a model predictive trajectory planner and a model-based Two-Degree-of-Freedom (2-DOF) controller. It is based on a model of the hydraulically driven compensation winch. The overall compensation performance as well as the estimation and prediction accuracy are evaluated using a full-scale AHC test bench.

1. Introduction

The offshore production of oil and gas is advancing into deeper waters at a fast pace. Following forecasts, in 2020 more than 10% of the world's oil and gas supply will come from deepwater (>300 m) offshore production (Chakrabarti, 2008). However, the oil and gas production from very deep waters is an enormous technical challenge. For these depths, a fixed installation of offshore platforms is not possible or no longer viable. As a result, conveying systems for oil and gas fields will be built to a large extent with all processing equipment on the seabed. For the construction and maintenance of these underwater installations, loads need to be transferred to the seabed. These so-called subsea lifts are typically done using large cranes installed on a ship. Fig. 1 shows a ship with attached crane suitable for these tasks.

However, such operations are continuously disturbed by environmental influences such as changing weather conditions, rough sea and wind. As a result, the ship is constantly moving in horizontal and vertical direction which significantly reduces the positioning accuracy. For offshore applications, the horizontal motion of the ship (i.e. surge, sway and yaw) is usually controlled by a dynamic positioning system (DP-system). Many different control strategies for DP-systems can be found in the literature, see for example Fossen (2011), Fossen and Strand (2001), Grimble, Patton, and Wise (1980) and Sorensen (2005). However, these systems only stabilize the horizontal position of the ship. The remaining vertical motion due to the ocean waves leads to several problems. One problem is the positioning operation. An accurate and safe positioning of the payload is not possible during harsh sea conditions. Also, the critical tension of the rope can be exceeded causing serious damage of the rope. Hence, compensation systems can be used in order to decouple the load motion from the wave-induced ship motion. As a result, the downtime between such lifting operations is reduced significantly whilst ensuring at the same time a high level of positioning accuracy.

Various types of compensation systems have been addressed in literature. An overview of many different compensation techniques can be found for example in the publication of Adamson (2003). Furthermore, Woodacre, Bauer, and Irani (2015) give a thorough review of the past developments of heave compensation systems. Basically, these systems can be divided into two main categories, i.e. passive heave compensation and active heave compensation. Passive systems are usually vibration isolators trying to isolate the load motion from the ship motion. Typically, a parallel spring–damper system is placed somewhere between the crane and the load in order to shift the resonance frequency of the lifting system far away from the expected frequency range of the ocean waves. The spring–damper system can be a gas-backed accumulator driven hydraulic piston as suggested by Huster, Bergstrom, Gosior, and White (2009) or, for example, a strictly pneumatic passive compensator as treated by Driscoll, Meyer, and Lueck (2000). Passive compensators are generally based on simple

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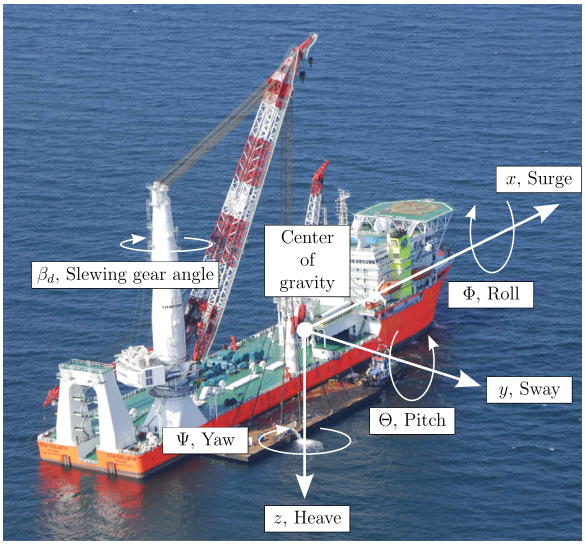

Fig. 1. Ship with installed crane for subsea lifts.
Source: Liebherr-Werk Nenzing GmbH.

designs. Also, they can often be retrofitted into an already existing system. However, the compensation performance, especially in irregular waves, is limited. According to Hatleskog and Dunnigan (2006), passive compensation is not more effective than 80%. Therefore, Hatleskog and Dunnigan extended their passive system by an active subsystem resulting in a simulated heave reduction of 90%–95% (Hatleskog & Dunnigan, 2007).

In contrast to passive systems, active systems require closed-loop control of the compensation system. Michel, Kemmetmüller and Kugi (2012), for example, presented an active heave compensation approach based on heave measurements and a constant tension approach based on the measured rope tension. Therefore, they also derived a distributed-parameter model of the lifting rope. Korde (1998), for example, used accelerometer feedback in order to remove the heave motion from a drill string. Using frequency-domain calculations, Korde could show the effectiveness of his approach within the bounds of linearity. Hatleskog and Dunnigan (2007) also used a vertical accelerometer in order to compensate heave for a drill string applying a feedforward compensation. In order to consider the effects of roll and pitch motion an inertial measurement unit (IMU) can be used to estimate the heave motion. Küchler, Pregizer, Eberharter, Schneider, and Sawodny (2011) presented an extended Kalman Filter approach to estimate the orientation of an IMU. Based on the work of Godhavn (1998), Richter, Schneider, Walser, and Sawodny (2014) presented phase correction algorithms to reduce the heave estimation errors using IMUs.

However, many heave compensation systems are suffering from delays due to the hydraulic drive system or the slow communication between the IMU and the control system (Woodacre et al., 2015). Hatleskog and Dunnigan (2007) already concluded that predictions can help to increase their active heave compensation performance. Neupert, Mahl, Haessig, Sawodny, and Schneider (2008) presented an inversion based approach using a prediction algorithm to overcome system delays. The prediction algorithm consists of a Fast Fourier Transform combined with a peak-detection algorithm in order to identify the dominant modes of the wave motion. A Kalman filter is initialized with the identified modes and estimated the amplitude and phase of each mode online. Küchler, Mahl, Neupert, Schneider, and Sawodny (2011) proposed a similar prediction algorithm and showed the effectiveness assuming a system delay of 0.7 s. The prediction of wave motion is also important for other applications. Fusco and Ringwood (2010), for example, presented a range of different short-term forecasting methods in order to improve the real-time control of wave energy converters.

Some compensation approaches proposed in the literature have been experimentally validated. Küchler, Mahl, et al. (2011) validated their approach using a 1-DOF test bench. Messineo, Celani, and Egeland (2008) tested their controller design for moonpool operations using a small-scale floating crane in a small pool including a wave generator. Kjelland and Hansen (2015) presented a loading and unloading operation of a load from a moving platform to a fixed structure. They used a Stewart platform in order to imitate a realistic ship motion and a hydraulically driven winch for the loading. A similar framework was presented by Sanfilippo, Hatledal, Zhang, Rekdalsbakken, and Pettersen (2015). The laboratory setup consists of a motion platform to imitate the relevant ship motion and an industrial robot for motion compensation. The presented work successfully demonstrates that heave motion can also be compensated using the entire crane structure. An alternative option was presented by Richter, Arnold, Schneider, Eberharter, and Sawodny (2014). They validated their model-predictive trajectory planning approach using a suspended platform capable of imitating all relevant ship motions.

Despite the existing work on validation, Woodacre et al. (2015) still recommend that more work should be done to experimentally validate active heave compensation systems. Therefore, the work presented in the following particularly contributes by validating a comprehensive AHC system on a full-scale test bench including the estimation and prediction of the ship motion as well as the trajectory planning and control of the winch. This paper also proposes a novel method for the real-time prediction of ship motion by applying the Levinson RLS algorithm (Strobach, 1991) in order to estimate the prediction model for a given time window. Furthermore, the trajectory planning approach of Richter, Arnold et al. (2014) is extended by using a simplified model of the hydraulically driven winch for the model predictive trajectory planning. A 2-DOF controller is presented which is able to cope with the uncertainties of the winch drive.

This paper is organized as follows. In Section 2, the experimental setup and the generation of wave motion are described. Also, the dynamic model of the hydraulically driven winch is derived. Section 3 presents the proposed algorithms for the active heave compensation system. This section mainly focuses on the prediction algorithm and the proposed control architecture. Following, the complete compensation approach is validated in Section 4 using measurement results from the test bench. Concluding remarks are given at the end of the paper.

2. Problem setting

The active heave compensation approach presented in this work is supposed to run on offshore cranes such as shown in Fig. 1. Therefore, an experimental validation of these safety-related algorithms is mandatory. However, testing on the actual ship is time-consuming and cost-intensive. For this reason, the company Liebherr has developed a full-scale test bench for validation purposes. The test bench is designed in such a way that it allows the imitation of all relevant ship motions, i.e. roll, pitch and heave. In addition, the test bench is featured with the same sensor setup as the actual Liebherr offshore cranes. In the following, the test bench will be presented in detail, before the generation of a realistic ship motion is described. Finally, this section derives a model of the compensation winch which is used for the actuation strategy later on.

2.1. Experimental setup

Fig. 2 shows the test bench used for validation of the active heave compensation algorithms. The body in the middle, called Tripod, is supposed to represent the ship with the attached crane structure. Hence, the motion z_c of the Tripod tip is supposed to represent the vertical motion of the crane tip of the offshore crane. The Tripod is suspended on three ropes with the lengths z_1, z_2 and z_3 which are actuated by hydraulically driven winches. Using these ropes, a realistic ship motion can be imitated following desired trajectories for the roll, pitch and