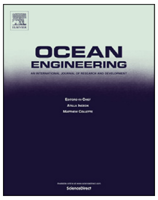
ARTICLE IN PRESS

Ocean Engineering xxx (2017) 1–8

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng



Detection of mooring line failures using Dynamic Hypothesis Testing☆

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ARTICLE INFO

Keywords:
Mooring line breakage
Fault detection
Dynamic positioning
Position mooring
Dynamic hypothesis testing

ABSTRACT

This article proposes a novel methodology for the detection of mooring line breakage in thruster assisted position mooring (PM) systems, when no measurements of the tensions on the mooring lines are available. For dynamic positioning (DP) of marine vessels moored to the seabed via a turret-based spread mooring system, thrusters provide only complementary assistance to the mooring system, which is responsible for generating a large part of the forces and moments required for station keeping. However, in extreme weather conditions thruster assistance is essential to avoid mooring line failure. Once a mooring line is parted, the remaining lines must withstand an increase in the tension forces required to compensate for the lost tension in the ruptured line. This in turn may lead to a cascade breakage of the mooring lines. Hence, it is of paramount importance to detect any line breakage as soon as it occurs to compensate for the lost tension by proper use of DP thruster assistance. As a contribution to solving this problem, in this paper we propose a methodology that builds on Dynamic Hypothesis Testing (DHT) whereby a set of hypotheses are assessed, at each sampling time, using the measured inputs and outputs of the thruster assisted position mooring system. While the first hypothesis corresponds to the assumption that all mooring lines are intact, the remaining hypotheses are built assuming that a single, or multiple line breakage events have taken place. At each sampling time, the inputs and outputs to the system are used to generate the conditional probability of each hypothesis being true. The conditional probabilities are then used to evaluate which hypothesis is more probable to be compatible with the collected measurements. In addition, we find conditions for any pair of hypothesis to be distinguishable. Numerical simulations, carried out using a high fidelity nonlinear PM simulator, illustrate the efficiency of the proposed methodology.

1. Introduction

Rising world oil demand, with only limited easy-to-access oil fields, is steadily pushing offshore oil and gas exploration and exploitation activities to increasingly remote, deeper areas under extreme environmental conditions. The latter expose offshore vessels and structures used for drilling and production of oil and gas to challenging operational conditions characterized by high winds reaching hurricane-force and temperatures dropping below zero. In such severe conditions, the reliability of offshore vessels and their equipments as well as the efficacy of the corresponding monitoring and control systems are fundamental to the safety and success of the operations. Some of the commercially attractive alternatives to permanent platforms for offshore oil and gas exploitation are dynamic positioning (DP) and Position Mooring (PM) systems. The research and development of thruster assisted position mooring systems follows the rich and by now mature applications of DP systems.

DP systems have been commercially available since the late 1960s for offshore drilling applications. Early DP systems were built around PID controllers driven by output measurements that were filtered using a cascade of notch and low pass filters aimed at suppressing thruster wear and tear caused by wave-induced motions. However, since notch filters introduce some phase lag around the crossover frequency, phase margin reduction and deterioration of the system performance were inevitable.

☆ This work was supported in part by FCT [UID/EEA/50009/2013] and the European Commission under the H2020-ICT-2014 WiMUST Project (Grant Agreement No. 645141) and was the result of a collaborative effort between ISR/IST and AMOS; the Norwegian Research Council is acknowledged as the main sponsor of AMOS.

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https://doi.org/10.1016/j.oceaneng.2018.01.021
Received 27 February 2017; Received in revised form 18 November 2017; Accepted 4 January 2018

Please cite this article in press as: Hassani, V., et al., Detection of mooring line failures using Dynamic Hypothesis Testing, Ocean Engineering (2017), https://doi.org/10.1016/j.oceaneng.2018.01.021

To overcome this problem, PID control solutions were replaced by more advanced control techniques based on optimal and Linear-Quadratic-Gaussian (LQG) control and Kalman filtering theory in Balchen et al. (1976), further modified and extended in Grimble et al. (1979, 1980); Balchen et al. (1980); Fung and Grimble (1983); Sælid et al. (1983); Sørensen et al. (1996); Fossen et al. (1996) and Fossen and Perez (2009a). Since the application of LQG techniques to DP systems involves the linearization of the vessel's kinematic and dynamic equations about different operating points and the tuning of design variables such as the covariance of process and sensor noise, simpler frameworks were developed using integrator back stepping techniques in Aarset et al. (1998); Fossen and Grøvlen (1998); Robertsson and Johansson (1998) and passive observers and nonlinear multivariate PID controllers in Fossen and Strand (1999); Strand and Fossen (1999); Strand (1999); Torsetnes et al. (2004); Fossen (2000). In recent years, other techniques such as gain-scheduling Torsetnes et al. (2004), robust control Hassani et al. (2012a, b, 2017), adaptive control Tannuri et al. (2006); Hassani et al. (2010, 2013b) and hybrid control Nguyen et al. (2007b); Hassani et al. (2013b) have come to the fore. The literature on modeling and simulation of DP systems and the application of different control techniques to the design of DP controllers is vast and defies a simple summary. The reader is referred to Sørensen (2005, 2011b); Hassani et al. (2013a) and the references therein for a short presentation of the subject and its historical evolution.

PM systems have been available since the late 1980s. While PM systems are built upon DP systems, there are some key differences between the two. Namely, the main function of thruster assistance in PM systems is to keep the heading angle at a desired value and add damping in the surge, sway and yaw motions while the mooring lines keep the position of the vessel in a predefined admissible region, see Strand (1999). This strategy leads to reduced activity of the thrusters in normal environmental condition; however, in harsh environmental conditions thruster assistance helps keeping the vessel in a predefined tolerable region in order to prevent the mooring lines tensions from rising above safety limits. A mathematical model of a thruster assisted mooring system and a mooring line were developed in Strand et al. (1998b) and Aamo and Fossen (2000), respectively. Back stepping techniques were applied to PM systems in Strand et al. (1998a); Chen et al. (2013). In Aamo and Fossen (1999), a dynamic line tensioning controller was developed to reject constant or slowly varying environmental disturbances, and hence, reduce the thruster force and consumed fuel. In Sørensen et al. (1999), a nonlinear multivariable controller and a passivity based observer were applied to a floating production storage and offloading (FPSO) unit with PM systems. A switching controller algorithm was proposed by Nguyen et al. (2007b) whereby the sea state is identified through power spectral density analysis of the vessel's motion and a suitable controller is automatically selected to increase the operation weather window of the PM system under study. The safety of DP and PM systems is of paramount concern in the marine industry, and hence, regulations are in place to define different levels of system redundancy, to prevent faults in equipment from causing accidents at the system level DNV (2014, 2015). Any failures in mooring lines can cause loss of position-keeping capability which, in turn, can lead to disasters on an unprecedented scale. In Strand et al. (1998b), a line break detection and compensation algorithm was coupled with an LQG based controller; then, any irregular tension measurement is monitored to detect a possible line break. Furthermore, a compensation mechanism is developed in Strand et al. (1998b), so that in case of line break detection, a feed-forward thrust in surge and sway and a feed-forward momentum in yaw are applied to compensate for the lost tension, due to line break, and to alleviate the load increase in the remaining mooring lines. In order to reduce the possibility of mooring line breakage in harsh environmental conditions, a setpoint chasing algorithm was introduced in Nguyen and Sørensen (2009). A structural reliability index for integrity of the mooring lines was proposed in Berntsen et al. (2004, 2006, 2009) where a new controller was developed to keep the probability of line failure below an acceptable level. A consistency based diagnosis technique was used to develop fault tolerant control of PM systems in Nguyen et al. (2007a) using the methodology developed in Blanke (2005); Blanke et al. (2006). A methodology to detect line breakage and loss of a buoyancy element in mooring lines was developed in Fang and Blanke (2011); Blanke et al. (2012) based on a structure-graph approach Blanke et al. (2006). Detection of line breakage was studied in Ren et al. (2015) using a supervisory control framework Hespanha (2001).

Common to all of the above-mention methods, except for Ren et al. (2015), is the need for measuring the tension of mooring line forces which makes all these techniques susceptible to measurement noise or sensor failure. As a matter of fact, not all the mooring lines are equipped with loadcells and even when they are, it is frequently reported that loadcells do not work properly and offshore personnel have little confidence in the reported values; see GL Noble Denton (2006). Furthermore, in the case of abnormal sensor reading for submerged turrets, it is laborious to figure out whether it was the line or the sensor that failed. A reported mooring line failure incident for an instrumented North Sea FPSO in GL Noble Denton (2006) confirms that it took two weeks of data processing of the measured tension from the other lines to conclude that a recorded tension spike was indeed a real failure rather than an instrumentation fault.

The above circle of ideas motivates us to further develop a model based algorithm to detect any changes in the dynamic behavior of a PM system due to breakage in the mooring lines. To this end, we use the dynamic model of a PM system and calculate the conditional probabilities of any line break using input and output measurements only. We further develop a Dynamic Hypothesis Testing (DHT) algorithm that will be used for failure detection in mooring lines. Our approach is motivated by the Response Learning System (RLS) strategy for Automatic Line Failure Detection proposed in GL Noble Denton (2006). In RLS, by taking into account the expected performance of the system in a measured weather condition, its true performance is analyzed to check if it is consistent with the expected performance and, if not, whether the inconsistency is due to change of system stiffness as a result of line failure. As pointed out in GL Noble Denton (2006), doing so is a fairly complicated procedure that requires further research, development, and testing. However, if successful, it has the real benefit of being a relatively simple retrofit to existing installations, avoiding the need for expensive intervention work such as installing load-cells and wiring.

The main contribution of the current article is the development of a model based supervisor in which by measuring the inputs and outputs of the PM system, mooring line failures are detected without the need for measuring the tension forces in mooring lines using load cells. To this end, a set of hypotheses are built and the conditional probability of each hypothesis is calculated in an iterative manner. Using the conditional probabilities, all hypotheses are tested in parallel at each sampling time to detect any possible line failure. Furthermore, a sufficient condition for distinguishability of any pair of hypotheses is developed. In order to validate our proposed algorithm we use a high fidelity nonlinear PM simulator to run a series of numerical simulations that illustrate the efficacy of the techniques proposed.

The structure of the paper is as follows. Section 2 proposes a representative dynamic model of a PM system. Section 3 describes the computation of the conditional probabilities of line breakage, a key step in the proposed DHT algorithm. Section 4 derives sufficient conditions for distinguishability of any pair of hypotheses. The results of numerical Monte-Carlo simulations with stochastic signals, carried out in the Marine Cybernetics Simulator, aimed at illustrating the performance of the proposed line breakage detection algorithm, are presented in Section 5. Conclusions and suggestions for future research are summarized in Section 6.

2. Control plant model of the PM systems

In this section we start by introducing the vessel model described in