Ocean Engineering 164 (2018) 712–721

Contents lists available at ScienceDirect

Ocean Engineering

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

Analytical solution to motion planning and modal-based tracking control for dynamic positioning of subsea equipment

Rafael Domenici Pereira Simões, José Oniram de Aquino Limaverde Filho, Emanuel Pereira Barroso Neto, Eugênio Libório Feitosa Fortaleza*

Automation and Control Group (GRACO), Department of Mechanical Engineering, University of Brasília, Brasília, Federal District, Brazil

ARTICLE INFO

Keywords:
Subsea equipment installation
Motion planning
Modal reduction
Trajectory tracking
Damped cable analytical solution

ABSTRACT

One of the challenges of the installation of subsea equipment is the precise positioning of the equipment in a desired location on the seabed. This positioning procedure is still commonly performed manually by an operator. This article presents a trajectory tracking control system design for the positioning of a subsea equipment. This work will be done in two stages. First, a motion planning for dynamic positioning system of platform is presented. For this, an analytical solution of motion equation of the riser, which is modeled as a damped cable, is detailed. This analytical solution when compared to numerical solutions has the advantage of generating more precise and smooth trajectories for the system input and output. Second, we propose a tracking control system to ensure that the subsea equipment follows the desired trajectory in the presence of disturbances. More precisely, a linear state-feedback control law is proposed using a reduced model, which is obtained from a modal reduction with delay insertion. This delay insertion provides a high precision low order model. This fact highly increase the robustness of the control system to the measurement noise. Numerical simulations and experimental tests are presented to evaluated the proposed control strategy.

1. Introduction

Nowadays, with the offshore exploration and production of oil and gas moving towards deeper waters (2000 m and more), subsea installation has become a major topic in the offshore oil industry. Several subsea equipment are constructed onshore and transported offshore to the installation site, such as the Christmas tree, the Blow-Out Preventer and the manifold.

One of the challenges of the installation of the subsea equipment in deep water is the precise positioning of the equipment in the desired location on the seabed.

According to Bai and Bai (2012), there are two methods that are widely used for positioning: the guideline method and the guideline-less one. The guideline method uses guides cables (typically four tensioned cables) to position the subsea equipment in the desired location on the seabed. The positioning using this method is very convenient, but limited by the very use of the guides cables. As highlighted in Bai and Bai (2012), for facilities in deep water, this method can be quite costly, both in time and value.

In turn, the guideline-less method positions the subsea equipment without any guides cables. The subsea equipment has its position changed indirectly by modifying the position of the vessel or by a crane system. However, due to the dynamic behavior of the system and the required space limitations, this method is relatively complex.

Sometimes, in the guideline-less method, it is also coupled with a propulsion system in the subsea equipment, in order to adjust its position directly, as can be seen in How et al. (2007, 2010, 2011). However, the range of this adjustment is limited to a certain area, determined by the capacity of the thrusters. Furthermore, for very heavy systems (like subsea systems), the required strength of the thrusters to move the system is too large, preventing the operation due to operational cost.

The precise positioning of subsea equipment is even more difficult in deep water due to the large distance between the surface vessel and the equipment to be placed on the seabed. Environmental disturbances, such as ocean currents, waves and winds, relatively small, can cause large gaps between the actual position of the submarine equipment and its expected position. In addition, severe weather conditions can force the positioning operation to wait several days until it becomes possible.

This paper address the case of positioning of a subsea equipment in deep waters by the guideline-less method and without adding the propulsion system to the equipment. The positioning of the structure

* Corresponding author.
E-mail address: efortaleza@unb.br (E. Libório Feitosa Fortaleza).

https://doi.org/10.1016/j.oceaneng.2018.07.008
Received 21 March 2017; Received in revised form 30 April 2018; Accepted 6 July 2018

top (riser, cable etc.) is determined by a dynamic positioning (DP) system and a crane system, whereas the subsea equipment is positioned indirectly by the motion transmission through the structure top (ST). Thus, the desired position for the subsea equipment is obtained only with the correct displacement of the ST.

Currently, this positioning procedure is still commonly performed manually. That is, an operator displaces the ST considering the images of the subsea equipment produced by a remotely operated vehicle (ROV). Thus, the operator can adjust the position of the ST in order to position and install the subsea equipment in the desired location. Therefore, this operation becomes totally dependent on the experience and skill of the operator. Another limitation is that this operation can only be performed in the presence of good weather and underwater visibility.

In this context, the continuous development of researches and technologies to increase the efficiency and reliability of the subsea installation operation is necessary, making it faster and safer, and also expand the range of climatic conditions in which it can be performed (i.e. ultrasonic sensors can be used to close the loop in the cases of low underwater visibility).

A typical subsea installation procedure is shown in Fig. 1, which basically consists of a platform, a marine riser and a subsea equipment to be positioned. The platform is equipped with a DP system, which allows modifying its position by thrusters and propellers. The upper end of the riser is connected to the platform and its lower end is connected to the subsea equipment. A ROV monitors the subsea position throughout the operation.

The system can be represented by a master/slave architecture (Fig. 2). The slave loop refers to the DP system and the platform, and its dynamics is much faster compared to the dynamics of the master loop. In turn, the master loop refers to the riser, the subsea equipment and the operator. The dynamics of the master loop is influenced mainly by the spread of mechanical wave along the riser. It is noteworthy that, in this paper, the analysis will be focused only on the master loop and will be considered that the DP system positions the platform at the desired position instantly.

The strategy consists of positioning the subsea equipment, in the desired position on the seabed, dynamically modifying the upper end of the riser, which displacement is determined by the DP system of the platform. This allows to determine the precise platform motion which is necessary to obtain the desired position of the subsea equipment (displacement and stabilization of the subsea equipment). The position of the subsea equipment is monitored by the images produced in real time by a ROV.

Thus, the installation of the subsea equipment may be carried out without the direct interference of the operator, even in the presence of external disturbances. This automated process also tends to increase the reliability and efficiency of operation, reducing the total time and the risk of damage to the subsea equipment.

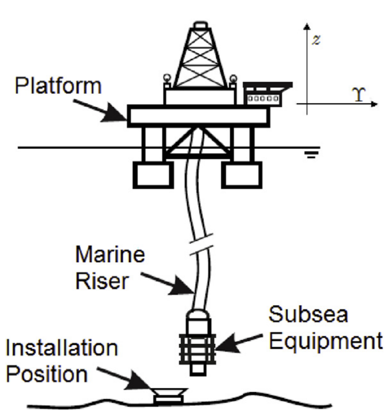

Fig. 1. Subsea installation procedure, adapted from Fortaleza et al. (2012).

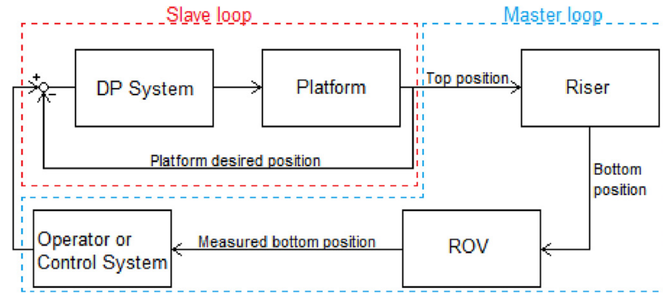

Fig. 2. Block diagram of the system (master/slave architecture).

From a control point of view, this papers deals with the control of an infinite order system defined by a partial differential equation (PDE). One can highlight the work of Meurer and Zeitz (2005) that used formal power series parametrization to represent a system of a tubular reactor, bringing similar representation to the modal basis. However, a high-order state observer is obtained from the model. In turn, Schröck et al. (2012) attempted the use of a spectral representation based on the natural frequencies of the system to represent piezo-actuated flexible structures, which also presents a representation of the dynamical system similar to a vibration modes representation.

This paper is organized as follows. Section 2 presents the governing equation of the system. Section 3 derives the analytical solution of the governing equation in the time domain. Section 4 presents the numerical simulation of the structure. Section 5 describes the reduced model obtained for the system. Section 6 presents the feedback control to track the trajectory. Section 7 discusses the experimental results. And in the last section, the conclusion and further works are presented.

2. Governing equation

Typically, structures used in the installation of subsea equipment, such as risers, are slender and their transverse displacements are small compared to their length. In the case of a riser with constant cross section and under traction, the dynamic behavior of an infinitesimal element of the riser toward its horizontal displacement can be modeled by the Euler-Bernoulli beam equation (1) under external forces from the fluid in which it is submerged.

$$m_s \frac{\partial^2 \Upsilon}{\partial t^2}(z, t) = -EJ \frac{\partial^4 \Upsilon}{\partial z^4}(z, t) + \frac{\partial}{\partial z}\left(T(z) \frac{\partial \Upsilon}{\partial z}(z, t)\right) + F_h(z, t) \tag{1}$$

where Υ is the position of the riser in the horizontal direction on the plane including the subsea equipment and its final destination. Υ is function of two parameters: the time t and the height z from the seabed. The other variables are: m_s the riser linear mass, $T(z)$ the function that describes the tension force along the structure's length, E the Young's modulus, J the second moment of area and F_h the external forces in the horizontal direction per unit length.

The external forces acting in the structure, except on its top and bottom-ends, where external forces are present due to the boundary conditions, can be approximated by the modified Morison's equation. Eq. (2) represents the hydrodynamic forces associated with the displacement of a submerged body and do not include side forces resulting from the oscillatory vortex shedding around the structure.

$$F_h(z, t) = -m_F \frac{\partial^2 \Upsilon}{\partial t^2}(z, t) - \mu \frac{\partial \Upsilon}{\partial t}(z, t)\left|\frac{\partial \Upsilon}{\partial t}(z, t)\right| \tag{2}$$

where m_F is the additional fluid mass per unit length and μ is the drag per unit length. The additional fluid mass is defined by $m_F = \rho\, C_m S$, where ρ is the fluid density, C_m is the added mass coefficient and S is the cross-sectional area of the riser. The drag is defined by $\mu = 1/2\rho\, C_d D$, where C_d is the drag coefficient and D is the outer diameter of the riser.

Denoting $m = m_s + m_F$ and considering the hydrodynamic forces