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SLIDING MODE CONTROL APPLIED TO OFFSHORE DYNAMIC POSITIONING SYSTEMS

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Abstract: The technique of Dynamic Positioning (DP) consists on keeping the position and heading of a vessel by the use of active thrusters. In Brazil, the offshore oil industry follows the recent tendency of performing several operations aided by DP systems, such as prospection, drilling, offloading and others. Currently, the DPS are based on conventional controllers (PD + Kalman Filter). This paper proposes the application of a controller based on nonlinear sliding mode control technique to the dynamic positioning of a floating vessel, as well as some simulations and experimental validation results.

Keywords: sliding mode control, vessel control, nonlinear systems, dynamic positioning systems.

1. INTRODUCTION

Dynamic Positioning (DP) Systems are defined as a set of components used to keep a floating vessel on a specific position or follow pre-defined path through the action of propellers**.** Several offshore operations are carried out using DPS, such as drilling, underwater pipe-laying, offloading and diving support. A DP system can be seen as a complex system composed of several sensors, a control algorithms and propellers. The sensors are used to measure the actual position of the floating vessel, while the control algorithm is responsible for the calculation of forces to be delivered by each propeller, in order to counteract all environmental forces, such as wind, waves and current loads.

The purpose of this paper is to design a new control algorithm based on the robust and nonlinear Sliding Mode (SM) Control theory. This controller contains a feedforward loop, responsible for the compensation environmental forces, and a feedback loop, responsible for the elimination of errors. A simplified block diagram of a DP System is presented in Fig. 1.

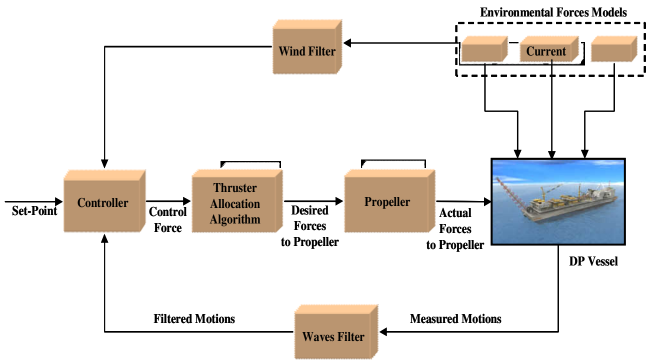

Fig. 1. DP System block diagram.

The nonlinear formulation of the controller assures performance and stability requirements for all heading angles. SM controller contains only nine parameters, which can be calibrated easily by simple equations. The controller can be applied in a large range of environmental conditions, without performance degradation in severe conditions.

The simulations and experiments were carried out to evaluate the performance of SM controller. The experiments were done with a scale model in the laboratory tank of the University of São Paulo. This model is equipped with main and side thrusters, a radio communication system and LEDs in the bow and stern to allow the artificial system to evaluate its position and heading.

The mathematical modeling of the system is described in the second section. In third section it is made a theoretical explanation about the sliding modes control technique. In the fourth section SM controller applied to DP system is described. Five and six sections describe the tuning of controller parameters and experimental set-up, respectively, while the seventh section shows the results of the experiments. Finally, the conclusions are present in the eighth section.

2. MATHEMATICAL MODELING

Dynamic Positioning Systems are only concerned with the low-frequency horizontal motions of the vessel, that is, surge, sway and yaw. The motions of the vessels are expressed in two separate coordinate systems (see Fig. 2): one is the inertial system fixed to the Earth, OXYZ; and the other, $O'x_1x_2x_6$, is a vessel-fixed non-inertial reference frame. The origin for this system is the intersection of the midship section with the ship's longitudinal plane of symmetry. The axes for this system coincide with the principal axes of inertia of the vessel with respect to the origin. The motions along of the axes O'x$_1$, O'x$_2$ e O'x$_6$ are call of surge, sway e yaw, respectively.

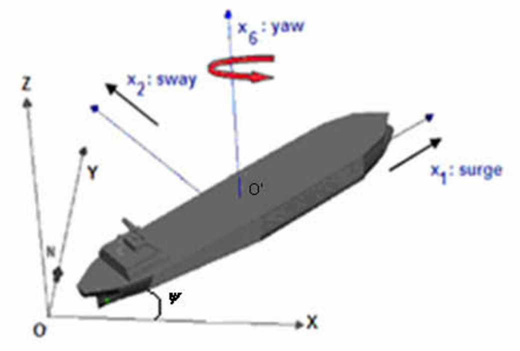

Fig. 2. Coordinate systems.

The mathematical model that describes the low frequency horizontal motions of the vessel are given by:

$$\begin{aligned}&(M+M_{11})\dot{u}-(M+M_{22})vr-(Mx_G+M_{26})\dot{r}^2=F_{1E}+F_{1T}\\&(M+M_{22})\dot{v}+(Mx_G+M_{26})\dot{r}+(M+M_{11})ur=F_{2E}+F_{2T}\\&(I_Z+M_{66})\dot{r}+(Mx_G+M_{26})\dot{v}+(Mx_G+M_{26})ur=F_{6E}+F_{6T}\end{aligned}\quad(1)$$

where M is the mass of the vessel, M_{ij} are added mass matrix terms, I_Z is the moment of inertia about the vertical axis, F_{1E}, F_{2E} and F_{6E} are surge, sway and yaw environmental loads (current, wind and waves) and F_{1T}, F_{2T} and F_{6T} are forces and moment delivered by the propulsion system. The variables u, v and r are the midship surge, sway and yaw absolute velocities. It has been assumed that the vessel's center of mass is x_G metric units ahead from the O' point.

The absolute position and heading may be written in terms of the vessel coordinate system according to:

$$\begin{pmatrix}\dot{X}\\\dot{Y}\\\dot{\psi}\end{pmatrix}=J(\psi)\cdot\begin{pmatrix}u\\v\\r\end{pmatrix};\qquad J(\psi)=\begin{pmatrix}\cos(\psi)&-\sin(\psi)&0\\\sin(\psi)&\cos(\psi)&0\\0&0&1\end{pmatrix}\quad(2)$$

where $J(\psi)$ is the coordinate transformation matrix and $\dot{\psi}=r$. Therefore, rewriting (1) in terms of the accelerations and velocities in the OXYZ fixed coordinate system, yields the complete model of the system, with three degrees of freedom:

$$\begin{pmatrix}\ddot{X}\\\ddot{Y}\\\ddot{\psi}\end{pmatrix}=\begin{pmatrix}f_{X,dyn}(\dot{\mathbf{X}})\\f_{Y,dyn}(\dot{\mathbf{X}})\\f_{\psi,dyn}(\dot{\mathbf{X}})\end{pmatrix}+\mathbf{C}\begin{pmatrix}F_{1E}\\F_{2E}\\F_{6E}\end{pmatrix}+\mathbf{C}\begin{pmatrix}F_{1T}\\F_{2T}\\F_{6T}\end{pmatrix}\quad(3)$$

where:

$\mathbf{X}=(X\quad Y\quad \psi)^T$;

$f_{X,dyn}(\dot{\mathbf{X}})=-\dot{Y}\dot{\psi}+f_{1,dyn}(\dot{\mathbf{X}})\cos\psi-f_{2,dyn}(\dot{\mathbf{X}})\sin\psi$;

$f_{Y,din}(\dot{\mathbf{X}})=\dot{X}\dot{\psi}+f_{1,din}(\dot{\mathbf{X}})\sin\psi+f_{2,din}(\dot{\mathbf{X}})\cos\psi$;

$f_{\psi,din}(\dot{\mathbf{X}})=f_{6,din}(\dot{\mathbf{X}})$;

$f_{1,din}(\dot{\mathbf{x}})=\dfrac{a_2vr+a_4r^2}{a_1}$; $\qquad f_{2,din}(\dot{\mathbf{x}})=\dfrac{-a_1a_3+a_4^{\,2}}{A}ur$;

$f_{6,din}(\dot{\mathbf{x}})=\dfrac{a_4\cdot(a_1-a_2)}{A}ur$;

$$\mathbf{C}^{-1}=\begin{pmatrix}a\cdot\cos\psi&a\cdot\sin\psi&0\\-b\cdot\sin\psi&b\cdot\cos\psi&d\\-d\cdot\sin\psi&d\cdot\cos\psi&c\end{pmatrix};$$

$a=(M+M_{11})$; $\qquad b=(M+M_{22})$;

$c=(I_Z+M_{66})$; $\qquad d=(Mx_G+M_{26})$;

3. SLIDING MODE CONTROL

The sliding mode (SM) control was successfully applied to several nonlinear systems, such as robot manipulators, ROV´s (Remotely Operated Vehicle), and assisted dynamic positioning of moored vessels (Tannuri et al., 2001). The main idea of this methodology is to reduce the control problem of a generic system, describe by nonlinear equations of order n, to a set of first-order system, with uncertainty in the parameters or mathematics model. The SM controller design procedure consists of two steps. The first step is to define a sliding surface $S(t)$, which renders the dynamic system stable when the system lies on the sliding surface and the second step is to select a control law for the system. Each step will be discussed below.

3.1 Sliding Surface

Considered nonlinear system with j inputs and i outputs given by (Slotine; Li, 1991):

$$x_i^{(n_i)}=f_i(\mathbf{x},t)+\sum_{j=1}^{m}b_{ij}(\mathbf{x},t)u_j+d_i(t)\quad(4)$$

where n_i is order of the system, u_j are the control input of system, $\mathbf{x}$ is the state vector composed of the control components x_i and their first (n_i-1) derivatives, $d_i(t)$ are the disturbance, $f_i(\mathbf{x},t)$ and $b_{ij}(\mathbf{x},t)$ are generally nonlinear functions of time an states and components of by the vectors $\mathbf{f}(\mathbf{x},t)$ and $\mathbf{B}(\mathbf{x},t)$, respectively. It will be supposed that the system is square, i.e., the same number inputs and controlled variables (i = 1,...,m and j = 1,...,m).

In SM Control, a time-varying surface $S(t)$ is defined in the state space $\Re^n$ by the vector $\mathbf{s}(\mathbf{x},t)$ of components s_i given by:

$$s_i=\left(\frac{d}{dt}+\lambda_i\right)^{n_i-1}\tilde{x}_i\quad(5)$$

where λ_i are strict positive constants and and $\tilde{x}_i$ is the tracking error associated the trajectory pre-defined x_{di} as

$$\tilde{x}_i=x_i-x_{di}\quad(6)$$

For the mechanical system considered in this paper, n_i = 2, for all i, because the dynamic equations are written in the second derivatives of the position variables. Thus, the definition of s_i is given by:

$$s_i=\dot{\tilde{x}}_i+\lambda_i\tilde{x}=\dot{x}_i-\dot{x}_{di}+\lambda_i\tilde{x}\quad(7)$$

A relationship between s_i and tracking error $\tilde{x}_i$ is defined as:

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