9th IFAC Conference on Control Applications in Marine Systems
The International Federation of Automatic Control
September 17-20, 2013. Osaka, Japan

Cooperative Control applied to DP Systems - Numerical Analysis

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Numerical Offshore Tank TPN-USP

Abstract: The present paper addresses the development of a cooperative control based on the consensus control concepts applied to Ships with Dynamic Positioning Systems (DP). The objective of the cooperative control is to maintain constant the relative distance between the two tugboats. The benefits of this control will be evaluated by numerical simulation.

Keywords: Cooperative control, Consensus control, Dynamic Positioning, Tugboats, Relative Distance.

1. INTRODUCTION

Nowadays with the increasing of ultra-deep water oil & gas exploration a new concept of "platform" is rising, where all extracting equipments are placed at the sea's bottom. This new concept is already used in many places around the World as in Ormen Lange in Norway and has proved to be economically viable. Since they are normally large and requires a fine positioning in the sea floor, the installation requires multi-vessels operations. Those operations require a high level of planning and coordination. Multi-vessels operations are cases where cooperative control could be applied.

A cooperative DP control applied to two offshore tugboats was evaluated in a previous paper by means of a conceptual small scale experiment (Queiroz and Tannuri, 2013). The advantage of the cooperative control was then demonstrated, with the reduction of the relative positioning during station keeping or transient maneuvers. In that work, the consensus control concepts were applied, following Ren et al. (2007), combined with the Dynamic Positioning (DP) System of each ship. In the present paper, the cooperative DP controller will be deeper investigated with the analysis of the coupled dynamics of the vessels. The influence of the cooperative control gains will be discussed, using the frequency response and the pole-placement analysis. Fully nonlinear time-domain simulations will be used to demonstrate the advantages of the cooperative control, and the previous experimental results are also addressed. All tests are carried out using the TPN's numerical simulator (as described in Nishimoto et al. 2003).

Considering the Oil & Gas industry, there are many other cases where cooperative control could be applied. In Queiroz et. al. (2012) an oil transfer operation was studied. Two shuttle tankers had to maintain their relative position while oil was transferred between them, in order to avoid the necessity of shore terminals. A fully numerical time domain simulation was carried on and the results showed the benefits of the cooperative control, when compared to the non-cooperative one. In that paper, the cooperative controller was designed using LQG-LTR control theory applied to the multivariable system model involving the states of both vessels.

2. MATHEMATICAL MODELING

The DP System is only concerned about the horizontal motions of the vessel, that is, surge, sway and yaw. The motions of the vessels are expressed in two separate coordinate systems (Fig. 1): one is the inertial system fixed to the Earth, OXYZ (also known as global reference system); and the other, $Ax_1^A\ x_2^A\ x_6^A$ or $Bx_1^B\ x_2^B\ x_6^B$, are the vessel-fixed non-inertial reference frames (also known as local reference system). The origin for this system is the intersection of the mid-ship 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 the local axes are called surge, sway e yaw, respectively.

Considering the two ships to be parallel to each other, with their local reference system aligned to the global reference system, small yaw rotation angles (smaller than 10°) and disregarding non-linear dynamics and damping terms the simplified systems' dynamics horizontal motion with respect to the global reference system are given by eqs. (1) and (2).

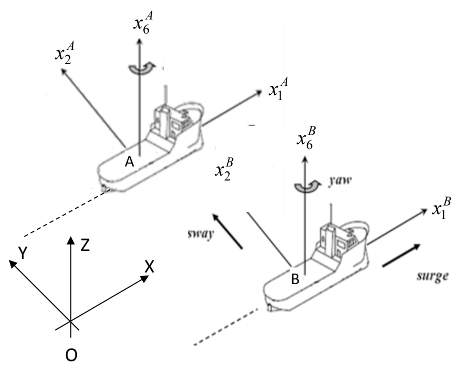

Fig. 1. Coordinate systems

$$\left(\boldsymbol{M}_A + \boldsymbol{M}_A^{ad}\right)\ddot{\boldsymbol{x}}_A + \boldsymbol{D}_A\dot{\boldsymbol{x}}_A = \boldsymbol{u}_A + \boldsymbol{F}_A^d \tag{1}$$

$$\left(\boldsymbol{M}_B + \boldsymbol{M}_B^{ad}\right)\ddot{\boldsymbol{x}}_B + \boldsymbol{D}_B\dot{\boldsymbol{x}}_B = \boldsymbol{u}_B + \boldsymbol{F}_B^d \tag{2}$$

where index A and B refer to vessel A and B and the vectors $\boldsymbol{x}_{A,B}$ are given by $\boldsymbol{x}_{A,B} = \left[x_1^{A,B}\quad x_2^{A,B}\quad x_6^{A,B}\right]^{\mathrm{T}}$ is the position of the local reference system of each ship with respect to the global one together with the yaw angle.

The system's parameters values and a short description can be found in Table 1.

Table 1. System's parameters description

Parameter	Description
$\boldsymbol{M}_{A,B}$	Vessel's horizontal displacement matrix
$\boldsymbol{M}_{A,B}^{ad}$	Vessel's added mass matrix
$\boldsymbol{D}_{A,B}$	Vessel's linear damping matrix
$\boldsymbol{u}_{A,B}$	Vessel's horizontal DP force vector
$\boldsymbol{F}_{A,B}^{d}$	Vessel's horizontal disturbance force caused by environmental agents

The dynamics of the relative motion can be obtained by eqs. (1) and (2):

$$\left(\boldsymbol{M}_A + \boldsymbol{M}_A^{ad} - \boldsymbol{M}_B - \boldsymbol{M}_B^{ad}\right)\ddot{\boldsymbol{x}}_A + \left(\boldsymbol{M}_B + \boldsymbol{M}_B^{ad}\right)(\ddot{\boldsymbol{x}}_A - \ddot{\boldsymbol{x}}_B) + (\boldsymbol{D}_A - \boldsymbol{D}_B)\dot{\boldsymbol{x}}_A + \boldsymbol{D}_B(\dot{\boldsymbol{x}}_A - \dot{\boldsymbol{x}}_B) = \boldsymbol{u}_A - \boldsymbol{u}_B + \boldsymbol{F}_A^d - \boldsymbol{F}_B^d \quad (3)$$

Defining the relative position as $\Delta\boldsymbol{x} \triangleq \boldsymbol{x}_A - \boldsymbol{x}_B$ and $\Delta\boldsymbol{F}^d \triangleq \boldsymbol{F}_A^d - \boldsymbol{F}_B^d$ as the difference of disturbance incidence between the vessels, the dynamics of the relative motion can be obtained as follows:

$$\left(\boldsymbol{M}_A + \boldsymbol{M}_A^{ad} - \boldsymbol{M}_B - \boldsymbol{M}_B^{ad}\right)\ddot{\boldsymbol{x}}_A + \left(\boldsymbol{M}_B + \boldsymbol{M}_B^{ad}\right)\Delta\ddot{\boldsymbol{x}} + (\boldsymbol{D}_A - \boldsymbol{D}_B)\dot{\boldsymbol{x}}_A + \boldsymbol{D}_B\Delta\dot{\boldsymbol{x}} = \boldsymbol{u}_A - \boldsymbol{u}_B + \Delta\boldsymbol{F}^d \quad (4)$$

If the two ships are considered to have the same parameters ($\boldsymbol{M}_A = \boldsymbol{M}_B = \boldsymbol{M}$; $\boldsymbol{M}_A^{ad} = \boldsymbol{M}_A^{ad} = \boldsymbol{M}^{ad}$; $\boldsymbol{D}_A = \boldsymbol{D}_B = \boldsymbol{D}$), eq. (4) can be simplified as:

$$\left(\boldsymbol{M} + \boldsymbol{M}^{ad}\right)\Delta\ddot{\boldsymbol{x}} + \boldsymbol{D}\Delta\dot{\boldsymbol{x}} = \boldsymbol{u}_A - \boldsymbol{u}_B + \Delta\boldsymbol{F}^d \quad (5)$$

2.1 The non cooperative control model

The non cooperative control model is given by 3-uncoupled PID controllers for each vessel. Fig. 2 shows the control layout.

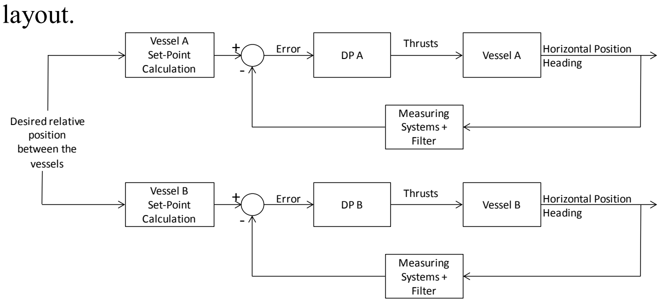

Fig. 2. Non cooperative control system

Considering that the two vessels are similar, in the present paper the same control gains are used. However eq. (6) allows to use different control gains. The control law $u_{A,B}$ are then given by:

$$\boldsymbol{u}_{A,B} = \boldsymbol{K}_P\boldsymbol{e}_{A,B} + \boldsymbol{K}_D\dot{\boldsymbol{e}}_{A,B} + \boldsymbol{K}_I \int \boldsymbol{e}_{A,B}dt \quad (6)$$

where $e_{A,B}$ refers to the position error signal (error in Fig. 2). The K_P, K_D and K_I refers to the PID's proportional, derivative and integrative diagonal gains matrixes respectively. Replacing eq. (6) in eq. (5) the non cooperative closed-loop system stays as:

$$\left(\boldsymbol{M} + \boldsymbol{M}^{ad}\right)\Delta\ddot{\boldsymbol{x}} + (\boldsymbol{D} + \boldsymbol{K}_D)\Delta\ddot{\boldsymbol{x}} + \boldsymbol{K}_P\Delta\dot{\boldsymbol{x}} + \boldsymbol{K}_I\Delta\boldsymbol{x} = \boldsymbol{K}_D\Delta\ddot{\boldsymbol{r}} + \boldsymbol{K}_P\Delta\dot{\boldsymbol{r}} + \boldsymbol{K}_I\Delta\boldsymbol{r} + \Delta\boldsymbol{F}^d \quad (7)$$

where $\Delta\boldsymbol{r}$ is the desired relative position between the vessels (relative position set-point).

2.2 The cooperative control model

The cooperative control model combines the existent DP system of each vessel with the consensus concepts, presented by Ren et al. (2007). In this paper, only a "proportional" consensus gain will be adopted. Fig. 3 shows the controller layout.

Again the same control law $\boldsymbol{u}$ will be applied to each vessel. For the cooperative control the $\boldsymbol{u}$ control law is given by:

$$u_{A,B} = K_P e_{A,B} + K_D \dot{e}_{A,B} + K_I \int e_{A,B}dt + K_c e_c^{A,B} \quad (8)$$

where $\boldsymbol{K}_c$ stands for the cooperative "proportional" control gain and $\boldsymbol{e}_c^A = -\boldsymbol{e}_c^B = \Delta\boldsymbol{r} - \Delta\boldsymbol{x}$.

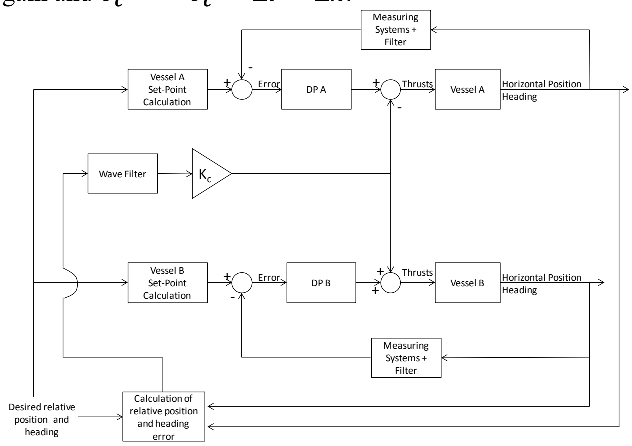

Fig. 3. Cooperative control system

By replacing eq. (8) in (5) the cooperative closed-loop system stays as:

$$\left(\boldsymbol{M} + \boldsymbol{M}^{ad}\right)\Delta\ddot{\boldsymbol{x}} + (\boldsymbol{D} + \boldsymbol{K}_D)\Delta\ddot{\boldsymbol{x}} + (\boldsymbol{K}_P + 2\boldsymbol{K}_c)\Delta\dot{\boldsymbol{x}} + \boldsymbol{K}_I\Delta\boldsymbol{x} = \boldsymbol{K}_D\Delta\ddot{\boldsymbol{r}} + (\boldsymbol{K}_P + 2\boldsymbol{K}_c)\Delta\dot{\boldsymbol{r}} + \boldsymbol{K}_I\Delta\boldsymbol{r} + \Delta\boldsymbol{F}^d \quad (9)$$

3. CASE STUDY

All experiments were conducted at the TPN's numerical simulator (more about the TPN's numerical simulator can be found at Nishimoto et al. 2003). The tests were chosen to validate the controller under two different situations: one is to verify the performance of the controller under tracking (set-point step change) and another one was chosen to verify the disturbance rejection of the controller. The experiments used two typical offshore tugboats. Theirs properties are indicated at Table 2.