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SESSION Design and Control

A General Approach for DP Weathervane Control

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Abstract

Some DP operations enable to change the vessel heading in order to reduce the DP thrust utilization. However, online calculation of the optimum heading is not simple, due to uncertainties at wave and current estimation. Moreover, these factors are not constant along time, and the system must adapt with the changes to keep the optimum position. This paper presents a new methodology to define the heading set-point based on the theory of Zero Power Control. This methodology has important advantages over traditional weathervane control methods, such as an effective control of all horizontal movements and the possibility to define any reference-point, not only points located at the vessel bow.

Introduction

Some DP Operations enable the modification of the heading angle in order to align the vessel with the resulting environmental force, what reduces the power and thrust DP consumption. Sometimes, the DP Captain performs this modification "manually", by changing the heading set-point using the information obtained from the wind sensor, current estimation and thrust utilization of the DP System. An example of this operation in a real case was presented by Tannuri et al. (2009). The Fig 1 shows the operation. Initially, the lateral current induced a large DP utilization. The vessel heading was then changed by approximately 30°, minimizing the power required to hold position during oil transfer. Fig 2 shows the thrust delivered by the DP thrusters before and after the heading correction.

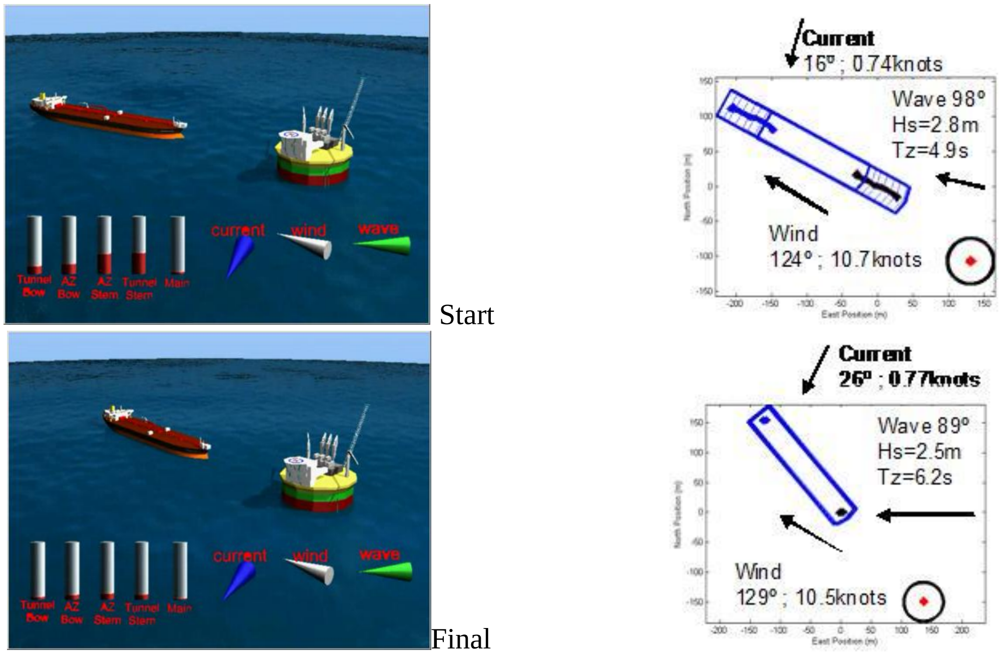

Fig 1. Heading modification to reduce DP consumption in an offloading operation (Tannuri et al., 2009)

Modern DP Systems presents the "weathervane mode", in which the vessel automatically reaches the best heading angle. The common approach for the weathervane mode is based on the control of the forward end of the vessel (Pinkster and Nienhuis, 1986; Davison et al., 1987). In that case, heading is not effectively controlled, and the vessel naturally searches the weathervane angle (analog to a "flag").

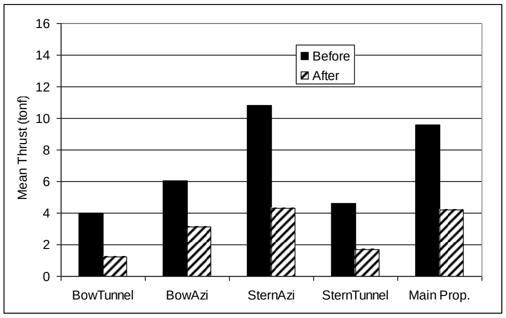

Fig 2. Mean forces delivered by each thruster (Tannuri et al., 2009)

One drawback of this strategy is that it only works for reference control points close to the bow of the vessel. Furthermore, sometimes it is necessary to impose limiting values to the heading angle, due to the proximity of a platform, for example. In that case, when the free-heading reaches the limit, this strategy must then be switched to a conventional 3-axis control.A broad discussion about the drawbacks of a simple free-heading weathervane control for offloading tandem operation was presented by Bravin and Tannuri (2004). In that paper, the authors alternatively proposed a controller that automatically switches to a 3-axis control when the vessel heading is larger than a limiting value. That strategy is based on a variable-gain angle control. This introduces non-linearities in the control system and increases the number of parameters to be adjusted.

Fossen and Strand (2001) developed a controller using the same principle proposed by Pinkster (1986), eliminating the first drawback of the previous controller, since it could control the midship positioning. The idea of the WOPC (Weather Optimal Position Control) is to update the set-point position for the bow-reference, in order to keep the mid-ship in a stationary position. This technology is proprietary, in the name of ABB Industry.

This paper presents a new approach to estimate the weathervane angle, without information about the environmental condition, eliminating all the drawbacks of the approaches previously mentioned.The proposed method is based on Zero Power Control (ZPC) techniques (Morishita et al., 1989) used to minimize the control action of a closed loop system. This methodology (named as ZPC-W) is very general, allowing the vessel to weathervane while controlling positioning for any reference point. Furthermore, heading angle is in fact controlled, and the set-point is constantly changing, searching for the weathervane angle. So, any limitation necessary to be imposed to the heading angle can be simply included in the definition of the set-point and time changing weather is not a limitation.

The method was implemented in the Numerical Offshore Tank 6-DOF non-linear dynamic simulator, and several numerical tests indicated its effectiveness. A comprehensive set of experimental tests in model scale also confirmed the good performance of the proposed method.

MATHEMATICAL MODEL

The 3-degree of freedom model for the horizontal motions of a DP vessel is given by the following dynamic equations:

$$(M + M_{11})\ddot{x} - (M + M_{22})\dot{y}\dot{\Psi} - (Mx_G + M_{26})\dot{\Psi}^2 = F_{env}^{x} + F_{DP}^{x} \qquad (1)$$

$$(M + M_{22})\ddot{y} + (Mx_G + M_{26})\ddot{\Psi} + (M + M_{11})\dot{x}\dot{\Psi} = F_{env}^{y} + F_{DP}^{y} \qquad (2)$$

$$(I_z + M_{66})\ddot{\Psi} + (Mx_G + M_{26})\ddot{y} + (Mx_G + M_{26})\dot{x}\dot{\Psi} = M_{env} + M_{DP} \qquad (3)$$

Where M is the vessel mass; I_Z is the vertical axis moment of inertia; M_{ij} are the added masses (as defined in Newman, 1977); F_{env}^{x} ,F_{env}^{y}, M_{env} are the environmental loads due to current, wind and waves and F_{DP}^{x}, F_{DP}^{y}, M_{DP} are propulsion system forces and moment . The center of gravity is assumed to be at the center line of the vessel, $x_G$meters ahead the midship. The variables$\dot{x}$, $\dot{y}$ and $\dot{\Psi}$ are the midship surge, sway and yaw absolute velocities.

The current mean forces are calculated following OCIMF (1994) formulation, given by the following equations:

$$F_{1C} = \frac{\rho_w V_c^2 LT}{2} \cdot C_{1C}(\alpha_{cr}) \qquad (4)$$

$$F_{2C} = \frac{\rho_w V_c^2 LT}{2} \cdot C_{2C}(\alpha_{cr}) \qquad (5)$$

$$M_{6C} = \frac{\rho_w V_c^2 L^2 T}{2} \cdot C_{6C}(\alpha_{cr}) \qquad (6)$$

Where:

- F_{1C}, F_{2C}, M_{6C}: Current surge force, sway force and yaw moment
- ρ_w: Water density
- V_c: Current relative velocity
- L; T: Vessel's length and draft
- C_{iC}: Non-Dimensional static current load coefficient for the i-th DOF
- α_{cr}: Relative angle between current direction and vessel heading, as indicated in Fig 3.

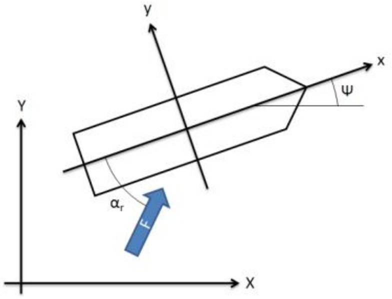

Fig 3. Coordinate System and α_r definition

For a DP positioned vessel, the vessel speed is assumed to be almost null. In this case, the current force only depends on the slow varying current velocity and on the angle between current direction and vessel heading. The current coefficients C_{iC} can either be calculated by CFD numerical methods, static drift small-scale experiments or considering previous results from literature (for example, OCIMF, 1994 for tankers).

As an example, the current coefficients for a full loaded tanker (OCIMF, 1994) are shown in the Fig 4:

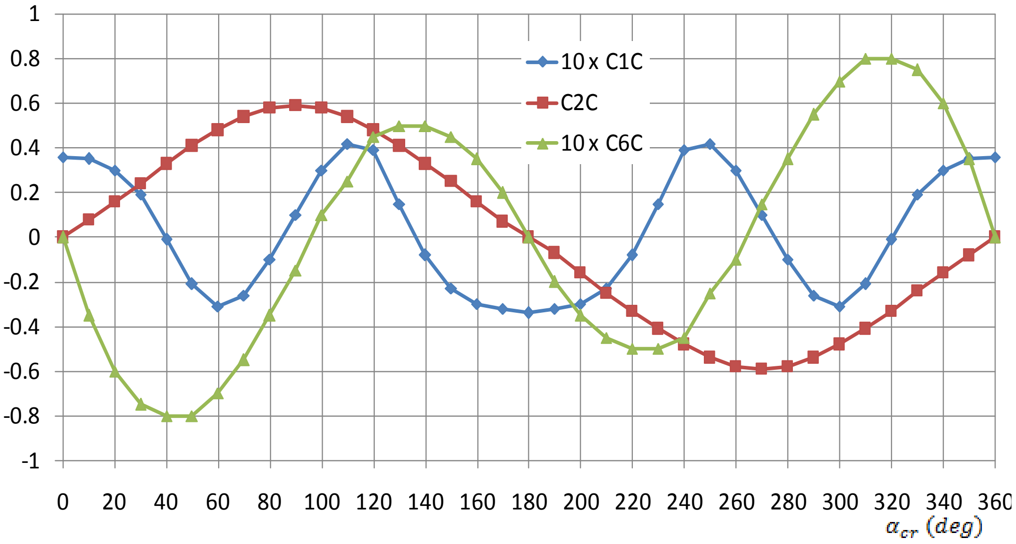

Fig 4. Current coefficients for a full loaded tanker

Wind forces are evaluated in a similar procedure as the current loads, using the wind drag static coefficients. Wave second-order effects are calculated using the QTF approximation proposed by Aranha and Fernandes (1995). Wave-drift damping effects are modeled following Aranha (1994). The wave coefficients are obtained from any commercial code for wave analysis (such as Wamit, AQWA and Hydrostar).

ZPC BASED WEATHERVANE (ZPC-W)

As can be verified in the Fig 4, for the illustrative case of current incidence, the weathervane heading ($\alpha_r = 180^o$) presents the following properties:

- Negative surge force
- Zero sway force
- Zero yaw moment

So, if the vessel is under a condition that produces null sway force and yaw moment, and the surge force is negative, it can be assumed that it is at the weathervane heading, or at the Weather Optimal Heading - WOH, as defined by Fossen (2000). For multiple non-aligned environmental agents, the simultaneous nullification of sway force and yaw moment may not be obtained. In these cases, the proposed Weathervane Control will head the vessel in such an angle that the sway force is zero. Discussions about the optimal heading for minimum power consumption (zero yaw moment or sway force) is beyond the scope of the present paper.

Zero power control techniques (Kim et al., 2011) can be used to nullify either sway forces or yaw moments. Environmental loads cannot be directly measured, but if the vessel positioning is kept by the DP system, with almost null acceleration, the following approximation can be assumed:

$$\vec{F}_{env} + \vec{F}_{DP} = 0 \tag{7}$$

Where $\vec{F}_{env}$ is the resulting environmental force applied on the ship and $\vec{F}_{DP}$ the total force generated by the DP system.

Thus, the vessel heading set point is constantly adapted, using the following adaptation law:

$$\dot{\Psi}_{SP} = K \cdot F_{DP}^{y} \tag{8}$$

where:

$\dot{\Psi}_{SP}$: Vessel heading set-point time-derivate
K: Adaptation gain
F_{DP}^{y}: DP controller sway force

The diagram of the proposed controller is presented in the Fig 5, where the sway and yaw controllers are shown. The yaw set-point adaptation law is indicated by the red path in the diagram. It must be stressed that different types of controllers can be used, and in this paper, an uncoupled PD controller is applied for each DOF. As can be verified, the implementation of the ZPC-W in a real DP System is quite straightforward, since it does not require any deep modification in the structure of the control and filtering algorithms.

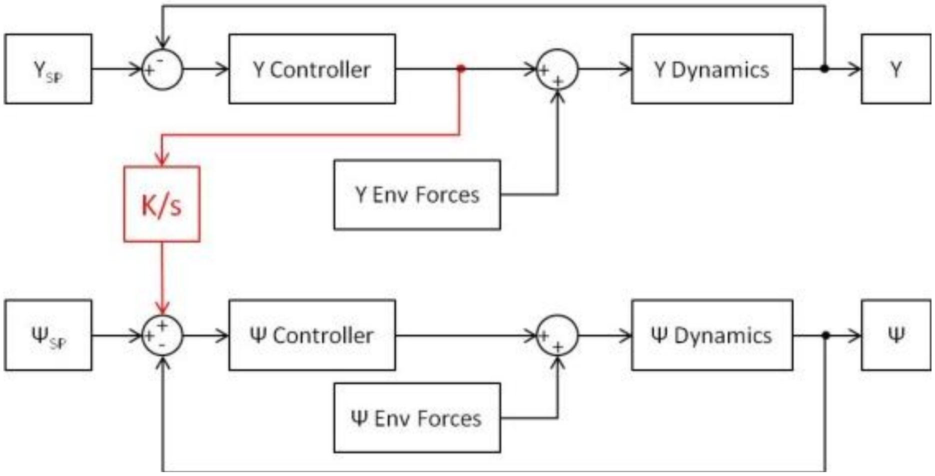

Fig 5.Block Diagram for the proposed ZPC-W

NUMERICAL SIMULATION RESULTS

The ZPC-W was implemented in the time-domain simulator of the TPN(Numerical Offshore Tank – USP). The simulator considers the 6-degrees of freedom of the body and non linear effects and dynamic effects, such as wave forces. A brief description of the simulator is presented in the Appendix.

The first set of tests considered a typical DP-barge, with the main properties indicated in the Table 1.The Barge DP layout is shown in Fig 6, and consists of three fore-body azimuth units and three stern ones. The maximum thrust of each unit is 220 kN.

In all simulations, from t = 0s to t = 2000s, the heading set point is fixed (headed to East).From t = 2000s onwards, ZPC-W is then turned on and the heading set point was adjusted following the adaptation law defined in the equation (8).

Table 1 - Typical barge properties

Property	**value**
Total length (m)	121.92
Length entre perpendiculars L_{PP} (m)	121.92
Beam B (m)	30.48
Draft T (m)	5.18
Mass M (ton)	17092
Moment of Inertia I_Z (ton.m^2)	2.4×10^7

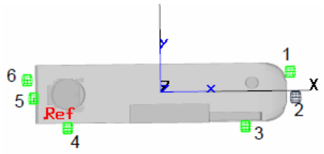

Fig 6. Barge thrusters layout

The fist case considers all the environmental agents coming from North, as indicated in Fig 7.In that figure, it is also presented the trace plot of the vessel and the time series of position, heading and total DP sway force. The good performance of the ZPC-W is verified, since the vessel yaw angle automatically reaches 90^o (heading to North) just after the weathervane controller is turned on. The motion of the midship point (PosX and PosY plots) is acceptable during the heading change.The total DP sway force is strongly reduced as expected.

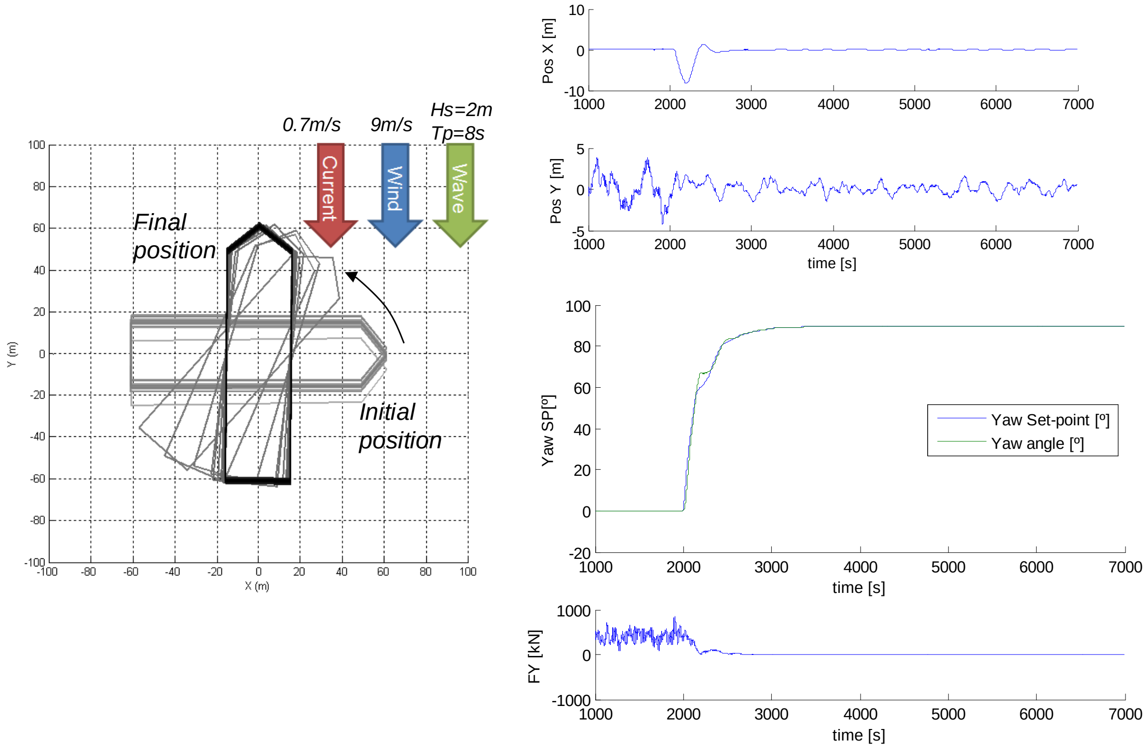

Fig 7.ZPC-W for a DP-Barge, midship control point, all environmental agents aligned

In order to illustrate the flexibility of the ZPC-W, the Fig 8 shows the results for a simulation with the reference control point located at a lateral position outside the physical limits of the vessel. The performance of the controller is similar to the previous case. The Fig 9 shows the simulation of a multi-modal sea state (local waves + swell). In that case, the final heading of the vessel is approximately 95^o, as expected since the resultant force of the environmental agents is slightly rotated due to the swell. The sway DP force is reduced to a null-mean value after the ZPC-W control is turned on.

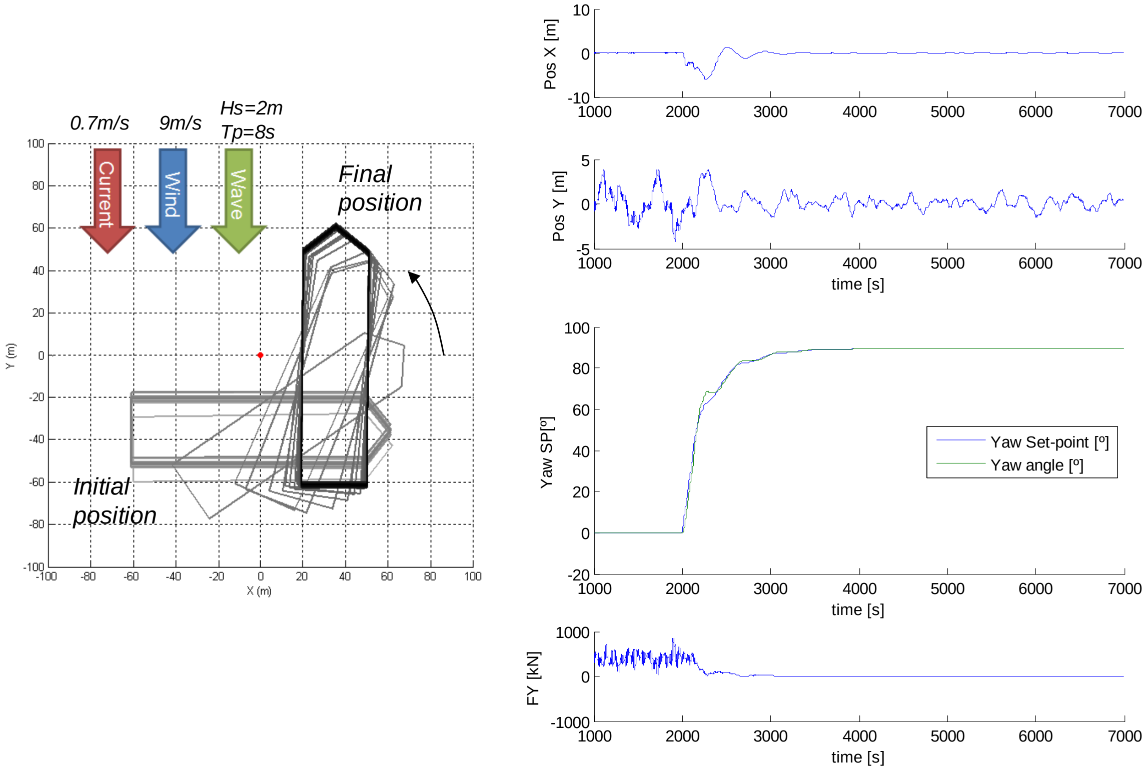

Fig 8.ZPC-W for a DP-Barge, lateral-midship control point, all environmental agents aligned

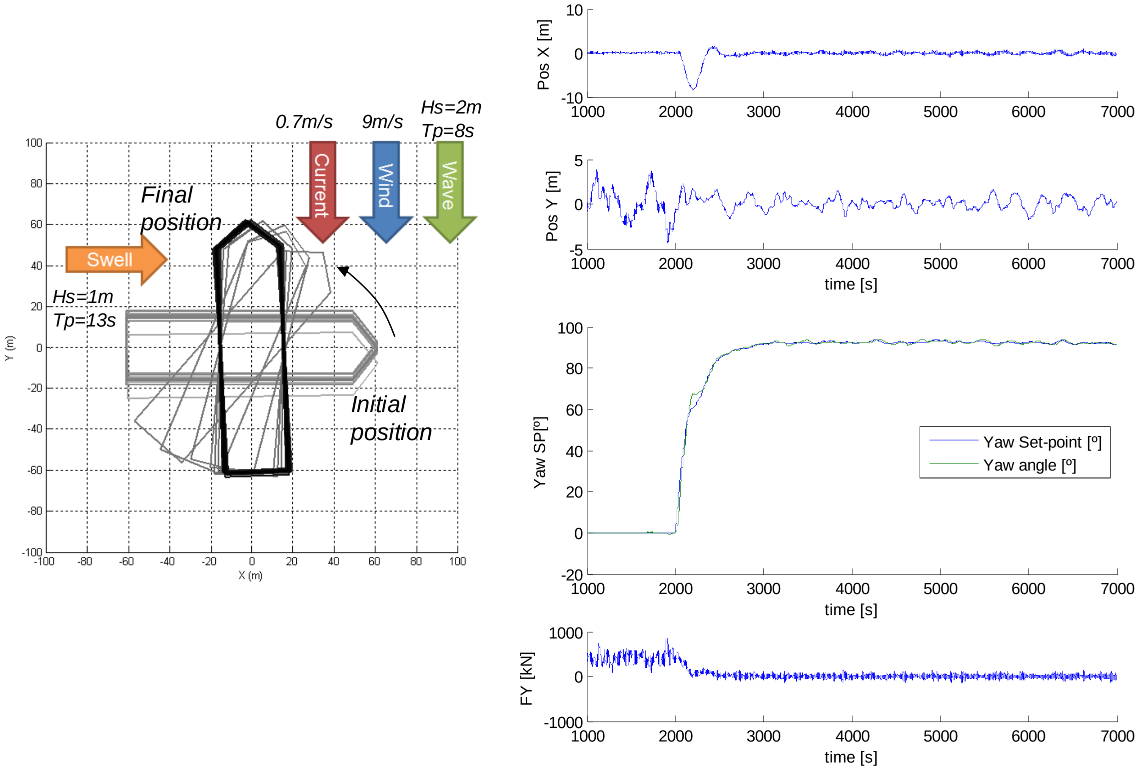

Fig 9.ZPC-W for a DP-Barge, midship control point, swell incidence

A final example (Fig 10) illustrates a quite common environmental condition in Brazilian offshore oil fields. As can be verified, the vessel final yaw angle is approximately 60°, corresponding to a position with null sway DP force, as expected. More simulation results can be found in Miyazaki and Tannuri (2012a).

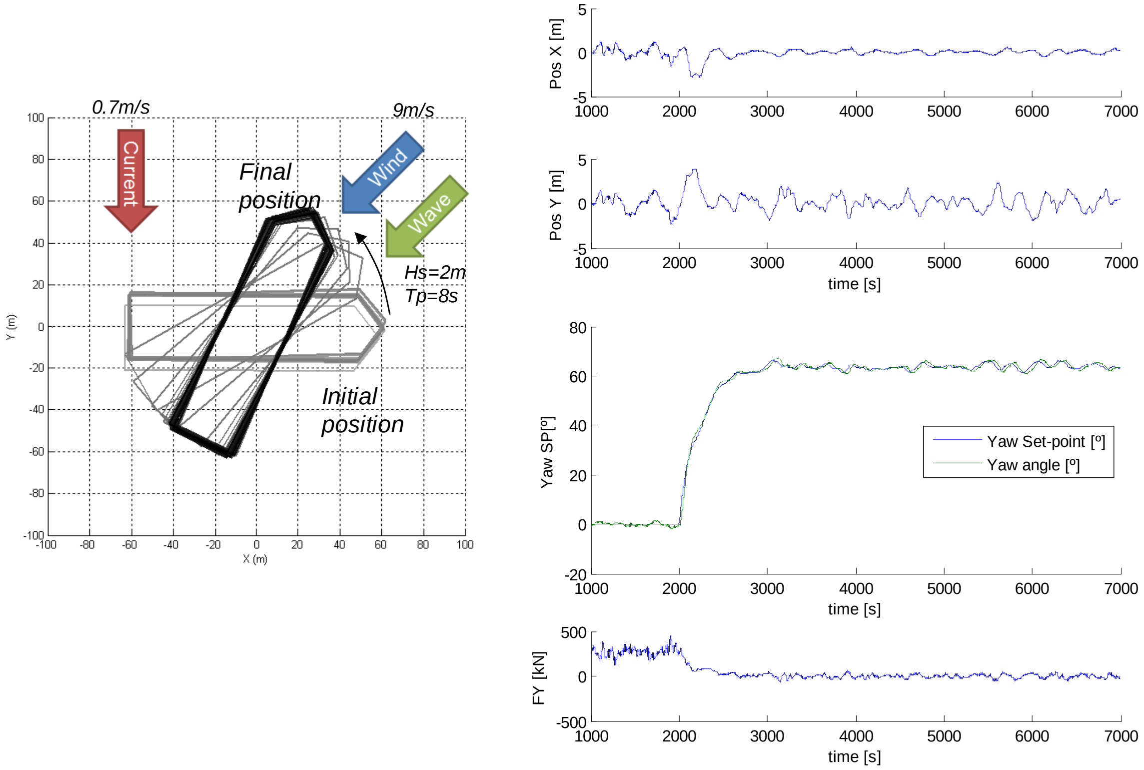

Fig 10.ZPC-W for a DP-Barge, midship control point, Brazilian typical environmental condition

EXPERIMENTAL RESULTS

Several experiments were conducted at the University academic tank, using the DP facilities described in Tannuri (2006). The experiments used a 1:125 reduced model of a typical Suezmax tanker in ballasted condition, with the following properties (full scale values):

Table 2 - Main properties of the tanker

Property	**Value**
Total length	276.96 m
Length between perpendiculars L_{PP}	262.00 m
Beam B	46.00 m
Draft T	8.00 m
Mass M	80,617 ton
Moment of Inertia I_Z	4.85×10^7 ton.m²

The vessel is equipped with a main propeller and two auxiliary thrusters, namely bow and stern thrusters (Fig 11).

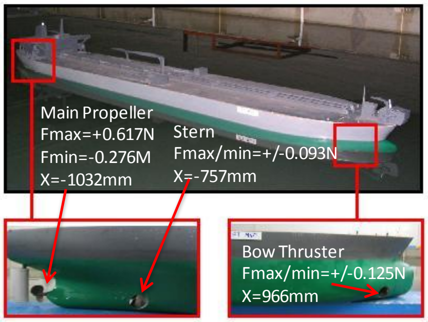

Fig 11.DP Model and Thrusters information.

The tank has a set of fans that produces wind parallel to the tank. For all experiments, a conventional 3-axis DP System is used in the initial phase of the test, with -45^{o}yaw set-point (position indicated in the Fig 12). After some time, the ZPC-W is then turned on to search for the weathervane angle, aligned with the incoming wind direction.

Fig 12.Test set-up and initial vessel position

The Fig 13shows the experimental results of tests considering four different control point positions. For all tests, the only environmental agent is the wind, and it comes from the Positive Y direction (as indicated). As can be verified, the ZPC-W could automatically take the vessel heading to the desired heading for all cases. The motion of the control point is also indicated in the figures (red line). For the stern point control case, a large heading oscillation can be verified as the vessel approaches the final heading. In that case, a better adjustment of the adaptation gain K could reduce this oscillation.

The Fig 14shows the summation of the squared thrusts. This value can be roughly considered as proportional to the total DP Power. The red line indicates the filtered value, since the thrust high frequency oscillations are even amplified by the square operation. For all cases (except the stern control point) the DP power is reduced when the vessel reached the weathervane angle, as expected. For the stern control point, the large heading oscillation is responsible for the power amplification. Indeed, Fig 15shows that the average DP sway force reduces after the ZPC-W is turned on. So, the weathervane action is working properly, and the oscillation problems may be mitigated by a fine tuning of the control gains.

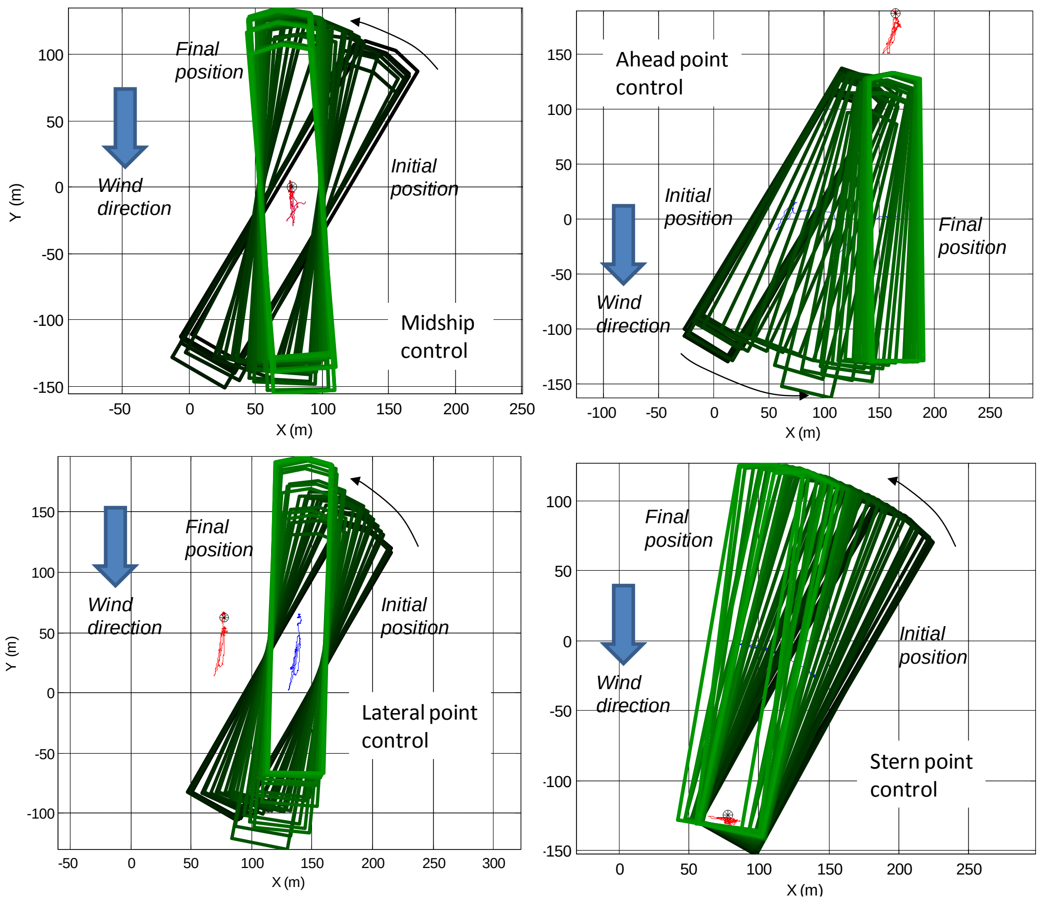

Fig 13.Experimental results for different control points (Vessel position)

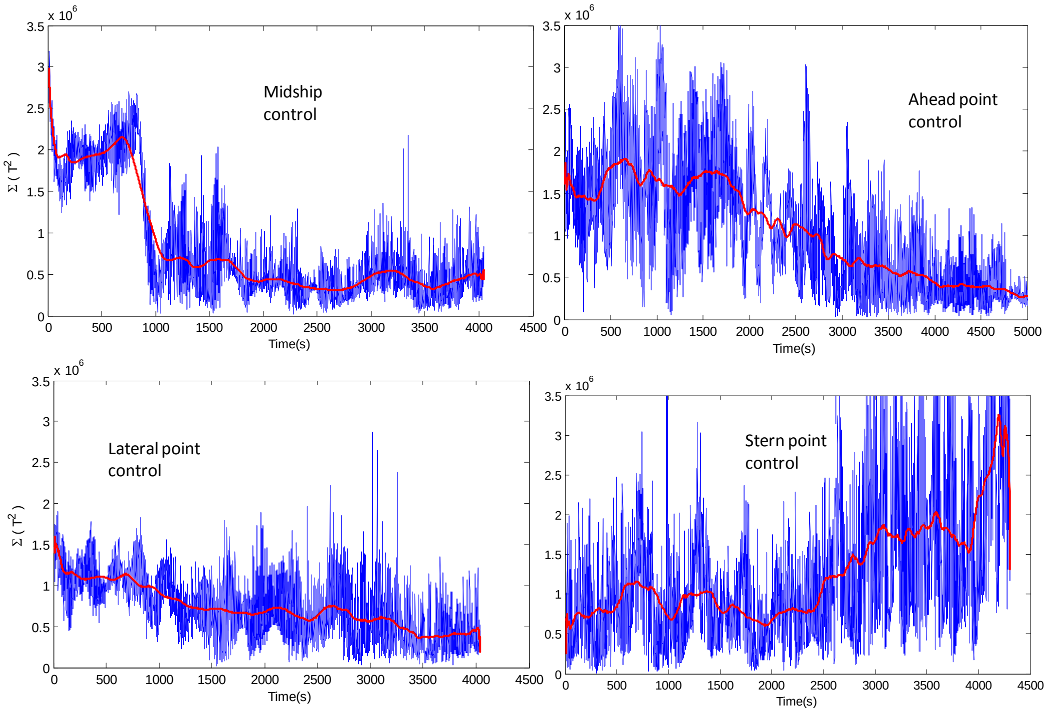

Fig 14.Experimental results for different control points (DP Power Estimate)

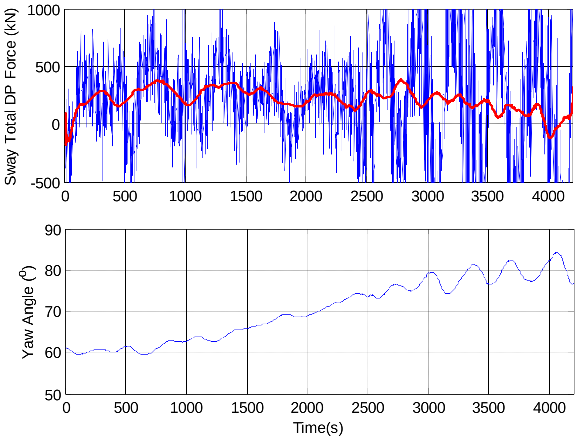

Fig 15.Detailed results for stern point control case

Another experimental analysis of the proposed ZPC-W, including comparisons between numerical and experimental results, is presented in Miyazaki and Tannuri (2012b).

CONCLUSIONS

In this paper, a new approach for weathervane control was developed, simulated and tested. The results so far showed that this new controller is able to align the vessel with the environmental force, thus minimizing DP system requirements. This fact can be stated by sway control forces decrease.

The implementation of the proposed controller isquite straightforward, since it is based on a simple correction on the heading set-point based on the total sway DP force. One of the main advantages of this controller is that the reference point does not need to be at the vessel bow, as required by traditional weathervane controllers.

Both experimental and numerical results attested the good performance of the proposed controller.

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APPENDIX: THE TPN OFFSHORE SYSTEM SIMULATOR

The TPN is a time domain numerical procedure designed for the analysis of moored and DP offshore systems. The inputs of the simulator are:

- Floating body main parameters (dimensions, mass matrix, etc.);
- Aerodynamic drag coefficients (following standard given by OCIMF, 1994);
- Current coefficients (following standard given by OCIMF, 1994) or hydrodynamic derivatives;

- Hydrodynamic coefficients (potential damping, added mass, first and second order wave force coefficients);
- Environmental conditions (wave and wind spectra, current);
- Mooring and risers system characteristics;
- Thrusters characteristics and layout;
- DP modes and parameters.

The non-linear time-domain simulation runs in a desktop computer and outputs time series describing the motions of up to two floating unities (FU) in six degrees of freedom (6dof), tensions on the mooring lines and hawser, propellers thrust and power, etc., and a corresponding statistical summary.

3D visualization outputs are also available. The floating body high frequency motion (HF) due to the wave action can be evaluated in two different ways. In the simpler one the HF motion evaluated by the RAO is added to the low frequency motion (LF) that is calculated by the 4rd order Runge-Kutta integration method. Alternatively, the wave 1st order forces are applied to the body and all motion components (6 dof) are obtained dynamically solving the equations of motion. The current force can be evaluated through 3 different models: OCIMF Model, Cross flow Model, Maneuvering Model or Short Wing Model (in-house development). It is possible to analyze 3D constant or oscillatory current profile. The simulator allows constant wind and gust wind. The wind spectra implemented in the code are Harris, Wills and API. The wave can be regular and irregular. For irregular waves the spectra formulations available are Pierson-Moskowitz, JONSWAP and Gaussian. The wave first and second-order effects are modeled besides wave-drift damping effects. The wave coefficients are evaluated by WAMIT.

Three main classes of algorithms used in commercial DP systems are also implemented in TPN. A low-pass filter, called wave-filter, is employed to separate high-frequency components (excited by waves) from measured signals. Such decomposition must be performed because the DP system must only control low-frequency motion, since high-frequency motion would require enormous power to be attenuated and could cause extra tear and wear in propellers. Furthermore, an optimization algorithm, called thrust allocation, must be used to distribute control forces among thrusters. It guarantees minimum power consumption to generate the required total forces and moment, positioning the vessel. At last, a control algorithm uses the filtered motion measurements to calculate such required forces and moment. Normally, a wind feedforward control is also included, enabling to estimate wind load action on the vessel (based on wind sensor measurements) and to compensate it by means of propellers. Furthermore, the simulator also includes models for propellers, taking into account their characteristics curves, being able to estimate real power consumption and delivered thrust. It also evaluates time delay between command and propeller response, caused by axis inertia.