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Improved Cost Efficiency of DP Operations by Enhanced Thrust Allocation Strategy

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I. Abstract

Dynamic positioning (DP) systems are intensely used in the naval and offshore industries. When not constrained by harsh environmental conditions, these systems provide an accurate control of position and heading. This enables complex maneuvers which have become mandatory for numerous operations. DP systems are even a standard technology assessed by certification societies since several years.

Today one of the main challenges is to minimize the average power consumed by the vessel for both sustainability and economic reasons. Relying on DP operators' expertise a first solution for alleviating the loads on the thrusters is to change the ship heading adequately considering external conditions. It is however not possible to command thrusters directly since the orders are computed by the DP system.

Recent improvements of control algorithms made by DCNS-Research/Sirehna lead to a significant reduction of operational costs while maintaining a responsive control of the ship. This involves optimizing the thrust allocation strategy to withstand external disturbances such as wind and current and improving the dynamic stability of the control loops. This solution has already been delivered to offshore industry customers. After several months of operations, they gave a very positive feedback on the behavior and the power consumption of their ships driven by a DCNS-Research/Sirehna EasyDP system.

In this paper the new design is benchmarked against a standard control strategy in a representative set of operational scenarios. Relative power consumption and ship reactivity in station keeping is analyzed for both designs. Simulation results demonstrate a significant reduction of power consumption without degrading DP performances.

II. Introduction

As defined by DNV, the DP systems are electrical systems aiming to control the ship position and heading by the only use of its thrusters [1]. The firsts DP systems have been delivered to the ship offshore industry in the early 60s but today those systems are a standard and are involved in a large bunch of ship operations. They can also been mandatory considering some operations like drilling for example. Nowadays, the DP technology is well established and recognized worldwide. The improvements in the domain of automatic control like Kalman Filtering techniques or model based control have permitted to have accurate, safe and reliable systems. An overview of the DP developments can be found in [2]. One of the major contributions of the DP technology is to change the ship location without the need of anchors. This represents a substantial gain of time and reduces therefore the exploitation costs drastically even if the vessel uses power continuously. Considering the actual economic context, reducing fuel consumption has become crucial both for environmental and economic matters. Today, the minimization of the ship consumption is mainly done by the expertise of DP operators (DPO) and is actually equivalent to the choice of the "best" economic heading. There is however no direct relationship between selected heading and thrusters regimes as they are calculated and applied by the DP systems to balance external disturbances adequately. Therefore, the optimization of the DP system control strategies combined to the DPO actions is an important lever for minimizing the ship consumption. In this paper, a new design of DP control algorithms is benchmarked in simulation in calm sea conditions against a "standard" solution for a ship equipped with azimuth thrusters. This strategy has been refined and fine-tuned according to on-field measurements and operator feedbacks from the Bourbon Supporter. In the first section, the ship mathematical model is presented while the azimuth thruster model is described in the next section. In section 5, the numerical simulation tool is presented. The results of the simulations are given in section 6 and discussed in section 7 including .

III. Ship mathematical modeling

III.1 Coordinates systems

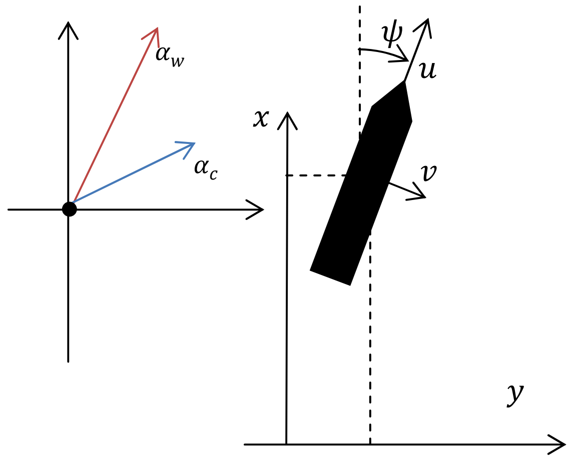


Figure 1 : Considered coordinates systems

In this paper, North East Down (NED) based frames are used. Only planar motions which are the degrees of freedom of interest for DP will be considered. The surge is then positive forward, the sway positive starboard and the yaw positive clockwise. The position of the ship in the geographical local frame is noted $[x \quad y \quad \psi]^T$. α_w and α_c represent the incidence between the bow and the incoming direction of respectively wind and current.

III.2 Vessel dynamics

In the ship body coordinate system, with the origin located in the center of gravity, the planar equations of motion are given by [2]

$$M\frac{d\vec{v}}{dt} + C_{RB}(\vec{v})\vec{v} = \sum \vec{F} \qquad (1)$$

where M is the generalized 3 degrees of freedom (3DOF) mass matrix, $\vec{v} = [u \quad v \quad r]^T$ is the velocity vector of surge, sway and yaw motions in the ship body frame, C_{RB} is the rigid body and centripetal matrix and finally $\sum \vec{F}$ is the sum of all forces acting on the ship.

III.3 Hydrodynamic forces

As stated in [3], the added masses effects can be included as additive terms in the generalized mass matrix. The other contributors of the hydrodynamic forces can be expressed as a sum of linear and quadratic terms [2]

$$\overrightarrow{F_{hydro}} = D(\vec{v})\vec{v} + f_c(\vec{v}) \qquad (2)$$

Where $D(\vec{v})$ is a linear damping matrix and

$$f_c(\vec{v})/u = \frac{1}{2}\rho C_{c/x}(\alpha_c)A_F^C v_c^2$$
$$f_c(\vec{v})/v = \frac{1}{2}\rho C_{c/y}(\alpha_c)A_T^C v_c^2 \qquad (3)$$
$$f_c(\vec{v})/r = \frac{1}{2}\rho C_{c/\psi}(\alpha_c)A_T^C v_c^2 L$$

- A_F^C is the front submerged area
- A_L^C is the lateral submerged area
- α_c is the velocity trough water angle of attack
- v_c is the velocity trough water norm
- L is the length between perpendiculars
- C_c are current coefficients for each motion
- ρ is the density of the water

III.4 Aerodynamic forces

The formulation of the aerodynamic forces is well documented in the literature. They classically take Rayleigh forms as stated in [3]. Expressed at the centre of gravity of a ship, the equations have then the following form:

$$F_{wind}/x = \frac{1}{2}\rho_a C_{w/x}(\alpha_w)A_F^W v_w^2$$
$$F_{wind}/y = \frac{1}{2}\rho_a C_{w/y}(\alpha_w)A_L^W v_w^2 \qquad (4)$$
$$F_{wind}/\psi = \frac{1}{2}\rho_a C_{w/\psi}(\alpha_w)A_L^W v_w^2 L$$

where

- $A_F^W$is the front emerged area
- A_L^W is the lateral emerged area
- α_w is the wind incidence as shown in Figure 1
- v_w is the wind velocity
- L is the length between perpendiculars
- C_w are polar coefficients for each motion
- ρ_a is the density of the air

III.5 Other forces

The other forces as wave forces are neglected within this study. The sea state will indeed supposed to be calm as it will be detailed in section 12. The thruster's forces are described in the next section.

Significant wave height, in m	Corresponding mean wind speed (kts)	Annual frequency, in %	ESKI, in %
0 - 1	0 - 4,8	25,2	25
1 - 2	4,8 - 11,6	32,2	57
2 - 3	11,6 - 17,5	20,9	78
3 - 4	17,5 - 24,3	11,1	89
4 - 5	24,3 - 29,1	5,4	95
5 - 6	29,1 - 34,0	2,5	97
6 - 7	34,0 - 37,9	1,2	98
7 - 8	37,9 - 41,8	0,6	99
8 - 9	41,8 - 46,3	0,3	99
9 and more	More than 46,3	0,3	99
For the calculations, a constant current of 1.5 kts is assumed, in the same direction as the wind and the waves (to sum up all the environmental forces effects).			

Table 1 – ESKI / Mean wind speed for North Sea

IV. Thrusters forces modeling

Nowadays ships can be equipped with various types of actuators, such as the tunnel thrusters, azimuth thrusters or propellers with rudders. The most common propulsor thruster considered for DP operation is the azimuth thruster.

As stated in [2], in general the steady-state force developed by an actuator can be expressed as:

$$F = k_T n^2 \qquad (5)$$

where k_T is the thrust coefficient and n is the revolution velocity of the propeller. The steady consumed power is given by

$$P = k_Q n^3 \quad (6)$$

Where $k_Q$is the torque coefficient. The coefficients k_T and k_Q depend on the advance ratio. In Dynamic Positioning theory, the relative velocity through water is small so that the dependency is often neglected. However, as stated in [5] [6] [7], the efficiency of an azimuth thruster depends on the azimuth angle with respect to the current angle. Nevertheless, this relationship is not well detailed in the literature. Numerical simulations and basin tests have been carried out in a more recent paper [8] in order to quantify this phenomena for a semi-submersible crane vessel. An example of thrust efficiency with 2 knots of current coming from the bow is represented on the Figure 2. However no mathematical model is proposed in the paper and furthermore due to confidentiality numerical values have been removed from the article.

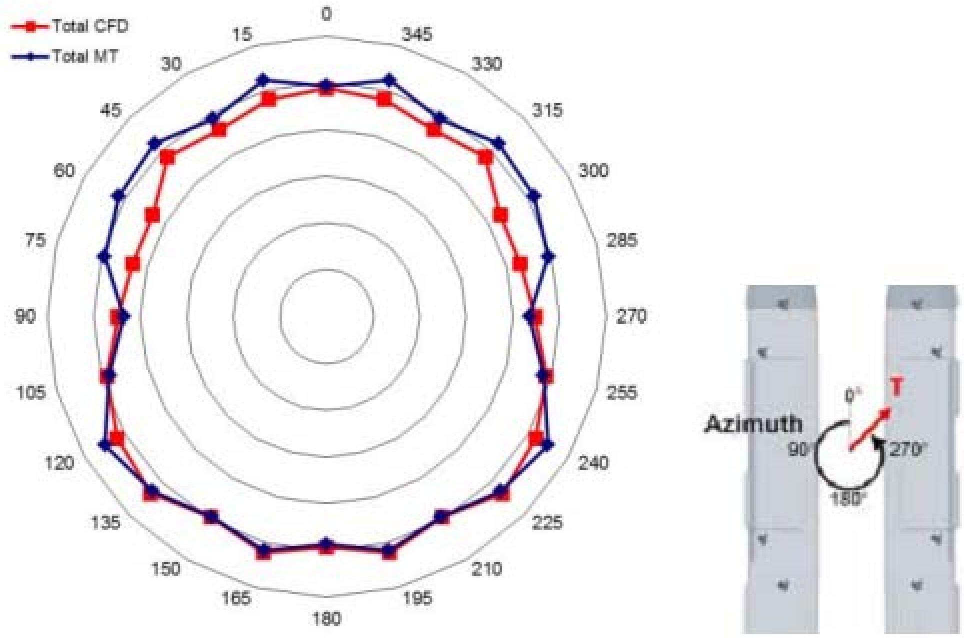


Figure 2 : Comparison thrust efficiency in 2kn current

Within this paper, it is proposed to consider the thrust modification as represented on the figure below.

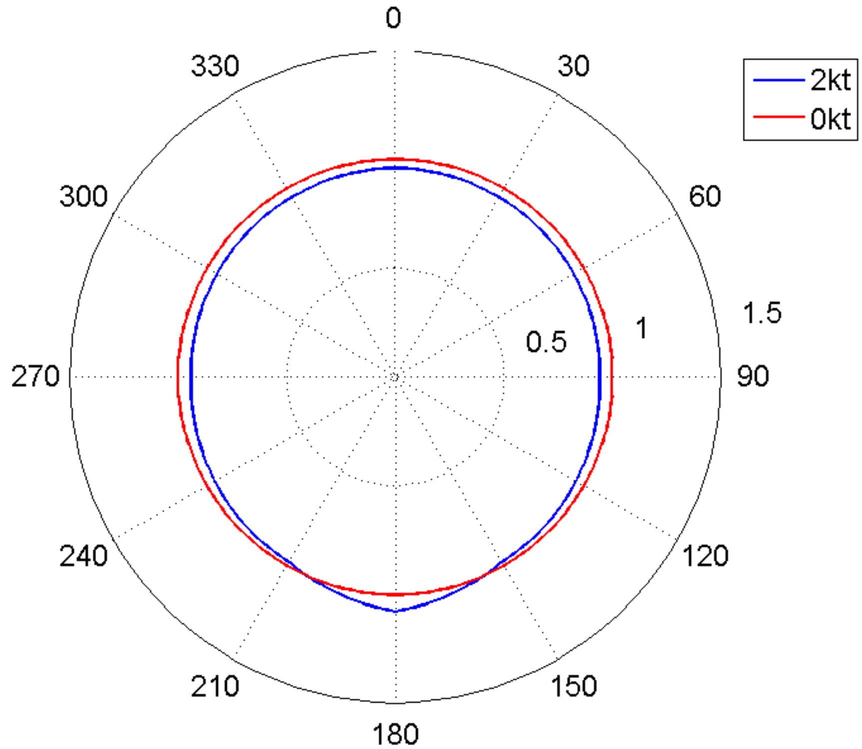


Figure 3 : Efficiency of an azimuth thruster with regard to current velocity and the azimuthing direction

For the blue-lined plot, the current is coming from 0° and has a steady state value of 2 knots. The proposed thrust reduction with regard to zero-current conditions is 4% at 0° and 6% at 90° azimuthing direction compared to the bollard pull thrust. At 180° (thruster pushing in the same way than the current), the thruster has an increased thrust of 7%. These values are purely stated with the proposed papers as theoretical bases.

The efficiency reduction of tunnel thruster is not taken in account within this paper and the mathematical model given above is used.

V. Numerical simulation tool

A simulator is built for the paper purpose based on the models given in the previous sections.

V.1 Sea current model

The sea current which affects the vessel is the result of several phenomena including tide, ocean circulation, etc. In general, the current velocity and direction are relatively constant and evolve slowly in time. In the simulator, the model for the current velocity as expressed [2] is used

$$\dot{v}_c(t) + \mu_0 v_c(t) = w(t) \quad (7)$$

Where w a zero mean Gaussian white noise, v_c is the current velocity and μ_0 a time constant.

Figure 4 shows the evolution of the current norm with this model. The targeted and the actual mean on these time series are 1.2 knots.

V.2 Wind model

In the literature, the wind model is generally described by a spectral representation. In the present paper, the wind gusts will be modelled by a Harris spectrum. The spectrum S_ω which represents the frequency distribution is given by [2]

$$S_\omega(\omega) = 0.05\frac{5286V_w}{\left(1+\left(\frac{286\omega}{V_w}\right)^2\right)^{5/6}} \quad (8)$$

where V_w is the average wind velocity and ω is the frequency of wind oscillations.

An example of the evolution of the wind velocity with an average value of 8 knots is shown on Figure 4.

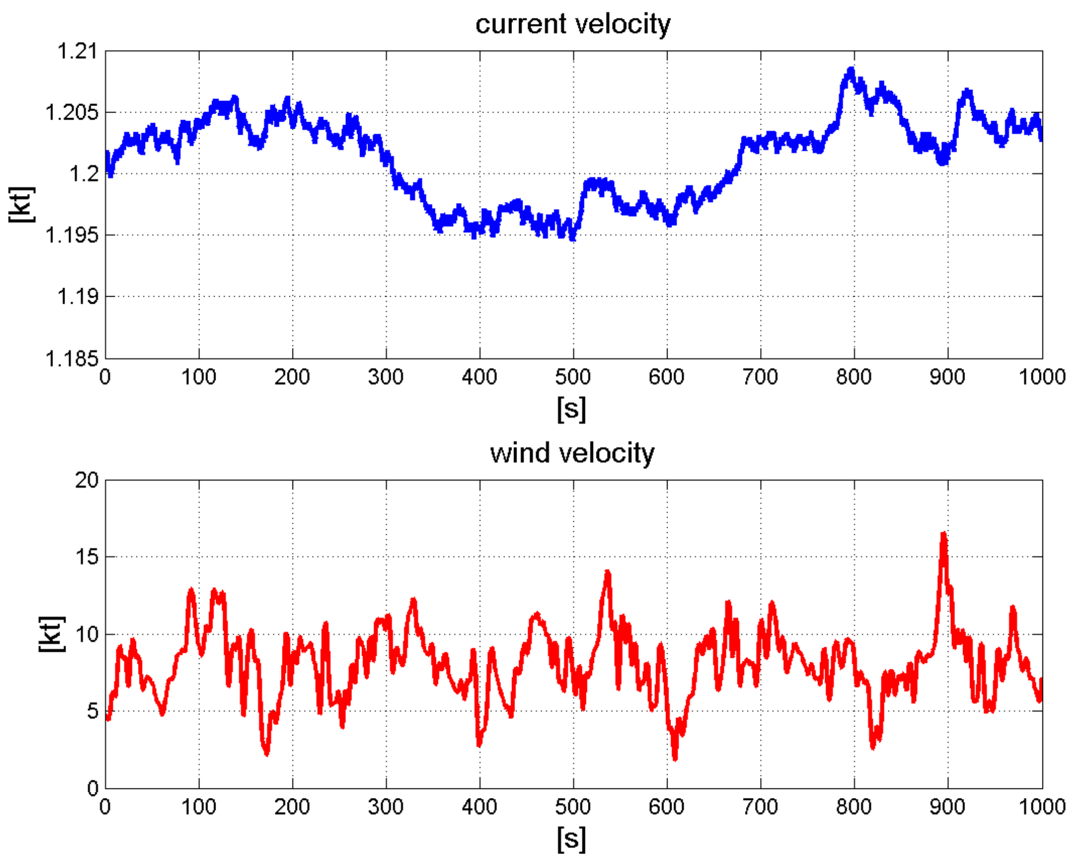


Figure 4 : Example of wind velocity and current velocity over the time

VI. DP Vessel

VI.1 Presentation

The ship used in the simulation framework is the BOURBON SUPPORTER [9] (or her sistership, the BOURBON ENTERPRISE [10]). This vessel has been built in 2010 at Socarenam Shipyards in France. She is a DP2 multipurpose supply vessel (MPSV) equipped with 2 tunnel thrusters at the bow and two azimuth thrusters as main propellers at the stern. The main characteristics of the vessel are given in the next table

Figure 5 : Bourbon Enterprise from [10] – courtesy BOURBON

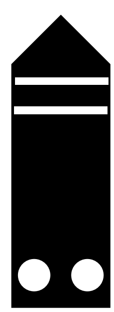
Length between perpendiculars	73.70 m
Breadth, moulded	19.50 m
Maximal draft	5.50 m
Deadweight at max draft	1 823 t
Gross tonnage	3052 UMS
Thruster arrangement	

Table 2 – Main characteristics of the simulated vessel

VI.2 Operations

After a two years hiring contract in Saudi Arabia as a support vessel for subsea seismic testing, the Bourbon Supporter is now operating for Chevron in Thailand. The vessel is devoted to Inspection, Maintenance and Repair (IMR) operations.

VII. DP control algorithms

In the presented paper, two control systems will be compared. The structures of the control laws are the same as presented in [11]. The thrust allocation algorithm is actually the only difference between the two systems since the tuning of the system is strictly equivalent. The problem of thrust allocation is well known and well documented in the literature. An implementation of a biasing strategy will be benchmarked against a new algorithm equipping the EasyDP system, the DCNS Research/Sirehna DP installed onboard the BOURBON SUPPORTER and BOURBON ENTERPRISE. The thrust allocation problem is actually a mathematical optimization problem. It lies in the dispatching of the desired forces on the available thrusters variables. As expressed in [11], the general problem of thrust allocation can be written as

$$minimize \sum_i P_i \quad \text{under constraints} \begin{cases} equality\ F_r = F_d \\ inequality |n_i| < n_i^{max} \end{cases} \qquad (9)$$

Where

- $\overrightarrow{F_r}$ the realized forces
- $\overrightarrow{F_d}$ the desired forces
- n_i rpm of the i-th thruster
- n_i^{max} maximal rpm of the i-th thruster
- P_i the power consumed by the i-th thruster

The proposed enhanced algorithm developed by DCNS Research/Sirehna lies actually in the modification of the problem formulation in order to take in account the variations of efficiency of an azimuth thruster according section IV. Furthermore, an additional objective is added in order to limit the temporal variation of the thruster orders. These two criteria are taken into account to turn the azimuthal thrusters towards the most adequate direction. The simulation results of the system using biasing strategy will be labelled “Bias” while the ones using the enhanced algorithm will be referenced as “New Design”.

VIII. Simulation results

The two systems are compared in a simulation study. The external conditions are varying as

- Current
  - direction 200° (South-West)
  - velocity : 0.2knot, 1 knots, 2 knots
- Wind
  - direction 180° (South)
  - velocity : 3 knots, 8 knots, 15 knots

The ship is in station keeping mode with 0° as heading set point. The sketch of the scenario is represented on Figure 6. The simulation length is 1000 seconds.

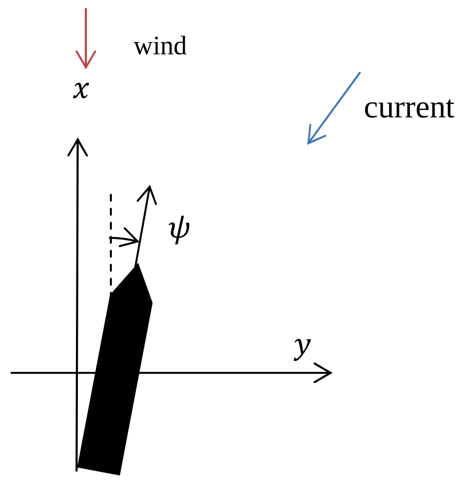


Figure 6: Simulation scenario

The station keeping is well ensured for both systems design. The errors means for surge, sway and yaw are really close to zero for all the considered simulations.
An example of the simulated signals for the worst conditions (2 knots of current and 15 knots of wind) is displayed on next figure.

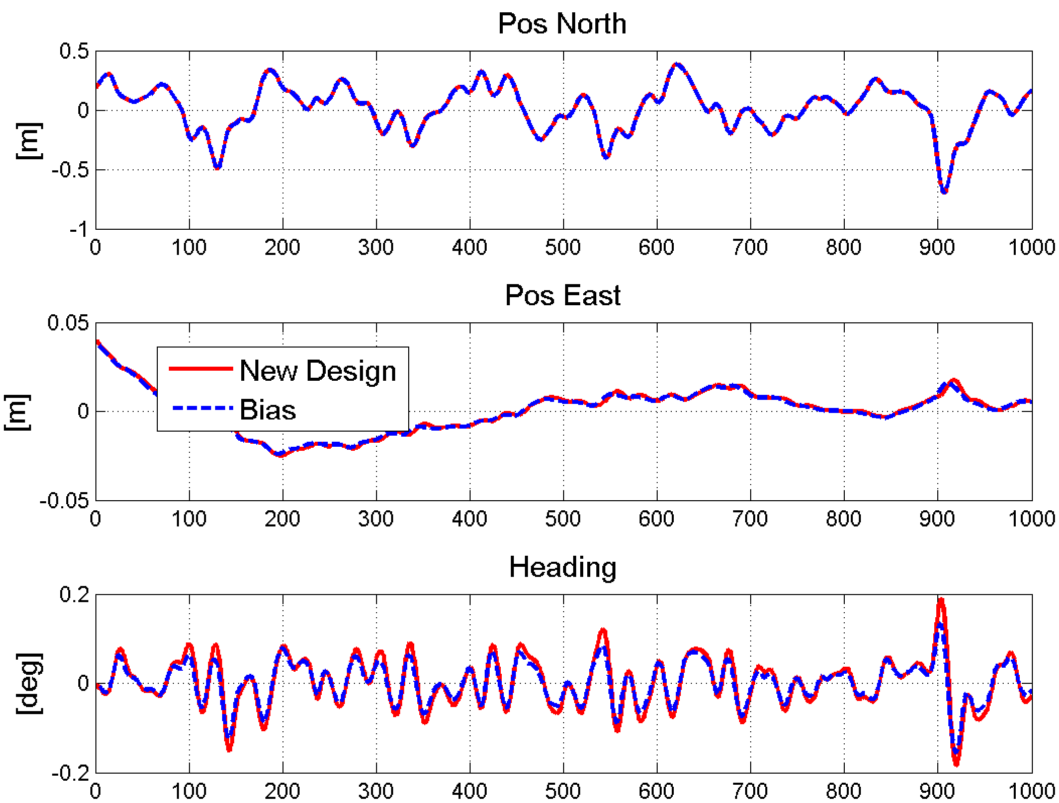


Figure 7: Station keeping performances for both systems with 2kt current and 15 knots of wind

On this figure, it can be shown that the performances are almost not affected by the differences in the thrust allocation module. The user tuning has actually a greater influence on the ship response. However, a really slight difference can be observed for the yaw motion and will be discussed in the next section.
In order to better characterize the differences and the performances of the station keeping, the variances of the signals are studied. They are summarized in the next table.

		Bias			New Design		
	Wind (kt)	X (m)	Y (m)	Heading (°)	X (m)	Y (m)	Heading (°)
Current 0.2kt	3	~0	~0	~0	~0	~0	~0
	8	0.1	~0	~0	0.1	~0	~0
	15	0.2	~0	~0	0.2	~0	0.01
Current 1kt	3	~0	~0	~0	~0	~0	~0
	8	0.1	~0	0.01	0.1	~0	0.01
	15	0.2	~0	0.02	0.2	~0	0.03
Current 2kt	3	~0	~0	~0	~0	~0	~0
	8	0.1	~0	0.01	0.1	~0	0.02
	15	0.2	~0	0.04	0.2	~0	0.05

Table 3 : Variances of surge sway and yaw in the simulations of both systems

Again, it can be noticed that the performances are satisfactory and the new design of the thrust allocation makes no difference in the results.
The power consumption can now be compared. The results are summarized in the next table while examples of time series are shown on Figure 8.

		Bias	New Design	New design compared to Bias (ratio)
	Wind (kt)	Power (kW)	Power (kW)	%
Current 0.2kt	3	0.68	0.74	**+9%**
	8	3.44	2.30	**-33%**
	15	14.08	10.11	**-28%**
Current 1kt	3	11.50	10.53	**-9%**
	8	14.87	11.98	**-19%**
	15	26.40	23.47	**-11%**
Current 2kt	3	66.00	59.98	**-9%**
	8	68.96	61.69	**-10%**
	15	81.64	80.31	**-2%**

Table 4 : Average power consumption during the simulation for both systems

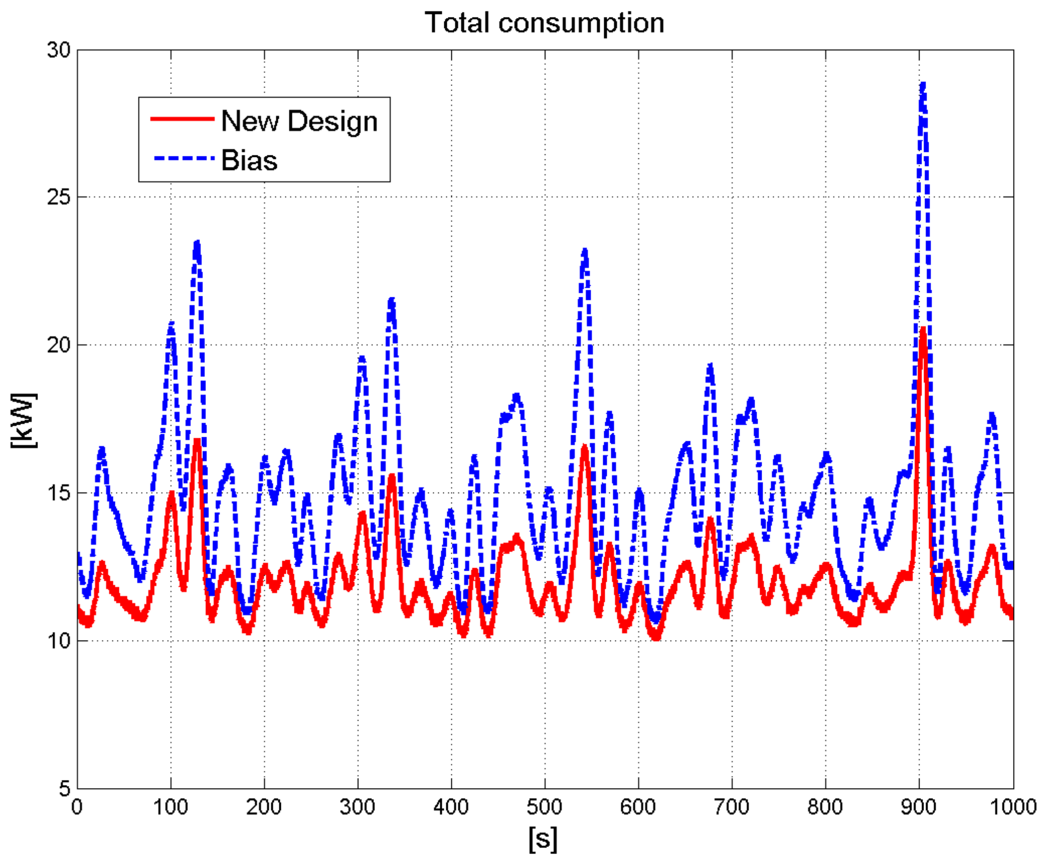


Figure 8: Thrusters consumptions during the simulations with 1kt current and 8 knots of wind

IX. Discussions

IX.1 Analysis of simulations

In average the DCNS-Research/Sirehna thruster allocation design efficiently reduces the fuel consumption. Even though the bias strategy provides a slightly better heading performance, it has no sustainable operational interest compared to the energy savings provided by the new design. Considering the energy costs and the absolute performance achieved in both cases, the trade-off between the two solutions is obviously in favor of the new design.

There is actually only one case (3kts of wind, 0.2kts of current) where the biasing strategy has better performances. The bias is actually the most stable thruster's position for delivering small efforts as it is known and applied by DPOs. However it can be noticed that the probability of occurrence of such very calm environmental conditions is rather low. As reported in [12], in West Africa, the average current is about 0.5 knot while the mean of wind velocity is around 8/9 knots. The new control law has been actually designed and tuned for a wind velocity of 10 knots and a current velocity of 1 knot. The results of Table 4 show indeed that the most significant reductions of fuel consumption occur for current values less than 2 knots and a wind velocity of 8 knots. The value of 1 knot of current has been chosen in order to include the extra forces due to swell and waves. The waves are indeed not usually measured and are even

less fed to the DP systems. Well known by DPOs, the DP system calculates actually an “equivalent current” which includes the effects of current and waves [13].
Finally, the simulations have been performed using an approximated model of azimuth thruster. A better characterization of the efficiency loss of an azimuth thruster and its use in the DP system could lead further strategy optimizations and to further reduction of the operational costs.

IX.2 On field measurements analysis

This new thrust allocation strategy has been implemented on two ships delivered in 2011. The low fuel consumption of the vessel under DP control has been reported by Bourbon after several months of operations and copes with the design and simulation results. The consumption of the vessel is about 3-4 m^3 of fuel per day compared to 7-8 m^3 concerning the other Bourbon vessel operating in the same area. However, the overall reduction of the fuel consumption rely on several parameters as

- Ship design including propulsion
- Ship operations
- Power equipment (engines, generators, …)
- Electrical equipment (PMS, DP system)
- Ship maintenance (clean hull, clean propellers, electrical devices, …)

Operations performed by the considered ships are similar. Moreover the differences of design, electrical and power equipment and maintenance between the considered Bourbon vessels are minor. This has an even lower impact since the ships are mainly used in station keeping. Therefore the only major difference is that only the Bourbon Supporter is equipped with the enhanced DP algorithms presented in this paper.

The DP system can thus been considered as the major contributor of the reduction of fuel consumption. Even if the associated costs in operations are borne by the clients, managing and optimizing the fuel consumption is really important for Bourbon as a proof of its operational excellence. Moreover the reduction of fuel consumption reduces directly NOx emission.

IX.3 Integration in the EasyDP system

This new allocation module is today a standard function implemented on the Sirehna EasyDP system. The DP operator can select this strategy by selecting “Free” on the HMI as presented on the next figure. The EasyDP HMI has been totally renewed using flat design and focusing on user experience. This leads to a more intuitive use of the system where important information are easily accessible. This allows the DP operator to focus more on the operation rather than on the screen. This new system will be installed on 4 ships (1 DP-2 and 3 DP-1 class vessels) until the end of 2014.

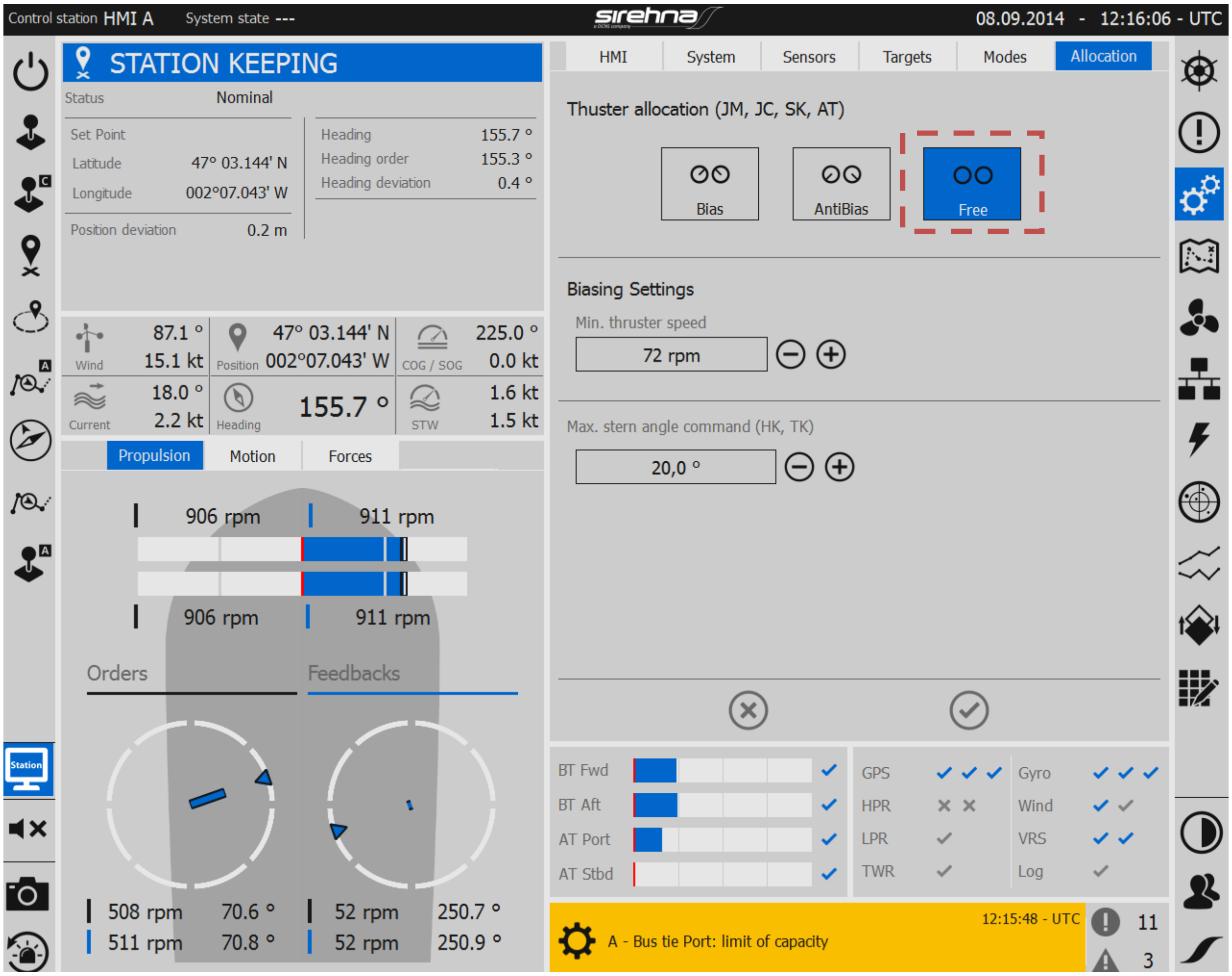


Figure 9 - HMI of the EasyDP system and Thrust allocation settings

X. Conclusions

The question of operational costs is today a great challenge for the offshore industry. A new thrust allocation strategy for an efficient reduction of the fuel consumption without noticeable effect on ship capability has been developed and presented in this paper. Benchmarked in simulations against a classic strategy, the new design shows enhanced performances in terms of thruster use without degrading the performances of the station keeping. This algorithm has been already implemented on two ships and the operators have given a really good feedback of the performances of the vessel.

XI. Acknowledgments

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XII. References

[1] Det Norske Veritas, 2011, Dynamic Positioning System – Enhanced Reliability DYNPOS-ER, DNV Guidance

[2] Fossen T.I., 2002, "Handbook of Marine Control System, Guidance, Navigation and Control of Ships, Rigs, and Underwater Vehicles"

[3] Isherwood, R.M., 1972, "Wind Resistance of Merchant Ships", *Transaction of the Royal Institution of Naval Architects, Vol.115, pp327-338.*

[4] Bureau Veritas, 2013, "Rules for the Classification of Steel Ships – Additional Class Notations Part E Ch 6 to 10", Chap 10, Sec 6, *pp150-151*

[5] Van Dijk, R.R.T, Aalberts, A.B., " What happens in water ? The use of hydrodynamic to improve DP", *Proceedings of the Dynamic Positioning Conference 2001, Houston, Texas, USA*

[6] Cozijn, J.L., Buchner, B., Van Dijk, R.R.T, "Hydrodynamic Research Topics for DP Semi Submersibles", *Proceedings of Offshore Technology Conference 1999, Houston, Texas, USA*

[7] Islam, M., Veitch, B., Akinturk, A., Bose, N., Liu, P., "Experiments with podded propulsors in static azimuthing conditions", *Proceedings of the 8th Canadian Marine Hydromechanics and Structures Conference, 16-17 October 2007, St. John's, NL*

[8] Ottens, H. and van Dijk, R. "Benchmark Study on Thruster-Hull Interaction In Current on a Semi-Submesible Crane Vessel", OMAE2012 – 83125, *Proceedings of the ASME 2012 31st International Conference on Ocean, Offshore and Arctic Engineering (OMAE2013), ASME, Rio de Janeiro, Brasil.*

[9] http://www.bourbon-online.com/media/offshore/mpsv/MPSV-BOURBON-SUPPORTER.pdf

[10] http://www.bourbon-online.com/media/offshore/mpsv/MPSV-BOURBON-ENTERPRISE.pdf

[11] Kerkeni, S., Dal Santo, X., Metrikin, I., 2013, "Dynamic Positioning in Ice – Comparison of control law in open water and ice", OMAE2013 – 10918, *Proceedings of the ASME 2013 32nd International Conference on Ocean, Offshore and Arctic Engineering (OMAE2013), ASME, Nantes, France.*

[12] Nerzic, R., Frelin, C., Prevosto, M., and Ramus, V. Q., 2007, "Joint Distribution of Wind/Waves/Current in West Africa and derivation of multivariate extreme I-FORM contours". *Proceedings of the 17th International Offshore and Polar Engineering Conference, Lisbon, Portugal.*

[13] Jenssen, N.A. 2006. "What is DP current", *Proceedings of the Dynamic Positioning Conference 2006, Houston, Texas, USA*