Station-keeping calculations in early design stage: two possible approaches

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Abstract. The continuous increase of offshore operations in deep or ultra-deep waters, makes, for modern units, Dynamic Positioning (DP) analysis mandatory since early design stage. The necessity to provide reliable solutions for the DP system to mount on board in order to maintain position requires the implementation of simulation codes to reproduce the dynamic behaviour of the unit under variable environmental circumstances. Usually, it is common practice to perform simplified quasi-steady calculations during the early design stage, in such a way to obtain a sufficient amount of indications, necessary to a rough estimation of DP system capability and dimensioning. Besides, time domain calculations can be also adopted, once sufficient information are already available, at the considered design phase, regarding hull form, thrusters system and superstructure geometry. In the present work the two mentioned approaches are compared in terms of the resulting capability plots evaluated for a reference ship. The results have been obtained from two self-developed codes (one quasi-steady and one dynamic), which are adopting the same thrusters allocation algorithm.

Keywords. Dynamic Positioning, time domain calculations, thrust allocation, vessel dynamics

1. Introduction

In the design process of offshore vessels, the thematic of DP is nowadays becoming of primary importance since early design stages. In fact, the necessity to operate in environmental ambient, where a traditional mooring is no more suitable, requires the installation on-board of devices ensuring the ability to keep autonomously the position during operations. Means that DP system is an essential part of the equipment that should be installed on board, so it is necessary to dedicate a proper attention since early design stage to the prediction of the capability of such a system. The necessity to understand phenomena governing DP to provide station-keeping solutions for a vessel, requires the implementation of simulation codes suitable to reproduce the behaviour of the vessel under predetermined environmental circumstances. The implementation of such a code requires the combination of several fields of engineering, since environmental loads should be determined but also the main algorithm involved in the DP system should be modelled

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together with vessel dynamics[1].

To easily determine a rough estimation of the DP system dimensioning, simplified quasi-steady calculations are performed[2]. However, the dynamic nature of the phenomena cannot be completely discarded. For such a reason, in a more advanced design stage, dynamic simulations are performed[3], having already determined the characteristics of the DP system. These kind of simulations generally reproduce the DP system behaviour considering also all the algorithms related to the measuring system of vessel position and state estimation in real time, resulting in a simulation more focused on control theory than on hydrodynamics.

Therefore a simplified dynamic simulation model has been implemented (using *Simulink* ambient), without simulate the position error measuring system. This model is considering the vessel dynamics in three DOF and is capable to simulate a realistic environmental condition, by means of an accurate estimate of wind, wave and current loads. The method is also oriented to the prediction of DP capability plot by selecting an appropriate acceptance criteria for the admitted position error for the required operation.

The implemented simulation model has been tested on a Drill-ship equipped with six azimuthal thrusters and the results, in terms of capability plot, are compared with a quasi steady simulation using the same thrust allocation algorithm and environmental loads coefficients.

2. Quasi-steady approach

The most diffused way to perform preliminary DP capability calculations is given by the adoption of quasi-steady programs. A quasi-steady approach is usually preferred during initial design stage because of its apparent simplicity, since it is based on a balance between the external loads and the thrust generated by vessel devices. At such a design phase, the DP calculation is to evaluate the maximum external load that the vessel can face with the thruster devices installed on board. It is common use to represent this loads in terms of a maximum sustainable wind speed for each encounter angle.

2.1. Environmental loads

The environmental loads considered in a quasi-steady calculation are principally wind, wave and current loads. Usually all the loads are considered as acting in the same direction, without specific offsets between them. Only in special cases, when some specific operation conditions should be tested, this scheme is not used and specific offsets are considered. Generally the current is set with a constant speed, while the wind speed is systematically increasing at each heading, varying consequently the incoming wave with a specific correlation.

Environmental loads are determined starting from predetermined non-dimensional coefficients varying with the heading angle. There are several way to determine them, starting from simple regression equations and class regulation up to model test or dedicated CFD computations. In an initial design stage it is more common to adopt statistical coefficients, since usually not all the information necessary to perform tests or complex calculations are present.

In the present study the Environmental loads coefficients used for the calculations have been obtained by statistics coming from experimental data concerning not only wind and current loads but also wave drift forces.

2.2. *Thrust allocator*

The core of a quasi-steady calculation is the thrust allocation algorithm. In fact, once the external loads are determined the static equilibrium between the external forces and the delivered thrust must be determined by solving the following equilibrium equations:

$$\begin{cases} \sum_{i=1}^{N} F_{X_i} = F_{X_{ENV}} \\ \sum_{i=1}^{N} F_{Y_i} = F_{Y_{ENV}} \\ \sum_{i=1}^{N} M_{Z_i} = M_{Z_{ENV}} \end{cases} \tag{1}$$

being N the number of thruster devices. As it is well known, system 1 is over-dimensioned, leading to possible infinite multiple feasible solutions for the equilibrium. For such a reason, particular resolution methods can be adopted to solve the equilibrium balance, starting from simple deterministic techniques up to complex non-linear optimisation theories[4]. Through this study, a deterministic method based on thruster group logic has been adopted[5], and to ensure a reliable comparison between static and dynamic calculations, the same allocation algorithm has been used for both approaches.

3. Dynamic simulations

There are typically two kind of dynamic simulation, a *complete* one, aimed to reproduce the DP system installed on board, and a *simplified* one, where the simulation of the observer can be neglected. A complete dynamic simulation uses a set of algorithms to evaluate the vessel position, evaluate the position error and then to correct this error in time domain.

As it can be seen in Figure 1, during a dynamic simulation the position is determined by the vessel dynamic module (which can include also the simulation of the measuring system), then position data together with environmental forces (wind) and mooring forces are sent to the Kalman Filter (KF) module (or Extended KF in case of non-linearities) to estimate the low frequency motion and speed of the vessel. The estimated position is then send to a controller estimating the required forces needed to correct error position by means of the actuators.

As mentioned, in this study a simplified simulation model has been considered, discarding the implementation of KF module, means sending directly the dynamics output to the controller.

3.1. *Vessel dynamics*

By considering the vessel as a 3-DOF mass-spring system, the response of a floating vessel in waves can be described, considering Cummins equations [6], in the following form with respect to the ship fixed reference system O(ξ, η, ψ):

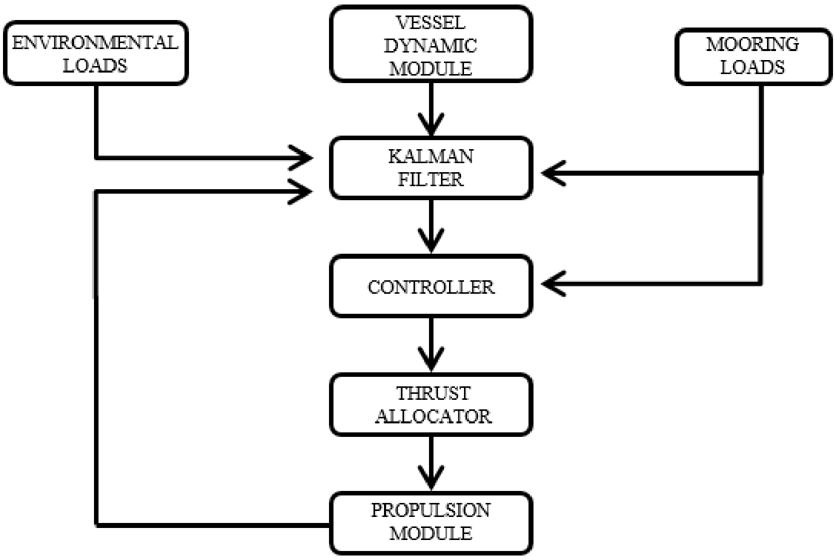

Figure 1. Calculation scheme of a complete DP dynamic simulation.

$$\begin{aligned}(M_{11}+a_{11}(\infty))\ddot{\xi} = {} & Mx_G\dot{\psi}^2+\int_0^t B_{11}(\tau)\dot{\xi}(t-\tau)\,d\tau+(M+a_{22}(0))\dot{\eta}\dot{\psi} \\ & -(a_{22}(0)-a_{11}(0))V_c\sin(\alpha_c-\psi)\dot{\psi}+F_{\xi_{ENV}}-F_{\xi_T}\end{aligned} \tag{2}$$

$$\begin{aligned}(M_{22}+a_{22}(\infty))\ddot{\eta} = {} & (Mx_G+a_{26}(\infty))\ddot{\psi}-\int_0^t B_{22}(\tau)\dot{\eta}(t-\tau)\,d\tau \\ & -\int_0^t B_{26}(\tau)\dot{\psi}(t-\tau)\,d\tau+(M+a_{11}(0))\dot{\eta}\dot{\psi} \\ & +(a_{22}(0)-a_{11}(0))V_c\sin(\alpha_c-\psi)\dot{\psi}-F_{\eta_{ENV}}+F_{\eta_T}\end{aligned} \tag{3}$$

$$\begin{aligned}(I_{66}+a_{66}(\infty))\ddot{\eta} = {} & (Mx_G+a_{62}(\infty))\ddot{\eta}-\int_0^t B_{66}(\tau)\dot{\psi}(t-\tau)\,d\tau \\ & -\int_0^t B_{22}(\tau)\dot{\eta}(t-\tau)\,d\tau+(Mx_G+a_{62}(0))\dot{\eta}\dot{\psi} \\ & -M_{\psi_{ENV}}+M_{\psi_T}\end{aligned} \tag{4}$$

where M is the ship mass, I the vessel inertia, a_{ij} the added masses, b_{ij} the retardation function coefficients, x_G the longitudinal centre of gravity and V_c and α_c are the current speed and incidence angle respectively. The retardation function coefficients can be determined comparing the solution of motion equations 2, 3 and (4) for a unitary amplitude harmonic oscillation, with the analytical frequency domain solution for the same motion[7]. This will led to the following formulations:

$$b_{ij}(\tau)=\frac{2}{\pi}\int_0^\infty b_{ij}(\omega)\cos(\omega t)\,d\omega \tag{5}$$

The above described equations are integrated with a fourth order Runge Kutta method, in order to obtain the vessel position and velocities, considering a fixed time step Δt of 0.01 seconds.

3.2. *Controller*

The estimated position and velocities coming out vessel dynamics calculations should be compared with the required values inherent to vessel position in order to evaluate the errors related to position and speed. The errors need to be corrected by the controller, determining the required thrust needed to correct the error. The implemented controller is of the PID type, being able to evaluate the required thrust as follows:

$$T_{\xi_{REQ}} = P_{\xi}\Delta\xi + I_{\xi}\int_{\Delta t}\Delta\xi dt + D_{\xi}\dot{\xi} \tag{6}$$

$$T_{\eta_{REQ}} = P_{\eta}\Delta\eta + I_{\eta}\int_{\Delta t}\Delta\eta dt + D_{\eta}\dot{\eta} \tag{7}$$

$$M_{\psi_{REQ}} = P_{\psi}\Delta\psi + I_{\psi}\int_{\Delta t}\Delta\psi dt + D_{\psi}\dot{\psi} \tag{8}$$

the P_i, D_i and I_i control coefficients should be set for each applications in order to ensure a stable positioning and make an effective use of all the thrusters. The parameters settings are influenced also by the entity of the total load acting on the vessel, leading to different optimal settings at each environmental condition.

However it is possible to adopt some general rules[8] in such a way to give an initial guess of the control coefficients:

$$P_i = \frac{T_{AV_i}}{0.6\Delta_{MAX_i}} D_i = 1.2\sqrt{(M+a)_i P_i} I_i = 0 \tag{9}$$

The integral coefficient is usually set to zero since it can be source of instability and it can be discarded because it is responsible of a mean positioning error with respect to the desired position, but DP is usually correcting fluctuations around a mean value.

3.3. *Environmental loads*

The management of the Environmental loads is somewhat different between quasi-steady and dynamic calculations. Once the entire DP system is analysed, usually only wind, or almost also current, loads are considered. In the proposed simplified methods all the loads are simulated, adopting the same coefficients of the quasi-steady simulations. In any case the necessity to describe an environment changing with time will led to some peculiarities in the modelling.

Concerning the current load, it has been hypothesised to discard time fluctuation of V_c and α_c, considering at each time step the relative velocity and angle resulting from vessel dynamics.

Different is the case of the wind, where a dedicated modelling has been implemented to reproduce also the effect of wind gusts. Wind gusts, as well as waves, can be modelled by means of spectra. Several kind of gust spectra can be found in literature, some specific for certain sea areas others more general. In the simulation program, Davenport spectrum [9] has been considered, in such a way to model only the oscillating part of the wind speed and add it to the constant wind one.

Table 1. Main dimension of the Drill-ship

	Symbol	Units	Value
Overall length	L_{OA}	m	226.50
Length between perpendiculars	L_{BP}	m	220.00
Design breadth	B	m	55.00
Design draught	T	m	12.22
Displaced volume	∇	m^3	114854.56

Table 2. Thruster layout and dimensioning

No.	Name	X (m)	Y (m)	T_{MAX} (ton)
1	AFT Centreline	-105.00	0.00	91.95
2	AFT Port side	-86.00	-16.50	91.95
3	AFT Starboard side	-86.00	16.50	91.95
4	FWD Port side	60.00	-16.50	91.95
5	FWD Starboard side	60.00	16.50	91.95
6	FWD Centreline	80.00	0.00	91.95

3.4. Limiting environment detection

For the definition of the capability plot it is necessary to determine the maximum wind speed that the vessel is able to face. For such a kind of calculations multiple simulations should be executed at each encounter angle. It has been decided to perform three simulations of 3 hours at each encounter angle and wind speed. For each simulation the reliability of the DP system is evaluated considering three limits (or *zones*), a *green zone* where the position error is below 5 meters and the yaw does not exceed ±3 degrees. A *yellow zone* where the position error is below 10 meters and the yaw does not exceed ±6 degrees and a *red zone* where the position error is below 15 meters and the yaw does not exceed ±10 degrees. When the vessel is outside the red zone the position can be considered lost.

As criteria of acceptance, it has been selected to consider the vessel able to keep the position when the 90% of the time is inside the *green zone*. According to these considerations, the capability plot can be determined.

4. Numerical example

The above mentioned approaches have been applied on a Drill-ship, having the characteristic reported as in Table 1 and a thruster system as described in Table 2.

As mentioned the same loads coefficients and the same thrust allocation algorithm have been used during the two simulations, means the differences between the two obtained capability plots represents the effect of the dynamics in the total prediction. In Figure 2 it can be observed that the dynamic prediction is giving a lower capability with respect to quasi-steady one, being almost always around 30% lower in terms of sustainable wind speed at each angle. This is in line with what observed in previous studies[10], considering comparable acceptance criteria.

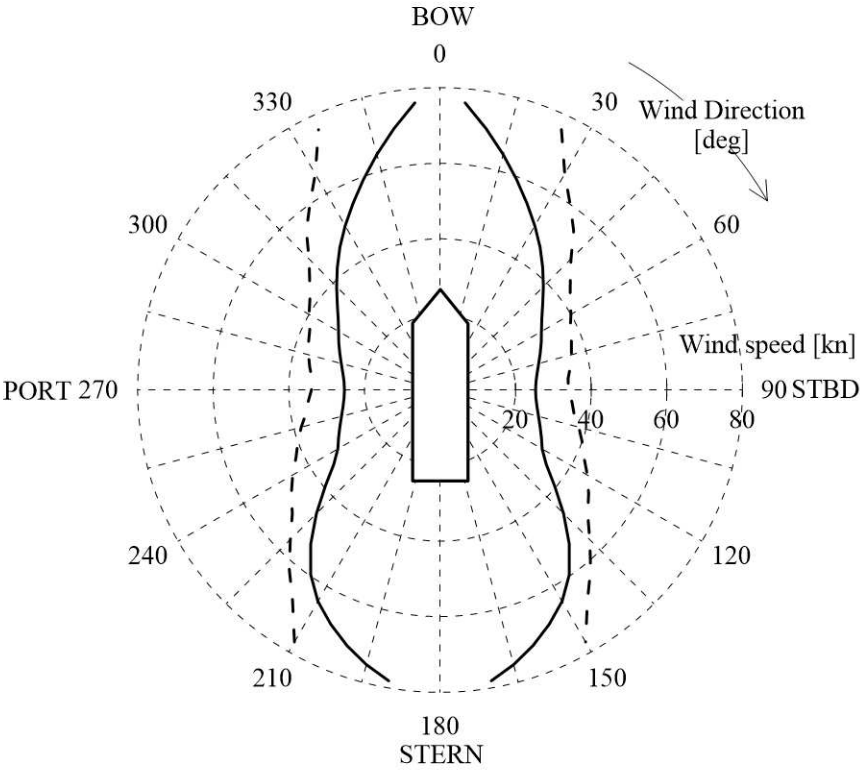

Figure 2. Comparison between the quasi-steady and dynamic capability plot.

5. Conclusions

The implementation of a simplified time domain DP simulation program together with the selection of specific acceptance criteria for position error allow to perform capability study in time domain. The results of dynamic simulation compared with standard quasi-steady calculations is suitable to highlight the effect of dynamics on the capability plot since the same allocation algorithm has been used in the two calculation approaches. This kind of analysis can be interesting to determine in a more accurate way the dynamic allowances that can be introduced in quasi-steady simulations, improving the quality of the results. In fact, in therms of calculation time, quasi-steady approach is for sure more convenient than dynamic one.

Further investigation will be for sure done in the implementation of more complex allocation algorithm inside the development program and in the implementation of a complete dynamic simulation.

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