Dynamic Positioning System as Dynamic Energy Storage on Diesel-Electric Ships

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***Abstract*—A dynamic positioning (DP) system on a diesel-electric ship applies electric power to keep the positioning and heading of the ship subject to dynamic disturbances due to the winds, waves and other external forces using electric thrusters. Vice versa, position and heading errors can be allowed in order to implement energy storage in the kinetic and potential energy of the ship motion using the DP control system to convert between mechanical and electrical power. New simple formulas are derived in order to relate the dynamic energy storage capacity to the maximum allowed ship position deviation, as a function of the frequency of the requested dynamic energy storage. The benefits of DP dynamic energy storage are found to be reduced diesel-generator maintenance need, reduced fuel consumption and emissions, reduced risk for blackout, and increased operational flexibility allowing power-consuming operations such as drilling and lifting to be safely prioritized over DP for short periods of time.**

Key words: Marine power plant, diesel-electric system, power management system, dynamic positioning, dynamic energy storage, consumer load control.

I. INTRODUCTION

Dynamically positioned (DP) vessels with diesel-electric power and propulsion systems are commonly used in offshore operations in order to keep the ship position and heading at their references. While the DP system is often the main consumer of electric power on the ship, other variable power consumers are connected on the same power buses as the electric thrusters. The relatively weak electric grid on a vessel is therefore subject to significant variations in voltage and frequency caused by the dynamics of several more or less independent consumers. This causes challenges due to increased wear and tear, maintenance costs, emissions, and fuel inefficiency of diesel generators in combination with increased risk for blackout due to over- or under-frequency condition causing protection relays to trip generators. Common variable load consumers include drilling drives, heave compensators, cranes, pumps and winches whose operation are often influenced by wave-induced ship motions and other external disturbances.

From a DP ship operator's point of view, the main goal is to maximize the operationally useful time of a DP vessel in order to maximize operational income, hence minimizing inefficient and costly downtime resulting from loss of position incidents. At the same time, minimizing running hours on equipment such as power generators and thrusters will reduce maintenance costs. Historically, these two goals have been in conflict because the demand to maximize operational uptime has required a conservative and redundant use of power and thruster equipment, as required by the International Maritime Organization (IMO) rules for DP vessels [6]. A new and more flexible DP notation called DYNPOS ER (Enhanced Reliability), [3], has recently been launched. It is "developed to allow owners to optimize fuel usage and reduce operational costs, while maintaining high integrity towards loss of position and heading" and enables a more "flexible, redundant and fuel-efficient way of structuring DP systems". Such a new development on the classification side, which is a result of new technological developments, opens up new possibilities for improved and integrated DP and power control functionality, thus motivating the dynamic energy storage on DP vessels.

Although large resistor banks and thrust allocation with thruster biasing are sometimes used to waste of power on DP ships in order to reduce the effects of power transients on the system, e.g. [7], it is clear that more efficiency and flexibility could be achieved with dynamic energy storage. While several concepts are currently being investigated, such as DC grids (e.g. [5]), hybrid power systems (e.g. [17]), battery banks, capacitive storage and increased mechanical inertia such as flywheels, the purpose of this paper is to study a much simpler approach that does not require any new equipment, i.e. the use of the inertia of the vessel hull itself as dynamic energy storage controlled by the DP system.

The forces that act on a DP vessel can be assumed to be limited to the environmental forces and the thruster forces commanded by the DP controller. Further, assume that the slowly-varying components of the environmental forces are sufficiently large. The vessel hull itself is an effective dynamic energy storage due to its inertia. For example, accelerating the vessel forward by an electrical thruster will convert electric energy to mechanical energy that is at first stored as kinetic energy (due to velocity resulting from the acceleration caused by the thrust) and later as potential energy (a change in position in the presence of the slowly-varying environmental force field) that can be converted back by returning the vessel back to the original position. Temporary energy storage can therefore be provided by the DP system by allowing the vessel to move away from the set-point within a given position tolerance. This is not a new idea, and some power control and thrust allocation methods that exploits this mechanical energy storage capacity have been studied and implemented in various forms [10], [12], [15], [16]. A benefit of dynamic energy storage is increased operational flexibility as it allows these consumers to have higher priority than DP thrusters with respect to load reduction and load shedding, without reduced safety or operational performance, for short periods of time. Dynamic energy storage is currently also much considered for power and energy management in micro-grids and for integration of renewable energy sources, e.g. [8], [9].

The main contribution of this paper is derivation and verification of a new and simple analytical formula that relates the amplitude of the position deviations that need to be allowed to achieve a given capacity of the dynamic energy storage characterized by the frequency and amplitude of the stored power. This allows bounds on the dynamic energy storage capacity provided by methods such as [10], [12], [15], [16] to be quantified using a very simple formula. Consequently, the need and benefits of new concepts for dynamic energy storage can be more easily discussed and compared in a wider perspective, as dynamic energy storage capacity can be provided within a reasonable range of frequencies and amplitudes simply through functions that can be realized in DP software without the need for any new power system hardware or other equipment.

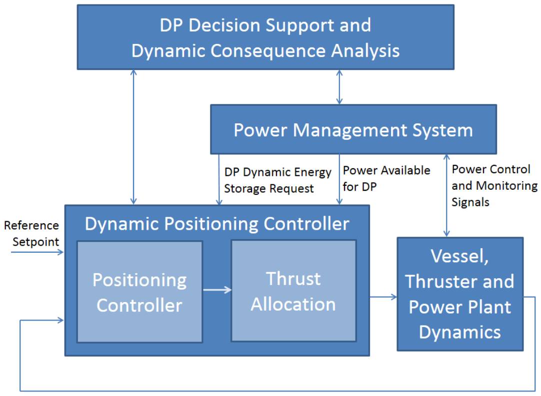

Fig. 1. The Power Management System is allowed to request dynamic energy storage from the DP controller. A supervisory control and monitoring systems may provide advice and control in order to minimize risk for DP loss of position and other hazards due to electric power shortage resulting from equipment failure or operational issues.

II. A CONCEPTUAL CONTROL ARCHITECTURE FOR DYNAMIC ENERGY STORAGE IN DYNAMIC POSITIONING

Figure 1 shows a control architecture that intends to illustrate the main idea. In a DP system there is a positioning controller that commands forces in surge and sway directions, as well as the yaw moment, in order to keep position and heading at their specified set-point, [4], [13]. Conventionally, a thrust allocation module allocates these forces to the individual thrusters in order to meet these commands whenever possible, where exceptions would be when the thrust demands cannot be met due to the static or dynamic limitations in the thruster system, machinery, or the electric power system. Those limitations are commonly managed through a power available signal from the power management system (PMS) that has the basic function of preventing overloading of the power plant due to equipment failures or protection trips due to under-frequency or under-voltage that would potentially lead to loss of position and emergency operation.

The architecture in Figure 1 deviates from conventional DP architectures since it allows the PMS to request dynamic energy storage to the DP controller. Such dynamic energy storage requests would typically either be issued to compensate for known or predictable load variations in other electric power consumers, e.g. heave compensators, or in response to failures or operational issues such as loss of generator capacity or partial blackout. Some further discussion on the potential benefits of dynamic energy storage in provided in section V. The DP controller can then implement dynamic energy storage functionality in many different ways, for example

- Modify the position set-point slightly to increase or decrease the power consumption during the transient.
- Modify the thrust request to the thruster controllers, [12], without any analysis of consequences for positioning errors.
- Modify the thrust request to the thrust allocation with an amount that corresponds to the requested dynamic energy storage rate. This is the approach that will be used in this paper for demonstration and analysis, for simplicity.
- Modify the power available and limits to the thrust allocation in order to implement the dynamic energy storage request in a smooth and efficient way with minimum impact on the operation of the system, [15], [10], [16].

Dynamic storage of energy as kinetic and potential energy in a DP vessel has some inherent limitations. First, the energy storage cannot change faster than the thruster dynamics. While the electric thruster power can be changed in much less time than one second using frequency converters, it should be realized that persistent fast changes will cause mechanical stress on the system and increased tear and wear. Hence, in practice we expect that energy storage dynamics faster than about 0.2 - 0.5 Hz cannot normally be accommodated by the DP system. Note that higher frequencies than this would be effectively handled by the mechanical inertia of the diesel-generators, and the capacitances and inductances in the electric system, [11]. In emergency situation the functionality with significant risk of black-out the functionality could be allowed fast energy storage regardless of thruster wear considerations. On the other hand, the DP system typically has a control bandwidth corresponding to a response time of 15-60 seconds for a typical diesel-electric vessel. This bandwidth is chosen due to the dynamics of thrusters as well as the desire to avoid to act against the first order wave induced motions, which is commonly achieved with wave filtering, [13]. Hence, dynamics slower than about 0.05 rad/sec, or about 0.01 Hz, will be typically counteracted by the DP controller unless special functionality is implemented to allow certain position deviations. Consequently, the DP dynamic energy storage will typically be mostly effective for power variations in the range of 0.01 Hz to 0.2 Hz. Although this is a limited frequency band, it is still very useful since it captures important dynamics such as heave compensation systems, some drilling drive systems, and other large consumers. Dynamic energy storage requests of lower frequency can be effectively handled by load changes on the diesel generators, including start of standby generators, as they typically will be able to follow frequencies of 0.01 Hz.

III. DYNAMIC ENERGY STORAGE CAPACITY ANALYSIS

Consider a vessel with mass m that is under DP control. For simplicity of analysis, we assume the vessel is headed against the weather (i.e. against the resultant steady-state environmental force vector) and consider only the surge axis position x. Assume further that a PID controller is used [13], and wind variations and first order forces due to ocean waves are neglected. It can be simplified as $F_{DP} = -(K_p x + F_I + K_d \dot{x})$ where a slowly time-varying force F_I (due to integral action) is assumed to cancel the slowly time-varying total environmental force F_E such that $F_I + F_E = 0$. Assume further that the DP system allocates a thrust according to F_{DP} except for a component that is requested as dynamic energy storage to compensate for electric power variations outside the DP:

$$F_{alloc} = F_{DP} + K_0 P_{req} \tag{1}$$

where P_{req} is the requested dynamic energy storage (power), and K_0 $[N/W]$ is the thrust/power factor that is assumed to be constant for a given thruster configuration near some operating point. The equation of motion for the ship along the surge axis is

$$m\ddot{x} + D\dot{x} = F_{alloc} + F_E \tag{2}$$

where D is the hydrodynamic damping coefficient. This leads to

$$m\ddot{x} + (D + K_d)\dot{x} + K_p x = K_0 P_{req} \tag{3}$$

Next, consider the allocated (stored) power that is derived directly from (1):

$$\begin{aligned} P_{alloc} &= P_{DP} + P_{req} && (4)\\ &= F_{DP}/K_0 + P_{req} && (5)\\ &= -\frac{1}{K_0}\left(K_p x + F_I + K_d \dot{x}\right) + P_{req} && (6) \end{aligned}$$

Disregarding the stationary power F_I/K_0 needed to compensate for stationary environmental forces F_E, and transforming eqs. (3) and (6) to the Laplace domain gives the following equations:

$$\begin{aligned} \frac{1}{K_0}\left(ms^2 + (K_d + D)s + K_p\right)X(s) &= P_{req}(s) && (7)\\ P_{alloc}(s) + \frac{1}{K_0}(K_p + K_d s)X(s) &= P_{req}(s) && (8) \end{aligned}$$

Combining with (4) leads to the following transfer functions after some straightforward algebra:

$$\begin{aligned} \frac{X}{P_{alloc}}(s) &= \frac{K_0}{ms^2 + Ds} && (9)\\ \frac{P_{alloc}}{P_{req}}(s) &= \frac{ms^2 + Ds}{ms^2 + (K_d + D)s + K_p} && (10) \end{aligned}$$

Simulations in section IV show that for a typical vessel and DP controller, the hydrodynamic damping force corresponds to less than 1-2 % of the power, so we get the following approximate transfer functions:

$$\begin{aligned} \frac{X}{P_{alloc}}(s) &\approx \frac{K_0}{ms^2} && (11)\\ \frac{P_{alloc}}{P_{req}}(s) &\approx \frac{ms^2}{ms^2 + K_d s + K_p} && (12) \end{aligned}$$

Assuming the dynamic energy storage request is sinusoidal $P_{req}(t) = P_a \sin(\omega_1 t)$, we get that for $\omega_1 >> \omega_0 = \sqrt{K_p/m}$

$$\begin{aligned} P_{alloc}(t) &\approx P_{req}(t) && (13)\\ x_a &\approx \frac{K_0}{m\omega_1^2} P_a && (14) \end{aligned}$$

where x_a is the amplitude of the resulting sinusoidal motion $x(t) = x_a \sin(\omega_1 t + \phi)$ of the ship. By also accounting for the hydrodynamic damping, a slightly more accurate approximation can be made

$$x_a \approx \frac{K_0}{\sqrt{m^2\omega_1^4 + D^2\omega_1^2}} P_a \tag{15}$$

Based on these simple formulas, some observations can be made.

- The dynamic energy storage capacity P_{alloc} decreases when the dynamic power load frequency ω_1 decreases, in particular when it becomes smaller than the bandwidth ω_0 of the DP controller. For ω_1 much larger than ω_0 we have $P_{alloc} \approx P_{req}$, i.e. full capacity is available. For ω_1 much smaller than ω_0 we get $P_{alloc}/P_{req} \approx 0$, cf. (12).
- The amplitude x_a of the ship motion required to accommodate the dynamic energy storage decreases rapidly as ω_1 increases, cf. (14). This is a natural physical interpretation since high-frequency motions require relatively higher force and power than low-frequency motions of the same amplitude. Conversely, smaller high-frequency motion amplitudes will be generated using the same power.
- Net power savings are possible only when the environmental force $F_E \neq 0$, and full dynamic energy storage capacity is available only when $|F_E| \geq K_0 P_a$. This may not be seen as a practical limitation since large dynamic energy storage capacity may primarily be needed when there are high waves, which usually result from high winds that also lead to large $|F_E|$.

The calculations can be easily generalized for dynamic power load variations that are not sinusoidal by considering power spectra or Fourier series.

IV. VERIFICATION - CASE STUDY

The simulation example considers a case where a sinusoidal electric power system disturbance, corresponding to a given power amplitude and period, is added to the thrust commanded by the DP controller to implement dynamic energy storage according to (1). The modification to the thrust command is allocate to the surge force only, before the command is sent to the thrust allocation module.

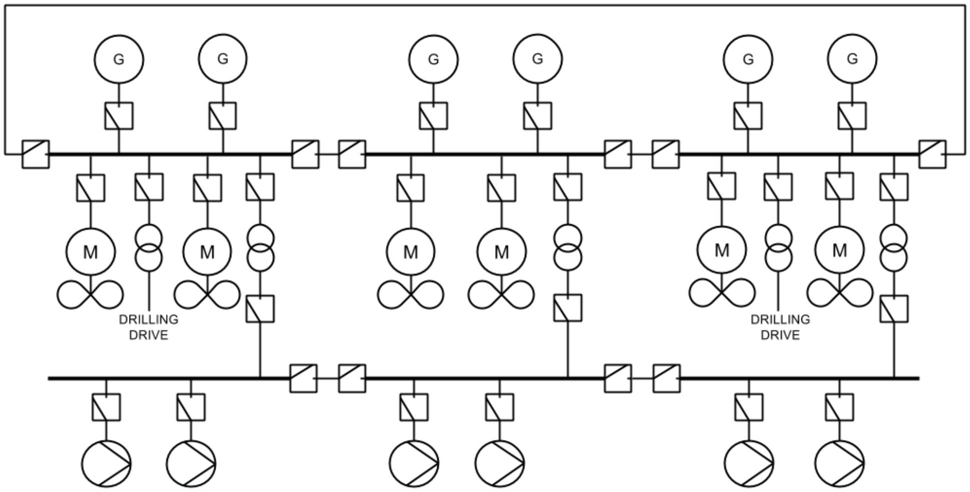

Fig. 2. Power plant of simulated drilling vessel used in case study.

The simulations are conducted using Matlab and the six-degrees-of-freedom Marine Systems Simulator, [4]. The DP vessel considered is a typical drillship, $m = 43,7 \cdot 10^6$ kg, where the main need for dynamic energy storage comes from active heave compensation of the drill-string or riser. The simulations consider a typical situation with a steady-state (constant) environmental force resulting from mean wind and current forces. In order to accurately analyze the dynamic energy storage functionality by itself, we have not included dynamic disturbance forces due to ocean waves and wind variations in the simulations. These forces could be superpositioned on the simulated forces to give additional dynamic variations in position, thrust and power consumption. In addition to the 6-degrees-of-freedom model of vessel motion with hydrodynamic and aerodynamic loads, the simulator contains a PID-based DP controller and a thrust allocation algorithm based on the pseudo-inverse. A simple model of the power plant dynamics is given by the diesel generators momentum balance, [16], inlet air pressure restrictions, [12] and electric system power balances, [1]. Based on this, other variables such as voltages and currents can be computed.The DP system is designed with a bandwidth in surge, sway and yaw of $\omega_0 = 0.033$ rad/s and critical relative damping $\zeta = 1.0$.

The power plant with diesel generators, distribution and consumers is illustrated in Fig. 2, and is characterized as follows

- There are three main 11 kV buses/switchboards with 2 diesel-generators having circuit breakers that allows them to be connected or disconnected. The generators operates with frequency-control by governors in droop mode.
- There is a ring bus and bus-tie breakers that allows the bus segments to be connected in as a single bus, or in 2-split or 3-split modes. In the simulations we operate with closed bus-ties.
- There are six azimuth thrusters arranged in a standard geometric layout, two for each power bus segment.
- There are several additional consumers connected through transformers or 440 V switchboards that are fed by the main switchboards. For simplicity the figure only shows some main other drilling consumers, i.e. active heave draw-works drive, mud pumps and top drive.

$P_{alloc}[MW]$	$P_{req}[MW]$	$\omega_1[rad/s]$	x_a $[m]$ (sim)	x_a $[m]$ (eq. (14))	x_a $[m]$ (eq. (15))
0.65	1.26	0.033	1.04	1.09	1.04
2.06	3.99	0.033	5.20	5.42	5.18
3.60	3.99	0.100	1.02	1.03	1.03
8.82	9.78	0.100	2.05	2.06	2.05
9.63	9.78	0.330	0.19	0.21	0.21
3.94	3.99	0.500	0.03	0.04	0.04
9.58	9.78	1.000	0.04	0.02	0.02

TABLE I
NUMERICAL RESULTS FROM CASE STUDY.

Simulation results are shown in Table I. They consider a number of cases with different power storage request amplitudes and frequencies, corresponding to different drilling loads that may result from compensation for wave-induced ship motions:

- Dominating wave amplitudes commonly correspond to the range 0.33 rad/s - 1.0 rad/s, e.g. [4], [14].
- Power variations with frequencies in the range 0.033 rad/s - 0.1 rad/s correspond to low-frequent wave motions such as swells or more exceptional waves that may occur in some geographical regions.
- Even in rough sea states an active heave drawwork and drilling drives has power consumption variations with amplitudes of less than 5 MW. The scenarios simulated are therefore to be considered as conservative worst cases.

The table reports the simulated and analytic (using (14)) position deviation amplitudes as well as dynamically stored energy. The simulations confirm that several megawatts of power variations can be managed by the power management and DP system by accepting relatively small position deviations on a typical mobile offshore drilling unit. Note that typical position deviation for a DP system in normal conditions is about 1 meter. At $\omega_1 = \omega_0 = 0.033\ rad/s$ the dynamic energy storage only has about 50% effect as the allocated (stored) power is only half of the requested dynamic energy storage, due to interactions resulting from the conflict with the primary position control objectives of the DP controller.

The simulations confirm the accuracy of the simple analytic formula (14) with accuracy typically better than 5 % error. For cases with very small surge amplitudes, the deviation between x_a predicted by the simple model and the advanced simulation model is relatively large in percent (up to 50 %) but negligible in absolute position deviations (a couple of cm). The main reason why higher relative deviations are observed in these cases is the "higher order" dynamic effects of couplings between surge/pitch (longitudinal) and sway/roll (lateral) ship motions included by variations in thruster forces and moments.

The simulations also verify that the dynamic energy storage has the benefit that it makes the variations in electric frequency very small (less than 1 % for all cases) and even less variations in voltage. Moreover, the dynamic energy storage it balances out the difference between consumed and produced power that results due to the dynamics of the diesel generators.

It has been verified by simulations that the formulas (14)-(15) qualitatively are in good agreement also with more advanced implementation of DP dynamic energy storage, [15], [16].

V. DP DECISION SUPPORT AND DYNAMIC CONSEQUENCE ANALYSIS

According to established industry standard system design and operational procedures for dynamically positioned ships, [6], it is up to the operator to enable or disable a sufficient amount of thrusters based on the DP decision support tools such as on-line consequence analysis, capability analysis, and motion prediction, while the PMS ensures that a sufficient amount of generators are running at all times to serve both operational and positioning power needs. Conventionally, a redundant number of on-line generators and thrusters are employed to guarantee safety and operational availability. However, such a redundancy leads to equipment running at low and inefficient loads, and increases both fuel and maintenance costs as well as exhaust gas emissions.

By increasing the information exchange and actively taking advantage of the dynamic energy storage capacity offered by the DP system, a less conservative use of generators and thrusters can be achieved. In particular, the following enhancements can be envisioned within the framework presented in Figure 1, see [10], [2] for further details. An on-line simulation-based dynamic consequence analysis can take into account information about the vessel dynamics, the weather situation (wind, waves and current), load situation, startup time of standby generators and thrusters, etc. to realistically calculate an optimal position reference for the DP system which minimizes the chance of drift-off or drive-off while simultaneously maximizing the available operational time after generator or switchboard failure, i.e., how long it is possible to prioritize the operational drives in favor of the thruster drives before safety is compromised. This knowledge can be used to reduce the amount of on-line generators and thrusters while still achieving operational availability and safety in case of a failure, sending the information back to PMS system for consumer load control.

Such integrated and simulation-based power management functionality can for instance be employed by drilling vessels, which have flexibility in positioning depending on the water depth and the corresponding length of the drill string. For such vessels, the functionality will ensure that safety will not be compromised if equipment fails even if a minimum power and thrust configuration is used, because there will be enough time to remedy the failure situation by enabling/disabling relevant power/thrust equipment. Examples include:

- If a generator fails and results in insufficient power, the power consumption must be reduced to avoid a blackout. In order to continue the drilling operation, the thrust consumption must be reduced instead of the drilling consumption. Hence, the vessel will experience a drift-off. However, using a simulator-calculated position reference, e.g. [2], the vessel is already located such that it can safely be allowed to drift for a certain period of time without having to reduce the drilling power consumption in favor of the positioning. During this time frame, the vessel will be able to start the necessary standby generators in order to restore sufficient power to stop the drift-off and bring the vessel back into position.
- In the worst case, if the vessel moves close to the safety limit during a drift-off, the power to the operational drives (e.g. drilling drives and mud pumps) must be reduced in favor of power to the thruster drives, in order to maintain the safety of the vessel, equipment and crew. Hence, the integrated system will automatically prioritize drilling versus positioning needs depending on the vessel drift pattern, in order to continue the drilling operation as long as safely possible.

VI. CONCLUSIONS

Simple formulas are derived in order to related the dynamic energy storage capacity to the maximum allowed ship position deviation, as a function of the frequency of the requested dynamic energy storage. The formulas are verified using a high-fidelity vessel simulator, and show that for dynamic energy storage requests at wave frequencies (resulting e.g. from an active heave compensation system) that power variations of several megawatt will result in position deviations that are no larger than normal position deviations resulting from the dynamics of ocean waves and winds, as well as inaccuracies in sensors and position reference systems.

The main advantage of this integrated approach is to maintain operational availability and safety while minimizing power consumption, which translates into lower fuel costs and exhaust gas emissions, as well as minimizing wear and tear of generators and thrusters, which translates into lower maintenance costs. Relevant applications include marine operations with positioning flexibility such as drilling.

It could also be mentioned that the method can be directly extended to other energy storage capacities on-board ships in order to allow more low-frequency dynamic energy storage requirements, e.g. thermal storage in cooling, cargo, ventilation, air conditioning and other systems. Such functionality is enabled by integrated automation systems that allows the required software functionality to be implemented.

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