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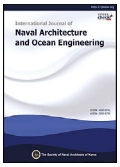

A study on the key performance indicator of the dynamic positioning system

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Abstract

The dynamic positioning system (DPS) maintains an offshore vessel's position and heading under various environmental conditions by using its own thrust. DPS is regarded as one of the most important systems in offshore vessels. So, efficient operation and maintenance of the DPS are important issues. To monitor the DPS, it is necessary to define an appropriate key performance indicator (KPI) that can express the condition of the DPS from the perspective of operational efficiency and maintenance. In this study, a new KPI for the DPS is proposed considering the efficiency of the machinery and controller, the energy efficiency, and the environmental conditions in which the DPS is operated. The KPI is defined as a function of control deviation, energy consumption, and environmental load. A normalization factor is used to normalize the effect of environmental load on the KPI. The KPI value is calculated from DPS simulation and model test data. The possibility of applying the KPI to monitoring of DPS condition is discussed by comparing the values. The result indicates the feasibility of the new KPI.

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Keywords: Dynamic positioning system; Key performance indicator; Condition monitoring

1. Introduction

Over the past few decades, Condition Monitoring (CM) and Condition-Based Maintenance (CBM) have been widely adopted in a variety of industries. CM involves the detection and collection of information and data that indicate the state of a machine (ISO 13372, 2004). CBM is a type of preventive maintenance based on the data collected from CM. It is conducted by forecasting the state of a machine based on analysis and evaluation of parameters related to the condition of the item to be maintained (Bengtsson, 2004). CM and CBM technologies have been shown to reduce the cost of maintenance, increase reliability, and improve operational safety (Rao, 1996). These technologies are gradually being applied to several types of equipment in ships and offshore structures. Li et al. (2012) developed a condition monitoring and fault diagnostic system for marine diesel engines using information fusion technology. Eriksen (2010) proposed condition indicators, Technical Condition Indexes (TCIs), for condition monitoring of ship engine auxiliary systems. Paik et al. (2010) developed a real-time monitoring system for a full-scale ship based on a wireless sensor network and data transmitted over power lines.

The Dynamic Positioning System (DPS) maintains the position and heading of an offshore vessel by controlling thrusters, propellers, and rudders. The DPS is one of the most important systems in offshore vessels. Because the DPS consumes more energy than other equipment, it is important to operate the DPS as economically as possible. In addition, as offshore vessels are increasingly being used in deep waters and harsh environments, it is necessary to ensure proper maintenance of the DPS. Therefore, CM and CBM technologies must be applied to the DPS.

Typically, a DPS is composed of three parts, as shown in Fig. 1: the generation, propulsion, and control elements. A diesel generator is the main component of the generation element. When power is generated, it is delivered to the propulsion elements via the switchboard. The propulsion element

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contains several electric motors, shafts, propellers, and thrusters. Thrust is produced by the power delivered from the generation element and by the control signal input from the control element. The control element generates control signals according to the required thrust. The control signals consist of rotational speed, azimuth angle, etc. The thrust required for the vessel is calculated in the control element considering the vessel's current position and heading, environmental conditions, and other user-inputted parameters.

As a DPS is a combination of the aforementioned components, a proper Key Performance Indicator (KPI) of the overall condition is necessary for monitoring of the DPS. The KPI can be used not only for condition monitoring but also for maintenance purposes. For instance, it can be assumed that the KPI signal will gradually decrease when monitoring the status of the DPS for a long period of time, as shown in Fig. 2. This results from various factors, such as degradation of the machinery and non-optimized tuning of the controllers. When the value drops below a certain level, it generally indicates that the condition of the DPS is worse than expected; it may indicate that maintenance actions need to be taken, such as checking the condition of the equipment and controllers. Therefore, the KPI provides a basis for determining the condition of the DPS and taking any necessary maintenance-related actions.

When monitoring the condition of the DPS, generation efficiency, propulsion efficiency, position and heading deviation, and energy efficiency could be considered as indicators. However, generation efficiency reflects mainly the efficiency of the machinery, specifically that of the generator system, rather than the efficiency of the DPS. Propulsion efficiency is subject to measurement error in that it is difficult to measure the exact thrust from a number of propellers; therefore, it is not a practical indicator.

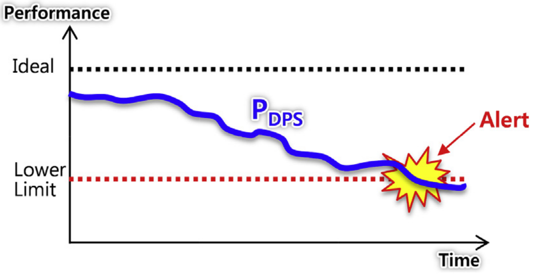


Fig. 2. Example of DPS KPI monitoring.

Other indicators have been used to reflect the condition of the DPS. Kongsberg Maritime described the effectiveness of the DPS controller *Green DP*, which is based on the energy consumption of the system (Hvamb, 2001), and ABB adopted a new control system, *Weather Optimal Positioning Control*, and verified its effectiveness by comparing control deviation (the position and heading deviation of the vessel) and energy consumption (Fossen and Strand, 2001). However, even in those cases, there is no direct relationship between position and heading deviation and energy efficiency. Furthermore, the influence of environmental conditions on the system was not included in those indicators.

To reflect the overall condition of the DPS properly, position and heading deviation and energy efficiency should be taken into account together, along with the influence of environmental conditions. Therefore, in this study, a new DPS KPI is suggested, which takes into account the condition of the relevant machinery and controller, energy efficiency, and environmental conditions.

To verify the feasibility of the DPS KPI presented in this paper, DPS simulation and model test data are used to

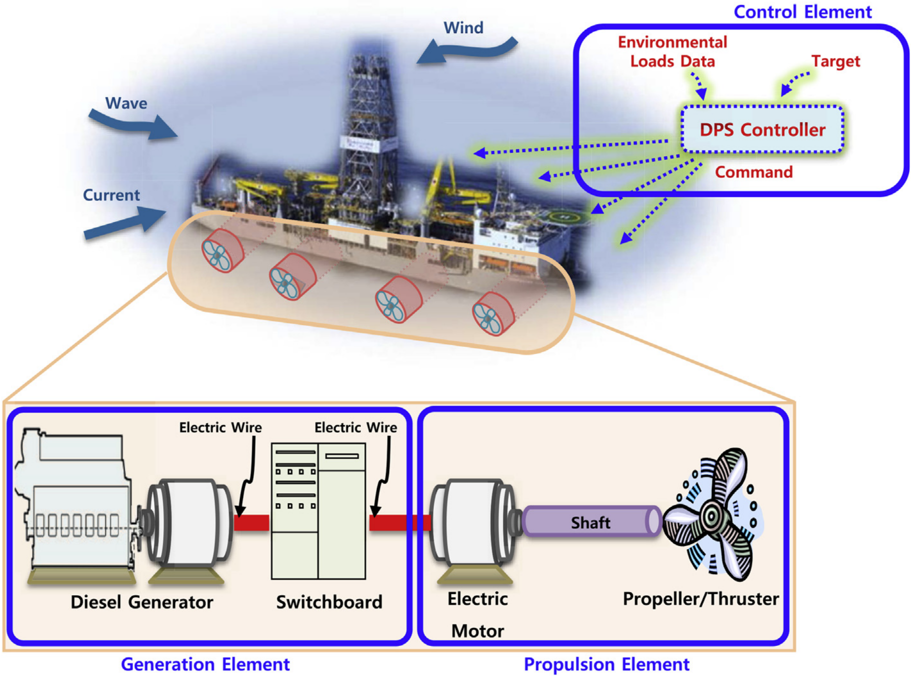


Fig. 1. Configuration of a DPS.

calculate the KPI values. It would be better to apply condition monitoring using our DPS KPI to real vessels. However, owing to practical limitations, this paper treats DPS simulation data as data obtained in an ideal state and model test data as though it were from a real vessel.

2. Definition of DPS KPI

2.1. DPS KPI (P_{DPS})

The condition of a DPS is considered good when the DPS consumes as little energy as possible. Large position and heading deviations imply that the condition is worse than expected. Here, deviation refers to the difference between the desired and current values, and is referred to as *control deviation*. The desired value is a fixed target position that the vessel is attempting to maintain. Consequently, the DPS KPI should be inversely proportional to the rate of energy consumption and to the extent of control deviation. The greater the energy consumed, the smaller the control deviation naturally becomes if the controller is properly designed and tuned. So, control deviation and energy consumption are inherently related to one another. For this reason, the term *performance index* is used to consider both simultaneously. The performance index, J, is a combination of the energy consumption and the control deviation. It will be minimized if the controller is well-tuned and optimized.

Accordingly, the DPS KPI, P_{DPS}, is inversely proportional to the performance index, J, as shown in Eq. (1).

$$P_{DPS} \propto \frac{1}{J} \tag{1}$$

Because the function of the DPS is to maintain the vessel's position and heading under specified environmental conditions, the performance index is significant only when environmental conditions are defined. For instance, if a DPS experiencing environmental conditions harsher than those of another, shows the same control deviation and similar energy consumption, then the former can be regarded as more efficient than the latter. Consequently, there is a need to consider the effect of environmental conditions on the KPI. In this study, the DPS KPI is defined as being proportional to the environmental load, F.

The relation between P_{DPS}, J, and F is given as:

$$P_{DPS} \propto \frac{F}{J} \tag{2}$$

The environmental load, F, and the performance index, J, can vary with any change in the ship's heading or in the direction of the environmental load even under identical environmental conditions. For instance, when a ship is exposed to wind at a constant speed, the wind load on the ship may change according to the incidence angle of the wind, and the energy consumption and control deviation will also change. Wind, especially, tends to change more than waves and currents. For this reason, the DPS operator controls the ship's heading angle to minimize the environmental load acting on the ship, which is called *weather vaning*.

The ship's motion may be different even under the influence of the same environmental load. Let us consider an ideal object with a shape that is symmetrical in all directions. The amount of load on such an object will always be equal regardless of changes in the direction of the load. Hence, the environmental load, F, remains constant. The amount of control deviation owing to the load and the energy necessary to control the ship's motion would also be the same. So, the performance index, J, would remain constant as well. For an actual ship, the amount of load does not change even if its direction changes. Thus, the environmental load, F, is constant. However, because a ship is generally streamlined, any change in the direction of the environmental load changes the motion of the ship. The energy required to control the ship's motion changes, which results in a change in the performance index, J. A ship's characteristics are dependent on its hull form, propulsion efficiency, and so on.

Therefore, a normalization factor, C_{Env}, is introduced to eliminate the influence of changes in the direction of the environmental load on the DPS KPI. The normalization factor is a function of environmental load. As mentioned above, it is unique to each vessel.

By including the normalization factor, C_{Env}, the relation between P_{DPS}, J, F, and C_{Env} becomes

$$P_{DPS} \propto C_{Env} \frac{F}{J} \tag{3}$$

In summary, the DPS KPI shown in Eq. (4) is proposed.

$$P_{DPS} = C_{Env} \cdot \frac{F}{J(\mathbf{x}, \mathbf{u})} \tag{4}$$

where $\mathbf{x}$ is the control deviation and $\mathbf{u}$ is energy consumption in a broad sense, which can be substituted for the fuel consumption of the generation element or for the electrical energy consumption of the propulsion element.

2.2. Performance index term (J)

The control deviation and the energy consumption are related, and so must be considered together. The relative importance of control deviation and energy consumption depends on the operational context. For instance, a ship's owner wants to take the energy efficiency into account rather than the control deviation, while the operator wants to consider the control deviation rather than the energy consumption. Therefore, this paper adopts a performance index that can adjust the weights of the two influences while taking both values into account. The Linear Quadratic Regulator (LQR) is a control approach that defines the performance index using both the control deviation and the controller input. The controller is optimized by minimizing the performance index (Anderson and Moore, 1989). The importance of each factor is determined by multiplying the weight factors.

The performance index term is given by

$$J(\mathbf{x},\mathbf{u}) = \int_{0}^{\infty} (\mathbf{x}^T\mathbf{Q}\mathbf{x} + \mathbf{u}^T\mathbf{R}\mathbf{u})dt \tag{5}$$

where **Q** and **R** are the weight factors for each term.

To apply this concept to a real system, we substitute the vessel's control deviation for **x**, the energy consumption of the DPS for **u**, and the boundary of integration for a certain time range, as shown in Eq. (6). The control deviation is defined as the difference between the current position and the average position during the time period under consideration, as shown in Eq. (7). The energy consumption can be calculated from Eq. (8) using the maximum output and utilization of the thruster.

The modified performance index becomes

$$J(\mathbf{x},\mathbf{u}) = \int_{t_{N-(D+1)}}^{t_N} (\mathbf{x}^T\mathbf{Q}\mathbf{x} + \mathbf{u}^T\mathbf{R}\mathbf{u})dt \tag{6}$$

in which

$$\begin{aligned}\mathbf{x} &= \mathbf{x}(t_i)\\ &= \left[x(t_i) \quad y(t_i) \quad \psi(t_i)\right]^T - \left[x_{Avg}(t_i) \quad y_{Avg}(t_i) \quad \psi_{Avg}(t_i)\right]^T\\ &= \left[x_{dev}(t_i) \quad y_{dev}(t_i) \quad \psi_{dev}(t_i)\right]^T\end{aligned} \tag{7}$$

$$\begin{aligned}\mathbf{u} &= [u(t_i)]\\ &= \left[\sum_{n=1}^{6} U(t_i)_n^{\frac{3}{2}} \cdot P_{Max \cdot n}\right]\end{aligned} \tag{8}$$

where t_N is the current time; $t_{N-(D+1)}$ is the time before the Dth step from the current time; $x(t_i)$, $y(t_i)$, and $\psi(t_i)$ are the surge, sway, and yaw, respectively, at time t_i, as depicted in Fig. 3; $x_{Avg}(t_i)$, $y_{Avg}(t_i)$, and $\psi_{Avg}(t_i)$ are the average position and heading during the period between $t_{i-(D+1)}$ and t_i; $U(t_i)_n$ is the utilization of the nth thruster; and $P_{Max,n}$ is the maximum output of the nth thruster.

Since a ship is affected by ocean waves, its motion contains an oscillatory motion term due to the first-order wave-induced disturbance. In reality, the oscillatory motion due to waves is negated by a wave filter, and the DPS counteracts only disturbances that vary slowly. In the same manner, since the motion is not related to the condition of the DPS, it must be removed using appropriate wave-filtering techniques. Therefore, this paper adopts a moving average filter as a wave filter to remove the oscillatory motion term before calculating the control deviation.

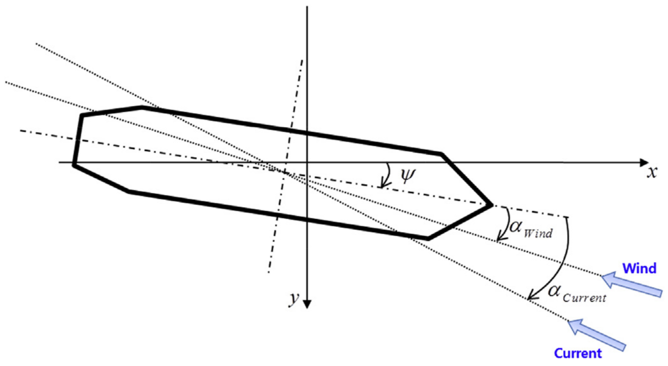


Fig. 3. Definition of a coordinate system and incidence angles.

2.3. Environmental load term (*F*)

The environmental load term is defined as

$$F = \mathbf{f}_{Avg}^T \mathbf{W} \mathbf{f}_{Avg} \tag{9}$$

where $\mathbf{f}_{AVG}$ is the average value of the environmental load caused by the environmental conditions, and **W** is the weight factor of $\mathbf{f}_{AVG}$.

If the instant or maximum value of the environmental load is considered in the DPS KPI, it will not represent the condition of the DPS accurately because this peak could result from abnormal conditions, such as sudden gusts. Accordingly, the average value of the environmental load must be considered instead, as shown in Eq. (10).

$$\mathbf{f}_{Avg} = \frac{\sum_{i=N-(D+1)}^{N} \mathbf{f}(t_i)}{D} \tag{10}$$

where $\mathbf{f}(t_i)$ is the summation of the environmental load acting on the vessel, which is calculated by Eq. (11).

$$\begin{aligned}\mathbf{f}(t_i) = {} & \mathbf{f}_{Wind}(\alpha_{Wind}, V_{Wind}) + \mathbf{f}_{Cur}(\alpha_{Cur}, V_{Cur})\\ & + \mathbf{f}_{Wave}(\alpha_{Wave}, H_S, T_P)\end{aligned} \tag{11}$$

where $\mathbf{f}_{Wind}$, $\mathbf{f}_{Cur}$, and $\mathbf{f}_{Wave}$ indicate the loads due to wind, currents, and waves, respectively; α_{Wind}, α_{Cur}, and α_{Wave} are the incidence angles of the wind, currents, and waves; V_{Wind} and V_{Cur} are the speeds of the vessel relative to the wind and currents; H_S is the significant wave height; and T_P is the peak period. As mentioned above, $\mathbf{f}_{Wave}$ includes only the drift force so that it includes only disturbances that vary slowly.

$\mathbf{f}_{Wind}$, $\mathbf{f}_{Cur}$, and $\mathbf{f}_{Wave}$ are given as

$$\begin{aligned}\mathbf{f}_{Wind}(\alpha_{Wind}, V_{Wind}) &= \left(F_{Wind \cdot x}, F_{Wind \cdot y}, M_{Wind \cdot \psi}\right)\\ F_{Wind,x} &= \frac{1}{2} \cdot \rho_{air} \cdot V_{Wind}^2 \cdot S_{Wind \cdot x} \cdot C_{Wind \cdot x}(\alpha_{Wind})\\ F_{Wind,y} &= \frac{1}{2} \cdot \rho_{air} \cdot V_{Wind}^2 \cdot S_{Wind \cdot y} \cdot C_{Wind \cdot y}(\alpha_{Wind})\\ M_{Wind,\psi} &= \frac{1}{2} \cdot \rho_{air} \cdot V_{Wind}^2 \cdot S_{Wind \cdot y} \cdot L_{OA} \cdot C_{Wind \cdot \psi}(\alpha_{Wind})\end{aligned} \tag{12}$$

$$\begin{aligned}\mathbf{f}_{Cur}(\alpha_{Cur}, V_{Cur}) &= \left(F_{Cur \cdot x}, F_{Cur \cdot y}, M_{Cur \cdot \psi}\right)\\ F_{Cur \cdot x} &= \frac{1}{2} \cdot \rho_{water} \cdot V_{Current}^2 \cdot S_{Cur \cdot x} \cdot C_{Cur \cdot x}(\alpha_{Cur})\\ F_{Cur \cdot y} &= \frac{1}{2} \cdot \rho_{water} \cdot V_{Current}^2 \cdot S_{Cur \cdot y} \cdot C_{Cur \cdot y}(\alpha_{Cur})\\ M_{Cur \cdot \psi} &= \frac{1}{2} \cdot \rho_{water} \cdot V_{Current}^2 \cdot S_{Cur \cdot y} \cdot L_{OA} \cdot C_{Cur \cdot \psi}(\alpha_{Cur})\end{aligned} \tag{13}$$

$$\begin{aligned}&\mathbf{f}_{Wave}(\alpha_{Wave}, H_S, T_P) = \mathbf{F}_{Drift}\\ &\mathbf{F}_{Drift} = 2\int_0^{\infty} S(\omega)H_i(\omega, \alpha_{Wave})d\omega\end{aligned} \tag{14}$$

where $F_{Wind,x}$, $F_{Wind,y}$, and $M_{Wind,\psi}$ are the wind force and moment components; $F_{Cur,x}$, $F_{Cur,y}$, and $M_{Cur,\psi}$ are the current force and moment components; ρ_{air} and ρ_{water} are the density of air and sea water, respectively; $S_{Wind,x}$ and $S_{Wind,y}$ are the horizontal and vertical projected areas of the floating body above the waterplane; $S_{Cur,x}$ and $S_{Cur,y}$ are the horizontal and vertical projected areas of the floating body below the waterplane; $C_{Wind,x}$, $C_{Wind,y}$, and $C_{Wind,\psi}$ are the non-dimensional coefficients of the wind force; $C_{Cur,x}$, $C_{Cur,y}$, and $C_{Cur,\psi}$ are the non-dimensional coefficients of the current force; F_{Drift} is the mean wave drift force; $S(\omega)$ is the wave spectrum; H_i is the ith component of the quadratic transfer function; and L_{OA} is the overall length of the vessel.

2.4. Normalization factor term (C_{Env})

As the DPS KPI is an index value that should not be affected by changes in the direction of environmental load, a normalization factor, C_{Env}, is introduced as described in Eq. (4). The normalization factor under various environmental conditions can be calculated as shown in Eq. (15).

$$C_{Env} = \frac{J(\mathbf{x},\mathbf{u})}{F}\cdot P_{DPS\cdot Ideal} \tag{15}$$

When C_{Env} is calculated for a given condition, the ideal DPS KPI, $P_{DPS.Ideal}$, is assumed to be unity. This means that the normalization factor makes the DPS KPI unity when the performance index is ideal under the given environmental conditions.

2.5. Weight factor (*Q*, *R*, *W*)

As the units of each component in the definition of the DPS KPI are different, it is difficult to properly evaluate the influence of each component. It is desirable to take into account the importance of the different components according to the problem. Therefore, the weight factors employed in Eqs. (6) and (9) are

$$\begin{aligned}&\mathbf{Q} = \begin{bmatrix} Q_1 & 0 & 0\\ 0 & Q_2 & 0\\ 0 & 0 & Q_3\end{bmatrix}\\ &Q_1 = \frac{1}{x^2_{dev\cdot\max}}\cdot q_1,\quad Q_2 = \frac{1}{y^2_{dev\cdot\max}}\cdot q_2,\quad Q_3 = \frac{1}{\psi^2_{dev\cdot\max}}\cdot q_3\end{aligned} \tag{16}$$

$$\begin{aligned}&\mathbf{R} = [R]\\ &R = \frac{1}{u^2_{\max}}\cdot r\\ &q_1 + q_2 + q_3 + r = 1\end{aligned} \tag{17}$$

$$\begin{aligned}&\mathbf{W} = \begin{bmatrix} W_1 & 0 & 0\\ 0 & W_2 & 0\\ 0 & 0 & W_3\end{bmatrix}\\ &W_1 = \frac{1}{F^2_{X\cdot Avg\cdot\max}}\cdot w_1,\ W_2 = \frac{1}{F^2_{Y\cdot Avg\cdot\max}}\cdot w_2,\ W_3 = \frac{1}{M^2_{Z\cdot Avg\cdot\max}}\cdot w_3\\ &w_1 + w_2 + w_3 = 1\end{aligned} \tag{18}$$

where Q_1, Q_2, and Q_3 are the weight factors for control deviation; $x_{dev.\max}$, $y_{dev.\max}$, and $\psi_{dev.\max}$- are the maximum allowable control deviations for the DPS; R is the weight factor for energy consumption; $u_{\max}$ is the maximum energy consumption; W_1, W_2, and W_3 are the weight factors for the environmental load terms; $F_{X.Avg.\max}$, $F_{Y.Avg.\max}$, and $M_{z.Avg.\max}$ are the maximum allowable force and moment values; q_1, q_2, q_3, and r are the pure weight factors for the performance index term; and w_1, w_2, and w_3 are the pure weight factors for the environmental load terms. Since each set of weight factors (e.g., q_1, q_2, q_3, r) is summed, the relative quantities, rather than the absolute quantities, have an effect on the DPS KPI. Consequently, the set of pure weight factors is defined as having a sum equal to unity to assess the influence of each term. For example, if the influences of the forces and moment terms are identical, w_1, w_2, and w_3 are each set to one-third.

3. Verification of the DPS KPI

3.1. Selection of a target for verification

The feasibility of the KPI is verified by calculating the values for a DPS. An ideal condition is assumed, in which the KPI has a maximum value of unity. The set of normalization factors is obtained under the assumption of an ideal condition. The KPI is then calculated for an operational condition using that set of normalization factors. In general, a system can be regarded as ideal when it is initially installed or when the system is modeled in a simulation. This study regarded the data from a DPS simulation as the ideal condition from which the normalization factor was calculated. A model test result was adopted as the operational data owing to practical limitations on the collection of data from a real vessel.

The principal components of the DPS that were used for verification are shown in Table 1.

3.2. Test cases for verification

The environmental conditions used for verification are shown in Table 2.

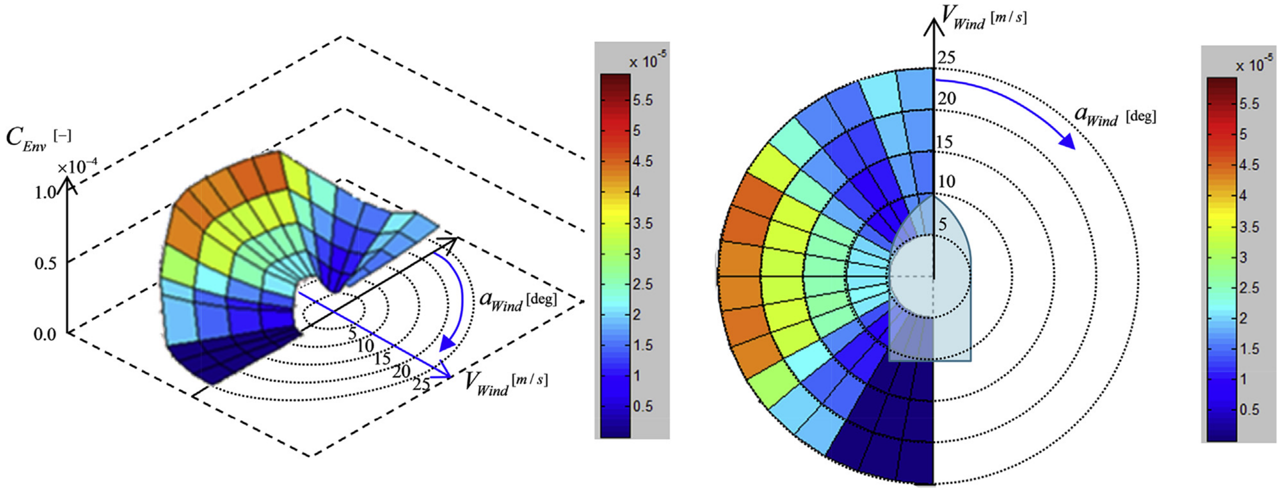
When the model tests were conducted under these conditions, the measured result fluctuated slightly over time. Therefore, wind and current speeds were measured and provided in the time domain in the model test, but wave data were not. An electromagnetic-type wind velocity meter and a Nobska-type current velocity meter were fitted on the model to

Table 1
Principal components of the DPS.

Item		Value
No. of thrusters		6
Max. power of thrusters	T1-T4	6000 kW
	T5, T6	8000 kW
Type of controller		PID controller

Table 2
Environmental conditions of the test cases.

Item	Test case 1	Test case 2
Heading set point	5°	0°
Incident angle of wind, wave, and current	180°	180°
Significant wave height	6.0 m	4.6 m
Peak period	10.0 s	9.3 s
Current speed	0.8 m/s	1.15 m/s
Wind velocity	25.0 m/s	25.7 m/s



(a) (b)

Fig. 4. Normalization factor (a) with respect to wind velocity and incidence angle (3D); and (b) with respect to wind velocity and incidence angle (2D).

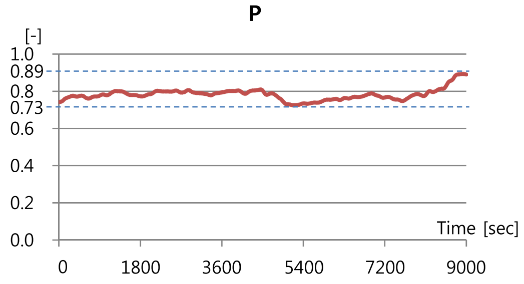


Fig. 5. Result of test case 1: DPS KPI.

measure the environmental conditions. As the data were obtained using sensors, a moving-average filter was adopted to smooth out the fluctuations in the signals (Oppenheim and Ronald, 1998). As mentioned above, a moving-average filter was also used as a wave filter for the surge, sway, and yaw signals to filter out the oscillatory motion before calculating the control deviation. The window length of the moving average filters was set to 120 s. In this study, several assumptions were made to simplify the environmental conditions, taking into consideration the limitations of the available data. The wave parameter was assumed to be constant. The incidence angles of the waves, wind, and currents were assumed to be identical to α.

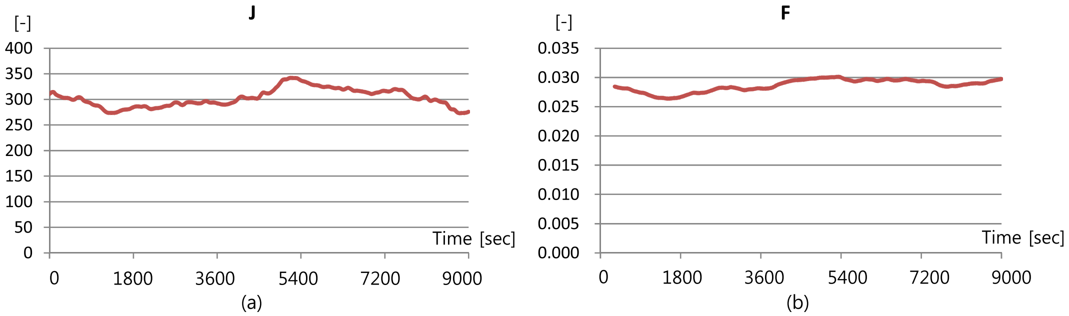
$$\alpha_{Wave}, H_S, T_P = Constant \tag{19}$$

$$\alpha_{Wave} = \alpha_{Wind} = \alpha_{Cur} = \alpha \tag{20}$$

In the first step, the normalization factor for each test case was calculated. As the environmental conditions were simplified, the normalization factor became a function of the incidence angle, α. The DPS simulation was performed under environmental conditions identical to those used in the model test. The time domain data for the normalization factor were obtained from simulation of the various parameters of incidence angle, wind speed, and current speed. As the parameters were nearly constant, the average value of the total simulation time was chosen as the representative normalization factor for the given environmental conditions. The normalization factors with respect to the speed and incidence angle of the wind at a specific current speed can be depicted as a three-dimensional graph, as in Fig. 4(a), or a two-dimensional graph, as in Fig. 4(b).

The DPS KPI values obtained from cases 1 and 2 are shown in Figs. 5 and 7, respectively, and the performance index and environmental loads are depicted in Figs. 6 and 8. The KPI values from the model tests are smaller than the ideal value (1.0). Based on these results, the DPS KPI presented in this study seems feasible.

There was a small difference between the maximum and minimum KPI values; the difference was ~0.16 in case 1 and



(a) (b)

Fig. 6. Results of test case 1: (a) performance index, and (b) environmental load.

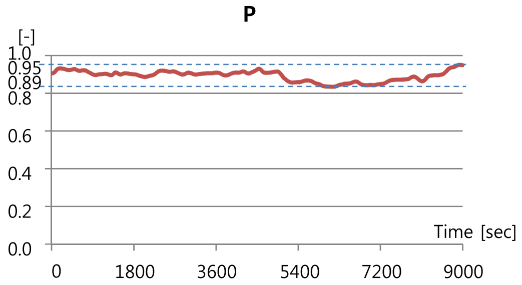
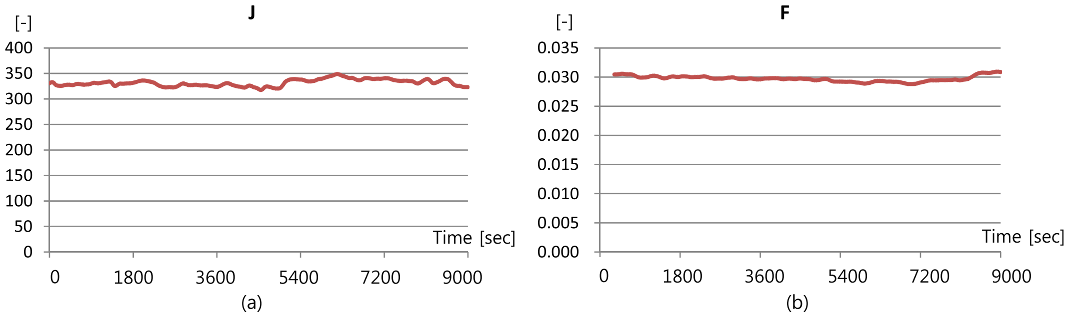


Fig. 7. Result of test case 2: DPS KPI.



(a) (b)

Fig. 8. Results of test case 2: (a) performance index, and (b) environmental load.

0.06 in case 2. This was caused by the unsteady performance index and the environmental load terms. Moreover, verification was conducted only for a short time period because of the lack of long-term data. The results could be improved by properly assigning the range of the integration for the performance index and the environmental load terms. Long-term trends will be investigated in future when our system is used to monitor the condition of a real DPS, as shown in Fig. 2.

4. Conclusion

In this study, a new KPI for a DPS was proposed that considered the efficiency of the machinery and controller, the energy efficiency, and the environmental conditions. The DPS KPI was defined as a function of control deviation, energy consumption, and environmental load. A normalization factor was added to eliminate the influence of changes in the direction of the environmental load on the DPS KPI. DPS simulation and model test data were used for DPS KPI verification. A comparison of the KPI value obtained from the simulated data and that obtained from the model test data showed that the DPS KPI proposed in this paper has value as an indicator of DPS condition.

In future work, the normalization factor will be fine-tuned using additional environmental conditions, and the DPS KPI will be verified using real long-term operational data. The DPS KPI proposed in this paper will likely be used in future as an indicator of DPS condition and to facilitate condition-based maintenance.

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