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UTILIZATION OF FMEA DURING THE PRELIMINARY DESIGN OF A DYNAMIC POSITIONING SYSTEM FOR A SHUTTLE TANKER

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ABSTRACT

The Dynamic Positioning mode operation of vessels, especially those related to the offshore oil industry, requires rigorous reliability analysis in order to eliminate the dangerous consequence of loosing position or to create a procedure when the consequence can not be eliminated. In general, the reliability analysis of the Dynamic Positioning System (DPS) is performed through Failure Mode and Effect Analysis (FMEA). In this paper the FMEA procedure is proposed taking into account the failure data reported in IMCA DP Incidents Reports. The idea of this procedure is to analyze and improve the system configuration during preliminary design in terms of the reliability considering critical failures. To complete the analysis, the consequence is evaluated through dynamical simulations for offloading operation in tandem configuration. The simulations results indicate the need to improve the DPS configuration and three modifications are proposed to compensate and create redundancy to avoid occasional failures of the propellers are proposed.

INTRODUCTION

The offshore oil industry operations require rigorous reliability analysis which in turn implications on ship design and its operations. An example of an operation that can result in unwanted results, used in the present paper, is the offloading operation with shuttle tanker.

The reliability of a system can be analyzed by qualitative and/or quantitative methods such as Failure Mode and Effect Analysis, Block Diagram and Fault Tree [15]. Those methods are complementary since one method alone cannot cover all aspects of the reliability analysis.

The reliability analysis of the DP vessel must consider the probability of failure of all DP subsystems such as power generation, power distribution, thrusters and propulsion, DP sensor, human factors and controller [19]. The FMEA method is required by classification societies and regulatory agency like ABS [1], DNV [5], Lloyd´s [14] and IMO [10]. FMEA comprises a standard worksheet to identify and eliminate failure modes during the design stage or to define procedures to prevent critical consequences of failures that may occur during operation.

In order to study the consequences of failures some approaches have been proposed. For instance, statistical and probabilistic analyses have been suggested [4; 11; 12; 19], as well as block diagram analysis to assess the DP reliability [6] and monitoring of the subsystem status during the operation [13]. All these proposals are very interesting and useful to design and operate the DP vessel but they are not fully adequate for the preliminary design stage in terms of reliability.

In the present paper the utilization of the FMEA approach combined with the evaluation of the consequences of failures using dynamic simulations is proposed. The data used in the FMEA analysis was obtained from DP Incidents [9].

Such a methodology can be used in the preliminary stage of a DP system design, enabling the engineers to identify critical failures and to propose alternatives of system configuration to avoid failures. A complete example of the application of such a methodology is presented in the paper.

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DP-INCIDENT–BASED FMEA

In a preliminary design of a DP System the most critical failures should be known. FMEA is very useful to structure information about the system and meet the failure modes and their consequences. In order to help the use of the FMEA, The International Marine Contractors Association (IMCA) proposes the specific guidelines for DPS [7,8]. Those guidelines emphasize particularities of the DP system and also some precautions to develop the FMEA worksheet.

To meet the most common failures the use of DP Incidents Reports [9] is proposed. A fault tree for each failure reported in the reference [9] that caused loss of the position is constructed. An example is shown in Figure 1, which corresponds to a position loss due to a failure in the main propeller control.

In the present work, a total of 67 incidents from [9] were analyzed in detail and converted to a typical FMEA worksheet, qualifying their failures in some modes which can be seen in [2; 8; 17; 18; 22]. A partial result from the FMEA worksheet is presented in Table 2, including the failure of Figure 1 at the end of the table.

Table 1: Results of FMEA Database Incidents.

Subsystem	Failure mode	Reports
Sensors	Measurement Error	16 (24%)
Thrusters	Overloading, Incorrect or Low Thrust	14 (21%)
Operator Errors	-	13 (19%)
Generators	Failure on Generator, Blackout, Overloading, Overspeed or Reverse power	13 (19%)
Controllers	Computer Freezing, Wrong read I/O or No Signal	7 (10%)
Electrical Faults	No Transmission	2 (3%)
Environment	Trigger Fault	2 (3%)
	Total	67

The results of the FMEA worksheet are quantified in Table 1, where every failure mode is grouped by subsystem. After the FMEA and the identification of the most common DP failures modes (Table 1), dynamical simulations are used to evaluate the consequence of each failure in a real operation scenario of a DP vessel. In the next section, such a procedure is applied to a shuttle vessel operation in Brazilian waters.

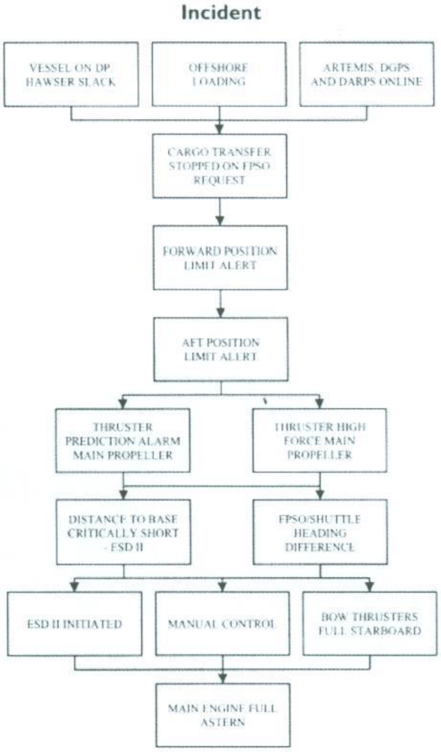

Figure 1: Example of DP incident extracted from [9].

Table 2: Part of FMEA Database Incidents.

Subsytem	Cause of failure			Failure mode	Effect of failure	Severity
-	Operator Error			-	Loss of position	High
Controller	Computer	-	Hardware	No Thrust	Loss of position	High
Generator	Power Generation	-	Generator	Overspeed / Reverse Power / Blackout	Drift off	High
Sensor	References	-	DGPS	Measurement Error	Loss of position	High
Thrusters	Thruster	-	Rudder	Incorrect or Low Thrust	Loss of position	High
Thrusters	DP Computer	-	Software	Incorrect or Low Thrust	Loss of position	High
Thrusters	Thruster	-	Cooling	Incorrect or Low Thrust	Misalignment ahead	Low

SIMULATIONS – AN EXAMPLE OF CONSEQUENCE ANALYSIS

A numerical simulator (Numerical Offshore Tank – TPN) [21] was used to evaluate the consequence of DP failures during a typical offloading operation in Campos Basin (Brazil). The dynamical model is based from equations (1) and the position and heading of the vessel related to the earth-fixed co-ordinate system are obtained from equation (2).

In equation (1), I_z is the moment of inertia about the vertical axis; M is the mass of the vessel, C_{ij} are damping coefficients, M_{ij} are added mass terms, F_{1E}, F_{2E}, F_{6E} are surge, sway and yaw environmental loads (current, wind and waves), F_{1T}, F_{2T}, F_{6T} are forces and moment delivered by the propulsion system and F_{1M}, F_{2M}, F_{6M} are forces and moment due to risers, mooring lines and hawser, if any. The variables $\dot{x}_1$ and $\dot{x}_2$ are surge and sway low-frequency velocities and $\dot{x}_6$ is the yaw rate.

$$
\begin{aligned}
&(M+M_{11})\ddot{x}_1-(M+M_{22})\dot{x}_2\dot{x}_6-M_{26}\dot{x}_6^{\,2}+C_{11}\dot{x}_1=F_{1E}+F_{1T}+F_{1M};\\
&(M+M_{22})\ddot{x}_2+M_{26}\ddot{x}_6+(M+M_{11})\dot{x}_1\dot{x}_6+C_{22}\dot{x}_2=F_{2E}+F_{2T}+F_{2M};\\
&(I_Z+M_{66})\ddot{x}_6+M_{26}\ddot{x}_2+M_{26}\dot{x}_1\dot{x}_6+C_{66}\dot{x}_6=F_{6E}+F_{6T}+F_{6M}.
\end{aligned}
\tag{1}
$$

$$
\begin{pmatrix}\dot{X}_L\\ \dot{Y}_L\\ \dot{\psi}_L\end{pmatrix}=T(\psi)\begin{pmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_6\end{pmatrix},\ with\ \ T(\psi_L)=\begin{pmatrix}\cos(\psi_L) & -\sin(\psi_L) & 0\\ \sin(\psi_L) & \cos(\psi_L) & 0\\ 0 & 0 & 1\end{pmatrix}
\tag{2}
$$

Current induced forces are determined via a heuristic model based on a low aspect ratio wing theory with experimental validation [2]. Wind forces are calculated employing coefficients suggested by [16] and wind gusts are also considered. Wave drift forces are evaluated using the hull drift-coefficients worked out by means of a standard second-order potential flow analysis performed by a computer software (Wamit). The interaction between current and waves (wave-drift damping) is also taken into account [20].

In order to address the performance of commercial DPS, a conventional control algorithm was implemented in the simulator, namely a 3-axis uncoupled PD controller, coupled to a feedforward wind compensator. Furthermore, an Extended Kalman Filter (EKF) was used as the wave filter. Such a filter also predicts the non-measured environmental forces, which can be used by the controller. The EKF estimator is widely used in commercial systems. Finally, a thrust allocation algorithm, based on a pseudo-inverse matrix technique, was implemented with extra features that are normally employed in real DPS. Figure 2 shows a diagram block of the EKF, controller and thrust allocation. The FPSO is moored by a Spread Mooring System, and the offloading is carried out by the bow part of the FPSO, as shown in Figure 3. The FPSO is a VLCC, and the Shuttle Tanker (ST) is a Suezmax class vessel. Main properties of both vessels are presented in Table 3.

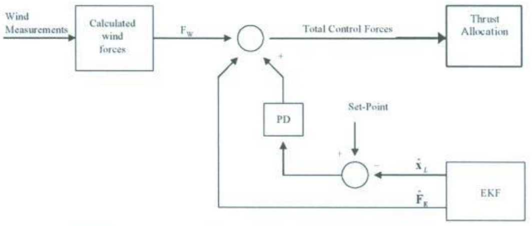

Figure 2: EKF , controller diagram block and thrust allocation.

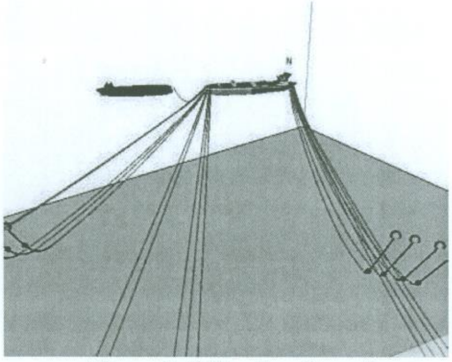

Figure 3: Offloading Operation.

Table 3: Vessels main properties.

Parameters	Ballasted VLCC (FPSO)	Full loaded ST
Total Length (m)	337.3	269.0
Beam m)	54.5	46.0
Draft m)	9.0	17.5
Depth (m)	27.0	24.4
Displacement (ton)	127510	175170

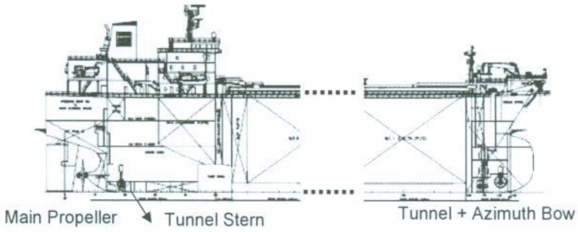

Figure 4: Thrusters positions.

The ST is equipped with four propellers: the main propeller with a rudder, a tunnel stern thruster, a tunnel bow thruster and an azimuth bow thruster. The locations of the each propeller, total power and maximum thrust are given in Table 4, and schematically showed in Figure 4. A 120m hawser is used for security reasons, but the DP system is required to keep both vessels aligned, with a 100m distance between them. Two common environmental conditions were considered in the simulations. The first one is shown in Figure 5. The most probable current (going to South, 0,4m/s velocity) is associated with the most probable wave (1,3m significant height – Hs – and 6.6s peak period – Tp) and wind (8.18m/s velocity). Such values are typical for Campos Basin. The environmental condition 2 is essentially the same as the previous one, with a stronger wave (Hs = 3,5m and Tp = 9.0s).

Table 4: Thrusters power and positions.

Thruster	Power (kW)	Thust (tf)	X (m)	Y (m)
1 – Azimuth Bow	2200	+35 / -18	110	0
2 – Tunnel Bow	1760	+/-25	120	0
3 – Tunnel Stern	1400	+/-18	-110	0
4 Main Prop. + Rudder	14000	+124/-19	-120	0

Simulations Results

For each simulation, a detailed set of results are presented, including time series of total forces, thrust delivered by each propellers, ST midship and connection point positions, ST heading, FPSO-ST relative distance and angles and hawser tension. Simulation 1 and 2, presented in Figure 6 and Figure 7, correspond to the intact DP under the environmental conditions 1 and 2. It can be seen that case 2 is in fact more critical, with higher DP forces and ST motion.

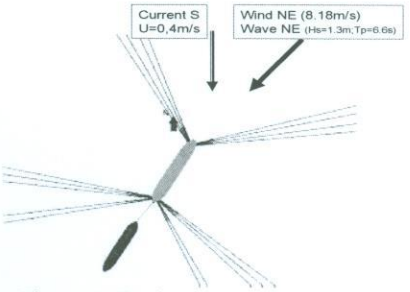

Figure 5: Environmental condition 1.

In order to evaluate the consequences of failures, two types of failures identified in Table 1 are simulated. Simulations 3 and 4 analyze the consequence of failure of the thrusters set and simulation 5 evaluates the failure of the power generation. Simulations 3 and 4 (Figure 8 and Figure 9) present cases of thruster failures, under environmental condition. The stern tunnel thrust (thruster 3) is turned off at t=6500s in Simulation 3, and it can be verified that the vessel cannot keep position (it drifted off). The main reason for such behavior is that the main propeller is not able, by itself to deliver the necessary lateral stern thrust to keep the vessel heading, even with the rudder action. Simulation 4 presents the case of the failure of main propeller (thruster 4) at t=6500s. In such a case, the failure is not catastrophic, and the vessel can keep position. The longitudinal thrust that is no more delivered by the main propeller is now delivered by the azimuth bow thruster (thruster 1). A small position deviation is verified just after the failure of the main propeller, but the DP system promptly takes the vessel back to the reference position. Obviously, under a stronger environmental condition, such failure could be catastrophic.

Finally, simulation 5 (Figure 10) presents the case of failure in generation system under environmental condition 2. It is considered that, at t=6500s, there is a 32% reduction in the power available for the DP system. A comparison between results of simulations 2 and 5 shows that the power generation failure is not a catastrophic failure in the present case since the ST can keep position (large excursion). However, it can be noticed that the ST motion increases significantly after the failure. For an offloading operation, such oscillatory motion is not critical. However, for drilling or pipe launching vessels such behavior may be critical.

DP modifications to improve reliability

Considering the particularities of an offloading operation, the simulations showed that the only critical failure is related to the inactivity of the stern thruster (Simulation 3). Even the case of power generation failure (Simulation 5) has not been shown to be critical. The offloading operation safety is not reduced considering the excursion of the shuttle vessel presented in Simulation 5. To improve the configuration of DP system considering the Simulation 3, three possible modifications to increase the lateral available thrust in the stern part of the vessel are proposed:

a) Utilization of a high lift rudder;

b) The installation of one azimuth thruster on stern;

c) The installation of second stern thruster.

CONCLUSIONS

The utilization of the incident data to develop an FMEA during the preliminary stage of the design of a DPS was proposed in this paper. The effect of the most common failure was predicted through dynamic simulation in order to assess the reliability of the ship. Furthermore, some critical failures were identified and improvement of the configuration of the DPS was suggested. The design of DPS integrating reliability issues and dynamic analysis of the vessel since the preliminary stage of the design of a DPS is a quite interesting approach because it allows the designer to improve the safety of the operation of the vessel and its dynamic performance as well.

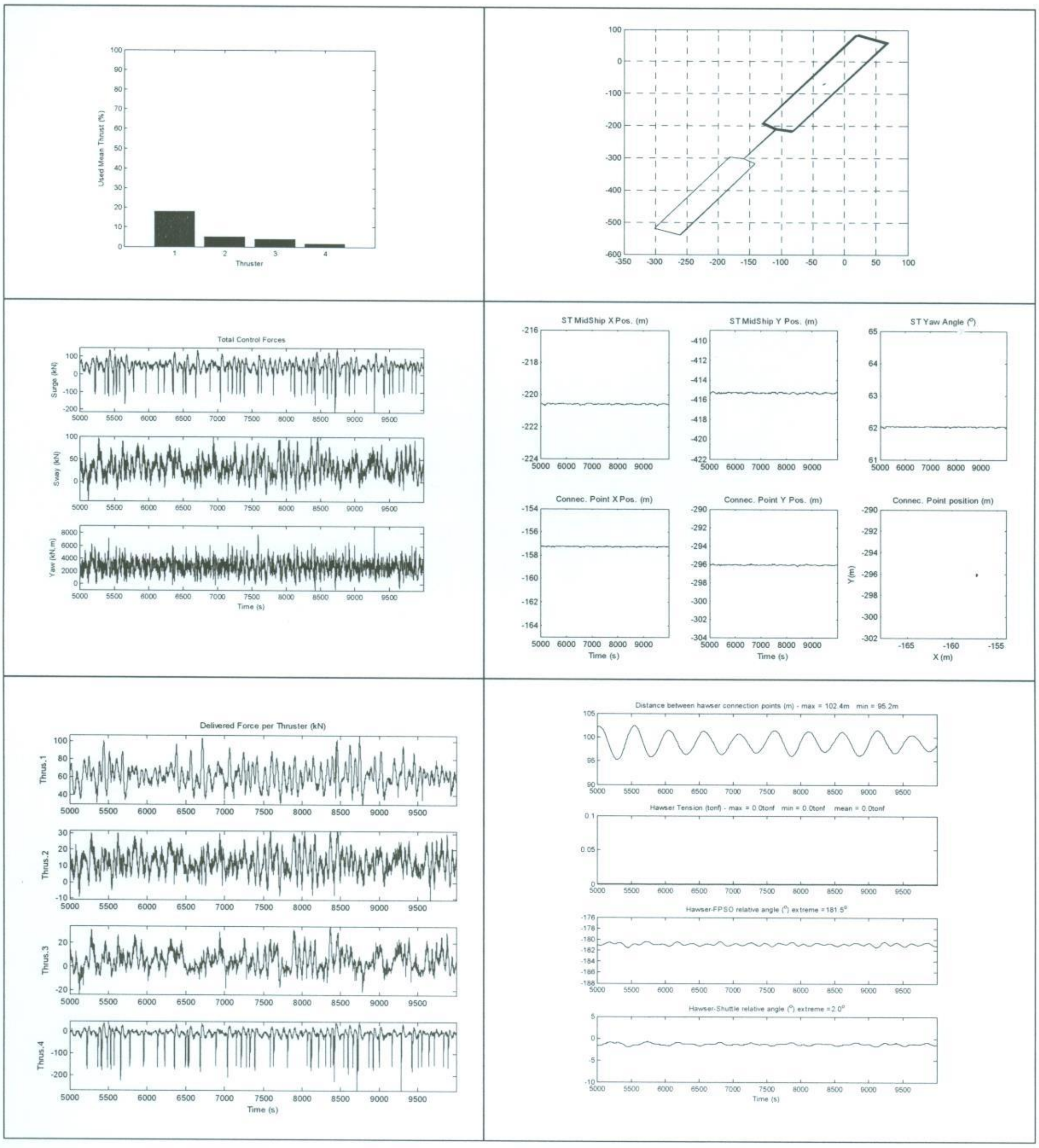

Figure 6: Simulation 1 – environmental condition 1 – intact DP system.

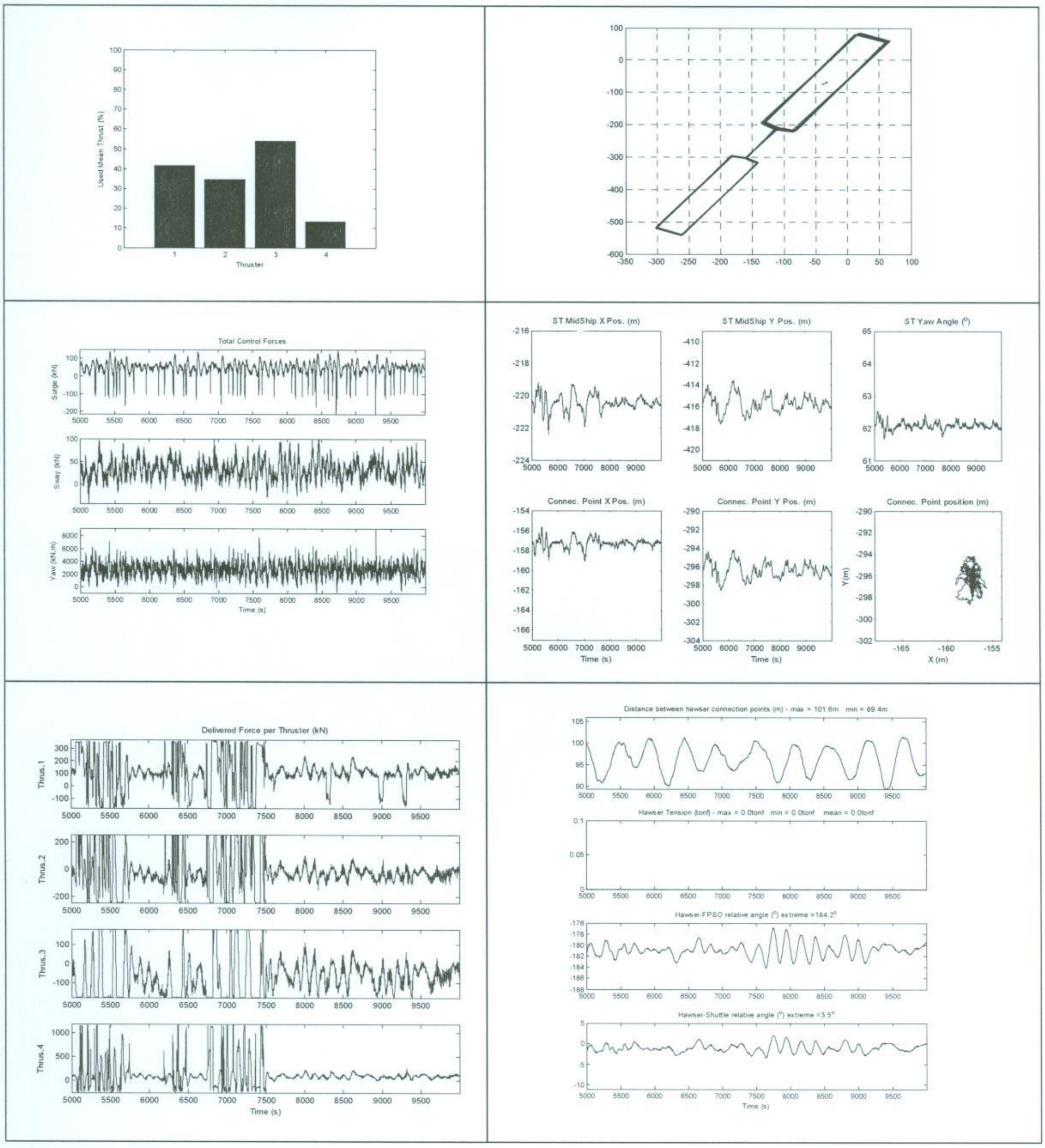

Figure 7: Simulation 2 – environmental condition 2 – intact DP system.

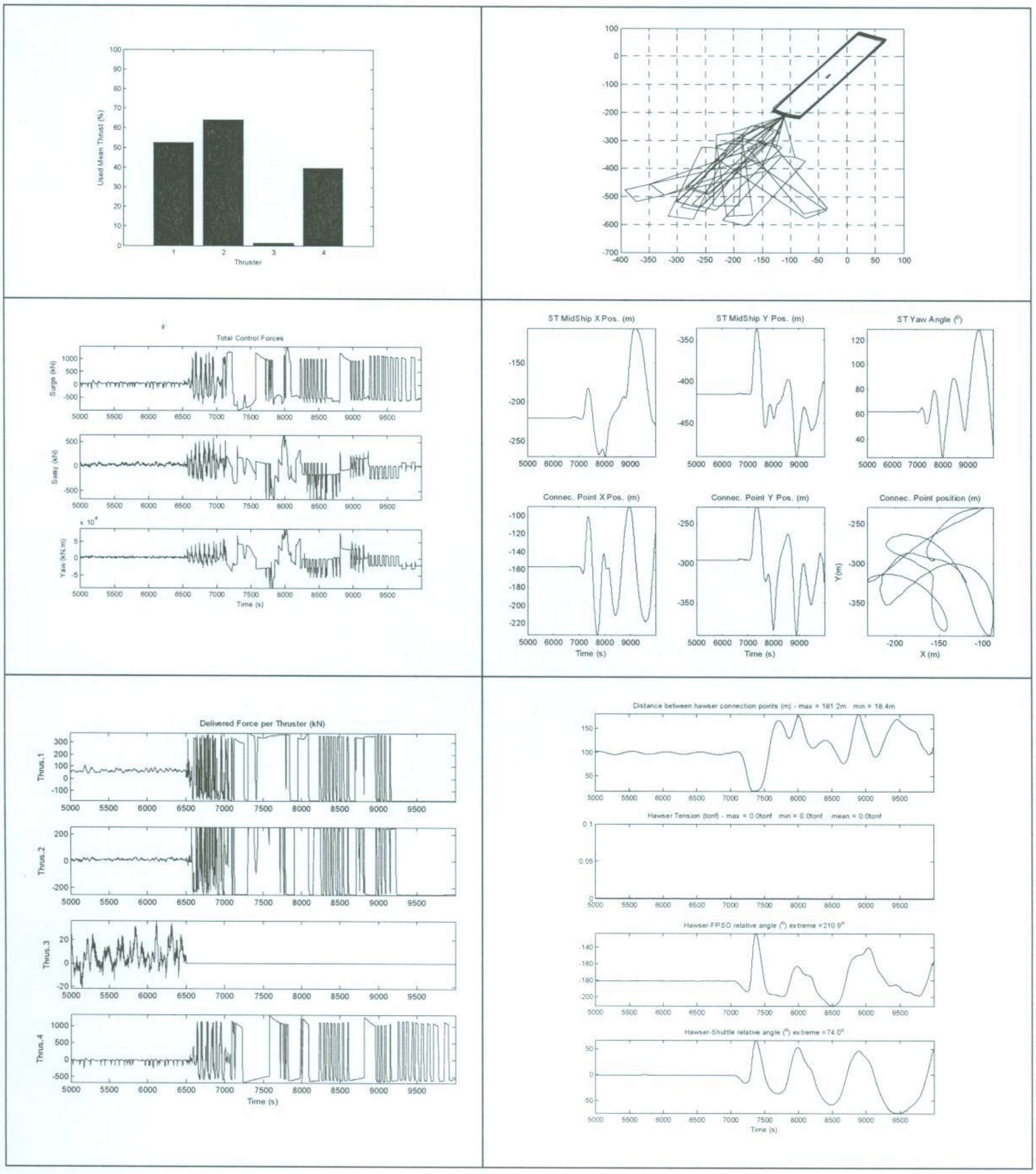

Figure 8: Simulation 3 – environmental condition 1 – failure of stern tunnel thruster.

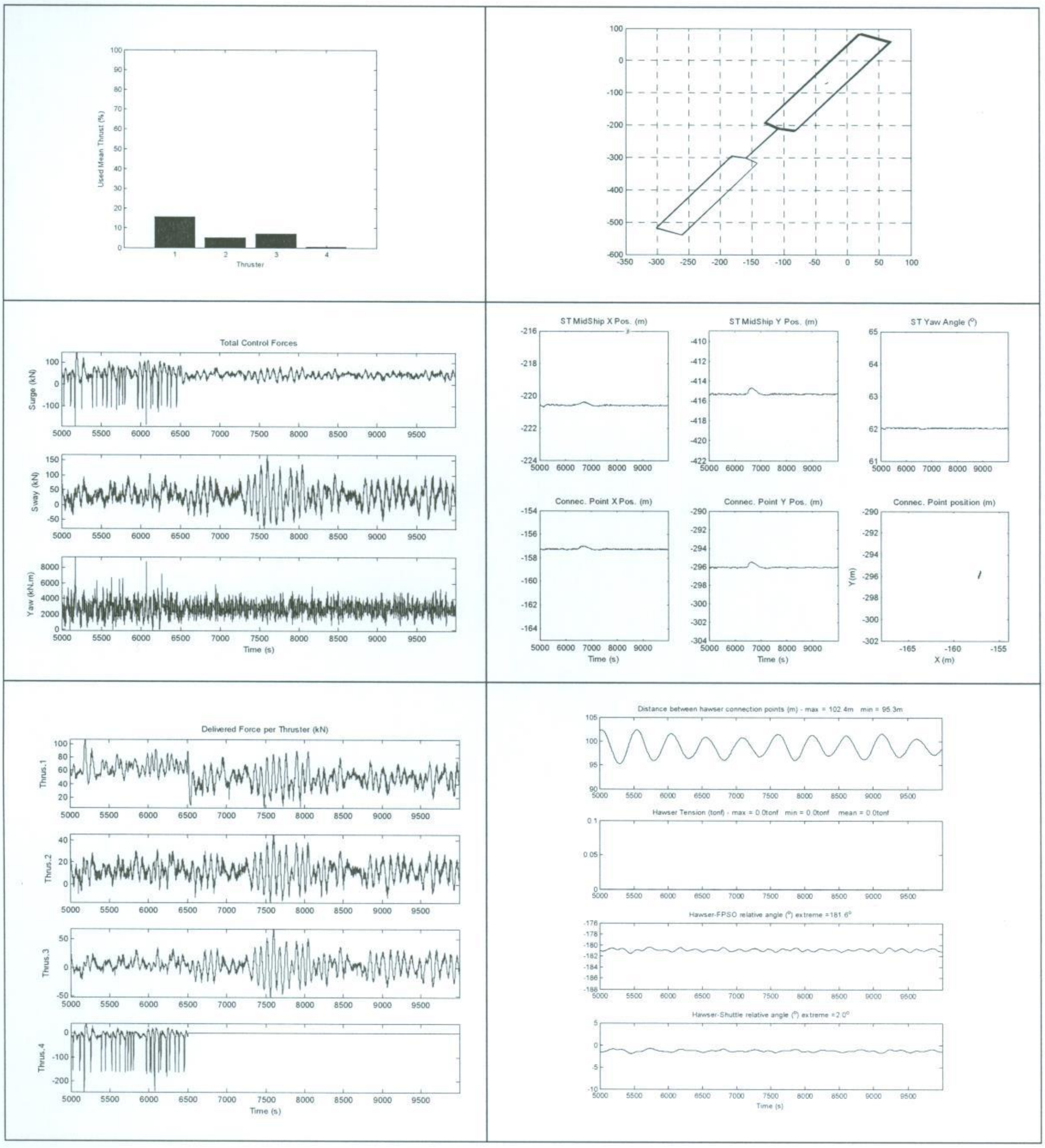

Figure 9: Simulation 4 – environmental condition 1 – failure of main propeller.

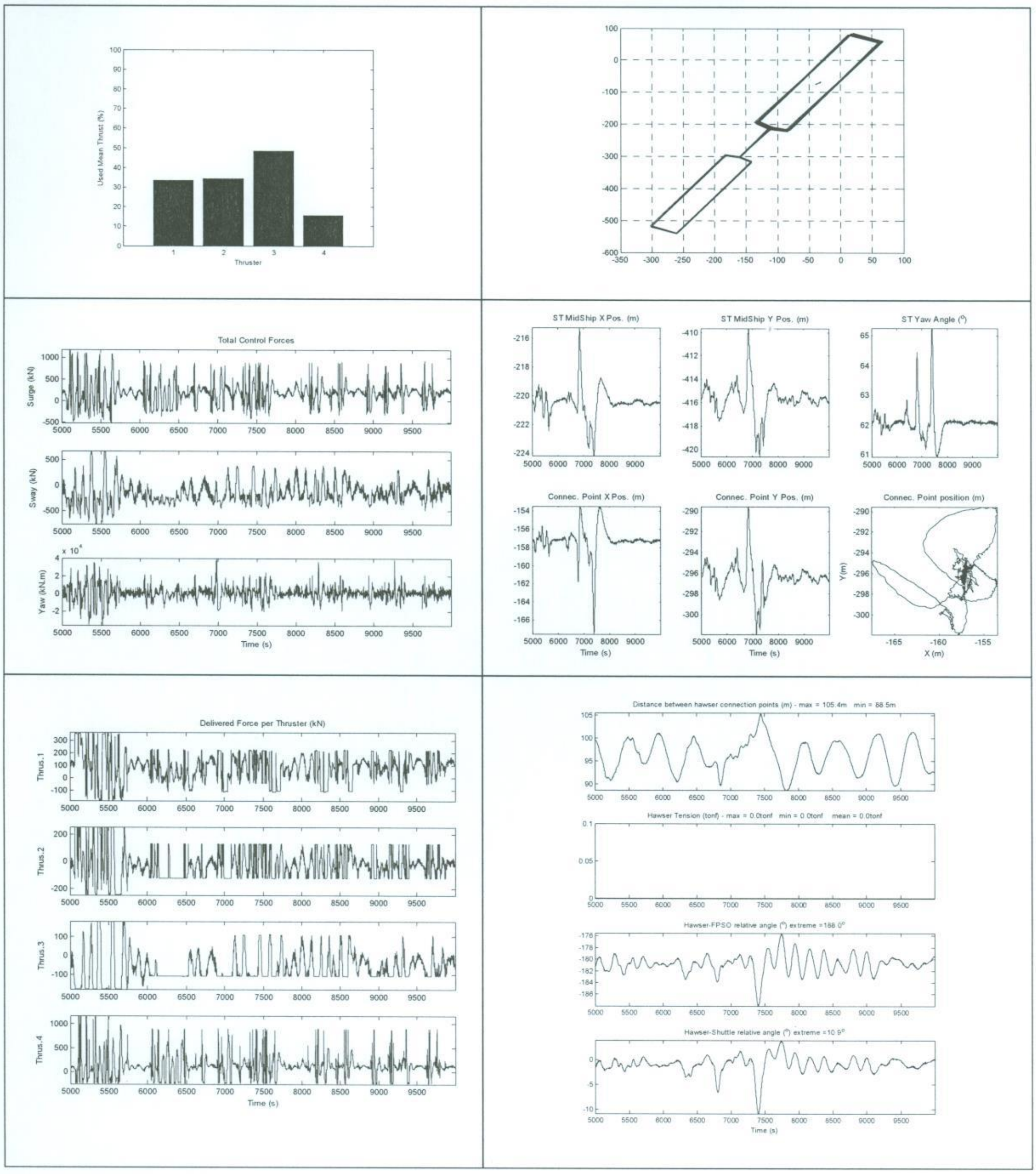

Figure 10: Simulation 5 – environmental condition 2 – 32% reduction in power available for DP system.

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