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Safety of Navigation During Dynamic Positioning on Mobile Water Transport Objects

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ABSTRACT: This paper presents an innovation methodology for quantity assessment the safety of dynamic positioning in locally confined area of technological work performance under nonlinear dynamic disturbances of environmental factors. The methodology is based on new integrated paradigm of prediction coordinated components interactions, which form dynamic positioning system. Proposed methodology implementation effect is based on the analysis of complex models that form the knowledge base. The comprehensive reserve of controllable thruster's reactions was adopted as quantitative characteristic of dynamic positioning safety.

1 INTRODUCTION

It is now more and more mobile water transport objects (MWTO) with dynamic positioning systems (DPS) onboard. Wide variety of DPS applications in maritime industry represent safety of navigation as a complex problem. High precision navigation processes interfere with environmental factors (EF): wind, current, waves (Fig. 1).

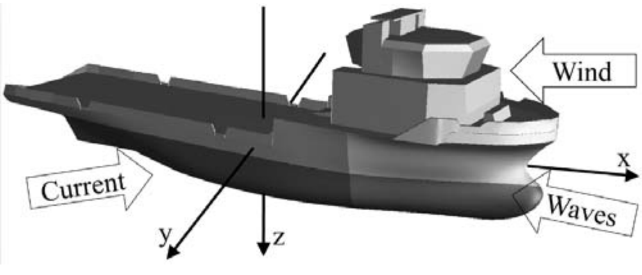

Figure 1. Environmental factors disturbances.

Wind, waves and current produce nonlinear external disturbances, which try to move MWTO outside of the locally confined area permitted boundaries. Environmental forces represent potential hazard to safety of navigation and technological work performance.

During dynamic positioning (DP), MWTO experiences motion in 6 degrees of freedom (DOF). The motion in the horizontal plane referred to as surge (longitudinal motion, usually superimposed on the steady propulsive motion) and sway (sideways safety of navigation motion). Heading or yaw (rotation about the vertical axis z). The remaining three DOFs are roll (rotation about the longitudinal axis x), pitch (rotation about the transverse axis y), and heave (vertical motion). DPS implies stabilization of the surge, sway and yaw modes.

DPS may be defined as a system that automatically controls MWTO to maintain position and heading exclusively by means of active thrust. DPS may set a target position, called a station, which can be fixed or a movable reference. DPS allows MWTOs to safely maneuver within the confines of ports and harbors. In modern MWTO, the DP system may form part of a MWTO integrated control system, communicating by means of a redundant Local Area Network.

DPS also provides a manual joystick control that may be used for joystick control alone or in conjunction with a position measuring system for combined manual or auto control. Without a position measuring system, DPS can provide automatic stabilization and control of the MWTO heading using the gyrocompass as the heading reference. In addition to the standard operational modes and functions, various tailored functions are available to optimize MWTO operation for a wide range of technological works (offshore loading, trenching, dredging, drilling, pipe and cable laying, etc.).

MWTO attitude is a necessary feedback into the DP system. The value of roll and pitch must be allowed for in the computations for position obtained from hydro acoustic position reference systems and, in some cases, taut wire systems. Both these systems generate positional data derived from angular measurements. In order to provide a geodetic datum, the vessel is provided with one or more Vertical Reference Sensors, or electronic inclinometers.

In order to provide a DP function, the vessel must be equipped with an adequate spread of propellers and thrusters. For DP purposes, a minimum of three thrusters are required, and most vessels are fitted with more than this minimum. A typical vessel may be fitted with twin propellers and rudders, a stern tunnel thruster and two (three) bow tunnel thrusters. Now more and more vessels are equipped with azimuth thrusters. Azimuth thrusters are reliable tool with high performance for DP. Also commonly used thrusters are retractable thrusters. A semi-submersible drilling rig may be fitted with six or eight azimuth thrusters. Many variations are possible. In some vessels, the rudders are DP active, to provide transverse forces aft, while in other vessels the rudders are not controlled by the DP system.

Vital to the safety of any DP operation is the continuity of the power supply. The power plant must always be considered as an integral part of the DP system. Any interruption in the supply of power can have heavy effects on the positioning capability of the MWTO. All MWTO with DP capability are particularly vulnerable to blackout or part-blackout situations.

DP-capable MWTO must have a combination of power, maneuverability, navigational ability and computer control in order to provide reliable positioning ability. This forms an integrated system, which consists of different elements.

Nonlinear forces of external disturbances play a major role. This forces (R_d) are generated by wind, current and waves and trying to move MWTO from holding position. DPS compensates these disturbances by means of controls that produce the necessary control forces R_c. Forces of controlled reactions should be equal or greater than forces of environmental disturbances.

$$\begin{cases} R_c \geq R_d, \\ M_c \geq M_d. \end{cases} \Rightarrow \begin{cases} \sum_{p=1}^{n} R_{Xcp} \geq \sum_{j=1}^{3} R_{Xdj}, \\ \sum_{p=1}^{n} R_{Ycp} \geq \sum_{j=1}^{3} R_{Ydj}, \\ \sum_{p=1}^{n} M_{XOYcp} \geq \sum_{j=1}^{3} M_{XOYdj}, \end{cases}$$

where R_c - force of controlled reaction; M_c - moment of controlled reaction; R_d - nonlinear force of EF disturbances (wind, current and waves forces); M_d – nonlinear moment of EF disturbance; R_{Xc}, R_{Yc}, R_{Xd}, R_{Yd} - projections of forces on the corresponding axis of MWTO coordinate system; p - number of MWTO thrusters; j – number of EF.

A comprehensive reserve of controlled thrusters reactions ΔR_c ($\Delta R_c = R_{c\ max} - R_c$) considered to be a quantitative characteristic of DP safety. The complex dynamic system of threshold type MWTO – EF functioning normally when the process of nonlinear disturbance and typical parameters of the system don`t extend beyond all established limits.

Presently safety of DP operations assessed by dynamic positioning operator (DPO) on the basis of Company Safety Management System (SMS) requirements, Failure Modes & Effects Analyses (FMEA) and using capability plot diagrams.

Capability plot diagrams commonly used for environmental forces affect assessment (Fig. 2).

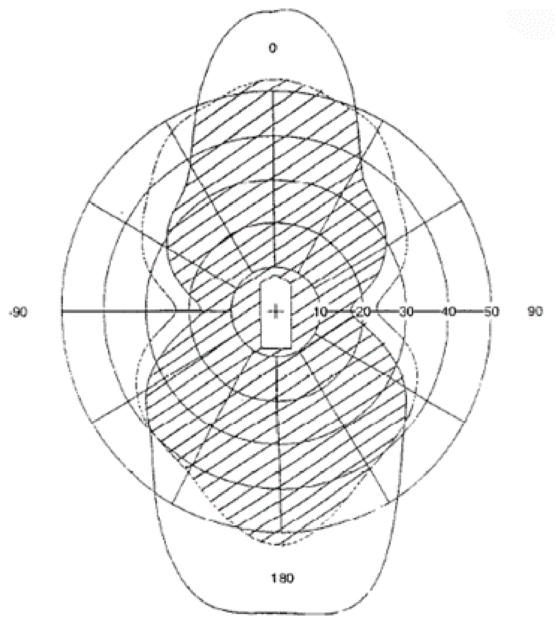

Figure 2. Typical DP capability plot diagram shape.

Capability plot diagrams provide DPO maximum safe acceptable wind speed with considered rotatable current in MWTO coordinate system. Almost all diagrams for self-propelled MWTO have large uninformative protrusions in sectors around 0 and 180 degrees (mostly more than 80 knots). Capability plot diagrams do not provide information about active thrust forces distribution under real environmental forces disturbances. All this lacks do not allow to form a clear picture for DPO.

Redundancy, according to the International Maritime Organization (IMO), is the ability of component or system to maintain or restore its function, when a single failure has occurred. The essence of redundancy is to enable the MWTO to safely terminate a DP operation after losing a critical component or system. This concept is referred to as "Single Point Failure" mode. Most MWTO have propulsion/thruster configurations beyond the minimum, as these provide control options such as minimum power consumption, fine position control, and barred zones for azimuth thrusters to protect equipment. It also allows redundancy, which is the ability of a vessel to maintain position and heading despite losing a component within its DP system. Redundancy gives a MWTO added time to safely shut down an operation should an failure occur in the DP system. Potential hazard associated with a DP operation is key in determining the level of redundancy. On this basis DP systems are divided into three classes.

The following methodology is proposed for guaranteeing safety of navigation during DP operations and DP process optimization. It also could be applicable for verification of the decision validity at real risks of commercial MWTO exploitation. It is applicable to MWTO of all DP classes.

2 DP PROCESS DECOMPOSITION

DP system is a complex combination of subsystems interacting to automatically maintain a MWTO position and heading with active thrust. Thrusters are positioned to provide optimum DP capability and movement, with minimum interference with other thrusters and sensors, using minimum fuel consumption. It is also important that thrusters are positioned to control the MWTO with minimal fuel consumption and to reduce the wear on the thruster.

The main element of MWTO system is a Hull that has mass, hydrodynamic and aerodynamic characteristics (Fig. 3). It contains all other subsystems. The EF influence on the Hull subsystem.

Energy subsystem acts as a resource of safety for the MWTO. Input and output data from different sensors, position measuring systems and MWTO subsystems form data flows.

Information subsystem distributes data flows circulation during the interaction of DPS functional elements. As well, it provides user interface and operation station inputs.

Computation subsystem on the basis of processed data, which Information subsystem provides, computes signals that should compensate forces of external influences. Mathematic model is designed to compute the difference between the set point values and offset values of heading and position. Mathematic model issues forces to counteract offsetting forces to return MWTO to the set point heading and position. This special calculating module continually calculates MWTO response to EF nonlinear disturbances. Forces distribution algorithm calculates force for each thruster. Computation subsystem should be considered as an appropriate open system that connects data from the various sources and produces control signals for the Controlled thrusters subsystem.

The number of control computers will depend upon the level of redundancy available, which in turn will relate to the DP equipment class. In simple terms, single computer systems are fitted in MWTO without a critical dependence upon position keeping. This provide no redundancy. Higher levels of reliability are required for MWTO undertaking technological work involving higher risk. Dual or triple control computer systems can provide extra redundancy.

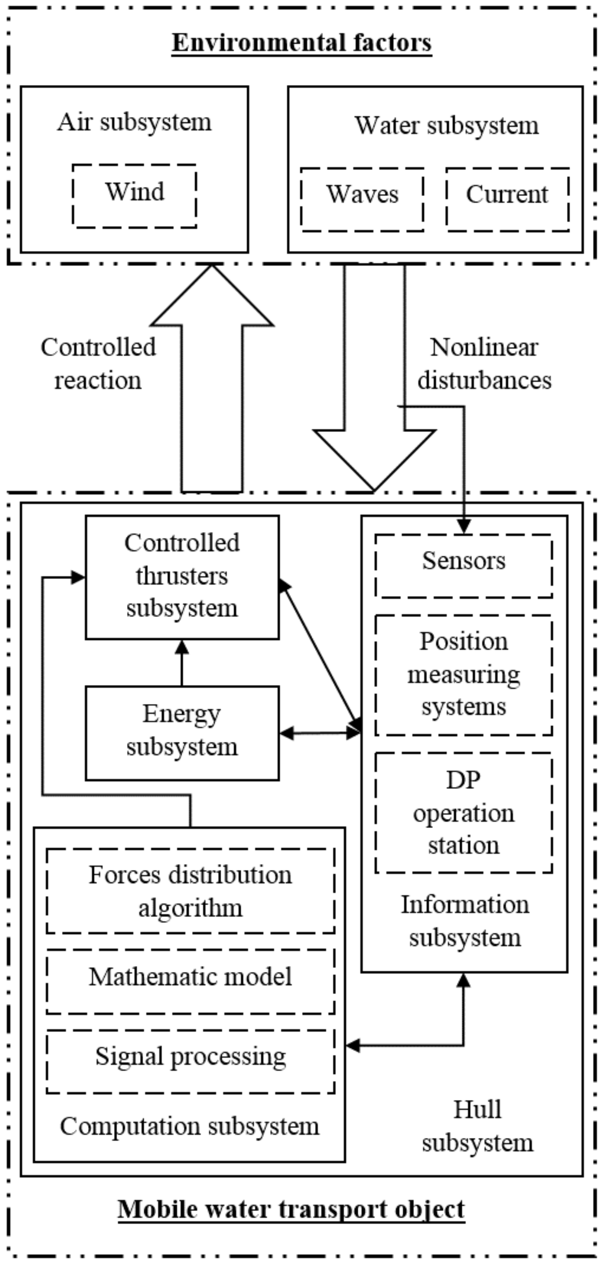

Figure 3. MWTO-EF systems complex interaction.

Controlled thrusters subsystem produces appropriate control force vectors, which are necessary for the MWTO reaction to EF nonlinear disturbances. At the next decomposition level, each of these subsystems could be represented as composition of interacted subsystems.

EF system EF consists of Water and Air subsystems. On the fluidity property basis, it is possible to describe these subsystems as various models of fluid. Models of fluid motion reflect following subsystems: Wind, Waves and Current.

Mathematical models of interacting subsystems represented by equations of a rigid body motion in a fluid, equations of hydrodynamics and aerodynamics, equations of electric drives electrodynamics, equations of thruster`s mechanics, equations, that describe processes in DP control systems.

3 METHODOLOGY

The proposed methodology is based on a new integrated paradigm of coordinated element actions to support decision-making process regarding DP safety in locally confined area of technological work (Fig. 4).

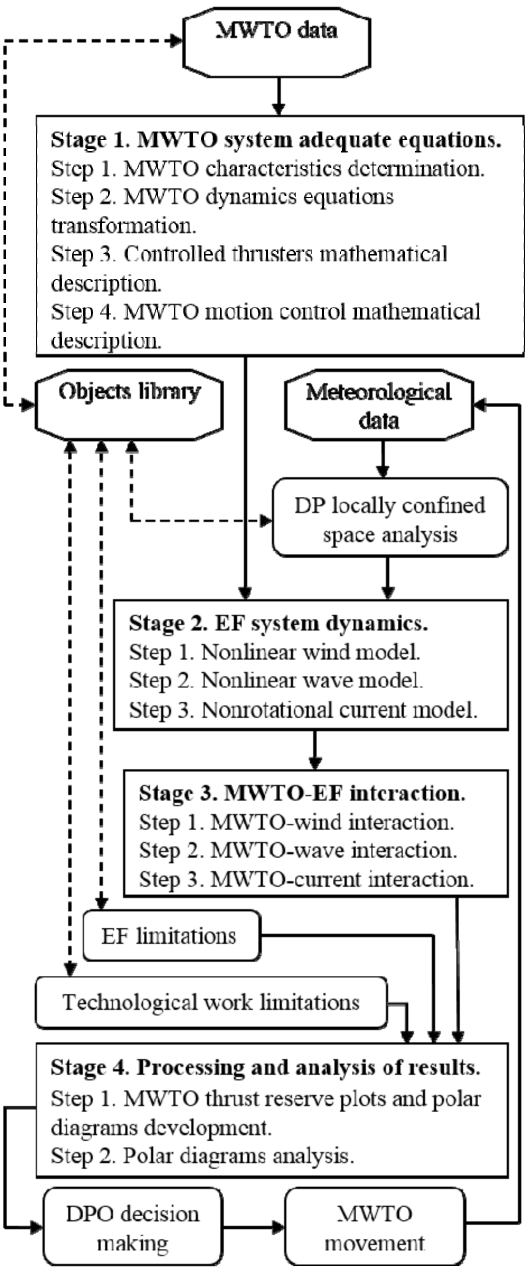

Figure 4. Information and logical model of methodology.

Data, that describe MWTO physical characteristics, enter at the beginning. These data could be entered manually or could be selected from the library of existing objects. Mathematical description of complex MWTO system is based on these data.

As an example proposed methodology applied for typical AHTSS vessel UT 733-2 project (Fig.5). The MWTO equipped with two bow thrusters (800 BHP each) and two azimuth stern thrusters (3600 BHP each).

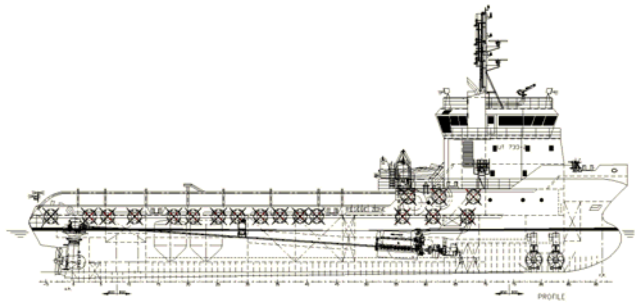

Figure 5. AHTSS UT 733-2.

Step 1. MWTO characteristics determination. The determination of hull characteristic require building an adequate hull model. At present, there are a lot surface-modeling programs, which allow to determine MWTO hull principal dimensions, hydrodynamic and aerodynamic characteristics, added masses and moments of inertia. Following models were built using FREE!ship software

When MWTO model is built, before proceeding with calculation of characteristics, appropriate surfaces should be checked for any errors and disjoint segments.

Gaussian curvature is most common method, which could be used to check the model (Fig.6). The model is shaded in colors, based on the discrete Gaussian curvature in each point. Most hulls are curved in two directions, called the principal curvatures. Gaussian curvature is the product of these two principal curvatures. There are 3 possibilities.

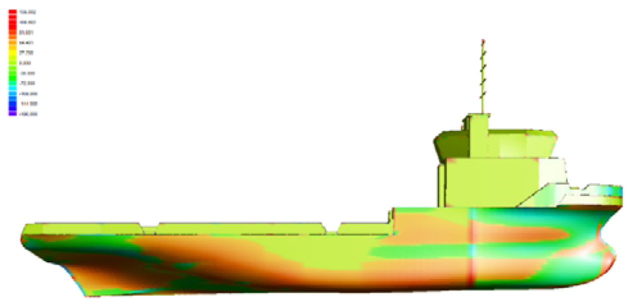

Figure 6. MWTO model Gaussian curvature.

Negative Gaussian curvature. These areas are shaded blue and have the shape of a saddle, since the curvature in one direction is positive while the curvature in the other must be negative.

Zero Gaussian curvature. At least one of the two principal curvatures is zero, so the surface is either flat or curved in only one direction. In both cases the surface is developable (This is in fact a very important property of developable surfaces). These areas are shaded green.

Positive Gaussian curvature. The curvature in both directions can be positive or negative, but must have the same sign. These areas are convex or concave and shaded red.

Zebra shading is another option method to check the model (Fig.6). Regions with a constant light-reflection intensity are shaded in bands.

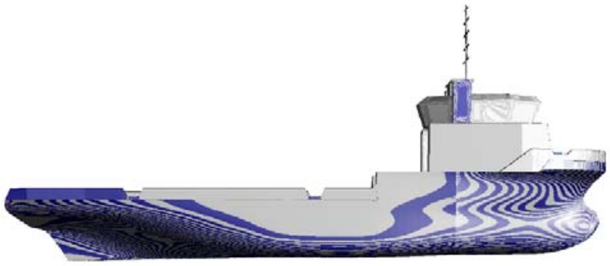

Figure 6. MWTO model zebra shading.

This is similar to the way the human eye detects unfair spots on a surface since the shininess and shadows vary in those areas. If the edges of the zebra stripes are curved smoothly then the surface is smooth in these areas. At knuckle lines they vary abruptly.

Wind forces are calculated by using well-known formula, where major role aerodynamic coefficients play:

$$\begin{cases} R_{AX} = C_x \dfrac{p_a}{2} F_{Sx} V_{wr}^2, \\ R_{AY} = C_y \dfrac{p_a}{2} F_{Sy} V_{wr}^2, \\ M_{AMZ} = C_{mz} \dfrac{p_a}{2} F_{Sy} L_{Sy} V_{wr}^2, \end{cases}$$

where R_{AX} - longitudinal force; R_{AY} - lateral force; M_{AMZ} - yawing moment; C_x - longitudinal force coefficient; C_y - lateral force coefficient; C_{mz} - yawing moment coefficient; p_a - density of air; F_{Sx} - transverse projected wind area; F_{Sy} - lateral projected wind area; L_{Sy} - distance to centroid of lateral projected area; V_{wr} - relative wind speed between water level and top of superstructure.

Determination of aerodynamic coefficients C_x, C_y, C_{mz} is carried out for MWTO hull (excluding underwater part) and superstructures using superposition method. As MWTO superstructure consists of many adjacent elements, which can overlap each other, care should be taken during calculation of appropriate wind exposed surfaces areas (Fig. 7).

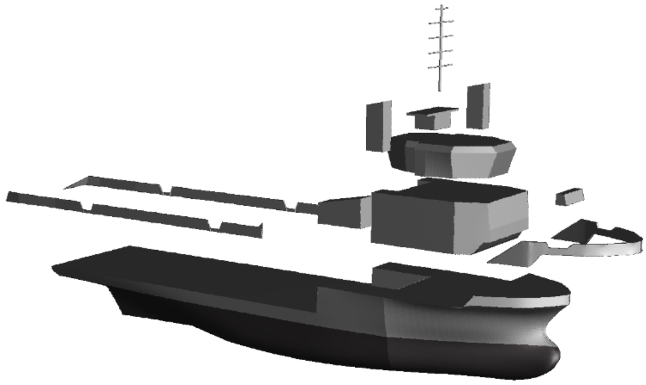

Figure 7. MWTO elements exposed to wind influence.

To increase accuracy of the model it is suggested to include in calculation bulwarks, masts, massive deck equipment (tow winch, windlass, etc.).

Added masses and moments of inertia can be understood as pressure-induced forces and moments due to a forced harmonic motion of the MWTO hull proportional to its acceleration.

The concept of fluid kinetic energy is used to derive the added mass terms. Moreover, any motion of the MWTO will induce a motion in the otherwise stationary fluid. In order to allow the MWTO to pass through the fluid, it must move aside and then close behind the MWTO.

For completely submerged MWTO it will be assumed that the added mass coefficients are constant and thus independent of the wave circular frequency. In generally it represents by matrix of added masses and moments of inertia.

$$\begin{vmatrix} \lambda_{11} & \lambda_{12} & \lambda_{13} & \lambda_{14} & \lambda_{15} & \lambda_{16} \\ \lambda_{21} & \lambda_{22} & \lambda_{23} & \lambda_{24} & \lambda_{25} & \lambda_{26} \\ \lambda_{31} & \lambda_{32} & \lambda_{33} & \lambda_{34} & \lambda_{35} & \lambda_{36} \\ \lambda_{41} & \lambda_{42} & \lambda_{43} & \lambda_{44} & \lambda_{45} & \lambda_{46} \\ \lambda_{51} & \lambda_{52} & \lambda_{53} & \lambda_{54} & \lambda_{55} & \lambda_{56} \\ \lambda_{61} & \lambda_{62} & \lambda_{63} & \lambda_{64} & \lambda_{65} & \lambda_{66} \end{vmatrix}$$

Matrix consists of 36 elements, which represent full added masses and moments of inertia.

For the MWTO with partly submerged hull definition is under the assumption of an ideal fluid, no incident waves, no sea currents, and zero frequency.

For most MWTO (like considered AHTSS) it is common to decouple the surge mode from the steering dynamics due to xz-plane symmetry. As well, the heave, pitch, and roll modes are neglected under the assumption that these motion variables are small and do not have great influence on the MWTO during DP operations in locally confined area of technological work. In this case, it is possible to represent simplified matrix of added masses and moments of inertia.

$$\begin{vmatrix} \lambda_{11} & 0 & \lambda_{13} & 0 & \lambda_{15} & 0 \\ 0 & \lambda_{22} & 0 & \lambda_{24} & 0 & \lambda_{26} \\ \lambda_{31} & 0 & \lambda_{33} & 0 & \lambda_{35} & 0 \\ 0 & \lambda_{42} & 0 & \lambda_{44} & 0 & \lambda_{46} \\ \lambda_{51} & 0 & \lambda_{53} & 0 & \lambda_{55} & 0 \\ 0 & \lambda_{62} & 0 & \lambda_{64} & 0 & \lambda_{66} \end{vmatrix}$$

Both matrices are symmetrical relative to the main diagonal. Further simplifications could be done on the assumption that during DP only MWTO movement in horizontal plane is controlled by DP system. It means that added masses on x and y axis and moment of inertia on z axis play significant role (numbers in the matrix 11, 22 and 66 respectively).

Added masses could be defined numerically by a method of successive approximations at the decision of integrated equations Fredholm of 2-nd sort concerning density of hydrodynamic features (sources - effluents) distributing continuously on surface MWTO hull with the account and without taking into account effect of a bottom and a trim. Thus we believe, that a fluid ideal, incompressible, and movement potential. MWTO hull is considered as the solid limited to the closed surface and moving in a boundless fluid.

Step 2. MWTO dynamic equations transformation. It is possible to represent MWTO movement mathematical dynamics model in Cauchy form by one nonlinear differential general equation:

$$\frac{dv}{dt} = f(d,c,t),$$

where *v* - MWTO state vector; *d* - vector of disturbances; *c* - vector of controlled reactions; *f* - non-linear function; $t_0 \le t \le t_1$- simulation step interval.

The MWTO state vector general form includes 12 variables:

$$v_i = [x_{ig}, y_{ig}, z_{ig}, V_{ix}, V_{iy}, V_{iz}, \theta_i, \varphi_i, \psi_i, \omega_{ix}, \omega_{iy}, \omega_{iz}].$$

When analyzing MWTO motion it is convenient to define the following well-known coordinate systems.

The North-East-Down (NED) coordinate system is defined as relative to the Earth's reference ellipsoid (World Geodetic System 1984). It is defined as the tangent plane on the surface of the Earth moving with the MWTO, but with axes pointing in different directions in comparison with the body-fixed axes of the MWTO. For this system, the x-axis points towards true North, the y-axis points towards East while the z-axis points downwards normally to the Earth's surface. During MWTO DP operations in a local confined area, it is possible to consider that longitude and latitude are constant. Therefore, it is convenient to use for navigation an Earth-fixed tangent plane on the surface. This is usually referred to as flat Earth navigation and it will for simplicity be denoted as the NED frame. For flat Earth navigation, it is possible to assume that the NED frame is inertial such that Newton's laws still apply.

MWTO coordinate system (Fig. 1) is a moving coordinate frame, which is fixed to the MWTO. The MWTO orientation uniquely determined by the appropriate angles between axis of coordinate systems.

In MWTO complex mass center flat movement consideration, some state variables were excluded, because they are not controlled by DPS. These state variables are: complex mass center movement along the vertical axis of the MWTO coordinate system, projection of the linear speed on a vertical axis of the NED coordinate system, angular movements around the longitudinal and transverse axes of the MWTO coordinate system, angular speeds around the longitudinal and transverse axes of the NED coordinate system. Thus, MWTO state vector includes six variables:

$$v_i = [x_{ig}, y_{ig}, V_{ix}, V_{iy}, \varphi_i, \omega_{iz}].$$

DPS controls the movement of MWTO in the plane of the horizon and doesn`t control the vertical movement, rolling and pitching. This significantly simplifies the model without harming desired scientific results. A Vector of controlled reactions represents the projection of forces and moments generated by controlled thrusters. A vector of external disturbances represents the projection of EF forces and moments.

Step 3. Controlled thrusters mathematical description. During mathematical description of controlled thrusters subsystem following should be the considered: thrusters and hull interaction, forbidden zones formation for each thruster, influence of MWTO dynamic on the thrust effect, all possible DP thrusters allocation modes. Forbidden zones and allocation modes are depend of MWTO type, position measuring equipment, nature of technological work.

Open water propeller characteristics could be described by following formula:

$$R_p = (T_{nn} n^2 + T_{Vn} V_{POBT} n + T_{VV} V_{MWTO}^2),$$

where R_p - propeller force; T_{nn}, T_{Vn}, T_{VV} - coefficients of dynamic influence; n - rotational speed of propeller; V_{MWTO} - MWTO speed.

Dynamic coefficients T_{nn}, T_{Vn}, T_{VV} are represented by formula:

$$\begin{cases} T_{nn} = K_{tp}(3) p_w D_p^4, \\ T_{Vn} = K_{tp}(2) p_w D_p^3, \\ T_{VV} = K_{tp}(1) p_w D_p^3, \end{cases}$$

where K_{tp} – specific polynomial, K_{tp} = (-0,1060; -0,3246; 0,4594), for particular case; p_w - density of water; D_p – diameter of propeller.

Mostly MWTO with azimuth thrusters are equipped with acceleration nozzles. Nozzles prevent propellers from damage and increase their efficiency. Where acceleration nozzles are applicable, open water propeller force should be multiplied by respective acceleration coefficient.

Power resources, which are represented by Energy subsystem, should be simulated according to MWTO classification society approved Power Management Plan.

Step 4. MWTO motion control mathematical description. During this step, hierarchical performance of Computation and Information subsystems are described. Computation subsystem mathematical description involves development of station keeping and low speed maneuvering algorithms on MWTO mathematical model basis. Information subsystem provides data from different sources for these algorithms. This data include MWTO position, kinematics and dynamics, disturbance and reaction forces in different coordinate systems, power reserve, thruster allocation and set point, etc. Forces distribution algorithm computes necessary forces for each available thruster to perform DP operations.

Stage 2. EF system dynamics mathematical description is carried out on the basis of meteorological data and DP locally confined area analysis. At this stage, depending on the used method and accuracy requirements, the following should be determined: EF characteristics, character of hydrological features (Froude number, tide heights, etc.). The EF conditions could be also defined as a one minute mean maximum wind velocity, a most-probable significant wave height, and a most-probable wave modal period.

The library of water areas is created on this stage. Systematic EF water area data include the following: general weather conditions in locally confined area of DP operations, characteristics of wind speed and its direction, characteristics of sea state (wave heights, swell direction), characteristics of current speed and its direction (peculiarities of changes).

Step 1. Nonlinear wind model. Wind is defined as the movement of air relative to the surface of the Earth. Mathematical models of wind forces and moments improve performance and robustness of the system in extreme conditions. The nature of the nonlinear component depends on the water area of MWTO operation. The appropriate spectral characteristics may also be used.

Step 2. Nonlinear wave model. The process of wave generation due to wind starts with small wavelets appearing on the water area surface. This increases the drag force, which in turn allows short waves to grow. Short waves continue to grow until they finally break and their energy is dissipated. A developing sea, or storm, starts with high frequencies creating a spectrum with a peak at a relative high frequency. A storm, which has lasted for a long time, creates a fully developed sea. After the wind has stopped, a low frequency decaying sea or swell is formed. These long waves form a wave spectrum with a low peak frequency. If the swell from one storm interacts with the waves from another storm, a wave spectrum with two peak frequencies may be observed. In addition, tidal waves will generate a peak at a low frequency. Hence, the resulting wave spectrum might be quite complicated in water areas, where the weather changes rapidly.

Step 3. Nonrotational current model. Current is defined as horizontal motion of water systems with a constant average speed. Vertical movement of water particles from one layer to another is not considered.

Stage 3. MWTO-EF interaction. Step 1. MWTO-wind interaction. Assumption of wind flow homogeneity and quasi-stationary properties plays a major role in the mathematical description of the MWTO reaction to wind disturbance. Calculation of wind forces and moments acting on MWTO results from relative wind speed and angle is done.

Step 2. MWTO-wave interaction. The interaction of MWTO hull with waves is a complex physical process. The mathematical description of the MWTO reaction on the wave disturbance requires consideration on regular and irregular waves. In the first case, the model will have deterministic nature, and in the second - a stochastic nature. Wave-induced forces and moment on MWTO are calculated using force transfer function. Wave height is a governing factor of this function. Research of the stochastic model is more complicated and time consuming, but results more accurately describe the reaction to the wave disturbance.

Step 3. MWTO-current interaction. The nature of the MWTO reaction depends on the current speed and direction. All hull protractions hydrodynamic effect is calculated on this step as well. Consideration of current speed changes, caused by hydrological features of the water area, improves the accuracy of results.

In order to receive parameters of the state vector to evaluate MWTO safety of DP operations, which undergo nonlinear EF disturbances, it is necessary to make description of the MWTO subsystems interaction, which are coordinated to solve the following tasks:

– Decomposition of complex systems and tasks into more simple (typical or standard).
– Relationship determination between selected components in the logic algorithms form.
– Distributed processing by Computation subsystem of various primary data from Information subsystem. During this process, navigation regarding MWTO dynamic positioning in locally confined space are formed and represented to DPO.
– Distributed secondary processing of aggregation or group data, which together reflect MWTO state vector characteristics and EF disturbance main vector characteristics (course over ground, heading, speed, direction and force of disturbances).
– Determination of threat directions that form extreme situation concerning DP safety.
– Parameters identification (for components of Controlled thrusters and Energy subsystems), which are required for safe and effective DP process realization in locally confined area.
– Realization of identified parameters by DP process control laws.

Stage 4. Processing and analysis of results. Step 1. MWTO thrust reserve (load) plots and polar diagrams development. EF disturbance lead to DPS reaction, which through the forces distribution algorithm specifies load set points to controlled thrusters. The comprehensive reserve of controllable thruster's reactions represents a quantitative characteristic of MWTO DP safety. The curves of thrust reserve received for specific weather conditions, together with the assessment of the MWTO state vector provide an opportunity to assess the DP safety and execution of technological work expediency.

However, these curves describe only one possible MWTO heading. The picture of thrust reserve will be different if MWTO heading will change during DP. This happened due to changes in MWTO-EF interaction parameters. A similar situation observed when parameters of EF changed.

For the complex situation assessment, it is necessary to know how thrust reserve distributes on all possible MWTO headings. For this purpose, it is convenient to use polar diagrams that characterize spatial distributions of thrust reserve.

Step 2. Polar diagrams analysis. Polar diagrams represent thrust reserve (load) on MWTO possible headings range (360 degrees) and expand proposed methodology opportunities. Polar diagrams allow DPO to ensure MWTO safety of navigation during DP, establish safe abortion route in case of any emergency, optimize DP process and reduce costs of MWTO commercial exploitation. Identified limitations, imposed by the character of technological work and EF, have a great importance and should be reflected in the diagram.

Library formation of existing MWTO objects, limitations due to EF disturbance and technological work take place during methodology performance.

Decision making by the DPO is a crucial part of the methodology. Accordingly to the philosophy of proposed methodology, the main control element, which ensure safety of DP is DPO. To make proper decision DPO should consider results of solving the following tasks during limited time horizon:

- Assurance of DP process safety and optimization in locally confined area of technological work execution.
- Assessment of the current situation, which can rapidly change because of external disturbances or because of MWTO factors (failure of DPS components, etc.).
- Situational decision-making, especially in the critical and extreme conditions of DP operations.
- Implementation of decisions taken according to identified resources and limitations of active control. That provided adaptation of the MWTO operative control synthesized laws to the practice of achieving targeted results.

4 IMPLEMENTATION

Implementation of proposed methodology was conducted on board DP-1 vessel project UT 733-2. Vessel performed DP in locally confined area during supply operations of offshore facility in Persian Gulf (Fig. 8).

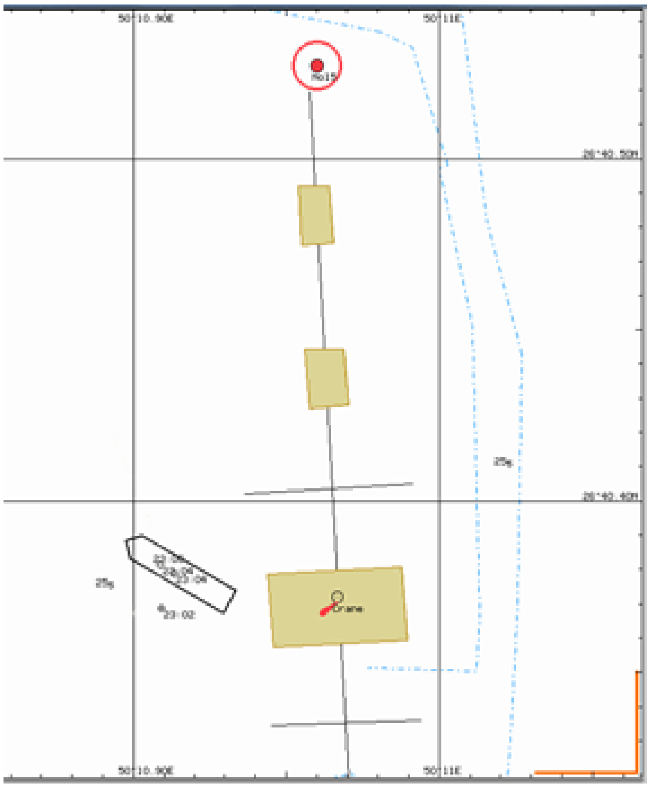

Figure 8. Supply operation process.

The following weather conditions were observed in the locally confined area of technological work: wind direction 25°, speed 11 knots; current direction 50°, speed 0.9 knots; wave direction 300° degrees, observed significant wave height 1 m.

Company SMS requirement: 80% maximum thruster load. Following polar diagram of thruster loads was calculated (Fig. 9). On the diagram, which referred to NED coordinate system, loads of the bow thrusters and azimuth stern thrusters were represented as MWTO DPS reactions on concrete EF disturbances. Reference to NED coordinate system allows DPO to plan easier MWTO movements and abortion route. This diagram could be attached to navigation chart or put near ECDIS screen for quick reference.

Loads greater than 80% form "EF limitation" sectors. These limitations correspond to currently observed weather conditions. If the EF values change, the polar diagram will also change.

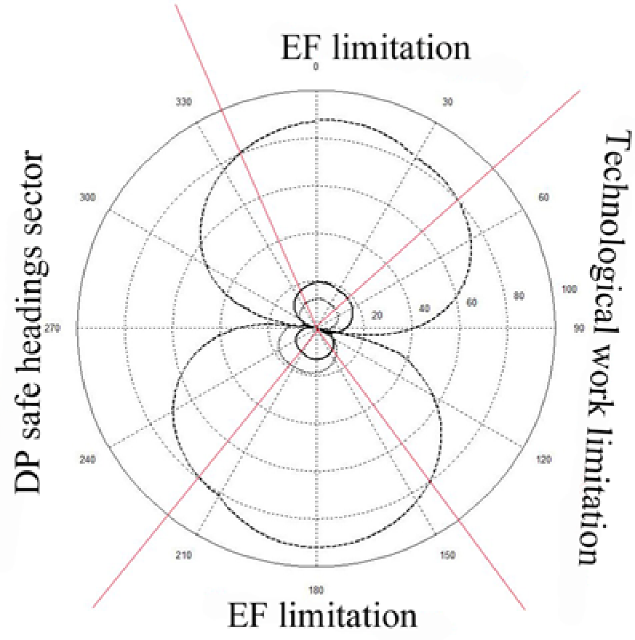

Figure 9. Polar diagram.

MWTO's cargo and cargo hoses connections are located on the stern of the vessel (which is common to all AHTSS). It means that during supply operations the vessel should be parallel or stern to the offshore facility. This condition superimposes with the "EF limitation" sectors and forms "Technological work limitation" sector.

The remaining sector forms "DP safe headings sector". All headings within this sector are safe and allow performing supply operations. 300° heading was selected as final practical heading to conduct DP.

Using described above methodology, it is also possible to predict the maximum weather conditions that the MWTO is able safely to continue DP operations (maintain position and heading within specified limits, taking into account both the average environmental load and the vessel dynamics).

Safety of DP process is guarantee according to the proposed methodology by using researched analytical regularities of interdependence of parallel processes of discrete navigation and continuous DPS control of MWTO state vector under nonlinear EF disturbances.

5 CONCLUSIONS

The proposed ergatic interaction structuration provides adaptation processes of high performance and operational problems solving, which arise during DP operations in extreme situations where the time factor is crucial. Described above methodology allows ensure safety and increase efficiency of DP operations and is applicable to all types of MWTO and their propulsion configurations.

The formed knowledge base allows DPO to ensure MWTO DP safety in various conditions. Introduced polar diagrams referred to NED coordinate system, have an adaptive and dynamic nature and favorably differ from known capability plot diagrams, which are static and referred to MWTO coordinate system.

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