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Preliminary Design of Dynamic Positioning System for A Drillship

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ABSTRACT: *An offshore vessel with a dynamic positioning system (DP system) needs fast response to produce thrust to counteract the environment forces acting on it for the purpose of maintaining its position and heading as close as possible to the working position. Therefore, quick and effective modulation of the thrust is the problem to determine the thrust and rotation angle of the thruster device of the ship. This project presents an effective optimum control for a thruster system, using MATLAB simulation to achieve economical and effective modulation of the thrust and direction of thruster. An optimum control study of a 53133 tons DP drillship with five rotary azimuth thruster marine positioning is studied in detail which can quickly and exactly estimate the thrusts and angles of direction of all thrusters. The results can provide a valuable thruster system for a dynamically positioned vessel.*
KEYWORDS: *dynamic positioning, drillship, modulation, azimuth thruster*

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I. INTRODUCTION

Dynamic positioning (DP) is any computer-controlled system that automatically maintains a vessel in a relatively fixed position with respect to the ocean floor, accomplished by two or more propulsive devices without using anchors. International Marine Contractors Association (IMCA) defines DP as “a system which automatically controls a vessel’s position and heading exclusively by means of active thrust” (Balchen, 1976). This definition includes remaining at a fixed location, precision maneuvering, tracking and other specialist positioning capabilities. Position reference sensors, combined with wind sensors, motion sensors and gyrocompasses, provide information to the computer as regards the vessel’s position, the magnitude and direction of environmental forces affecting at its position. DP may either be absolute in that the position is locked to a fixed point over the bottom, or relative to a moving object like another ship or an underwater vehicle. One may also position the ship at a favorable angle towards wind, waves and current, called weathervaning (Balchen, 1980).

The DP system consists of a number of components/systems that enables its functionality. They are the position reference systems, heading reference systems, sensors, control systems, power and propulsion systems. The DP control system consists of three main parts and they are: state estimator, positioning controller and thrust allocation algorithm (Fossen,1999). The positioning controller calculates forces in surge, sway and yaw needed to maintain position and heading, while the thrust allocation algorithm takes the vector containing these forces, and calculates thrust and direction for each active thruster. The DP system generally includes an acoustic sensor system, control system, thruster system and power system as shown in Fig.1.

For safety reasons, DP vessels are typically designed with redundancy in mind (Fossen, 1996). As such, they usually have more actuators than are needed for motion control. In these cases, optimization theories are useful in finding thrust allocation solutions that minimize fuel consumption and regulate peak thrust levels to reduce “wear and tear” on a thruster.

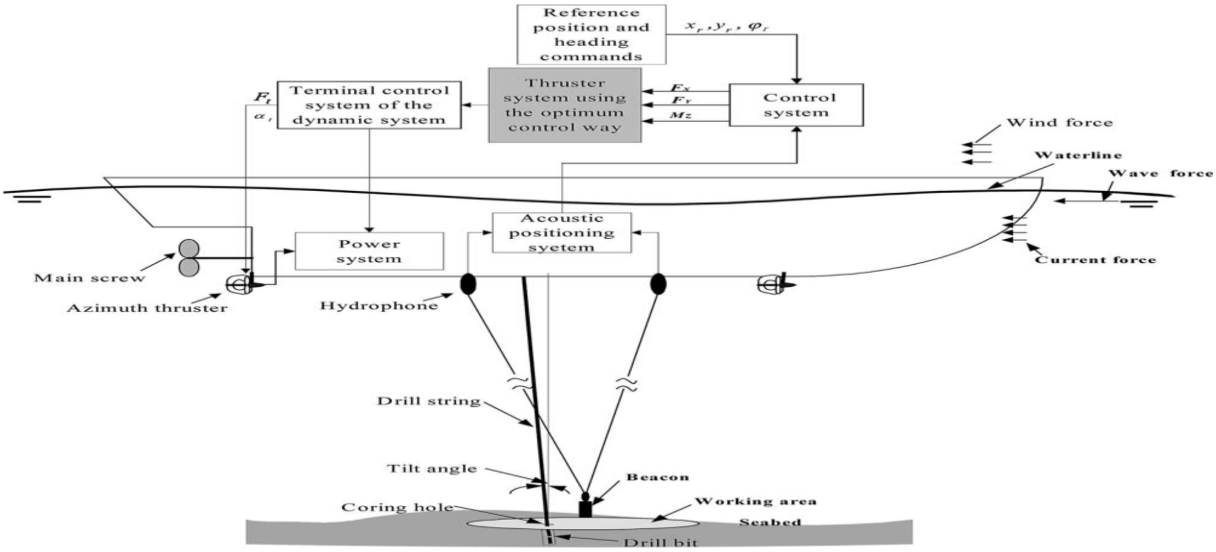


Fig. 1 Dynamic Positioning System of a Drill Ship

Some maritime applications of a DP system include cable and pipe laying, anchor handling, vessel-to-vessel fluid transfers, deep water drilling, dredging, crane barge operations, station keeping among others. DP system may also be used to hold station without anchors, perform maneuvers along predetermined tracks, and automatically follow other vehicles (Grimble, 1980). DP systems are used extensively in the offshore oil industry and they may as well be found wherever precise, low-speed motion control of a surface vessel is required.

The computer program to implement the DP system contains a mathematical model of the vessel that includes information pertaining to the wind and current drag of the vessel and the location of the thrusters. This knowledge, combined with the sensor information, allows the computer to calculate the required steering angle and thruster output for each thruster (IMCA, 2003). This allows operations at sea where mooring or anchoring is not feasible due to deep water, congestion on the sea bottom (pipes, templates) or other problems.

DP is concerned primarily with control of the ship in the horizontal plane that is the three axes: surge, sway and yaw. It is therefore make engineering sense to research on other methods to enhance the efficient operability and precise/accurate response of DP system to environmental changes. This work focuses on the need for a DP vessel that can rapidly and accurately distribute thrust, rotate the angle of thruster and provide an effective/optimal control of thruster system, using the sequential quadratic method (SQM) with constraints on the azimuth thrusters for a thruster system (Lindfors, 1993). The vessel considered is a 2,280 tons DP coring vessel (drillship) with five rotary azimuth thrusters.

II. METHODOLOGY

The parameters of the drill ship used for this work are shown below: Ship data

Dimensions:	117.9 M Long / 96.7 M Wide
Drafts:	23 M Drilling / 9.94 M Transit
Displacements: Transit	53,133 Tons Drilling / 38,000 Tons
Variable Load: Transit	7,000 Tons Drilling / 6,250 Tons
Max Water Depth:	3,000 M Designed / 3,000m Outfitted
Max Drilling Depth:	10,670 M
Dynamic Positioning:	Dynpos Autro, Posmoor Ata, Dp Class 3
Thrusters:	5x Rolls Royce 4,694 HP Azimuthing, 37 Tons
Transit Speed:	Up To 6 Knots
Mooring Lines:	4x 1,700 M 84 MM Chain
Mooring Winches:	2x Double Pusnes 450 KW
Main Engines:	8x WARTSILA 6,312 HP At 720 RPM
Main Generator:	8x ABB 6,312 HP

Behaviour of thrusters

At sea, when the vessel is moved by environmental forces and moments, the control system of the DP of the vessel computes the total desired thrust and moment commands - ΣFtx, ΣFty and ΣMtz, sufficient to move the vessel back to the reference position. If the vessel is equipped with a total of n thrusters, the thruster system commands the thrusters to produce the thrust F_{ti}, $i = 1,2,\ldots n$, and to rotate the direction of the thrusters α_{ti}, as shown in Fig. 2.

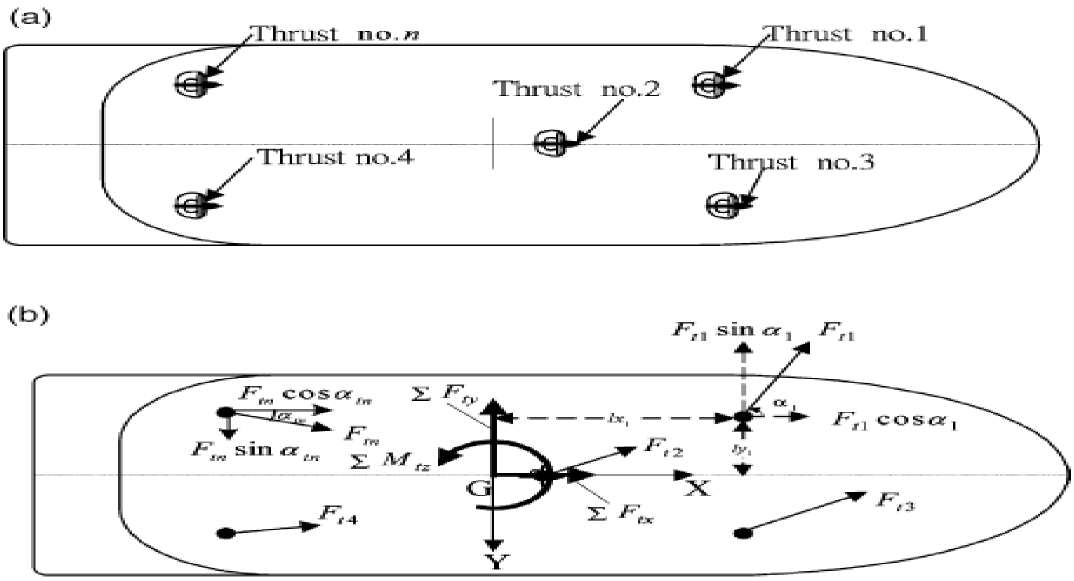


Fig. 2 Thrust allocation scheme for the thruster system:
(a) General arrangement of azimuth thrust. (b) The forces in surge and sway and moment in the yaw direction

The thrust need to determine in the surge (X-axis) and sway (Y-axis) directions, and the moment in the yaw direction, according to Fossen (1996) and Loria (2000) these are shown in the expressions below:

$F_{ti}\cos\alpha_{ti}$ *and* $F_{ti}\sin\alpha_{ti}$, (1)

$F_{ti}\sin\alpha_{ti}\cdot ly_{ti}$ *and* $F_{ti}\cos\alpha_{ti}\cdot lx_{ti}$. (2)

The thrust has to satisfy the desired resulting surge and sway forces as express in equation (3) and (4) follows:

$$\sum F_{tx} \geq F_{t1}cos\alpha_{t1} + F_{t2}cos\alpha_{t2} + \cdots + F_{tn}cos\alpha_{tn} \quad (3)$$

$$\sum F_{ty} \geq F_{t1}sin\alpha_{t1} + F_{t2}sin\alpha_{t2} + \cdots + F_{t2}sin\alpha_{tn} \quad (4)$$

The moment has to satisfy the desired resulting yaw moment as follows:

$$\sum M_{tz} \geq F_{t1}cos\alpha_{t1}\cdot lx_1 + F_{t2}cos\alpha_{t2}\cdot lx_2 + \cdots + F_{tn}cos\alpha_{tn}\cdot lx_n + F_{t1}sin\alpha_{t1}\cdot ly_1 + F_{t2}sin\alpha_2\cdot ly_2 + \cdots + F_{tn}sin\alpha_{tn}\cdot ly_n \quad (5)$$

Where F_{t1}, F_{t2}, F_{t3},...,F_{tn} is the unknown thrusts from the first to nth thruster respectively.

α_{t1}, α_{t2}, α_{t3} ,....,α_{tn} is the unknown directions of the thrust from the first to *nth* thruster respectively.

$l_{x1}, l_{x2}, \ldots, l_{xn}, l_{y1}, l_{y2}, \ldots, l_{yn}$i is the known distance from the center of rotation of the vessel to the thrust, respectively.

The structure of azimuth thruster for deriving the low-frequency, desired azimuth angle α_{ti} of a given thruster is shown in Fig. 2 (b), where $F_{ti}sin\alpha_{ti}, F_{ti}cos\alpha_{ti}$ are the two-dimensional vector forces F_{ti} corresponding to the actual azimuth thruster (10). From equations (3) to (5), the thrusts from the thrusters must satisfy the desired thrust and moment commands subject to nonlinear equality and inequality constraints.

Optimum Control using Matrix method

The thrust $F_{ti}, i = 1,2 \ldots n$ and the azimuth angles α_{ti} are just sufficient to counteract the mean environmental force over a given time period. Therefore, an objective function ensures that the total thrust commands given by each of the n thruster devices under these constraints will be minimum.

In the light of the analysis of thruster system, the design variables are the thrust F_{ti} and the azimuth angles $\alpha_{ti}, i = 1,2,3 \ldots n$. The design variables are:

$$X = \{x_i\} = \{F_{t1}, \alpha_{t1}, F_{t2}, \alpha_{t2}, \ldots, F_{tn}, \alpha_{tn}\} \quad (6)$$

Objective Function

For economy and effectiveness of the thruster system, the total thrust commands given by each of the n thruster devices will be the minimum according Milne (1983).

$$Min.f(X) = (F_{t1}cos\alpha_{t1} + F_{t1}sin\alpha_{t1} + F_{t2}cos\alpha_{t2} + F_{t2}sin\alpha_{t2} + \cdots + F_{tn}cos\alpha_{tn} + F_{tn}sin\alpha_{tn}) \quad (7)$$

Constraint on the behavior of the thrust in the X direction: The sum of the minimum thrust of n thrusters in the X direction, $F_{tn}cos\alpha_{tn}$, must satisfy (non negative) the thrust requirement (Fig.2b):

$g_1(X) = \sum F_{tx} - (F_{t1}cos\alpha_{t1} + F_{t2}cos\alpha_{t2} + \cdots + F_{tn}cos\alpha_{tn}) \leq 0$ (8)

Constraints on the behaviour of the thrust in the Y direction: The sum of the minimum thrust of *n* thrusters in the Y direction, $F_{tn}sin\alpha_{tn}$, must satisfy (nonnegative) the thrust requirement(Fig.2b):

$g_2(X) = \sum F_{ty} - (F_{t1}sin\alpha_{t1} + F_{t2}sin\alpha_{t2} + \cdots + F_{tn}sin\alpha_{tn}) \leq 0$ (9)

Constraints on the behaviour of the moment in Z direction: The sum of minimum moment of *n* thruster in the Z direction must satisfy (equal) the thrust requirement (Fig.3 b):

$h_1(X) =$
$\sum M_{tz} - (F_{t1}cos\alpha_{t1}.lx_1 + F_{t2}cos\alpha_{t2}.lx_2 + \cdots + F_{tn}cos\alpha_{tn}.lx_n + F_{t1}sin\alpha_{t1}.ly_1 + F_{t2}sin\alpha_{t1}.ly_2 + \cdots +$
Ftnsinαtn.lyn=0 (10)

Equation (7) to (9) will be used in the present optimum control design for a dynamic positioning system

Design Variables

There were design variables for the thrust and the angle of the five azimuth thrusters. Based on Eq. (6), we can list these variables as follows:

$X = \{x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8, x_9, x_{10}\} = \{F_{t1}, \alpha_{t1}, F_{t2}, \alpha_{t2}, F_{t3}, \alpha_{t3}, F_{t4}, \alpha_{t4}, F_{t5}, \alpha_{t5}\}$ (11)

The objective function is the minimum total desired thrust output by the five thruster devices under these constraints. Therefore, using Eq. (7), we could determine the objective function as

$Min.f(X) = (F_{t1}cos\alpha_{t1} + F_{t1}sin\alpha_{t1} + F_{t2}cos\alpha_{t2} + F_{t2}sin\alpha_{t2} + F_{t3}cos\alpha_{t3} + F_{t3}sin\alpha_{t3} + F_{t4}cos\alpha_{t4} +$
$F_{t4}sin\alpha_{t4} + F_{t5}cos\alpha_{t5} + F_{t5}sin\alpha_{t5})$ (12)

The design constraints to the DP system are given in the expressions of equation (13) to (15)

$g_1 = \sum F_X - (F_{t1}cos\alpha_{t1} + F_{t2}cos\alpha_{t2} + F_{t3}cos\alpha_{t3} + F_{t4}cos\alpha_{t4} + F_{t5}cos\alpha_{t5}) \leq 0$ (13)

$g_2 = \sum F_y - (F_{t1}sin\alpha_{t1} + F_{t2}sin\alpha_{t2} + F_{t3}sin\alpha_{t3} + F_{t4}sin\alpha_{t4} + F_{t5}sin\alpha_{t5}) \leq 0$ (14)

$\square_1 = \sum M_Z - (F_{t1}cos\alpha_{t1}.lx_1 + F_{t2}cos\alpha_{t2}.lx_2 + F_{t3}cos\alpha_{t3}.lx_3 + F_{t4}cos\alpha_{t4}.lx_4 + F_{t5}cos\alpha_{t5}.lx_5 +$
$F_{t1}sin\alpha_{t1}.ly_1 + F_{t2}sin\alpha_{t2}.ly_2 + F_{t3}sin\alpha_{t3}.ly_3 + F_{t4}sin\alpha_{t4}.ly_4 + F_{t5}sin\alpha_{t5}.ly_5$ (15)

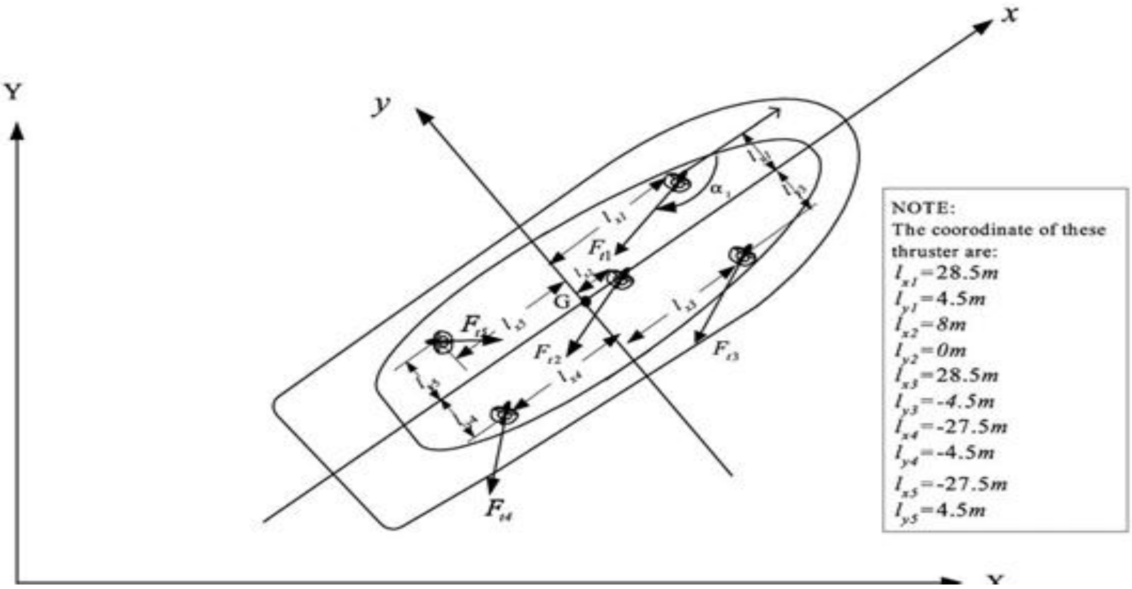


Fig. 3 Thruster Coordinate

The values of $ly_1 to\ ly_5$ are given as follows:

$ly_1 = 4.5m\,; lx_1 = 28.5m$
$ly_2 = 0m\,; lx_2 = 8m$
$ly_3 = -4.5m\,; lx_3 = 28.5m$
$ly_4 = -4.5m\,; lx_4 = -27.5m$
$ly_5 = 4.5m\,; lx_5 = -27.5m$

Equation Modification

Given: Mass of the thrusters, M = 37 tons = 37000kg

But $F = M \times A$

$F = M \times \frac{l}{t^2}$ (16)

Let $K = \frac{M}{t^2}$ therefore

$F = K \times l$ (17)

Where F is thrust force in Newton, L is distance in Meter and t is Time in seconds

Substitution equation (17) into equations (11) to (14)

$Min. f(X) = K[(lx_1 cos\alpha_{t1} + ly_1 sin\alpha_{t1} + lx_2 cos\alpha_{t2} + ly_2 sin\alpha_{t2} + lx_3 cos\alpha_{t3} + ly_3 sin\alpha_{t3} + lx_4 cos\alpha_{t4} +$ *ly4sinat4+lx5cosat5+ly5sinat5]* (18)

$g_1 = \sum F_X - K[(lx_1 cos\alpha_{t1} + lx_2 cos\alpha_{t2} + lx_3 cos\alpha_{t3} + lx_4 cos\alpha_{t4} + lx_5 cos\alpha_{t5})] \leq 0$ (19)

$g_2 = \sum F_y - K[(ly_1 sin\alpha_{t1} + ly_2 sin\alpha_{t2} + ly_3 sin\alpha_{t3} + ly_4 sin\alpha_{t4} + ly_5 sin\alpha_{t5}) \leq 0$ (20)

$\square_1 = \sum M_Z - K[(lx_1 cos\alpha_{t1}.lx_1 + lx_2 cos\alpha_{t2}.lx_2 + lx_3 cos\alpha_{t3}.lx_3 + lx_4 cos\alpha_{t4}.lx_4 + lx_5 cos\alpha_{t5}.lx_5 + ly_1 sin\alpha_{t1}.ly_1 + ly_2 sin\alpha_{t2}.ly_2 + ly_3 sin\alpha_{t3}.ly_3 + ly_4 sin\alpha_{t4}.ly_4 + ly_5 sin\alpha_{t5}.ly_5)]$ (21)

Equations (17) to (20) will be simulated using MATLAB for a time interval of 25secs each for a period of 250secs to obtain the thrusts and directions of thrusts of the five thrusters.

III. RESULTS

The simulated results are shown in table 3.1.

Table 3.1 Table of Resultant forces with respect to Time

S/N	TIME	$\sum F_X$	$\sum F_Y$	$\sum M_Z$
1	0	0	0	0
2	25	592	0	592
3	50	148	0	148
4	75	65.78	0	65.78
5	100	37	0	37
6	125	23.68	0	23.68
7	150	16.4	0	16.4
8	175	12.08	0	12.08
9	200	9.25	0	9.25
10	225	7.3	0	7.3
11	250	5.92	0	5.92

Table 3.2 Table of Thrust forces and angles in Surge direction with respect to Time

S/N	TIME	F_1	α_1	F_2	α_2	F_3	α_3	F_4	α_4	F_5	α_5
1	0	0	1	0	1	0	1	0	1	0	1
2	25	1687.2	103.95	473.6	0	1687.2	170.09	1628	41.93	1628	97.29
3	50	421.8	103.95	118.4	0	421.8	170.09	407	4193	407	97.29
4	75	187.46	92.86	52.6	0	187.46	101.78	180.89	81.12	180.89	75.10
5	100	105.45	103.95	29.6	0	105.45	170.09	101.75	41.93	101.75	97.29
6	125	67.48	100.66	18.94	0	67.48	60.63	65.12	111.73	65.12	100.66
7	150	46.86	92.86	13.15	0	46.86	101.78	45.22	81.12	45.22	75.10
8	175	34.43	87.47	9.66	0	34.43	79.62	33.22	97.81	33.22	92.43
9	200	26.36	103.95	7.4	0	26.36	170.09	25.73	41.93	25.73	97.29
10	225	20.82	77.15	5.84	0	20.82	24.75	20.09	133.29	20.09	92.35
11	250	16.87	83.10	4.73	0	16.87	60.63	16.28	111.73	16.28	100.66

Table 3.3 Table of Thrust forces and angles in Sway direction with respect to Time

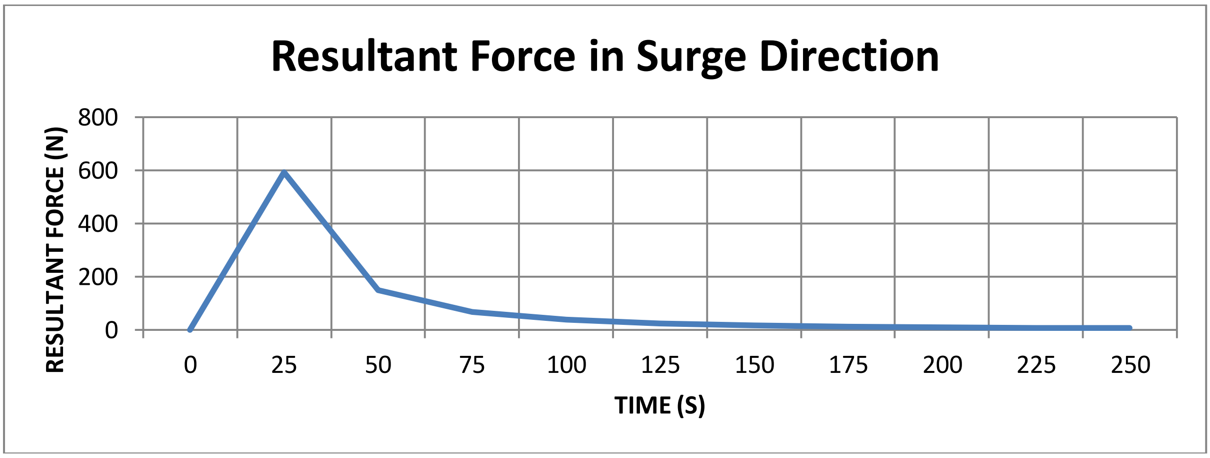
S/N	TIME	F_1	α_1	F_2	α_2	F_3	α_3	F_4	α_4	F_5	α_5
1	0	0	0	0	0	0	0	0	0	0	0
2	25	266.4	-13.95	0	0	266.4	-80.09	266.4	48.06	266.4	-7.29
3	50	66.6	-13.95	0	0	66.6	-80.09	66.6	48.06	66.6	-7.29
4	75	29.6	-2.86	0	0	29.6	-11.78	29.6	8.87	29.6	14.89
5	100	16.65	-13.95	0	0	16.65	-80.09	16.65	48.06	16.65	-7.29
6	125	10.65	-10.66	0	0	10.65	29.36	10.65	-21.73	10.65	-10.66
7	150	7.4	-2.86	0	0	7.4	-11.78	7.4	8.87	7.4	14.89

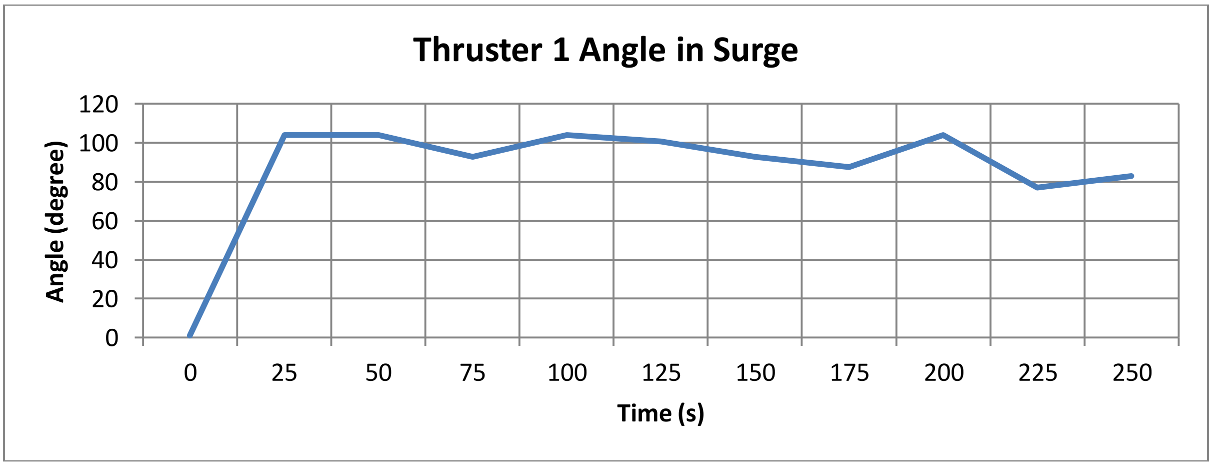
8	175	5.43	2.53	0	0	5.43	10.37	5.43	-7.81	5.43	-2.43
9	200	4.16	-13.95	0	0	4.16	-80.09	4.16	48.06	4.16	-7.29
10	225	3.28	12.84	0	0	3.28	65.24	3.28	-43.29	3.28	-2.35
11	250	2.66	6.89	0	0	2.66	29.37	2.66	-21.73	2.66	-10.66

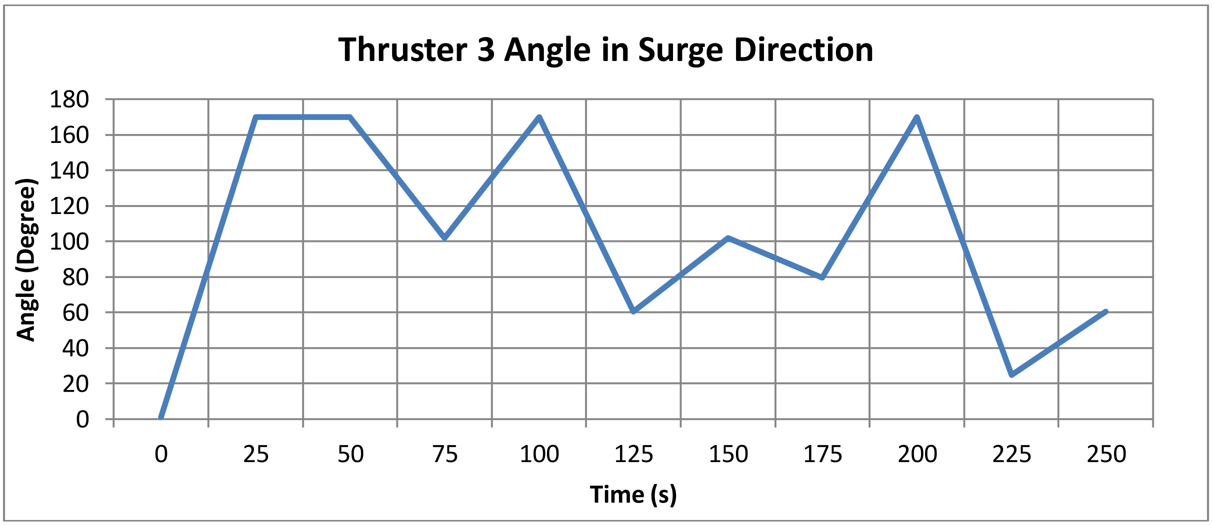
Table 3.4 Table of Moment and angles in Yaw Direction with respect to Time

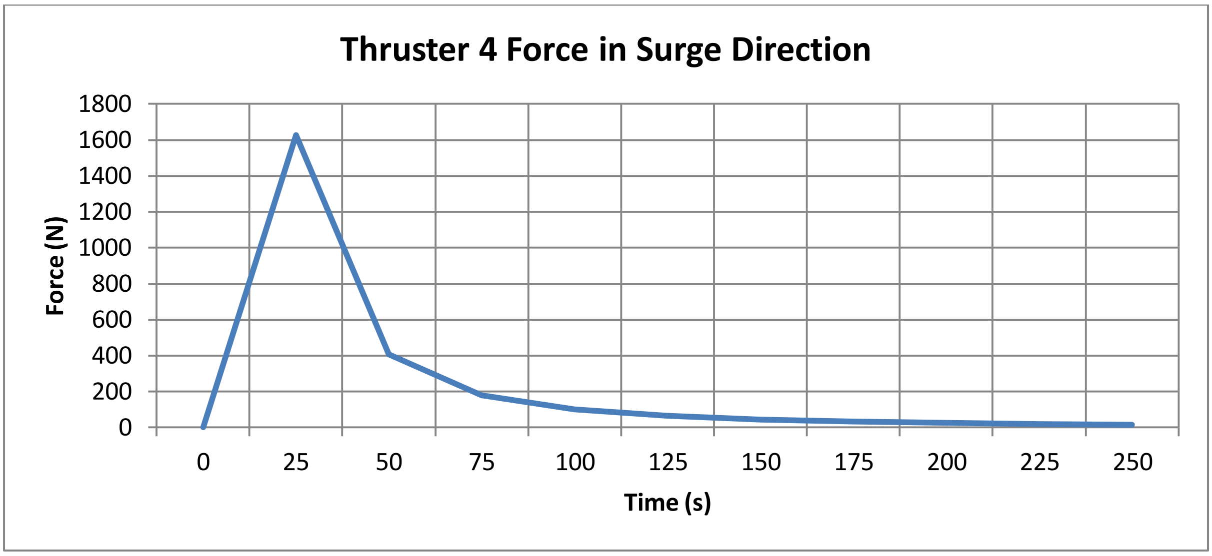
S/N	TIME	F_1	α_1	F_2	α_2	F_3	α_3	F_4	α_4	F_5	α_5
1	0	0	1	0	1	0	1	0	1	0	1
2	25	49284	90	3788.2	90	49284	90	45969	90	45969	90
3	50	12321	90	947.2	90	12321	90	11492	90	11492	90
4	75	5476	90	420.98	90	5476	90	5107.6	90	5107.6	90
5	100	3080.3	90	236.8	90	3080.3	90	2873.1	90	2873.1	90
6	125	1971.4	90	151.55	90	1971.4	90	1838.8	90	1838.8	90
7	150	1369	90	105.24	90	1369	90	1276.9	90	1276.9	90
8	175	1005.8	90	77.32	90	1005.8	90	938.14	90	938.14	90
9	200	770.06	90	59.2	90	770.06	90	718.26	90	718.26	90
10	225	608.4	90	46.77	90	608.4	90	567.51	90	567.51	90
11	250	492.84	90	37.88	90	492.84	90	459.18	90	459.18	90

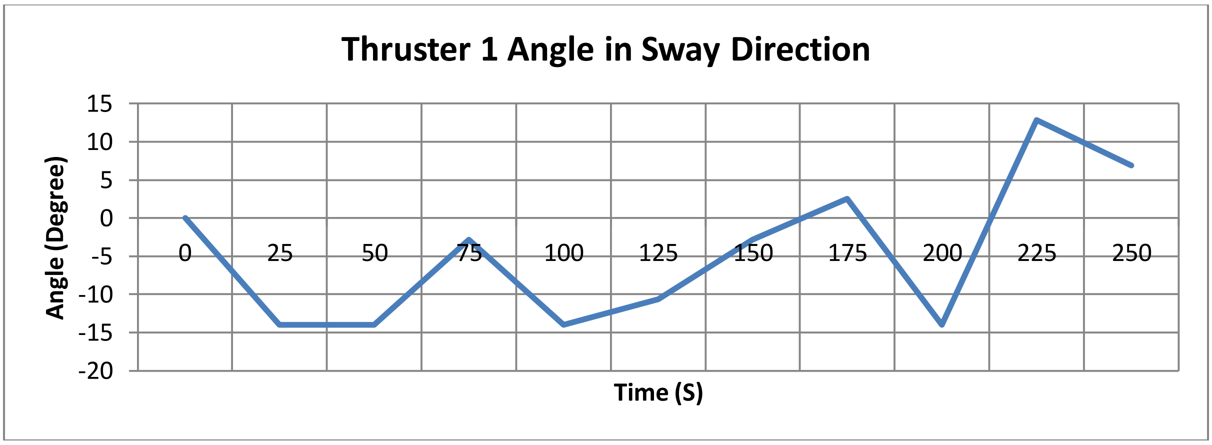
Graphs showing the relationship between thrust force and angle with respect to time is shown below in surge, sway and yaw direction

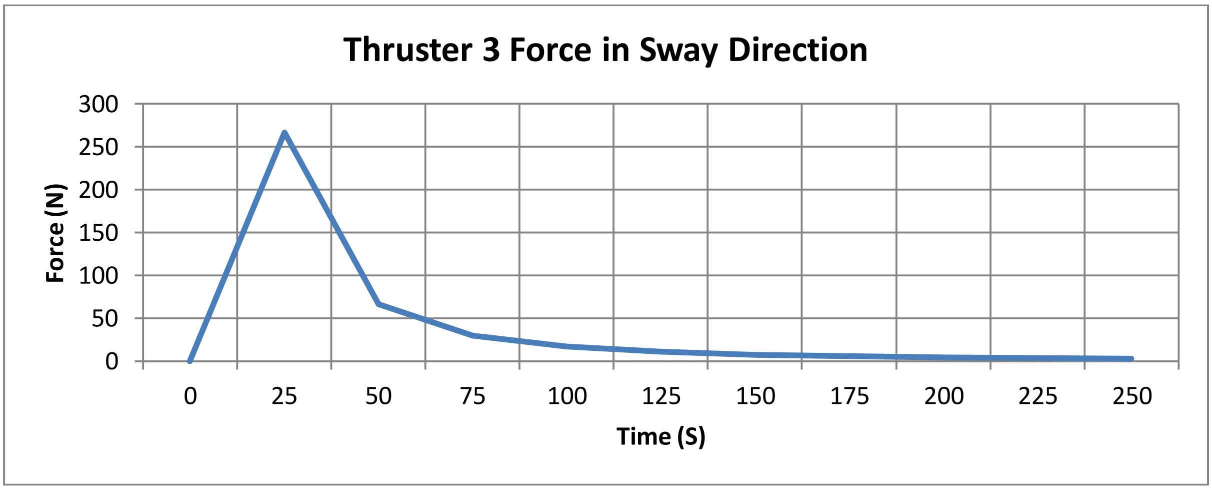


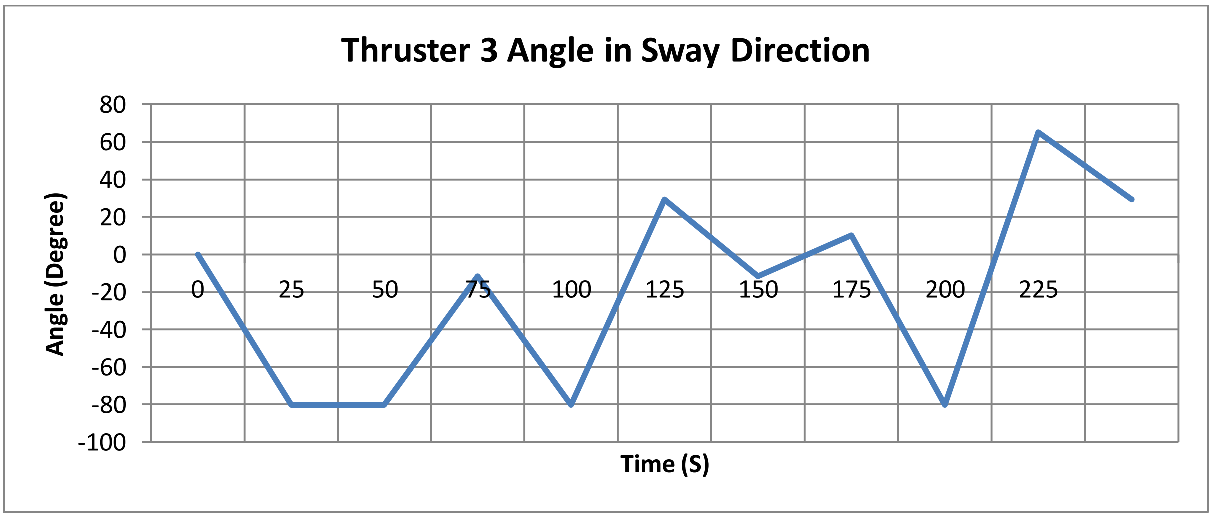


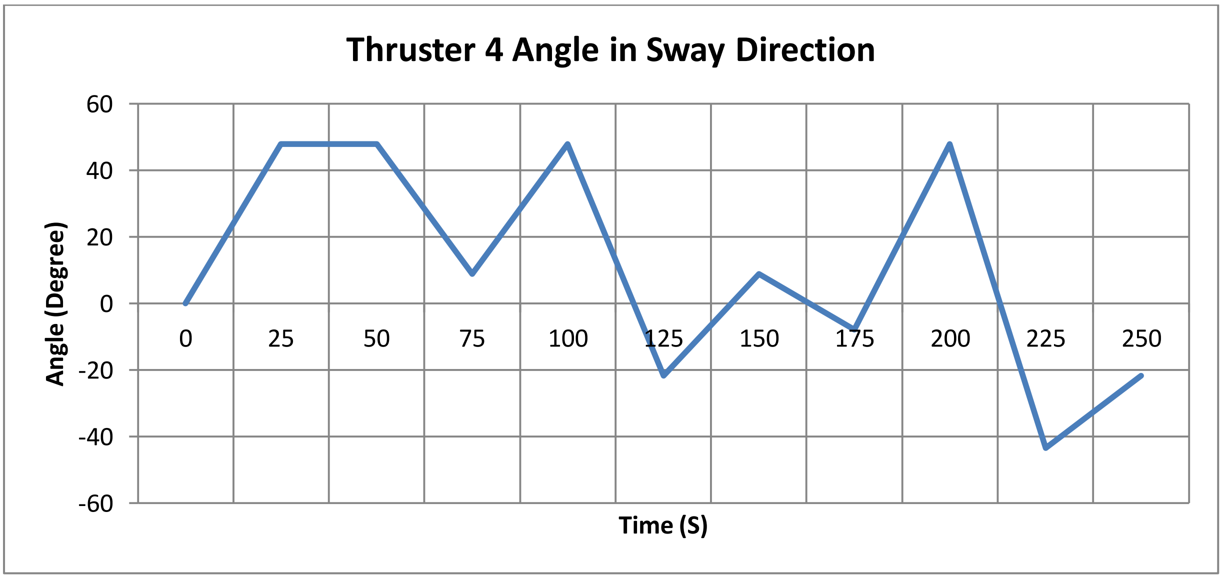

Thruster 3 Angle in Surge Direction
Angle (Degree)
180
160
140
120
100
80
60
40
20
0
0 25 50 75 100 125 150 175 200 225 250
Time (s)


Thruster 4 Force in Surge Direction
Force (N)
1800
1600
1400
1200
1000
800
600
400
200
0
0 25 50 75 100 125 150 175 200 225 250
Time (s)


Thruster 1 Angle in Sway Direction
Angle (Degree)
15
10
5
0
-5
-10
-15
-20
0 25 50 75 100 125 150 175 200 225 250
Time (S)







IV. DISCUSSION OF SIMULATION RESULTS

Using Matlab Matrix method on the mathematical model in section III, the above results was obtained displayed in table 3.1 to table 3.4.

Thrust force and rotational angle is dependent on time, while the mass of thruster and distance of thruster from the centre of gravity of the vessel is constant. The Azimuth thruster produces thrust in the surge, sway and yaw direction. The essence of thrust modulation and optimization is to ensure that the thrusters are able to counteract wind, wave and current forces effectively without increasing power consumption to maintain vessel position.

Since there are five thrusters on the vessel, and based on the arrangements as shown in section III, the figure showing thruster 1 angle in surge, the thrusters cannot exert forces at 180^o so as to improve thruster-thruster relationship while the vessel is positioned to counter external forces. Distances of center of gravity taking the negative form indicates the position.

From table 3.2, it is seen that the thrust force for all five thrusters is irregular with respect to time. There is also continuous reduction of thrust force as time increases. The control system responsible for thrust modulation only takes into account the mass of the thrusters, distance of thrusters from center of gravity of the vessel and the time. At 25 seconds interval for 10 trials, thrust force reduces and so power consumption from the main engine is reduce because power is directly proportional force. Also, the rotational angle of the thrusters is irregular as time changes at a constant rate. The rotational angle of thruster 2 is zero indicating that the thruster will only exert thrust force and not rotate irrespective of the wind, wave and current changes.

From table 3.3, it indicates that thrust force reduces as time increases. Thruster 1, 3, 4 and 5 exerts exactly the thrust force. Thruster 2 does not exert any force irrespective of time. The rotational angles of all thrusters except thruster 2 are irregular. It can also be observed that the thrust forces are exerted at negative angles or angle in the opposite direction. Again, since power is directly proportional to force, the power consumption is reduced as time increases from 25 seconds to 250 seconds.

Table 3.4 provide information on moment of thrusters and angles in the yaw direction, it indicates that thrust force decreases with increase in time. This results to reduced power consumption. The rotational angles of all thrusters are constant, indicating that all five thrusters will exert force at same angles irrespective of time.

From the above tables it is seen that at a particular time each thruster exerts thrust force at a particular angle in surge, sway and yaw direction. In reality, it is not possible for a thruster to exert force at an angle in both surge, sway and yaw direction. But it is possible that at a particular time each thruster based on their arrangement will exert force in either the surge, sway or yaw direction at a particular angle. Thruster arrangement is crucial for any vessel to be able to counter external forces effectively. Poor thruster arrangement will have negative impact and lead to damages to the vessel and crew on board.

V. CONCLUSIONS

The main purpose of equipping any vessel with the dynamic positioning system is to ensure that the vessel is able to maintain position and heading by effective control and modulation of thrusters against external forces. The thrusters to properly exert force at any angle, the control system must interpret the mathematical model installed in the system and send signals to the thrust allocation controller to effect changes in the thrusters. Hence it is necessary that an efficient mathematical model is developed to achieve effective and efficient thrust control.

The main purpose of a thruster system is to maintain a vessel within a designed weathervaning window from a desired position using a thrust-producing mechanism as quickly and accurately as possible. This work has presented an optimum control making, effective and reduced lost thrust modulation for a thruster system using Matlab.

It has been shown that the dynamic positioning drillship using Matlab method can easily, quickly and accurately solve a positioning problem with sufficient variables and constraints. Thus, the optimum control of the thruster system using Matlab is economical and effective. It can automatically modulate the thrusts and angles of the thrusters, thus reducing wear and tear, and minimizing the required thrust and power.

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