**Conceptual design of dynamic positioning system for tugboat to improve safer operation in Indonesia, case study: port of Cilacap**

I M Ariana¹, T A Akbar², M S B Prakosa¹, J Prananda¹, W Tyasayumranani³

¹ Department of Marine Engineering, Faculty of Marine Technology, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia
² Center of Excellences for Maritime Safety and Marine Installation, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia
³ Department of Maritime Transportation System, Mokpo National Maritime University, South Korea

Email: thariqakb@gmail.com

**Abstract.** Due to increasing demand of the port activity it requires rapid operations of ship assisting and tug. Complex operations combined with challenging environmental disturbance often lead to ship accident that caused damaged to the jetty or the ship itself that also disrupt the overall port operation. On of the cause that lead such accidents is the limited capability of the tugboat to handle manoeuvre in extreme environment condition. Beside the safety of the operation are threatened this is also one factor that lead to decreased in tug operation effectiveness. This study intend to analyse the potential of dynamic positioning (DP) system used in the tugboat. Port of Cilacap used as study case due to special requirement as well as challenging location that lead in extreme condition of port operation. Two type of propulsion are used which is Azimuth and Void-Schneider propulsion. The conceptual system design is analysed by perform modelling simulation in Matlab software. Several condition of operation among the type of propulsion are assessed. The result is that DP system on tugboat could reduce the potential uncontrolled movement of the ship that lead to the accident. The analysis also proved that DP system of the ship can increase effectiveness of the operations by reducing the response time during manoeuvring.

**1. Introduction**

Rapid growth in the shipping industry especially in Indonesia compel a requirement of enhanced port operation as well as improvement of the safety aspect. One of the key aspects in the port operation is tug assisting for the ship entering the port. According to Indonesia’s regulation PM No. 93 2014 it state that every ship regardless its size has to be escorted and assisted by pilot and tugboat(s) [1]. The main reason of obligatory escort and tug assisting is to ensure the safe approach in the passage as well as governing the well-organized vessel traffic in the port and channel. Even though the obligatory assisting by tug is already performed there are still occur several cases accident happen related to tug assisting in the port. One of the main sources of the accidents is extreme environmental disturbance at the port. Even though in general the tug operation is limited by environmental state criteria, the sudden change in environment sometimes cannot be avoided. Besides, the dynamic and rapid operation of port...
also often require quick and responsive action as the wharf time allocation is limited and the berthing allocation has been determined.

Port of Cilacap is one of the ports that limited to serve a refinery unit, so most of the ship being handled is a tanker ship with crude oil cargo. The location of the port of Cilacap is located at southern part of Central Java province and headed directly to the Indian Ocean create challenging condition for the operator. High current speed from the Indian Ocean is one of the challenges beside the fluctuation of the weather in general also escalates the level of complexity to assist the ship into the port. As the main port used to provide crude oil to the refinery, port of Cilacap encounter high frequency of ship occupancy. The rapid operation combined with the environmental condition often lead to minor and major accident prior to tug assisting operation especially in berthing and un-berthing process. The common accidents mode occurs is the ship was slammed and damaged a berthing dolphin which occurred due to slow response of tug operation to an environmental disturbance that applied to the ship. Number of cases been occurred at port of Cilacap, at least from 2014 to 2016 interval there are five cases related to ship accident during berthing and un-berthing operation. The detail data of the cases are shown in Table 1.

Table 1. Number of Ship Accidents Occur at Port of Cilacap

| No. | Accident in Operation and Assist of Tug Services                      | Date       |
|-----|-----------------------------------------------------------------------|------------|
| 1   | MT. Gamalama crashed Berthing Dolphin CIB 2                           | August 12th, 2014 |
| 2   | MT. Martha Petrol Grounded at the Outside of Voyage Line              | May 3th, 2015          |
| 3   | MT. Permata Niaga crashed Jetty II, Area 60                           | August 10th, 2015     |
| 4   | MT. Fastron crashed Jetty I, Area 70                                  | September 18th, 2015  |
| 5   | MT. Atlantic Point crashed MT. Sinar Busan and Berthing Dolphin Jetty II, Area 70 | March 28th, 2016 |

Based on the number of cases and the necessity to improve the level of safety aspect therefore on this study Port of Cilacap been chosen as study case. One of the proposed methods to improve is by enhancing the capability of the tugboat used to overcome the challenging operation at Port of Cilacap. One of the limitations of the tug to overcome the environment disturbance is due to limited maneuverability of the tugboat. The conventional configuration of propulsion and steering system of the tugboat is seen as main cause of the limited maneuverability. To improve those issue there are several methods can be taken, but the one seen as the most effective way is to use advanced propulsion and station-keeping for the tugboat. One of the advanced types of propulsion is dynamic positioning system by using Azimuth Thruster and Voith Schneider Propeller. The intent of this study to arrange a concept design of DP tugboat that could increase the effectiveness and safety of tug operation in CIB and SPM operation areas at Port of Cilacap. Also, to analyze the response of DP tugboat in variation condition such as static and dynamic movement of tug operation and variation in propulsion system with Azimuth Thruster and Voith Schneider Propeller.
2. Model development of dynamic positioning system

2.1. Dynamic positioning system of tugboat
Dynamic positioning is a system main purpose is to maintain ship positioning using its own propulsion system [2]. The following Figure 1 is the DP system components.

**Figure 1. DP System Components [2]**

Figure 1 shown the main components of DP system which are environmental reference systems, position reference systems, heading reference systems, thrust and propulsion systems, and power generation. These components are needed to make DP system works. Moreover, the following Figure 2 is the DP system working scheme.

**Figure 1. DP System Working Scheme**
2.2. Ship Dynamic Modelling

The following equation is the basic formula for ship dynamical modelling is come from the derivative of Second Law of Newton [3].

\[ M \ddot{\mathbf{v}} + C(\mathbf{v})\mathbf{v} + D(\mathbf{v})\mathbf{v} + \mathbf{g}(\mathbf{\eta}) = \mathbf{u} \]  

(1)

Therefore, the equation presented will follow the nomenclature as shown below:

- \( M \) \quad \text{Inertia Matrix}
- \( C(\mathbf{v}) \) \quad \text{Coriolis Matrix}
- \( D(\mathbf{v}) \) \quad \text{Damping Matrix}
- \( \mathbf{g}(\mathbf{\eta}) \) \quad \text{Force Vector and Moment of Gravity}
- \( \mathbf{u} \) \quad \text{Control Input}
- \( M \) \quad \text{Ship mass}
- \( X_G \) \quad \text{Specific gravity}
- \( I_z \) \quad \text{Inertia moment at z-axis}
- \( u_0 \) \quad \text{Linear velocity at x-axis}
- \( Y_s \) \quad \text{Force derivative of sway direction against } \dot{\mathbf{v}}
- \( Y_r \) \quad \text{Force derivative of sway direction against } \dot{\mathbf{r}}
- \( Y_p \) \quad \text{Force derivative of sway direction against } \mathbf{p}
- \( N_s \) \quad \text{Moment derivative of sway against } \dot{\mathbf{v}}
- \( N_r \) \quad \text{Moment derivative of sway against } \dot{\mathbf{r}}
- \( N_p \) \quad \text{Moment derivative of sway against } \mathbf{p}
- \( Y_a \) \quad \text{Actuator force at y-axis}
- \( N_a \) \quad \text{Moment actuator around z-axis}

Thus, this following equation is the derivative equation from equation (1) shown in equation (2) until (7).

\[ m[\ddot{u} - \dot{v}r + \dot{w}q - x_G(q^2 + r^2) + y_G(pq - \dot{r}) + z_G(\dot{r}w + \dot{q}r)] = \dot{X} \]  

(2)

\[ m[\ddot{v} - \dot{w}p + \dot{u}r - y_G(r^2 + p^2) + z_G(qr - \dot{p}) + x_G(qp + \dot{r})] = \dot{Y} \]  

(3)

\[ m[\ddot{w} - \dot{u}q + \dot{v}p - z_G(p^2 + q^2) + x_G(rp - \dot{q}) + y_G(qr + \dot{p})] = \dot{Z} \]  

(4)

\[ I_x \ddot{\mathbf{q}} + (I_z - I_y)qr + m[y_G(\dot{w}uq + \dot{vp}) - z_G(\dot{v}wp + \dot{u}r)] = \dot{K} \]  

(5)

\[ I_y \ddot{\mathbf{q}} + (I_x - I_z)r\dot{p} + m[z_G(\ddot{u}vr + \dot{w}q) - x_G(\dot{u}wp + \dot{vq})] = \dot{M} \]  

(6)

\[ I_z \ddot{\mathbf{r}} + (I_y - I_x)pq + m[x_G(\ddot{v}wp + \dot{u}r) - y_G(\dot{v}cr + \dot{w}q)] = \dot{N} \]  

(7)

There is some assumption in control equation as follows:

1. Mass distribution is homogeny and xy field is symmetric (\( I_{xy} = I_{yx} = 0 \))
2. Pitch, roll, and heave are neglected (\( \omega = \gamma = \mathbf{p} = \dot{\gamma} = \dot{\mathbf{p}} = 0 \))

The following equation (8) and (9) is the transformation of equation (2) until (7) because of the assumption in control equation.

**Sway:**

\[ m(\ddot{\mathbf{v}} + \dot{\mathbf{u}}r + x_G\dot{r}) = \dot{Y} \]  

(8)
Yaw:

\[ I_x \ddot{r} + mx_c (\dot{v} + ur) = N \]  (9)

In this research, ship dynamical modeling which used is the Model of Davidson and Schiff. According to hydrodynamic force and moment for linear theory, equation (8) and (9) could be modify to equation (10) and (11) as follows.

\[
\text{Sway} : m(\ddot{v} + ur + x_c r^2) = Y_s \ddot{v} + Y_r \ddot{r} + Y_{cr} v + Y_{rr} r + Y_{sr} \delta_s
\]  (12)

\[
\text{Yaw} : I_x \ddot{r} + mx_c (\dot{v} + ur) = N_x \ddot{v} + N_x \ddot{r} + N_{cx} v + N_{cr} r + N_{xr} \delta_s
\]  (13)

Then, equation (12) and (13) are transformed into equation (14) and (15) as follows.

\[
(m - Y_s) \ddot{v} + (mx_c - Y_s) r^2 - Y_s v + (mu - Y_r) r = Y_s \delta_s
\]  (14)

\[
(mx_c - N_s) \ddot{v} + (I_x - N_s) \ddot{r} - N_c v + (mx_c u - N_r) r = N_s \delta_s
\]  (15)

According to ship motion equation (16) with \( \dot{v} = [v, r]^T \) state vector and \( \delta_R \) is ship’s rudder angle. Thus, given inertia matrix or M (17), damping matrix (18), and force matrix (19) as follows.

\[
M \ddot{v} + N(u_\theta) v = b \delta_s
\]  (16)

\[
M = \begin{bmatrix}
  m - Y_s & mx_c - Y_s \\
  mx_c - N_s & I_x - N_s
\end{bmatrix}
\]  (17)

\[
N(u_\theta) = \begin{bmatrix}
  -Y_s & mu - Y_r \\
  -N_s & mx_c u - N_r
\end{bmatrix}
\]  (18)

\[
b = \begin{bmatrix}
  Y_s \\
  N_s
\end{bmatrix}
\]  (19)

It is known that \( N(u_\theta) \) matrix is the equation that comes from the sums up of linear damping D and Coriolis and centripetal terms \( \mathbf{C}(u_\theta) \), then

\[
N(u_\theta) = \mathbf{C}(u_\theta) + D
\]  (20)

Given the model of state space (Rowell, 2002) which related to ship motion equation (16) by making \( \dot{x} = [v, r]^T \) as state vector and \( u = \delta_R \). The following equation (21) until (23) are the model of state space.

\[
\dot{x} = Ax + b_t u
\]  (21)

\[
A = -M^{-1} N = \begin{bmatrix}
  a_{11} & a_{12} \\
  a_{21} & a_{22}
\end{bmatrix}
\]  (22)

\[
b_t = M^{-1} b = \begin{bmatrix}
  b_1 \\
  b_2
\end{bmatrix}
\]  (23)
In equation (22) and (23), there are determinant of matrix M and matrix N which value comes from equation (24) and (25) as follows.

\[
det(M) = (m - Y_p)(I_r - N_r) - (mx_r - N_r)(mx_r - Y_r)
\]  

(24)

\[
det(N) = Y_p(N_r - mx_r u_n) - N_r(Y_r - mu_n)
\]  

(25)

Besides determinant of matrix M and matrix N, there are some coefficient in equation (22) and (23) which value could be found using equation (26) until (31).

\[
a_{11} = \frac{(I_r - N_r)Y_p - (mx_r - Y_r)N_p}{\det(M)}
\]  

(26)

\[
a_{12} = \frac{(I_r - N_r)(Y_p - mu_n) - (mx_r - Y_r)(N_p - mx_r u_n)}{\det(M)}
\]  

(27)

\[
a_{21} = \frac{(m - Y_p)N_p - (mx_r - N_r)Y_r}{\det(M)}
\]  

(28)

\[
a_{22} = \frac{(m - Y_p)(N_r - mx_r u_n) - (mx_r - N_r)(Y_r - mu_n)}{\det(M)}
\]  

(29)

\[
b_1 = \frac{(I_r - N_r)Y_p - (mx_r - Y_r)N_p}{\det(M)}
\]  

(30)

\[
b_2 = \frac{(m - Y_p)N_p - (mx_r - N_r)Y_r}{\det(M)}
\]  

(31)

Moreover, hydrodynamic coefficient that used in equation (17) until (19) are the result from linear regression Clarke (1982) which is empirical equation as follows from equation (32) until (43).

\[
\frac{-\gamma_p}{\pi (\tau/L)^2} = 1 + 0.16 \frac{C_p B}{T} - 5.1 \left( \frac{B}{L} \right)^2
\]  

(32)

\[
\frac{-\gamma_F}{\pi (\tau/L)^2} = 0.67 \left( \frac{B}{L} \right) - 0.0033 \left( \frac{B}{T} \right)^2
\]  

(33)

\[
\frac{-N_p}{\pi (\tau/L)^2} = 1.1 \left( \frac{B}{L} \right) - 0.041 \left( \frac{B}{T} \right)
\]  

(34)

\[
\frac{-N_F}{\pi (\tau/L)^2} = \frac{1}{12} + 0.017 \frac{C_p B}{T} - 0.33 \left( \frac{B}{T} \right)
\]  

(35)

\[
\frac{-\gamma_p}{\pi (\tau/L)^2} = 1 + 0.40 \frac{C_p B}{T}
\]  

(36)

\[
\frac{-\gamma_F}{\pi (\tau/L)^2} = \frac{1}{2} + 2.2 \left( \frac{B}{L} \right) - 0.08 \left( \frac{B}{T} \right)
\]  

(37)

\[
\frac{-N_p}{\pi (\tau/L)^2} = \frac{1}{2} + 2.4 \left( \frac{T}{L} \right)
\]  

(38)

\[
\frac{-N_F}{\pi (\tau/L)^2} = \frac{1}{4} + 0.039 \left( \frac{B}{T} \right) - 0.56 \left( \frac{B}{L} \right)
\]  

(39)
It is known that hydrodynamic coefficient from Clarke regression in equation (32) until (43) are in non-dimension form. Therefore, it is needed normalization method to transform from non-dimensional into dimensional form which is using Prime System SNAME. This method has three types, which are Prime System I, Prime System II, and Bis System. Prime System I used 2 parameters, which are ship velocity ($U$) and ship length ($L = LPP$). Prime System II used as the result of wing theory while Bis System used for static offshore building. Therefore, the given hydrodynamic coefficient is normalized using Prime System I as follows in Table 2.

The following normalization equation (44) is combination normalization between actual condition variable with non-dimensional model parameter.

$$\begin{bmatrix}
\frac{1}{L}m_{11}' \\
\frac{1}{L^2}m_{21}' \\
\frac{1}{L^3}m_{31}' \\
\frac{1}{U}n_{11}' \\
\frac{1}{U^2}n_{21}' \\
\frac{1}{U^3}n_{31}' \\
\frac{1}{U}n_{12}' \\
\frac{1}{U^2}n_{22}' \\
\frac{1}{U^3}n_{32}'
\end{bmatrix} = \begin{bmatrix}
P_1' \\
P_2' \\
P_3'
\end{bmatrix}, \quad \text{(44)}$$

### 2.3. PID Control System

On this study PID control system is used, this is because PID control system have high level of simplicity and reliability in various operation scenario. Equation (45) is the function from PID control system.

$$u(t) = K_p e(t) + K_i \int_0^t e(t) dt + K_d \frac{de(t)}{dt}, \quad \text{(45)}$$

From equation (45), there are three main parameters PID control system, which are $K_p$ (Gain Proportional), $K_i$ (Gain Integral), and $K_d$ (Gain Derivative). These three parameters have their own function in response control system so that by setting these three parameters, an optimal response of control system could be generated. An optimal response of control system also means a response with perfect value in minimize the value of time response, error steady-state, and overshoot.

### Table 2. Prime-System I Components

| Units             | Prime-System I |
|-------------------|----------------|
| Length            | L              |
| Mass              | $\rho L^3$     |
| Inertia Moment    | $\rho L^3$     |
| Time              | $\frac{L}{U}$  |
| Reference Area    | $L^2$          |
| Position          | L              |
| Angle             | 1              |
| Linear Velocity   | U              |
| Angular Velocity  | $\frac{U}{L}$ |
| Linear Acceleration| $U^2/L$       |
| Angular Acceleration| $U^2L^2$    |
| Force             | $\rho U^2L^2$  |
| Moment            | $\rho U^2L^3$  |

### Table 3. Characteristics of PID Control System

| Controller Response | Rise Time | Overshoot | Settling Time | Steady-State Error |
|---------------------|-----------|-----------|---------------|-------------------|
| $K_p$               | Decrease  | Increase  | Small Change  | Decrease          |
| $K_i$               | Decrease  | Increase  | Increase      | Eliminate         |
| $K_d$               | Small Change | Decrease  | Decrease      | Small Change      |

---

7
From Table 3, it is shown that each parameter characteristic of PID control system are connected with each other. One of its connection is when the value of Kp increased, then the value of overshoot is also increased. Thus, it is needed to decrease the value of overshoot by increasing the value of Kd which decreasing the value of overshoot so that the value of overshoot becomes stable at the desired value.

The working scheme of PID control system is starts from error set point which is the error from output as an input of the system. Error set point then received by P, I, and D parameters of control system. The function of PID parameters are to correct the error value so that it could produce output values as desired. Therefore, tuning is needed for PID control system to produce output values as desired. In this research, tuning is done by using a trial and error method.

3. Result and discussion

3.1. Data of the ship
Even tough there are various size of the ship handled in the port of Cilacap, on this study the biggest ship is considered in term of its dead weight tonnage (DWT). The data of the ship can be seen on Table 4.

| Table 4. Tanker ship data |
|---------------------------|
| Ship’s Data               | Value | Units |
| LPP                       | 320   | m     |
| LWL                       | 329,6 | m     |
| U (Velocity)              | 2,057776 | m/s |
| B (Breadth)               | 58,04 | m     |
| T (Draft)                 | 20,8  | m     |
| C_b (Block Coefficient)   | 0,861340997 | -   |
| X_G (Centre of Gravity)   | 10,90165184 | m   |
| A_r (Rudder Areas)        | 104,832 | m²  |
| Δ (Displacement)          | 341067 | ton  |
| r (Radius of Gyration)    | 56,24394095 | m   |

Meanwhile the tugboat data used is shown on table 5 below.

| Table 5. Tugboat data |
|-----------------------|
| Ship’s Data           | Value | Units |
| LPP                   | 32,5  | m     |
| LWL                   | 5,14444 | m   |
| U (Velocity)          | 10,6  | m/s   |
| B (Breadth)           | 4,4   | m     |
| T (Draft)             | 0,527425048 | m   |
| C_b (Block Coefficient)| 1,146532421 | -  |
| X_G (Centre of Gravity)| 2,8890939 | m   |
| A_r (Rudder Areas)    | 795   | m²    |
| Δ (Displacement)      | 7,291322498 | Ton  |
| r (Radius of Gyration)| 32,5  | m     |
3.2. Safety parameters during tug operations
Safety parameters in tug operation is the maximum safety velocity of berthing ship. This safety parameter is based on standards which used by Port of Cilacap itself (Lacet, 2002). The following Table 6 is the safety parameters that used in this research.

| Vessel Displacement in tonnes | Favorable Conditions | Moderate Conditions | Unfavorable Conditions |
|------------------------------|----------------------|---------------------|------------------------|
| Under 10,000                 | 0.20 – 0.16          | 0.45 – 0.30         | 0.60 – 0.40            |
| 10,000 – 50,000              | 0.12 – 0.80          | 0.30 – 0.15         | 0.45 – 0.22            |
| 50,000 – 100,000             | 0.08                 | 0.15                | 0.20                   |
| Over 100,000                 | 0.08                 | 0.15                | 0.20                   |

3.3. Ship trajectory
Ship trajectory is determined according to coordinate points which is passed by the ship in berthing operation. The ship trajectory is divided in two condition which are in static condition and dynamic condition. Static means the ship is maintaining its position in one coordinate points and dynamic means the ship is maintaining its position in a berthing track. These are the coordinate points of ship trajectory.

1. Ship’s Coordinate in Static Condition
   - Position of Ship
     7° 45’ 35.19” SL and 109° 1’ 16.57” EL. This coordinate is presented in XY-coordinate in quadrant 1 with a point of \((X_0, Y_0)\) meter, which is (0, 0) meter.

2. Ship’s Coordinate in Dynamic Condition
   - Position of Ship I
     7° 45’ 24.98” SL and 109° 2’ 22.10” EL. This coordinate is presented in XY-coordinate in quadrant 1 with a point of \((X_0, Y_0)\) meter, which is (0, 0) meter.
   - Position of Ship II
     7° 45’ 27.63” SL and 109° 2’ 10.78” EL. This coordinate is presented in XY-coordinate in quadrant 1 with a point of \((X_0, Y_0)\) meter, which is (359.6, 82.33) meter.
   - Position of Ship III
     7° 45’ 37.64” SL and 109° 1’ 57.25” EL. This coordinate is presented in XY-coordinate in quadrant 1 with a point of \((X_0, Y_0)\) meter, which is (758.77, 398.61) meter.
   - Position of Ship IV
     7° 45’ 37.64” SL and 109° 1’ 40.92” EL. This coordinate is presented in XY-coordinate in quadrant 1 with a point of \((X_0, Y_0)\) meter, which is (1357.34, 553.32) meter.
   - Position of Ship V
     7° 45’ 38.86” SL and 109° 1’ 25.56” EL. This coordinate is presented in Y-coordinate in quadrant 1 with a point of \((X_0, Y_0)\) meter, which is (1898.99, 470.49) meter.
   - Position of Ship VI
     7° 45’ 35.19” SL and 109° 1’ 16.57” EL. This coordinate is presented in Y-coordinate in quadrant 1 with a point of \((X_0, Y_0)\) meter, which is (2198.92, 353.31) meter.

The dynamic condition trajectory is started from the starting position until the last position while the static condition is only at the last position. In this research, the analysis is only focused in Y-coordinate of dynamic condition and static condition at the last position of ship.
3.4. Model response simulation design of DP tugboat

Block diagram arrangement of DP control system. The following Figure 3 is the arrangement of DP control system block diagram which used as the basic logic in designing the model response simulation of DP tugboat. It is shown the logic thinking of DP control system. This logic thinking is started with an input in a form of ship desired coordinate as the reference for the desired output. This system needs PID controller and tug assist to maintain the ship positioning. PID controller used to translate the desired coordinate into rudder angle of tugboat so that tugboat could maintain the desired ship position. This system also has disturbance force to represent the actual condition in the field. Thus, it is needed to design a feedback response as the correction position of ship after getting some disturbance forces.

![Block Diagram of DP Control System](image)

**Figure 3.** Characteristics of PID Control System DP control system block diagram

3.4.1. Dynamic model of berthing ship. The method that used for designing the dynamical model of berthing ship in this research is the Model of Davidson and Schiff Method. Before finally using that method, there are several steps needed to be done, namely as follows.

1. Hydrodynamic coefficient calculation

   The value of hydrodynamic coefficient obtained using Clarke regression with equation (32) until (43). It is known that the result of Clarke regression is in non-dimensional form. Thus, it’s needed to transform it to dimensional form using Prime-System I as follows in Table 2 and equation (44). Then, the following Table 7 is the normalization of ship berthing data needed for hydrodynamic coefficient calculation.

   | Table 7. Normalization of Ship Berthing Data |
   |--------------------------------------------|
   | Non-dimensional Ship’s Data | Value | Units |
   |------------------------------|-------|-------|
   | \( U' \) (Non-Dimensional Velocity) | 1     | -     |
   | \( m' \) (Non-Dimensional Mass)    | 0.02031| -     |
   | \( X_g \) (Non-Dimensional Velocity) | 0.03407| -     |
   | \( r' \) (Non-Dimensional Radius of ) | 0.17576| -     |

   According to Table 4 and Table 7, given the result of ship berthing hydrodynamic coefficient calculation as follows in Table 8.

2. Non-dimensional hydrodynamic coefficient

   Non-Dimensional Hydrodynamic Coefficient Matrix is obtained by using equation (17) until (19) which result this following matrix.
3. Dimensional hydrodynamic coefficient
Dimensional hydrodynamic coefficient matrix is obtained by normalized the matrix (46) until (48) with Prime-System I method. The following matrix (49) until (51) is the result of the normalization.

Table 8. Normalization of Ship Berthing Data

| Non-Dimensional Hydrodynamic Coefficient | Value     |
|----------------------------------------|-----------|
| \( Y''_w \)                             | -0.0161424|
| \( Y''_r \)                             | -0.0012713|
| \( N''_w \)                             | -0.0011291|
| \( N''_r \)                             | -0.0008535|
| \( Y''_p \)                             | -0.0260208|
| \( Y''_r \)                             | 0.0043011 |
| \( N''_w \)                             | -0.0087028|
| \( N''_r \)                             | -0.0034129|
| \( Y''_d \)                             | 12.6728438|
| \( N''_d \)                             | -6.3364219|
| \( I''_r \)                             | 0.0006274 |
| \( I''_z \)                             | 0.0013193 |
| \( Y''_b \)                             | -0.0161424|

\[
M' = \begin{bmatrix}
0.0364521 & 0.001963 \\
0.0018210 & 0.002173 \\
\end{bmatrix}
\]  
(46)

\[
N'(u_0) = \begin{bmatrix}
0.026021 & 0.016008 \\
0.008703 & 0.004105 \\
\end{bmatrix}
\]  
(47)

\[
b' = \begin{bmatrix}
12.67284 \\
-6.33642 \\
\end{bmatrix}
\]  
(48)

\[
M = \begin{bmatrix}
2.754688 & 47.474783 \\
0.137611 & 52.545119 \\
\end{bmatrix}
\]  
(49)

\[
N(u_0) = \begin{bmatrix}
0.0012645 & 2.489409 \\
0.004229 & 0.638323 \\
\end{bmatrix}
\]  
(50)

\[
b = \begin{bmatrix}
12.67284 \\
-6.33642 \\
\end{bmatrix}
\]  
(51)

After obtained the matrix \( M \), matrix \( N(u_0) \), and matrix \( b \), it is time to obtained the value of matrix \( A \) and matrix \( b_1 \) in equation (21). The following matrix is the value of matrix \( A \) and matrix \( b_1 \).

\[
A = \begin{bmatrix}
-0.0033547 & -0.7271567 \\
7.1697529 & -0.0162437 \\
\end{bmatrix}
\]  
(52)

\[
b_1 = \begin{bmatrix}
6.992313 \\
0.1380023 \\
\end{bmatrix}
\]  
(53)

The state space equation could be obtained by substitute the matrix \( A \) and \( b_1 \) into the equation (21) as follows.
3.5. PID control system arrangement. In this method, design control or tuning PID is using trial and error method to get the right value of P, I, and D. There are three parameters that have to be obtained to ensure that the result of tuning PID is valid. These parameters are maximum overshoot that has to be not more than 20%, 10 seconds of maximum time settling, and 5% of maximum error steady-state. Figure 4 is shown the result of tuning PID when the value of P, I, and D designed to be 0.01, 0, and 0.1.

\[
\begin{bmatrix}
\psi
\end{bmatrix} = 
\begin{bmatrix}
-0.0033547 & -0.7271567 \\
-7 & 1697529 \\
0.0102437 & n
\end{bmatrix}
+ 
\begin{bmatrix}
6.992313 \\
n 1389023
\end{bmatrix}
\delta_R
\]  

(54)

From Figure 4, it is shown that the maximum overshoot obtained is 10.27%, 14.1499 seconds of time settling, and 5% value of error steady-state.

3.6. Model response simulation design of non-DP tugboat

In this model, the input is a value of position, the plant is the ship berthing, and the output is response position. The following Figure 7 is the result of this response model.
Figure 5 is showing the result of Non-DP tugboat response. The result showed that the ship is move continuously without control if the input value was not being controlled by the DP. It also means that the ship couldn’t maintain its position without DP.

3.7. Model response simulation design of non-DP tugboat

3.7.1. Model response simulation of DP tugboat in static condition against step-current velocity. In this model, the input is Y-coordinate which value is constant at zero because of the static condition of the berthing ship. The value of step-current velocity as the disturbance is up to 0.15 m/s in the 5th second of simulation. The output of this model are velocity and actual coordinate of the berthing ship and the result of this model could be observed in Figure 6.

Figure 6. Model Response Velocity Simulation of DP Tugboat in Static Condition against Step-Current Velocity

Figure 6 shown that the velocity of ship at the maximum error position is already equal to 0 m/s. It’s also means that DP tugboat could decrease the velocity of ship after received the disturbance down to 0 m/s in 3.3955 seconds. Last, the value of time settling in this model simulation is 11.833 seconds with 1.54% maximum error steady-state.

3.7.2. Model response simulation of DP tugboat in static condition against random number-current velocity. The input in this model is Y-coordinate which value is constant at zero because of the static condition of the berthing ship. The mean value of random-current velocity added is 0.15 m/s, 0.01 variance, and sample time every 100 seconds. It’s important to note that the random-current velocity has an impulse characteristic. The result of this model could be observed in Figure 7 as follows.
Figure 7. Model Response Velocity Simulation of DP Tugboat in Static Condition against Random-Current Velocity

Figure 7 shown that the velocity of ship becomes 0.13957 m/s after received 0.26284 m/s of current velocity as the disturbance. It’s also known that it takes 0.6099 seconds for DP tugboat to reduced ship berthing velocity down to 0.09 m/s which is the minimum safety velocity of berthing ship.

3.7.3. Model response simulation of DP tugboat in dynamic condition against step-current velocity. The input in this model is Y-coordinate which value is equal to 9 meters before the berthing ship bumped into the berthing dolphin. The berthing ship velocity is setting on 0.09 m/s. The value of step-current velocity is up to 0.3 m/s in the 89th second of simulation which is 1 meter before the berthing ship bumped to the berthing dolphin. Figure 8 as follows are the result of this model.

Figure 8. Model Response Velocity Simulation of DP Tugboat in Dynamic Condition against Step-Current Velocity

From Figure 8, it is known that the berthing ship velocity is setting on 0.09 m/s and the disturbance is added in the 89th seconds. It’s also known that in 10 seconds or less than a meter position, the DP tugboat could decrease the berthing ship down to 0.065371 m/s from 0.38995 m/s.

3.7.4. Model response simulation of DP tugboat in dynamic condition against random number-current velocity. The input in this model is Y-coordinate which value is equal to 54 meters before the
berthing ship bumped into the berthing dolphin. The berthing ship velocity is sets on 0.09 m/s. The mean value of random-current velocity added is 0.3 m/s, 0.01 variance, 150 seed, and sample time every 50 seconds.

**Figure 9.** Model Response Velocity Simulation of DP Tugboat in Dynamic Condition against Random-Current Velocity

As the result, according to Figure 9, it is shown that the berthing ship velocity when bumping with the berthing dolphin is equal to 0.060587 m/s while received the value of current velocity that equal to 0.19136 m/s. It’s also known that the highest error velocity of berthing ship is 0.20252 m/s when it received 0.30701 m/s current velocity in the 450th second. Moreover, Figure 10 is the berthing ship trajectory with DP tugboat against random-current velocity disturbance.

**Figure 10.** The Berthing Ship Trajectory with DP Tugboat in Dynamic Condition against Random-Current Velocity

3.8. *Analysis of the relation between propulsion and DP system of the tugboat*

From all the simulation, there are some specifications needed and it could be observed from Figure 6. Thus, to ensure those specifications are fulfilled, DP tugboat needs propulsion system. The propulsion systems observed in this research are Azimuth Thruster and Voith Schneider Propeller. For analyzing which propulsion system fits better with the DP tugboat, these are the following characteristics of each propulsion system.
3.8.1. **Analysis response of DP tugboat using Azimuth thruster**

1. The ability of Azimuth Thruster to produce optimal thrust in all directions. Compared to existing or conventional propulsion system, Azimuth Thruster has the advantage of producing thrust in 360° direction with an average rotation speed of 180°/12 seconds. This value allows the system to able to provide a response to the desired thrust direction within 12 seconds which also means has 12 seconds of time settling.

2. Thrust inefficiency during direction transitions because there is unwanted thrust while the propulsion is rotating to its desired direction of thrust which results in error position on the ship. In the response of DP tugboat, this position error reduces the value of time settling that should be 12 seconds and also the value of steady-state error.

3.8.2. **Analysis response of DP tugboat using Voith-Schneider thruster**

1. VSP has sensitive response so that it can provide variations in the speed and direction of thrust more effectively and efficiently with an average rotation speed of 180°/6 seconds. This means that VSP can minimize the overshoot value and maximize the value of time settling of the DP tugboat.

2. Symmetrical distribution of power in each direction between the propeller and the end of the ship (minimize the steady-state error). This characteristic allows the propulsion system to give thrust only in the desired direction by the DP tugboat so that it can increase the thrust efficiency and minimize the presence of thrust forces that can cause position errors which lead the ship to crash a nearby stationary building.

3. Voith Roll Stabilization (VRS) is the nature of VSP to be able to improve the ship by eliminating ship roll movements even in extreme environmental conditions. This characteristic increases the ability of the DP tugboat to minimize the value of steady-state error.

4. VSP required less energy used when activating the DP tugboat so that it saves more fuel usage.

4. **Conclusion**

Dynamic positioning concept design of tugboat that could increase the effectiveness and safety of tug operation at Port of Cilacap is designed with PID control or DP tugboat that have these three parameters which are 10.27% overshoot, 14.1499 seconds time settling, and 5% of error steady-state with P, I, and D sets to 0.1, 0, and 0.01. Moreover, the type of propulsion drive used is Voith Schneider Propeller because it has more sensitive response with an average rotation speed of 180°/6 seconds, VRS, and symmetric force distribution which all that characteristics are support the system to have minimum overshoot, error steady-state, maximize the value of time settling.

The concept design of DP tugboat could increase the effectiveness and safety of tug operation better than the existing tugboat which approved by the result of the DP tugboat model simulation that DP tugboat could reduce ship velocity when bumping into the berthing dolphin down to the speed of 0.065371 m/s when receiving current velocity valued at 0.38995 m/s and where the allowed safe speed was between 0.09 m/s and 0.15 m/s

**References**

[1] Kementerian Perhubungan Republik Indonesia, "Peraturan Menteri Perhubungan Indonesia Nomor PM 93 Tahun 2014 Tentang Sarana Bantu dan Prasarana Pemanduan Kapal," Kementerian Perhubungan Republik Indonesia, Indonesia, 2014.

[2] C. H. a. F. R. Chas, "Introduction to Ship Dynamic Positioning System," *Journal of Maritime Research*, vol. V, no. 1, pp. 79-96, 2018.

[3] T. I. Fossen, Guidance and Control of Ocean Vehicles, England : John Wiley & Sons Ltd., 1994.

[4] S. Donnarumma, M. Figari, M. Martelli, S. Vignolo and M. Viviani, "Design and Validation of Dynamic Positioning for Marine System: A Case Study," *IEEE Journal of Ocean Engineering*, 16
vol. 43, no. 3, pp. 677-688, 2018.

[5] Voith, [Online]. Available: http://voith.com/corpen/drives-transmissions/voith-schneider-propeller-vsp.html. [Accessed 27 02 2019].

[6] D. Roswell, "State-space Representation of LTI System," 2002.

[7] P. Lacet, "Guidelines for Design Fender System," International Navigation Association, Belgium, 2002.