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# Heading Control of a Turret Moored Offshore Structure Using Resolved Motion and Acceleration Control †

**Young-Shik Kim[1,2*], Hong-Gun Sung[1] and Jin-Ha Kim[1]**
[1]*Korea Research Institute of Ships and Ocean Engineering, Daejeon 34103, Korea*
[2]*Korea Advanced Institute of Science and Technology (KAIST), Daejeon 34141, Korea*

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## Abstract

This paper addresses the heading control of an offshore floating storage and regasification unit (FSRU) using a resolved motion and acceleration control (RMAC) algorithm. A turret moored vessel tends to have the slewing motion. This slewing motion may cause a considerable decrease in working time in loading and unloading operation because the sloshing in the LNG containment tank might happen and/or the collision between FSRU and LNGC may take place. In order to deal with the downtime problem due to this slewing motion, a heading control system for the turret moored FSRU is developed, and a series of model tests with azimuth thrusters on the FSRU is conducted. A Kalman filter is applied to estimate the low-frequency motion of the vessel. The RMAC algorithm is employed as a primary heading control method and modified I-controller is introduced to reduce the steady-state errors of the heading of the FSRU.

**Keywords:** Floating storage and regasification unit (FSRU); resolved motion and acceleration control (RMAC); heading control; turret moored vessel; model test

## 1. Introduction

Floating storage and re-gasification unit (FSRU) is a relatively recent concept of floating offshore structure for downstream gas supply to general consumers. FSRU has benefits compared to onshore re-gasification plants; such as the small environmental impact on the seashore, high level of safety to neighborhood area of residence, and low initial cost. Recently KRISO has studied on the conceptual design of a FSRU through a collaborative national research project with Korean Shipbuilders (DSME, SHI, HHIC, STX), Korean Register (KR) and Korea gas corporation (KOGAS). As the result of this study, a concept of a turret moored FSRU was developed as shown in the Fig. 1.

A turret moored vessel, which also can be referred as a single point moored vessel, tends to have fish-tailing (or slewing) motion. This fish-tailing motion may cause a considerable decrease in working time during loading and offloading process because of the possibility of the collision between FSRU and LNG carrier (LNGC), discomforts for the crew, and the possible sloshing in the liquefied natural gas (LNG) containment tank. In order to deal with this problem, we considered a heading control sys-

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† It is noted that this paper is revised edition based on proceedings of ISOPE 2011 in Hawaii
[*] Corresponding author. Tel.: +82-42-866-3951, Fax.: +82-42-866-3919,
E-mail address: yskim@kriso.re.kr

tem for the turret moored FSRU. The heading control system is composed of motion estimator, controller, and thruster system. Three azimuth thrusters are located at the aft part of the vessel.

The environmental forces acting on the floating vessel induce two distinct kinds of motions, which are the high-frequency motion and the low-frequency motion. The high-frequency motion is mainly produced by waves, so they have nearly same frequency range with waves. On the other hand, the low-frequency motion is caused by the wind, the current and the high-order wave components. The controller for regulating the motion of the vessel cannot directly compensate all motions of floating vessel, which contains high- and low-frequency components together. Only the low-frequency motion could be suppressed by the control system because the enormous amount of power for thrusters is required to compensate the high-frequency motion. That is the reason why the control system should have a motion estimator or a filter system in the control loop, which separates low-frequency motion and high-frequency motion from the vessel motions. In this study, a Kalman filtering technique is applied to perform such separation of the low-frequency motion. The resolved motion and acceleration control (RMAC) algorithm is employed as a primary heading control method, and the modified Integral (I) controller is introduced to suppress steady state errors. Minimum power consumption (MPC) algorithm is used to allocate thrust for each azimuth thruster. An experimental study on heading control of the FSRU was conducted in ocean engineering basin of KRISO.

In the present paper, a RMAC algorithm is introduced as the heading control algorithm for the FSRU. A modified I control algorithm is also presented as the steady-state error compensator. Several experimental results are presented to show the performance of the proposed control algorithm for the heading control of a turret moored FSRU.

## 2. Resolved Motion and Acceleration Control

The resolved motion and acceleration control (RMAC) algorithm had been originally adopted in the continuous path tracking control for robot manipulators (Hyun et al., 1988). Recently, this RMAC algorithm has been used as the path tracking control algorithm for a torpedo shape AUV (Kim et al., 2009). The RMAC algorithm needs desired path, speed, and acceleration defined in the Cartesian coordinate system as the input for the running of the algorithm. And a proportional and derivative (PD) control actions calculated from the resolved force based on the mathematical model of the control plant is working as the main control action for the RMAC.

In order to implement the RMAC algorithm to the heading control of the FSRU, an earth-fixed frame {E} and a body-fixed frame {B} should be defined as shown in the Fig. 2. It is assumed that the origin of body-fixed frame coincides with the center of mass of the vessel, while its axes are along the principal axis of inertia of the vessel. Hence, the kinematic equation for the horizontal mode of a vessel's motion can be written as the following equation.

$$\begin{aligned} &\dot{\eta} = Jv, \\ &where,\ \dot{\eta} = [\dot{X} \quad \dot{Y} \quad \dot{\Psi}], \\ &\qquad \boldsymbol{v} = [\dot{x}_1(=u) \quad \dot{x}_2(=v) \quad \dot{x}_6(=r)], \\ &\qquad J = \begin{bmatrix} cos(\Psi) & -sin(\Psi) & 0 \\ sin(\Psi) & cos(\Psi) & 0 \\ 0 & 0 & 1 \end{bmatrix}. \end{aligned} \tag{1}$$

where the variables $\dot{X}$, $\dot{Y}$ and $\dot{\Psi}$ are the velocities in X, Y and Z direction in the earth-fixed frame, respectively. The variables $\dot{x}_1(=u)$, $\dot{x}_2(=v)$, and $\dot{x}_6(=r)$ are the surge, sway and the yaw velocities in the body-fixed frame. The other remaining mode of motion such as heave, roll, and pitch are discarded in this modeling.

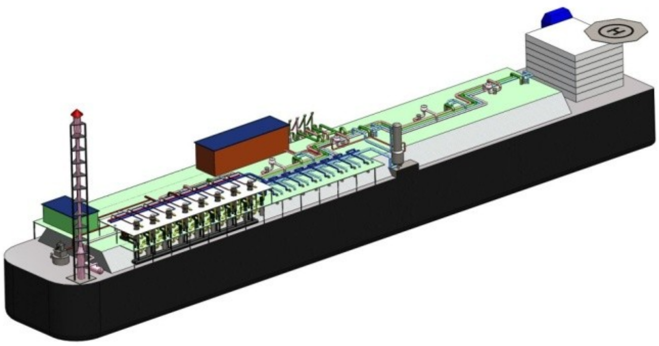


Fig. 1. A design of conceptual study on a floating storage and re-gasification unit(FSRU) by KRISO

The following dynamic model governs the low-frequency horizontal motions of a vessel:

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

where $I_Z$ is the moment of inertia about the vertical axis. $M$ is the mass of the vessel, $M_{ij}$ is the added mass in direction $i$ due to acceleration in direction $j$. $F_{1E}$, $F_{2E}$, $F_{6E}$ are the surge, the sway and the yaw environmental loads which are caused by currents, winds and wave. $F_{1T}$, $F_{2T}$, $F_{6T}$ are the forces and the moment delivered by the propulsion system. $C_{ij}$ is damping coefficient in direction $i$ due to motion in direction $j$.

From the low-frequency dynamic model of a vessel we could have a matrix form of equation as follows:

$$M\dot{v}=F_E+F_T \tag{3}$$

where $M$ is the system inertia matrix including added mass at low frequency, $v$ is the low-frequency velocity vector defined in the body-fixed frame, $F_E$ is the environmental force vector, $F_T$ is propulsion force vector.

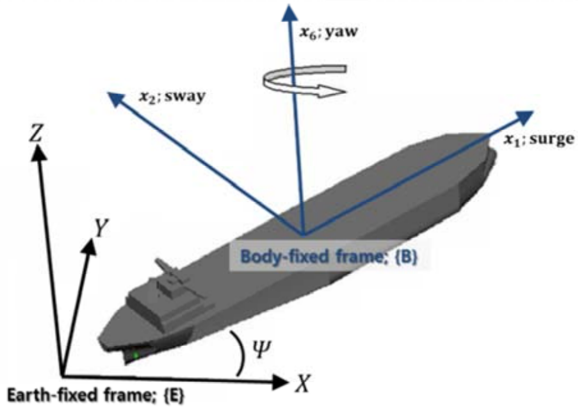


Fig. 2. Coordinate system for a moored vessel: earth-fixed frame {E} and body-fixed frame {B}

From the kinematic equation we could derive the relationship between the acceleration in the body-fixed frame and the acceleration in the earth-fixed frame as follows:

$$\ddot{\eta} = \dot{J}v + J\dot{v} \tag{4a}$$

$$\dot{v} = J^{-1}(\ddot{\eta} - \dot{J}v) \tag{4b}$$

$$\dot{v} = J^{-1}(\ddot{\eta} - \dot{J}\,J^{-1}\dot{\eta}) \tag{4c}$$

Now the equations of motion of a vessel could be written as the following equation from adopting Eqs. (3) and (4),

$$MJ^{-1}\left(\ddot{\eta} - \dot{J}\,J^{-1}\dot{\eta}\right) - F_E = F_T \tag{5}$$

From the Eq. (5), it is obvious that the control forces (i.e. propulsion forces) $F_T$ can be calculated by the acceleration and the velocity defined in the earth-fixed frame with the Jacobian matrix ($J$) and environmental loads $F_E$. In this study, $F_E$ is not considered in control system for simplicity of control algorithm.

In order to control the heading of a FSRU, we need to calculate the necessary control force to compensate errors. Thus we define error dynamics as follows:

$$\ddot{\eta} = \ddot{\eta}_d + K_V(\dot{\eta}_d - \dot{\eta}_a) + K_P(\eta_d - \eta_a) = \ddot{\eta}_d + K_V\dot{\eta}_e + K_P\eta_e \tag{6}$$

where the variables $\ddot{\eta}_d$, $\dot{\eta}_d$, $\eta_d$ are the desired acceleration, velocity and position defined in the earth-fixed frame, respectively. The variables $\dot{\eta}_a$, $\eta_a$ are the actual velocity and position of the vessel in the earth-fixed frame. The variables $\dot{\eta}_e$, $\eta_e$ are the errors for the velocity and position of the vessel. The variables $K_V$, $K_P$ are the constant diagonal gain matrices.

We could derive control force equation by taking Eq. (6) into Eq. (5):

$$F_T = MJ^{-1}\left(\ddot{\eta}_d + K_V\dot{\eta}_e + K_P\eta_e - \dot{J}\,J^{-1}\dot{\eta}_a\right) \tag{7}$$

From the Eq. (7) we can calculate required control forces and moment from the errors which are defined by desired states and actual states.

## 3. Thrust Allocation

After calculation of $F_T$, a minimum power consumption algorithm is applied to find out optimal thruster allocation. Before applying thrust allocation algorithm to turret moored vessel, we need to define the new coordinate system for defining thruster location which its origin coincides with the center of the turret as shown in the Fig. 3. In this study, three azimuth thrusters are equipped on the vessel, and the locations from the turret center are described as follows:

- Thruster No.1: (-a, 0)
- Thruster No.2: (-b, c)
- Thruster No.3: (-b, -c)

where a, b, c are positive real numbers.

To find the optimal set of thruster acting condition which has the characteristic of the minimum power consumption, firstly the equilibrium condition between the required forces and moment and generated thruster forces and moment should be defined by the Eq. (8). And then the cost function that represents the power consumption and equilibrium condition is defined as shown in the Eq. (9).

$$F_T = \begin{bmatrix} F_{X\_req} \\ F_{Y\_req} \\ M_{Z\_req} \end{bmatrix} = \begin{bmatrix} F_{1X} + F_{2X} + F_{3X} \\ F_{1Y} + F_{2Y} + F_{3Y} \\ -aF_{1Y} - b(F_{2Y} + F_{3Y}) - cF_{2X} + cF_{3X} \end{bmatrix}, \tag{8}$$

$$J = \sum_i^n F_i^2 + \sum_j^m (\lambda_j \times equilibrium_j), \tag{9}$$

$$where, \quad \sum_i^n F_i^2 = {F_{1X}}^2 + {F_{2X}}^2 + {F_{3X}}^2 + {F_{1Y}}^2 + {F_{2Y}}^2 + {F_{3Y}}^2,$$

$$\sum_j^m (\lambda_j \times equilibrium_j) = \lambda_1 \left(F_{1X} + F_{2X} + F_{3X} - F_{X_{req}}\right) + \lambda_2 \left(F_{1Y} + F_{2Y} + F_{3Y} - F_{Y_{req}}\right)$$
$$+\lambda_3 \left(-aF_{1Y} - bF_{2Y} + bF_{3Y} - cF_{2X} + cF_{3X} - M_{Z_{req}}\right),$$

where, the variable $F_{X_{req}}$, $F_{Y_{req}}$, and $M_{Z_{req}}$ represent the required forces and moment in order to control the vessel in the horizontal plane.

After having the partial derivatives of the cost function as shown in the Eq. (10), we can have a set of coupled equations and they can be written in matrix form as shown in the Eq. (11).

$$\frac{\partial J}{\partial F_i \, \partial \lambda_i} = 0, \tag{10}$$

$$\mathrm{P}\,\mathrm{F}_{TH} = \mathrm{F}_{REQ}, \tag{11a}$$

$$\mathrm{F}_{TH} = \mathrm{P}^{-1}\,\mathrm{F}_{REQ}, \tag{11b}$$

$$where, \quad \mathrm{F}_{TH} = [\,F_{1X}\ \ F_{2X}\ \ F_{3X}\ \ F_{1Y}\ \ F_{2Y}\ \ F_{3Y}\ \ \lambda_1\ \ \lambda_2\ \ \lambda_3]^T,$$
$$\mathrm{F}_{REQ} = \left[0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ F_{X\_req}\ \ F_{Y\_req}\ \ M_{Z\_req}\right]^T.$$

And P is a 9×9 matrix which has the information of optimal distribution of the thrust. Hence, if we get the required forces and moment $\mathrm{F}_{REQ}$ from the controller, then we can calculate component forces for each thruster in vector form.

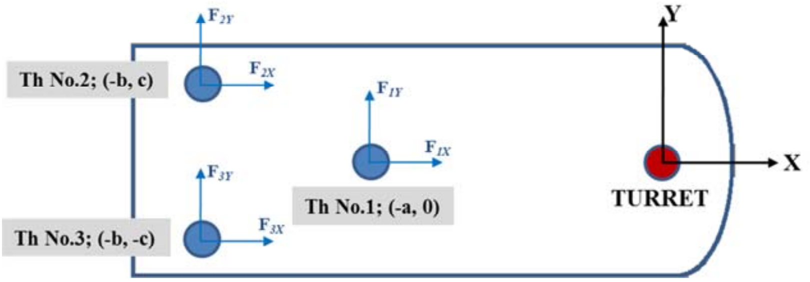


Fig. 3. The location of three azimuth thrusters from the turret center

Table 1. The environmental condition for heading control of the FSRU

| Case | Wave | | | Wind | | Current | |
|---|---|---|---|---|---|---|---|
| | Hs [m] | Tp [s] | β [deg.] | Uw [m/s] | β [deg.] | Uc [m/s] | β [deg.] |
| Case I | 3.00 | 11.00 | 225 | 13.00 | 180 | - | - |
| Case II | 4.00 | 12.5 | 225 | 13.00 | 180 | 1.60 | 180 |

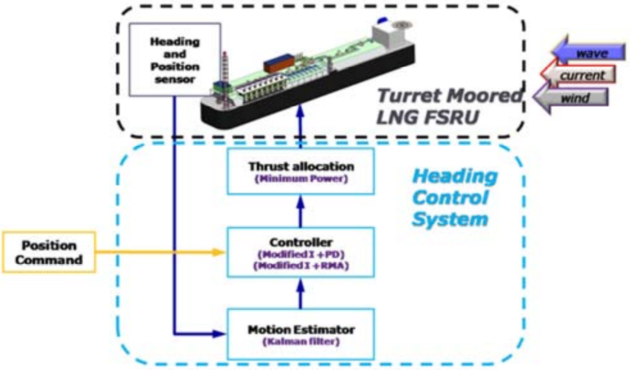


Fig. 4. A conceptual diagram of the heading control system for a FSRU

## 4. Model and Experimental Setup

The concept of the heading control system for the FSRU is depicted in Fig. 4. The heading control system is composed of a low-frequency motion estimator, a feedback controller, and a thrust allocator. In this experimental study, a Kalman filter which is based on the Eq. (2) is used. The RMAC works as the main feedback controller. And a modified I controller is used as the steady-state error compensator. This modified I controller has a time window (or a buffer) for averaging errors with much longer time interval when compared to the main controller. Fig. 5 shows the structure of RMAC with modified I controller.

The experiment of heading control of a turret moored FSRU was conducted in the ocean engineering basin of KRISO. Three azimuth thrusters are equipped in the aft part of the FSRU as shown in the Fig. 6. The environmental conditions are selected as listed in Table 1.

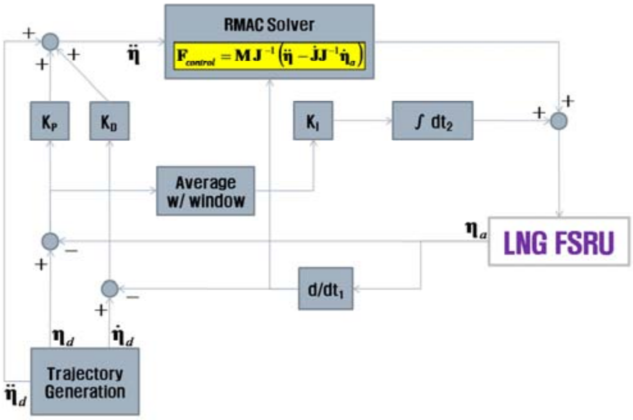


Fig. 5. A block diagram of the RMAC with modified I controller

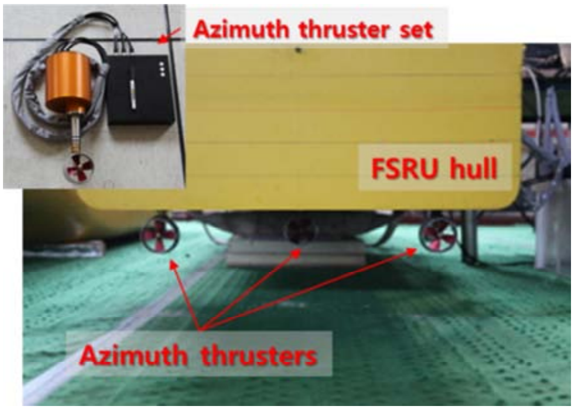
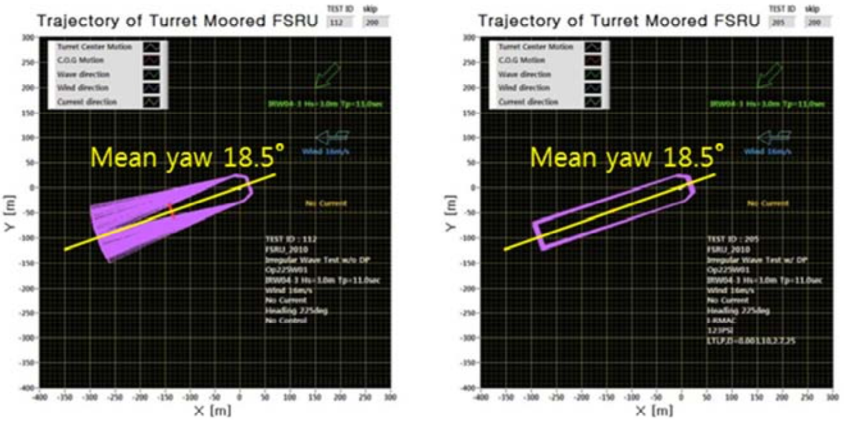


Fig. 6. Thrusters are located at the aft part of the vessel

## 5. Results of Experiment

For the sake of evaluation of the effectiveness of the propose heading control algorithm, the motion response of the FSRU was tested without the heading control system in the operational condition, Case I. In this case, the turret moored FPSO has 18.5° of the mean heading angle during the experiment even though it encounters waves in 225°. Because the wind blows in 180 °, the FPSO keeps its heading along the direction in which the resultant force vector due to the wave and wind force directs. It is also observed that the significant yaw slewing motion, so-called the fish-tailing motion, occurs with the relatively long period compared with the wave period, which is the main cause of oscillating motion of the vessel, as shown in the Fig. 7, (a) and Fig. 8. The maximum fish-tailing yaw motion 13.6° is observed in the time series of yaw motion as shown in Fig. 8. On the other hand, the fish-tailing yaw motion is hardly observed in the test with the heading control system operating as shown in the Fig. 7, (b). The reference yaw target for the heading control is set to 18.5°. The maximum yaw variation is reduced to 1.7° which is the just 12.5% of the fish-tailing motion without the heading control as shown in the Fig. 8. Therefore, it can be insisted that the heading control of a turret moored FSRU dramatically reduce the fish-tailing motion of the vessel which can cause downtime in FSRU operation especially in the transfer of LNG from the LNGC to the FSRU.



(a) Not controlled (b) Controlled w/ I-RMAC

Fig. 7. Trajectory of the turret moored FSRU in Case I with and without the heading control action

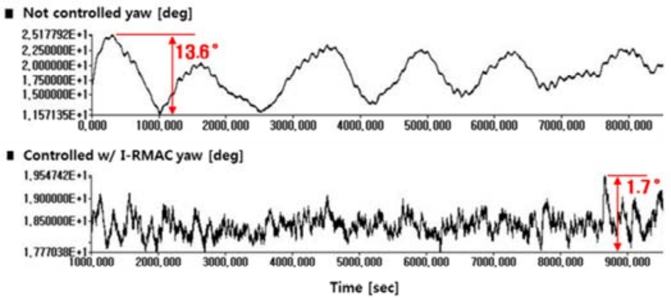


Fig. 8. Yaw response of the turret moored FSRU in Case I with and without the heading control action

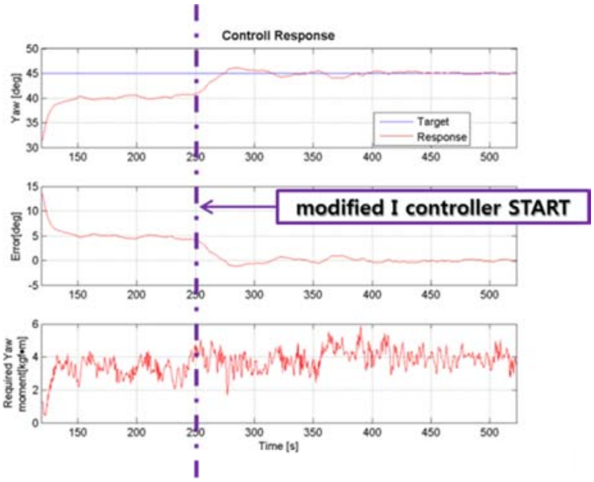


Fig. 9. The performance of the modified I controller in the heading control of the turret moored FSRU in Case II

In the case of the control experiment with Case I, a steady state error compensation is not needed because the target reference yaw angle 18.5° is selected as the stable point in the sense of equilibrium of the environmental forces. However, if the vessel needs another set yaw angle which is not in the equilibrium condition, then the vessel could not achieve to keep its target angle. Thus, the integral control action should be required when the vessel needs to keep its heading along the direction which is not the direction of the resultant force due to the environmental forces. However, the I controller in general easily makes the vessel motion diverge in the application of dynamic positioning including heading control. Therefore, a modified I controller for the application of dynamic positioning is developed to have reasonably stable I control action in the DP application. The modified I controller has a buffer (or a time window) to average the errors with the reasonably long period enough to capture the low-frequency motion such as the fish-tailing motion for a turret moored vessel. The stable response of the heading control vessel with the modified I controller under the OpL225W01C01 condition is shown in the Fig. 9. At the beginning of the test, the reference target yaw angle set to 45° but the heading angle of the vessel stays around 40° due to force equilibrium between environmental force and the control force. However, after starting to use modified I controller, the yaw angle of the vessel approaches to the set target yaw reference 45° and settles down.

## 6. Conclusions

This paper presents the methodologies of the model test for FSRU with the heading control system. A heading control system was built up through this study and used in the model test. The system has a Kalman filter as the low-frequency vessel motion estimator, a resolved motion and acceleration control (RMAC) with a modified integral control algorithm as the primary feedback controller, and a minimum power consumption algorithm as the thrust allocator. This heading control system is successfully applied to heading control of a turret moored FSRU and shows reasonable results like the 87.5% reduction of yaw oscillation in the given environmental condition. Moreover, a modified I controller is introduced which has a buffer (or time window) for averaging position errors with long period enough to capture the fish-tailing motion. This modified I controller works as a steady state error remover, and which is proved in the model test.

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