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# ACTIVE CONTROL OF VERTICAL ACCELERATION WITH T-FOIL AND TRIM TAB SYSTEMS IN A FAST FERRY*

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## *ABSTRACT*

*This study is concerned with the active T-foil placed near the bow on the keel line of the fast ferry and two active trim tab controls placed at the stern to improve the maritime performance of a fast ferry, whilst improving the comfort and safety of passengers and crew. In the scope of the study, the vertical direction of the fast ferry under the random head waves, heave and pitch motions were taken into account. For the control of T-foil and trim Tabs, PID and LQR control methods were used. The purpose of these controllers is to reduce the acceleration of the heave and pitch motions of the fast ferry by changing the operating angles of the T-foil and trim tab wings. A random wave model was created using the Pierson-Moskowitz model, and simulations were done assuming that the fast ferry was subjected to random head waves. Finally, in order to see the effect of vertical acceleration on passengers, the rate of seasickness (MSI) change of the fast ferry in uncontrolled and controlled states was examined. Mathematical models of fast ferry, T-foil and trim tab and their simulations were carried out in MATLAB / Simulink environment. The simulation results show that T-foil and trim tab Active systems can effectively reduce vertical acceleration by improving heave and pitch motions.*

***Keywords:*** *Fast Ferry, T-foil, Trim Tab, Pitch and Heave, PID Control, LQR Control, Motion Sickness Index*

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[*] This article has been prepared from the master's thesis with the same title.

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# HIZLI BİR FERİBOTUN DÜŞEY İVMELENMESİNİN T-FOİL VE TRİM TAB SİSTEMLERİ İLE AKTİF KONTROLÜ

## ÖZ

*Bu çalışma, hızlı bir feribotun denizcilik performansını iyileştirmek, yolcu ile mürettebatın konfor ve güvenliğini artırmak için hızlı feribotun omurga hattında pruvaya yakın bir noktaya yerleştirilen hareketli T-foil ve kıç tarafına yerleştirilen iki adet hareketli trim tab kontrolü ile ilgilidir. Çalışma kapsamında baştan gelen düzensiz dalgaların etkisindeki hızlı feribotun düşey yönde yaptığı baş kıç vurma ve dalıp çıkma hareketleri dikkate alınmıştır. T-foil ve trim tabların kontrolü için ise PID ve LQR kontrol yöntemleri kullanılmıştır. Bu kontrolörlerin amacı, T-foil ve trim tab kanatlarının çalışma açılarının değiştirilmesiyle hızlı feribotun pozisyonunu kontrol ederek baş kıç vurma ve dalıp çıkma hareketlerinin ivmelenmesini azaltmaktır. Pierson-Moskowitz modelinden yararlanılarak düzensiz bir dalga modeli oluşturulmuş ve çalışmalar hızlı feribotun baştan gelen düzensiz dalgalara maruz kaldığı varsayılarak yapılmıştır. Son olarak düşey ivmelenmenin yolcular üzerindeki etkisini görebilmek için hızlı feribotun kontrolsüz ve kontrollü durumda deniz tutması oranı (MSI) değişimi incelenmiştir. Hızlı feribotun, T-foilin ve trim tabın matematiksel modelleri MATLAB / Simulink ortamında elde edilerek simülasyonları gerçekleştirilmiştir. Simülasyon sonuçları, T-foil ve trim tab aktif sistemlerinin baş kıç vurma ve dalıp çıkma hareketlerini iyileştirerek düşey ivmelenmeyi etkili bir şekilde azaltabildiğini göstermektedir.*

***Anahtar Kelimeler:*** *Hızlı Feribot, T-foil, Trim Tab, Baş Kıç Vurma ve Dalıp Çıkma, PID Kontrol, LQR Kontrol, Deniz Tutması Oranı*

## 1. INTRODUCTION

Since the construction of marine vehicles began, continuous improvements have been made and these developments which have led to expectations for improvement of criteria such as performance, operational capability, fuel saving and comfort. Over time, systems and devices designed to meet these expectations have become an indispensable part of the maritime industry. Stability enhancing systems are one of these applications. The main purpose is to make the ship more stable by ensuring the comfort and safety of the passengers and by maintaining the ship speed. Waves, which cause vertical acceleration on ships, potentially cause seasickness. This is the biggest disadvantage for passengers. In addition, the ship's extreme vertical movements can cause hazards such as slamming, swaying or wet deck. There are many ways to soften the vertical motion caused by waves. These methods are classified as active and passive systems depending on whether the system is moving or fixed. Passive systems were first designed and implemented for ships. However, passive systems could not be efficient because they could not react to changes depending on ship speed and wave height. With the development of technology and the importance of the criteria such as performance, comfort, route handling and fuel economy expected from ships, active controlled systems have emerged. Active systems are systems that have a control mechanism that have variable effects depending on environmental conditions such as wave, wind, current, human and load movements on the ship. Control of active systems is of great importance in terms of damping the disruptive effects that ships are exposed to. With the increase in the use of fast ferries in recent years, the use of active actuators and the problem of driving control have arisen. Trim tabs and T-foils are used as moving actuators to reduce vertical acceleration in fast ferries. Studies on the application and control of moving actuators on fast ferries began at the beginning of the 21st century. Esteban et al. (2000) modelled the active control surfaces of a ferry consisting of flap and T-foil in his study, which he restricted to the heave and pitch motions created by the effect of the head waves. The model it obtained was easily combinable with the ship's SIMULINK model to provide a simulation environment for control studies. In their study, they used the PID control method to control the actuators. Later, Giron-Sierra et al. (2001) created a model for testing by adding flap and T-foil to a ferry model that was downsized by 1/25 percent. First, he carried out experiments by fixing flap and T-foil at a certain angle. Firstly, he carried out the experiments by fixing the flap and T-foil at a certain angle. He then designed the controller for the active flap and T-foil using the traditional PD control method, and repeated the experiments by controlling the actuators. As a result of the experiments, it can be said that fixed actuators eliminate vertical acceleration by approximately 50% and active actuators applied to the controller by 75%. Different control designs were needed to improve the active control of actuators. Therefore, Aranda et al. (2001) presented a comparative study on the reduction of seasickness rate in high-speed ferries using different and multivariate classical controllers. As a result of the study, although a minimum reduction was achieved for the PD controller, the maximum reduction was achieved with the second order filter. This is because the number of parameters that need to be set in the PD controller is greater than the second order filter. However, the difference between them is not very high. 40 knots speed and the difference in the case of SSN=4 is 6,3% while in the case of SSN=5 the difference is 4%. Cruz et al. (2004) reconsidered experimental studies to study the vertical acceleration of fast ferries at different sea conditions and speeds. Cruz et al. (2004) in his study focusing on the course of the ship in the head waves, he tested the 4-meter-long model they created with two active flaps at the stern and a T-foil close to the bow in the towing tank. In the first part of his study, a model for computer-based control design was developed to create a simulation. In the second part of his study, he designed controllers for the model he developed. The simulation he created includes the ship's mathematical model, actuators, sea states and rate of seasickness. In this study, they used PD controllers based on genetic algorithm (GA) as controllers. He has also conducted experimental studies to establish a model of the ship's vertical movements and verify developments resulting from active control. At the end of the study, simulation results and experiment results were compared. Although the simulation and test studies carried out so far have been successful, studies have continued to obtain more accurate results. Santos et al. (2005) used Neuro-Fuzzy Systems using an artificial intelligence technique for the first time to improve both the model and the controller. Models obtained by this time for fast ferries were under certain conditions (wave height, speed, etc.) while consisting of different models for each application point, Santos et al. (2005) obtained a model suitable for various cruising conditions. A neuro-fuzzy inference system has been applied to estimate the nonlinear model using data from previous studies and experimental results. With this study, a general neuro-fuzzy model that can be used for any condition and control method has been obtained. Zhang et al. (2014) used the LQG control method to smooth the vertical motions of a catamaran. In their work, they designed a ride control system adopting the LQG optimum control theory and analyzed the motions of a catamaran in different sea states. The results show that reducing pitch and heave motions using the LQG controller is effective. Yazici and Cakici (2017) conducted maritime analysis of a passenger ship at a constant speed of 20 knots in the head waves. Then, by designing a controller with static output feedback, it aimed to reduce vertical accelerations in mixed sea conditions. The results show that the static output feedback controller has an important potential in controlling ship motions under wave disturbance. Ticherfatine and Zhu (2018) tried to reduce the vertical acceleration of a fast ferry under random waves with active T-foil. They designed an intelligent PD controller based on model-free control approach to control the T-foil. As a result of the study, thanks to the i-PD controller's ability to continuously update the estimated dynamics of the system, it showed a better reduction in both vertical motions of passengers and seasickness levels. Kucukdemiral et al. (2019) designed a model predictive controller (MPC) to smooth the vertical motions of a cruise ship under irregular waves. They used two active t-foil stabilizers, which they placed at the bow and stern of the passenger ship. The MPC discrete-based controller they designed reduced the vertical accelerations in the bow, centre and stern locations by approximately 75%, 64% and 49% respectively.

In this study, the effect of T-foil and trim tab used as a stability enhancing system on heave and pitch motions with the application of a fast ferry was examined. Unlike previous studies, linear quadratic regulator (LQR) control method was used in the control of active T-foil and trim tab actuators to reduce the vertical acceleration of the fast ferry. Simulation results are given in Section 4. The uncontrolled and controlled responses of the fast ferry are compared, and the advantages of different controller designs are examined. In Section 5, motion sickness index (MSI) is examined, where vertical acceleration of the fast ferry in an uncontrolled and controlled state had an effect on passengers. In Section 6, information about the results obtained is given and general comparisons are made between the results.

## 2. MATHEMATICAL MODEL

Generally, Lagrange method and Newton's second law are used when creating motion equations. Two approaches have been used in the literature to derive hydrodynamic forces and moments acting on the ship. The first approach uses mathematical equations based on the Taylor series of force function. The second approach is to use hydrodynamic pressure acting on the wet surface of the ship to derive external forces and moments (Ibrahim and Grace, 2009).

The general state of the moment equations obtained by Newton motion laws according to the center of mass is as follows (Fossen and Fjellstad, 1995):

$$I_0\dot{\omega}+\omega\times(I_0\omega)+mr_G\times(\dot{\upsilon}_0+\omega\times\upsilon_0)=m_0 \tag{1}$$

In the above equations, $\omega$ angular velocity vector, $\dot{\omega}$ the time dependent derivative of $\omega$ on the ship-bound reference axis, the moment of inertia, m ship mass, $r_G=[x_G, y_G, z_G]^T$ center of gravity, $\upsilon_0$ linear velocity vector, $\dot{\upsilon}_0$ acceleration of the center of mass on the ship-bound reference axis namely the time-dependent derivative of linear velocity, $m_0$ is represented as the moment caused by external forces.

In this study, the effect of T-foil and trim tab systems on the vertical acceleration of the fast ferry will be examined, so it will be sufficient to model the heave and pitch motions that determine the characteristic of this motion. Therefore, the following equations of vertical motion developed by Lloyd are taken into account (Lloyd, 1989).

$$\begin{aligned}&(m+a_{33})\ddot{x}_3(t)+b_{33}\dot{x}_3(t)+c_{33}x_3(t)+a_{35}\ddot{x}_5(t)+b_{35}\dot{x}_5(t)\\&+c_{35}x_5(t)=F_3\cos(\omega_e t+\beta_3)\end{aligned} \tag{2}$$

$$\begin{aligned}&(I_5+a_{55})\ddot{x}_5(t)+b_{55}\dot{x}_5(t)+c_{55}x_5(t)+a_{53}\ddot{x}_3(t)+b_{53}\dot{x}_3(t)\\&+c_{53}x_3(t)=F_5\cos(\omega_e t+\beta_5)\end{aligned} \tag{3}$$

In the equations above, $m$ mass of the ship, $A_{33}$ additional water mass of the heave motion, $A_{55}$ additional mass moment of inertia of the pitch motion, $B_{33}$ damping force coefficient of the heave motion, $B_{55}$ damping moment coefficient of the pitch motion, $\ddot{x}_3$ acceleration of the heave motion, $\dot{x}_3$ speed of the heave motion, $x_3$ heave motion, $\ddot{x}_5$ acceleration of the pitch motion, $\dot{x}_5$ speed of the pitch motion, $x_5$ pitch motion, $F_3$ force of the heave motion, $F_5$ moment of the pitch motion, $\beta_3$ phase difference of the heave motion force, $\beta_5$ phase difference of the pitch motion moment, $I_5$ moment of inertia of the pitch motion, $C_{33}$ restoring force coefficient of the heave motion, $C_{55}$ restoring moment coefficient of the pitch motion.

Since the control of the system includes multiple inputs multiple outputs, the dynamic equation given in Equations 2 and 3 is rewritten as follows in the state-space expression.

$$A_1=\begin{bmatrix} m+a_{33} & a_{35} \\ a_{53} & I_{55}+a_{55} \end{bmatrix},$$

$$B_1=\begin{bmatrix} b_{33} & b_{35} \\ b_{53} & b_{55} \end{bmatrix}, \tag{4}$$

$$C_1=\begin{bmatrix} c_{33} & c_{35} \\ c_{53} & c_{55} \end{bmatrix}$$

$$\begin{bmatrix} F \\ M \end{bmatrix}=\begin{bmatrix} F_{wave}+\ F_{T-foil}+F_{T-tab} \\ M_{wave}+\ M_{T-foil}+M_{T-tab} \end{bmatrix} \tag{5}$$

$$[A_1]\begin{bmatrix}\ddot{\eta}_3\\ \ddot{\eta}_5\end{bmatrix}+[B_1]\begin{bmatrix}\dot{\eta}_3\\ \dot{\eta}_5\end{bmatrix}+[C_1]\begin{bmatrix}\eta_3\\ \eta_5\end{bmatrix}=\begin{bmatrix}F\\ M\end{bmatrix} \tag{6}$$

$$\underset{\dot{x}}{\begin{bmatrix}\ddot{\eta}_3\\ \ddot{\eta}_5\\ \dot{\eta}_3\\ \dot{\eta}_5\end{bmatrix}}=\underbrace{\begin{bmatrix}-A_1^{-1}B_1 & -A_1^{-1}C_1\\ I_{2x2} & 0_{2x2}\end{bmatrix}}_{A}\underset{x}{\begin{bmatrix}\dot{\eta}_3\\ \dot{\eta}_5\\ \eta_3\\ \eta_5\end{bmatrix}}+\underbrace{\begin{bmatrix}A_1^{-1}\\ 0_{2x2}\end{bmatrix}}_{B}\times\underset{u}{\begin{bmatrix}F\\ M\end{bmatrix}} \tag{7}$$

$$\begin{aligned}\dot{x}&=Ax+Bu\\ y&=Cx\end{aligned} \tag{8}$$

Here state variables are expressed with $x=[\dot{\eta}_3\,\dot{\eta}_5\,\eta_3\,\eta_5]^T$. The control input ''u'' consists of trim tab and wing angles of the T-foil. The output vector is expressed as $y=[\ddot{\eta}_3\,\ddot{\eta}_5\,\eta_3\,\eta_5]^T$.

The characteristics of the high speed ferry named Silvia Ana, which is used as a model, are given in Table 1.

**Table 1:** Dimensions and Characteristics of the Silvia Ana Fast Ferry

| **Dimension** | **Symbol** | **Value** | **Unity** |
|---|---|---|---|
| Length overall | $L_{OA}$ | 125 | m |
| Waterline length | $L_{WL}$ | 110 | m |
| Maximum beam | B | 14,696 | m |
| Draft | T | 2,405 | m |
| Mass | m | 1770 | ton |
| Maximum velocity | $V_{max}$ | 42 | knot |

Source: Esteban et al. 2000.

The values of the fixed parameters of the fast ferry under random head waves are given in Table 2.

**Table 2:** The Fixed Parameters of the Fast Ferry

| **Parameters** | **Value** |
|---|---|
| $m_{33}$ | 1770 |
| $I_{55}$ | 1339100 |
| $c_{33}$ | 12128 |
| $c_{55}$ | 841900 |
| $c_{35}$ | -22857 |
| $c_{53}$ | -22857 |

Source: Esteban et al. 2005.

## 2.1. T-foil Mathematical Model

The main purpose of using this type of actuators is to ensure the safety of passengers on the ship, increase their comfort and maintain the speed of the ship by balancing the movement of the ship by generating lifting forces by changing the wing angles. These actuators are considered to be the most powerful and effective motion controllers for high speed applications and their efficiency increases with the square of the speed.

Designed to reduce the vertical acceleration of the fast ferry, the T-foil system is placed near the bow of the ferry and has the ability to move about $15^0$ wings in up or down direction. The geometry of the T-foil wing is given in Figure 1.

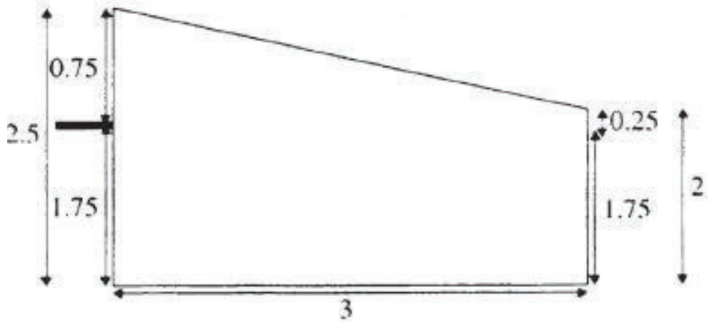

**Figure 1:** T-foil Geometry
Source: Esteban et al. 2000.

The force and moment equations generated by the T-foil actuator on the fast ferry are as follows (Dallinga, 1993; Fossen, 1994).

$$F_{Foil} = \frac{1}{2} \rho A_{Foil} V^2 C_{LFoil} \delta_{Foil} \tag{9}$$

$$M_{Foil} = F_{Foil} l_{Foil} \tag{10}$$

In the Equations (9) and (10), $F_{Foil}$ the force of the T-foil, $A_{Foil}$ the surface area of the T-foil, $\rho$ the density of the fluid, $V$ the speed of the ship, $C_{Foil}$ the lift coefficient of the T-foil, $M_{Foil}$ the moment of the T-foil, $\delta_{Foil}$ the wing angle of the T-foil, $l_{Foil}$ the distance to the center of gravity of the T-foil.

The characteristic of the T-foil is given in Table 3.

**Table 3:** T-foil Characteristic

| Dimension | Value | Unity |
|---|---|---|
| Span | 3 | m |
| Chord | 2,25 | m |
| Surface Area | 6,75 | $m^2$ |
| Operating Range | ±15 | $^0$ |
| Lift Coefficient | $6{,}9*10^{-3}$ | $KN/^0/m^2/knot^2$ |
| Maximum Rotational Speed | 13,5 | $^0/s$ |
| Distance to Center of Gravity | 58,4 | m |

Source: Esteban et al. 2000.

## 2.2. Trim Tab Mathematical Model

The geometry of the trim tab actuator used in this study, which can achieve a wingspan of up to $15^0$ with hydraulic drive, is given in Figure 2.

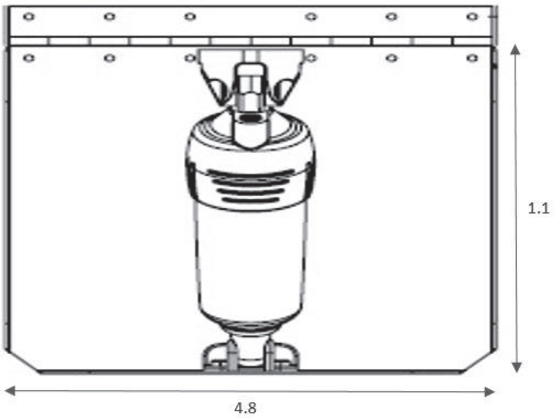

**Figure 2:** Trim Tab Geometry
Source: Esteban et al. 2000.

The force and moment equations generated by the trim tab actuator on the fast ferry are as follows (Dallinga, 1993; Fossen, 1994).

$$F_{Tab} = \frac{1}{2}\rho A_{Tab} V^2 C_{LTab}\delta_{Tab} \tag{11}$$

$$M_{Tab} = F_{Tab} l_{Tab} \tag{12}$$

In the equations above, $F_{Tab}$ the force of the trim tab, $A_{Tab}$ the surface area of the trim tab, $C_{Tab}$ the lift coefficient of the trim tab, $M_{Tab}$ the moment of the trim tab, $\delta_{Tab}$ the wing angle of the trim tab and $l_{Tab}$ the distance to the center of gravity of the trim tab.

The features of the trim tab actuators used in the study are given in Table 4.

**Table 4:** Trim Tab Characteristic

| Dimension | Value | Unity |
|---|---|---|
| Span | 4,8 | m |
| Chord | 1,1 | m |
| Surface Area | 5,5 | $m^2$ |
| Operating Range | 15 | $^0$ |
| Lift Coefficient | $9{,}19*10^{-3}$ | $KN/^0/m^2/knot^2$ |
| Maximum Rotational Speed | 13,5 | $^0/s$ |
| Distance to Center of Gravity | 41,6 | m |

Source: Esteban et al. 2000.

## 2.3. Random Wave Model

Winds cause waves to form over the ocean. The winds blowing continuously at distances far from the coast of the ocean create huge waves. Pierson and Moskowitz measured the wind speed at 19,4 meters above the ocean surface by 12 m/s and formed the Pierson-Moskowitz spectrum (Pierson and Moskowitz, 1964).

The basis of the modern wave parametric spectrum was laid by Philips (1957) and created a wind-based constant called Philips constant. Then, Pierson and Moskowitz obtained a spectral density function based on the data they obtained as a result of their experiments, based on the saturation balance range limitations described by Philips (Fossen, 1994).

$$S(\omega) = \frac{\alpha_P g^2}{\omega^5} \exp\left[ -0.74 (\frac{g}{\omega U_{19.4}})^4 \right] \tag{13}$$

$S(\omega)$ spectral wave function, $\omega$ angular frequency, $\alpha_p$ Philips constant ve $U_{19.4}$ wind speed at a height of 19,4 meters above the ocean surface. Philips constant is given as $\alpha_p$=8,1x$10^{-3}$.

In this study, based on the Pierson-Moskowitz measurements and equation, a random wave model was created in the MATLAB environment, characteristic of which is seen in Figure 3. Simulations have been conducted assuming that the fast ferry was subjected to this random wave effect.

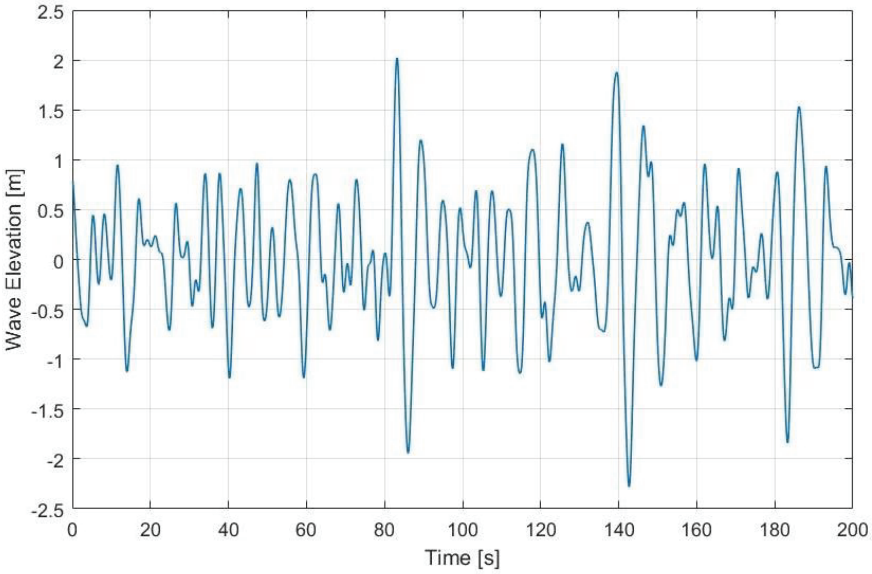

**Figure 3:** Variation of the Time-dependent Wave Height of the Random Wave

The World Meteorological Organization (WMO) has coded sea states according to wave height. According to this coding, waves with wave height between 1,25-2,5 meters are coded as sea states 4 (WMO, 2019).

The dominant wave height value of the random wave model obtained is 1,25 meters. Therefore, the random wave model falls under the sea condition 4 category. The frequency of the wave model is $\omega = 0,7$ rad/s and the frequency of encounter is $\omega_e = 2,69$ rad/s.

The relation between the wave frequency and the frequency of encounter for the initial waves is as follows.

$$\omega_e = \omega + \frac{\omega^2 V}{g} \tag{14}$$

## 3. CONTROLLER DESIGN

PID and LQR control methods are applied for the control of T-foil and trim tab active systems used in damping vertical acceleration of the fast ferry.

### 3.1. PID Controller

The PID controller is a feedback control method that creates the control output by processing and summing up the system error in three separate mathematical operations. In other words, by comparing the signal coming from the output with the input signal, it creates an error and tries to minimize this error and send it back to the output. It is one of the most commonly used control methods. The PID control method includes three different parameters as proportional (P), integral (I) and derivative (D). The proportional term $k_P$ of these terms tries to reduce the error by multiplying the error coming from the system with the coefficient. The term integral calculates the area of the $k_I$ error. If the derivative term is $k_D$, it calculates the time between two samples in the system. The PID algorithm, consisting of these three parameters, produces a control input $u(t)$ so that the error between the output of the system $y(t)$ and the reference $r(t)$ value is $e(t)$. $k_P$, $k_I$ and $k_D$ values in the algorithm are randomly selected and changes are made to make observations to find the optimum value of the coefficients. Schematic representation of the PID controller is given in Figure 4.

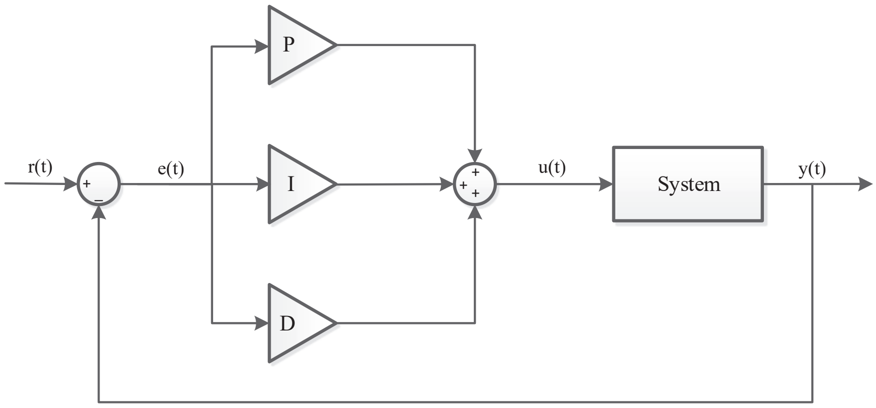

**Figure 4:** PID Controller Schematic Representation

### 3.2. LQR Controller

A linear quadratic regulator (LQR) is a method that provides feedback gains that are best controlled to ensure closed-loop stable and high-performance system design. The purpose of this method is to determine the feedback coefficients and ensure that the targeted performance criterion of the system is minimum or maximum. The schematic representation of the LQR controller is given in Figure 5.

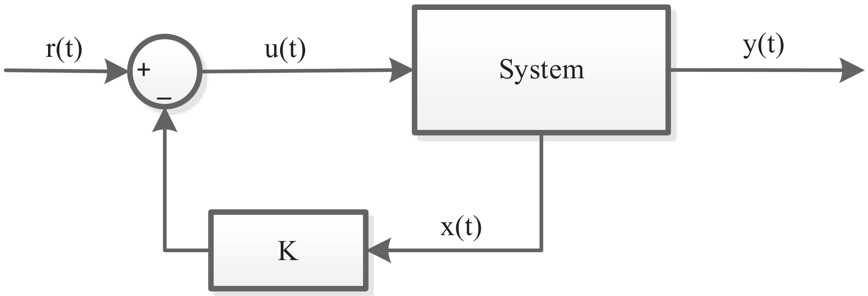

**Figure 5:** LQR Controller Schematic Representation

$$[K, S, e] = lqr[SYS, Q, R, N] \tag{15}$$

calculates the optimal gain matrix *K*.

For a continuous time system, the state-feedback law *u=-Kx* minimizes the quadratic cost function $\dot{x} = Ax + Bu$ dependent on the system dynamics.

$$J(u) = \int_0^\infty (x^T Q_x + u^T Ru + 2x^T Nu)dt \tag{16}$$

In addition to the status feedback gain *K*, LQR returns the *S* solution of the corresponding Riccati equation and the closed loop eigenvalues *e=eig(A-B*K)*.

$$A^T S + SA - (SB + N)R^{-1}(B^T S + N^T) + Q = 0 \tag{17}$$

Feedback gain *K* is obtained by using *S* as in Equation (15).

$$K = R^{-1}(B^T S + N^T) \tag{18}$$

# 4. SIMULATION RESULTS

## 4.1. Uncontrolled Motions of Fast Ferry Model

Modelling was done in MATLAB program by using the mathematical model of the heave and pitch motions given in Equations (2) and (3) and the dimensions and parameters of the Silvia Ana fast ferry given in Table 1 in Section 2. A random wave model obtained in Section 2.3 based on the Pierson-Moskowitz spectrum was added to the resulting mathematical model. It was simulated for 100 seconds in a step range of 0,01 seconds, assuming that the irregular wave came from the head side of the fast ferry (Figure 6 and 7).

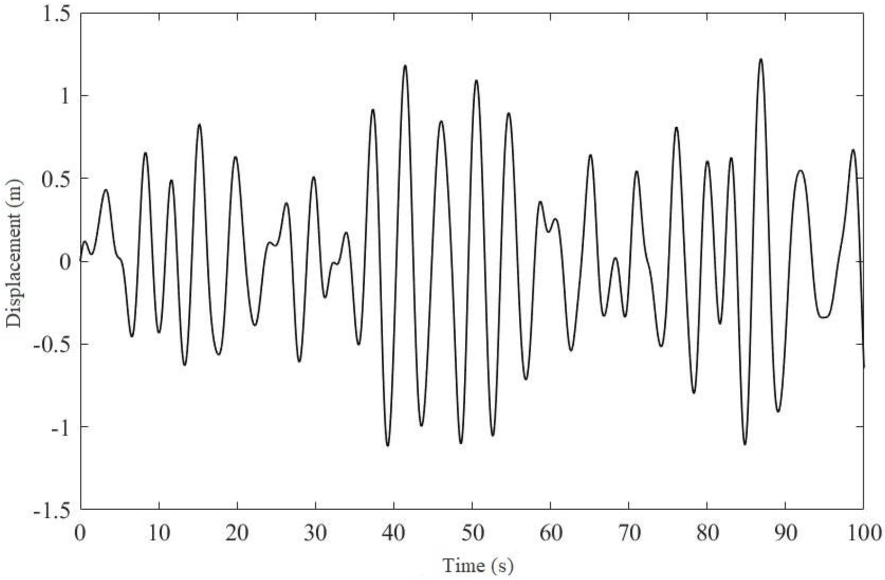

**Figure 6:** Change of Heave Motion Under Random Head Waves

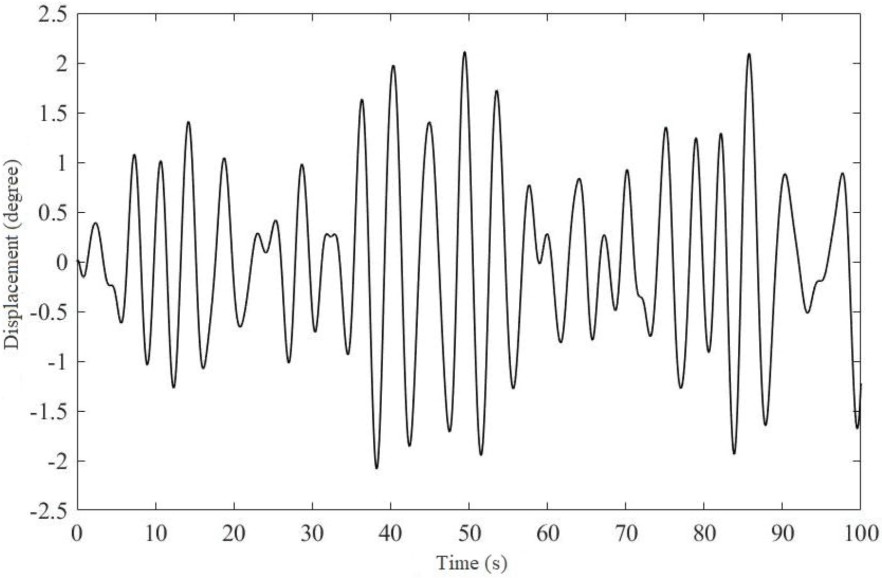

**Figure7:** Change of Pitch Motion Under Random Head Waves

As seen in the simulation results above, the displacement of the fast ferry, which is exposed to random head waves, due to the heave motion, comes up to 1,2 meters. Likewise, the displacement resulting from the pitch motion goes up to $2^0$.

In order to dampen this increase in the heave and pitch pounding of the fast ferry, the results were analysed by applying control methods to T-foil and trim tab actuators in the next section.

## 4.2. PID Controller Response of Fast Ferry Model

Using the PID Tuning tool of the MATLAB program, parameters to control the wing span of the T-foil and trim tab actuators have been determined. The PID control parameters are $k_p = 0{,}5$, $k_I = 2{,}2$, $k_D = 0{,}12$. The controller responses obtained for the selected PID parameter values are given in Figure 8 and Figure 9.

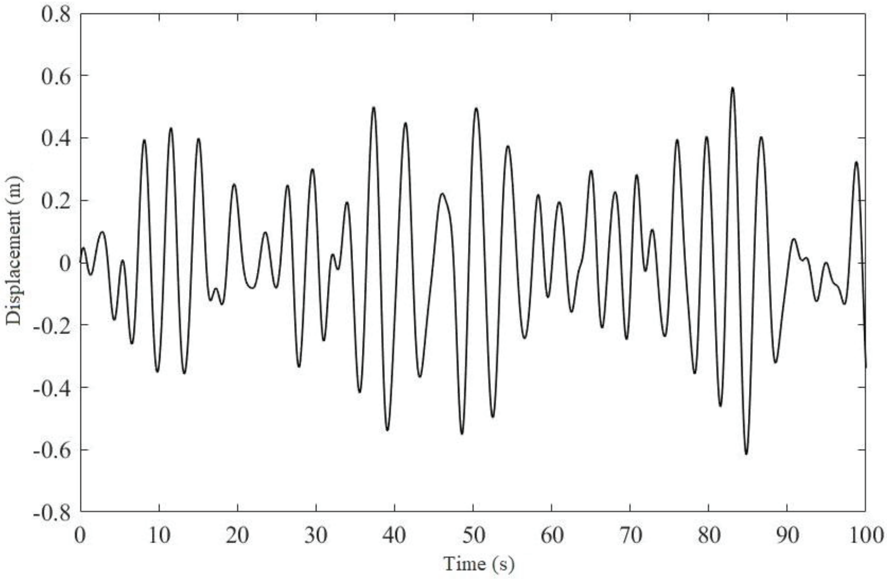

**Figure 8:** PID Controller Response of Heave Motion

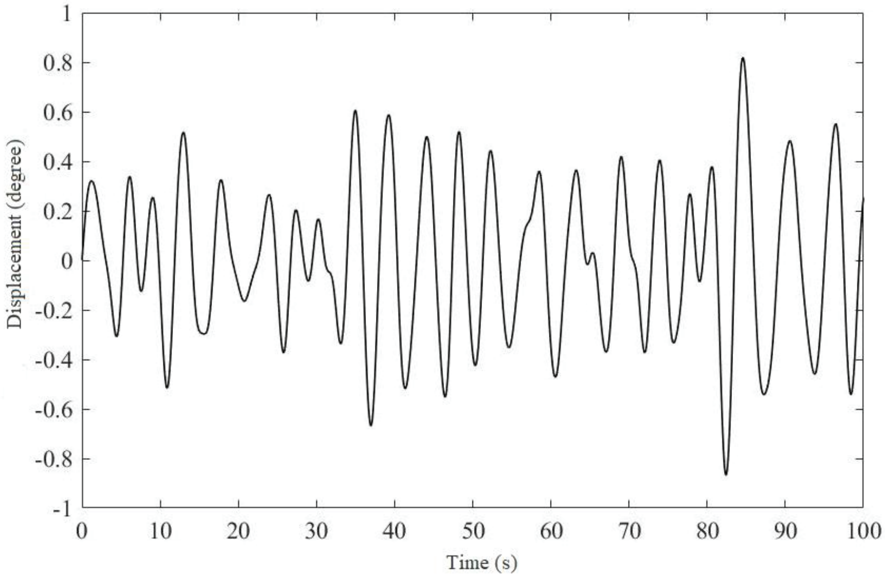

**Figure 9:** PID Controller Response of Pitch Motion

## 4.3. LQR Controller Response of Fast Ferry Model

As a result of the LQR controller design, the state weight matrix Q and the control weight matrix R were found as follows.

$$Q = [53559\ \ 0\ \ 0\ \ 0;0\ \ 222740\ \ 0\ \ 0;0\ \ 0\ \ 141580\ \ 0;0\ \ 0\ \ 0\ \ 456550] \quad (19)$$

$$R = [4929\ \ 0;0\ \ 1549] \quad (20)$$

The gain matrix is obtained as follows, depending on the weight matrices.

$$K = [0{,}0369\ \ -0{,}3353\ \ 0{,}9613\ \ -4{,}3101;\ 0{,}5436\ \ 1{,}4458\ \ 1{,}8792\ \ -4{,}3076] \quad (21)$$

The controller response obtained as a result of controlling the T-foil and trim tab actuators designed to reduce the vertical acceleration of the fast ferry exposed to random head waves with the LQR control method is as in Figure 10 and Figure 11.

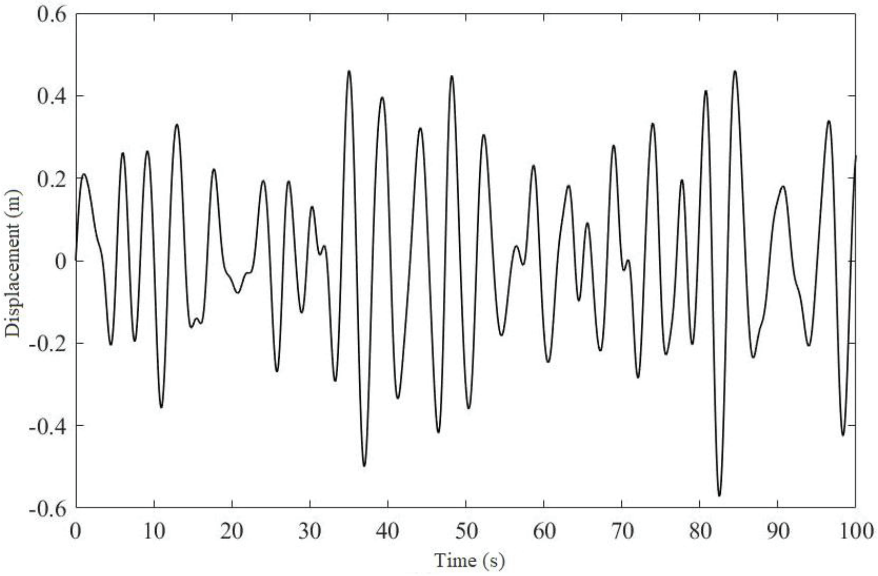

**Figure 10:** LQR Controller Response of Heave Motion

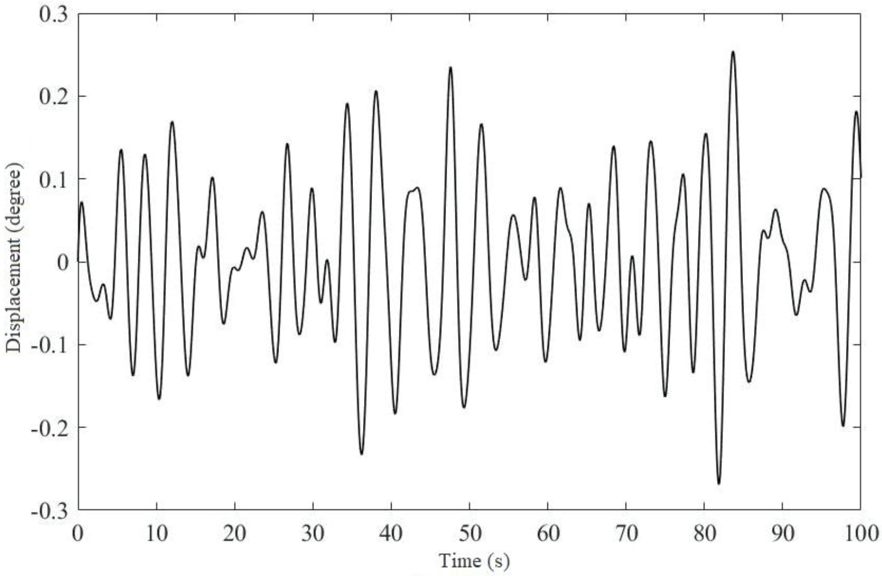

**Figure 11:** LQR Controller Response of Pitch Motion

### 4.4. Comparison of Uncontrolled and Controlled Responses

In this study, the control of T-foil and trim tab actuators with PID and LQR control methods, and the effect of actuators on damping vertical acceleration of the fast ferry was compared for uncontrolled and controlled situations. Figure 12 shows the comparison of the uncontrolled motion of heave motion with the PID controller response. In Figure 13, the comparison of the uncontrolled state of pitch motion with the PID controller response is seen.

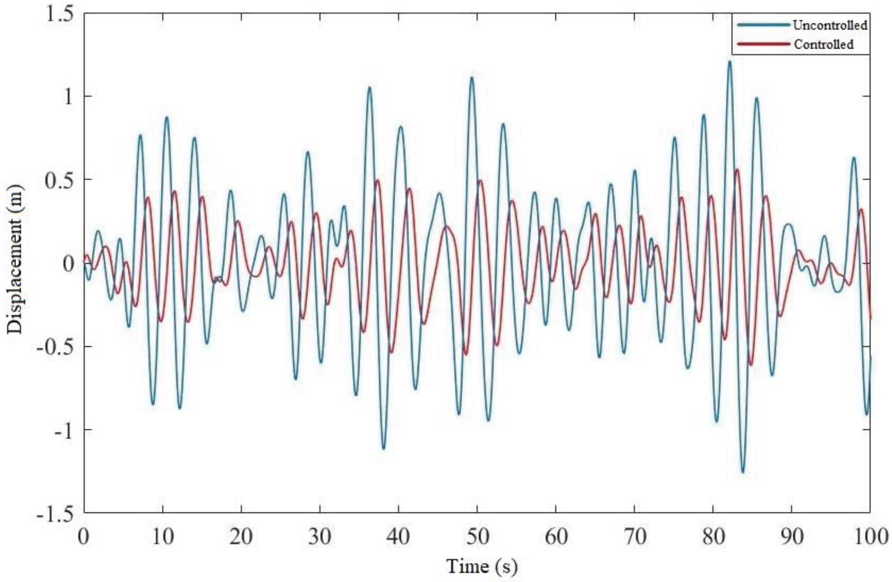

**Figure 12:** Comparison of Uncontrolled and PID-controlled Responses of the Heave Motion

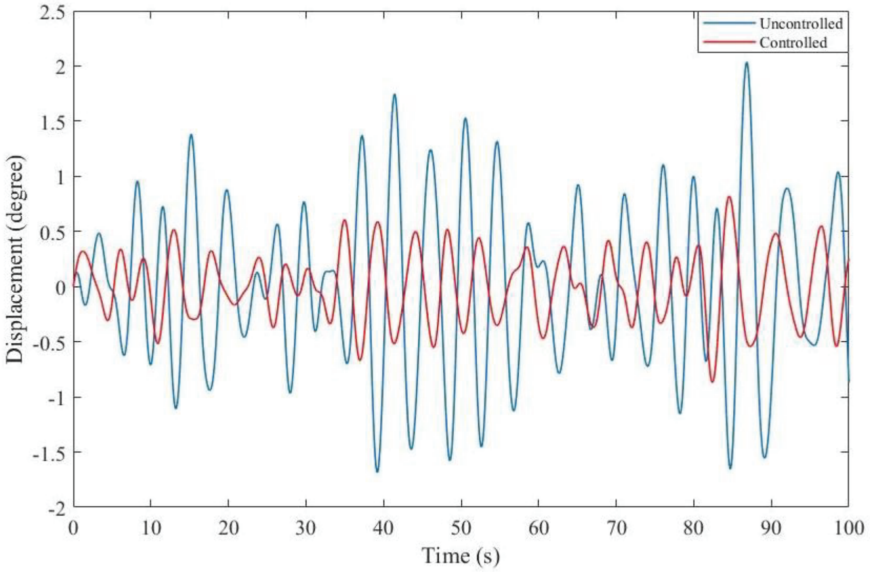

**Figure 13:** Comparison of Uncontrolled and PID-controlled Responses of the Pitch Motion

In Figure 14 and Figure 15, respectively, the uncontrolled state of heave and pitch motions and the effect of the LQR controller on damping can be compared.

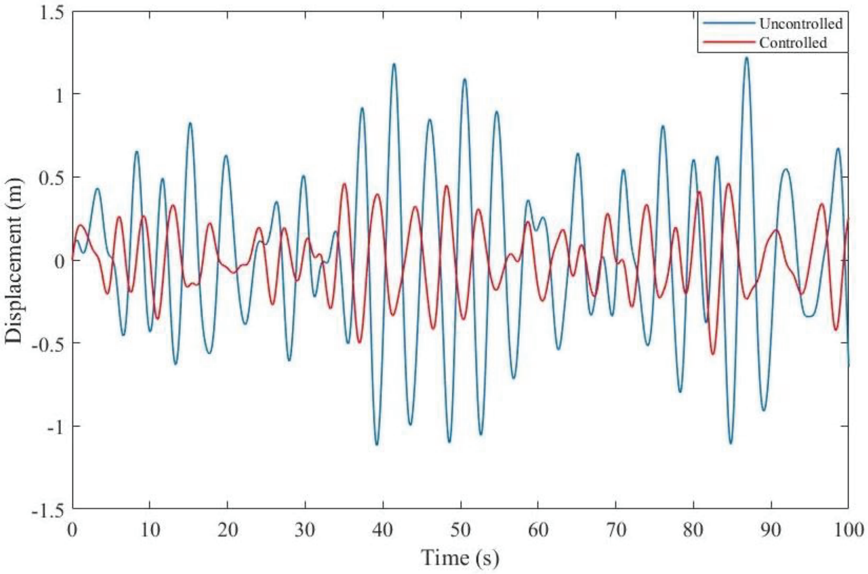

**Figure 14:** Comparison of Uncontrolled and LQR Controlled Responses of Heave Motion

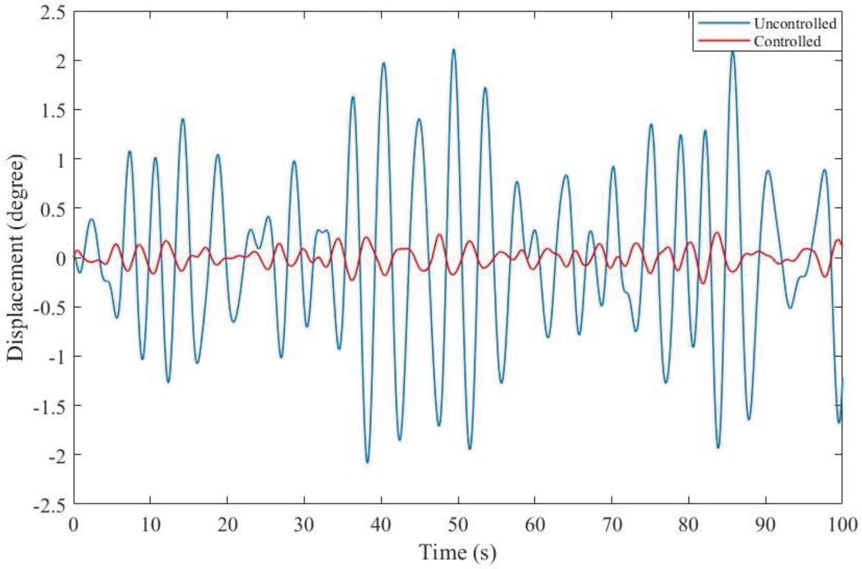

**Figure 15:** Comparison of Uncontrolled and LQR Controlled Responses of Pitch Motion

When the graphic results above are analysed, it is seen that heave motion is damped by 47,46% with the PID controller and 48,24% with the LQR controller. Similarly, it is seen that pitch motion is damped by 54,36% with the PID controller and 78,74% with the LQR controller.

## 4.5. Comparison of Controllers

The controller model designed to control a system can give different results according to the control method. If we compare the behaviour of the controllers obtained with the control methods applied, the effects of the LQR and PID controllers on heave and pitch motion can be seen in Figure 16 and Figure 17.

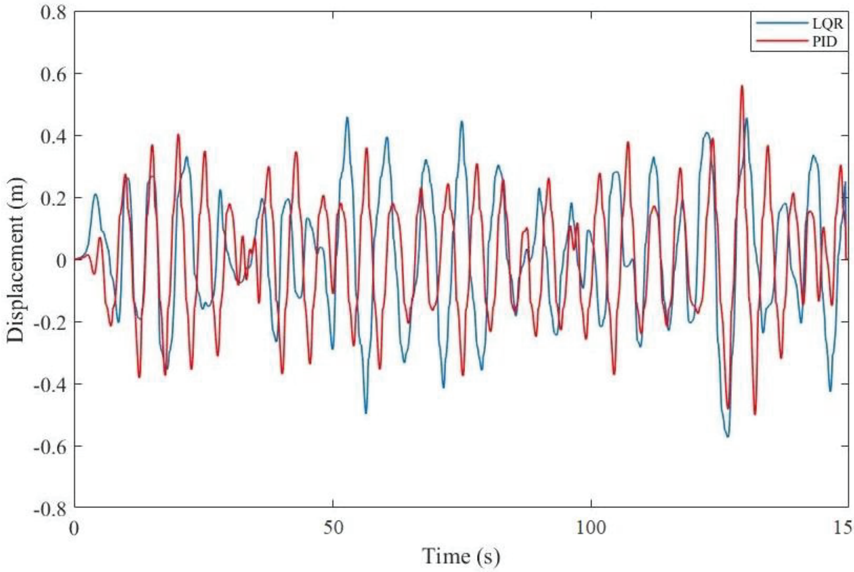

**Figure 16:** Comparison of the Effects of LQR and PID Controllers on Heave Motion

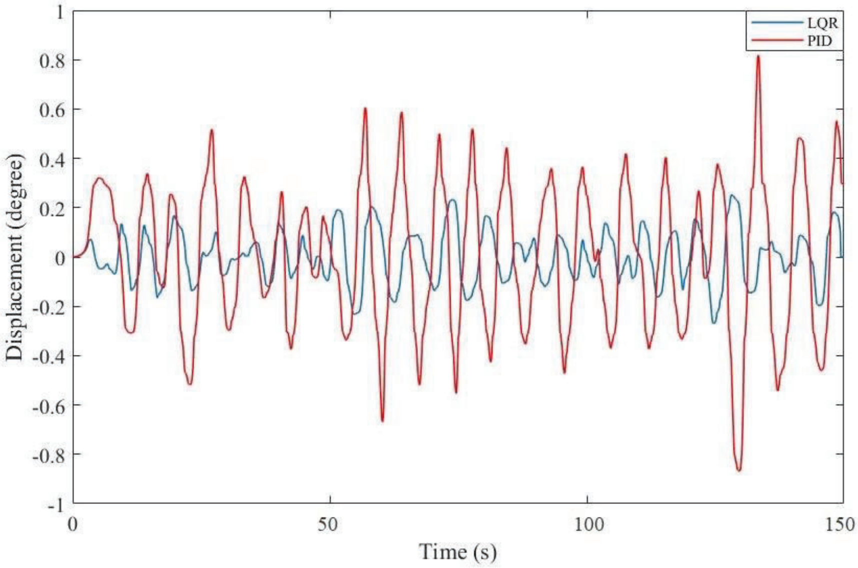

**Figure 17:** Comparison of the Effects of LQR and PID Controllers on Pitch Motion

## 5. MOTION SICKNESS INDEX

Ships directly under the influence of wind and waves in open seas, as a result of motion and acceleration, negatively affect the human body and can cause movement diseases. This condition, especially caused by the vertical acceleration of ships, is called seasickness (Cepowski, 2012).

McCauley and O'Hanlon concluded that seasickness had a cumulative effect on vertical acceleration at certain frequencies and quantified the effect of ship motions on the percentage of people suffering from seasickness. According to this study, Motion Sickness Index (MSI) is the probability integral of motion sickness, and the given formulation shows the percentage of passengers caught seasickness after two hours of exposure for the stated Frequency and acceleration (O'Hanlon and McCauley, 1974). MSI is obtained from the following equations:

$$MSI = 100\left[0.5 \pm erf\left(\frac{\pm\log_{10}\frac{a_v}{g} \pm \mu_{MSI}}{0.4}\right)\right] \tag{22}$$

$$\mu_{MSI} = -0.819 + 2.32(\log_{10} \omega_e)^2 \tag{23}$$

Here, $a_v$ vertical acceleration is defined as the average value, $\omega_e$ is the dominant frequency of vertical acceleration.

The error function is obtained from the equation given below.

$$erf(\mathrm{x}) = \frac{1}{\sqrt{2\pi}} \int_0^x \exp\left( \frac{-z^2}{2} \right) dz \tag{24}$$

MSI values for uncontrolled, PID controlled and LQR controlled situations are given in Table 5. When the results are examined, a considerably decrease in MSI values is observed in controlled states.

**Table 5:** MSI Change in Uncontrolled and Controlled States

| **States** | **MSI (%)** |
|---|---|
| Uncontrolled | 7,62 |
| PID Control | 1,33 |
| LQR Control | 0,87 |

## 6. CONCLUSIONS

Fast ships are subject to high accelerations caused by waves. Some active actuators can be used to alleviate these accelerations, which have negative effects on passengers, crew and ship safety. A good control design should be made for the active actuators to operate effectively. To realize the control design, it is necessary to have a suitable model.

In this study, a fast ferry model is created under random head waves and T-foil and trim tab actuators are controlled with PID and LQR control methods in order to minimize adverse effects such as seasickness, endangerment of the safety of cargo, passenger and crew. The scenario is based on the study of the vertical acceleration of the fast ferry, which sails under the random waves at a speed of 40 knots, in a sea with a sea state number 4, consisting of heave and pitch motions.

The simulation results show that heave motion is damped by 47,46% with the PID controller, 48,24% with the LQR controller pitch motion with the PID controller is 54,36% and the 78,14% with the LQR controller. Although the PID controller is easier to implement than the LQR controller, it has been poor in terms of control performance.

In the continuation of the study, uncontrolled and controlled seasickness rates of the fast ferry are examined. Although the rate of seasickness affecting passengers was 7,62% in uncontrolled condition, it decreased to 1,33% with PID control method to T-foil and trim tab actuators and 0,87% with LQR control method. These results show that the PID controller reduced seasickness rate by 82,54% and the LQR controller by 88,58%.

In this study, the simulation results showed how functional the T-foil and trim tab actuators, which are active stability enhancing systems used on ships, are in terms of damping the vertical acceleration of ships.

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