Journal of Engineering and Development, Vol. 17, No.2, 2013, ISSN 1813- 7822

Dynamic stability of ships via unbalanced mass systems

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Abstract:

In this paper, a new mechanism is introduced and a control law is designed for the dynamic stability of ships. This accomplished based on the action of the inertia forces induced from the movement of unbalanced mass systems, where these forces are coupled to produce a torque that is determined by a designed control system to force the disturbed ship to its stable equilibrium state. The basic idea of this mechanism can be employed in attitude control of space-vehicles, antirollover systems in automobiles and other different applications.

Keywords: Dynamic stability, antirollover systems, nonlinear systems, ship control, stabilizer, unbalanced mass systems.

الاستقرار الحركي للسفن بواسطة أنظمة كتلة غير متزنة

ماسي فيصل مالك الميالي
كلية الهندسة /جامعة القادسية

الخلاصة:

تم في هذا البحث تقديم آلية جديدة و تصميم منظومة سيطرة لتحقيق الاستقرار الحركي للسفن، و ذلك بالاعتماد على تأثير قوى العطالة الناشئة من حركة أنظمة كتلة غير متزنة، حيث تتم المزاوجة بين هذه القوى لإنشاء العزم الذي يتم تحديده من خلال منظومة السيطرة المصمم لقسر السفينة المعرضة للقوى الخارجية للرجوع إلى حالة الاتزان المستقرة. إن الفكرة الأساسية لهذه الآلية يمكن أن تطبق في مجال السيطرة على الوضع الجسماني للمركبات الفضائية، أنظمة السيطرة على اتزان المركبات و تطبيقات مختلفة أخرى.

1.Introduction

In the literature of naval architecture and ship design, several systems have been designed in order to reduce the effects of waves or wind gusts. These systems are classified into passive systems and active systems. Passive systems include bilge keel systems, antiroll tanks systems, outriggers systems and other systems in which there is no need to the input energy to the system. Active systems, on the other hand, are defined by the need to input energy to the system such as gyroscopic stabilizer, stabilizer fines attached to the side of the ship and other systems **[4].**

At present, safety regulations with regard to ship capsize are based primarily on static stability concepts. The efficient calculation of GZ curves that is possible nowadays permits quick and accurate determination of a ship's static stability. Although it is well accepted that capsizing of ships is a dynamic phenomenon, static stability considerations are still used almost exclusively to gauge the propensity of a ship to capsize in waves **[9].**

Two active systems (these have some sort of actuator) have been developed for controlling the heeling moment produced by an external disturbance. In the first and oldest one ,the transfer of water between tanks (also called U-tanks) is carried out by the action of a water pump that is installed in the pipe of connection between them. In the second one there is an electric motor driven force draft blower that supplies compressed air to air valve group. The valves are controlled by the electronic control unit and can pressurize one of the list control tanks and vent the other to create a differential pressure that would move the water between the tanks. The water difference produces the restoring torque necessary to carry out the ship to an equilibrium position with a null angle of inclination**[10].**

In recent years there have been reports of serious accidents of parametric rolling for modern container ships and car carriers. For avoiding such accidents, a prediction method of parametric rolling in irregular seas is required. Since parametric rolling is practically non-ergodic, repetitions of numerical simulations or experiments could be not feasible to ascertain the behaviour. Therefore, a modify method combining a stochastic approach with a deterministic approach in order to estimate the probabilistic index without such simple repetitions is developed. The ship's response in regular seas is estimated by solving an averaged system of the original 1-DoF roll model, and random waves necessary for occurrence of parametric rolling is achieved by using Longuet-Higgins's or Kimura's wave group theory**[11].**

In this paper, a new active system is proposed to produce a torque that is required to reduce the effects of external forces and achieve the dynamic stability of the disturbed ship.

2. Literature review

The coupling effects of six degrees of freedom in ship motion with fluid oscillation inside a three-dimensional rectangular container was investigated by using a novel time domain simulation scheme. During the time marching, the tank-sloshing algorithm is coupled with the vessel-motion algorithm so that the influence of tank sloshing on vessel motions and vice versa can be assessed. Several factors influencing the dynamic behavior of tank–liquid system due to moving ship are also investigated. These factors include container parameters, environmental settings such as the significant wave height, current velocity as well as the direction of wind, wave and flow current acting on the ship. The nonlinear sloshing is studied using a finite element model whereas nonlinear ship motion is simulated using a hybrid marine control system. Computed roll response is compared with the existing results, showing fair agreement. Although the two hull forms and the sea states are not identical, the numerical result shows the same trend of the roll motion when the anti-rolling tanks are considered. Thus, the numerical approach presented in this paper is expected to be very useful and realistic in evaluating the coupling effects of nonlinear sloshing and 6-DOF ship motion **[12].**

The effect dueto parametric rolling motion on the transverse stability of ships is stil lone of the popular subjects . the possibility of parametric resonance dueto fluctuations in the restoring moment is examined. Twenty years later, the existence of parametric resonance under the action of sea waves is exhibited by the help of experiments it is confirmed that capsizing associated with parametric rolling is more likely to occur in following seas than in quartering seas **[13].**

The ship anti-rolling tank test platform is a specific designed synthesis system used to imitate the ship's movement in the sea waves. An electro-hydraulic servo system featuring high accuracy and fast response is employed. This latter has highly nonlinear phenomena such as fluid compressibility, the flow pressure relationship and dead band due to the internal leakage and hysteresis. Usually, conventional controllers are adopted because of theirs simplicity, however these control methods could not get high performances, because of the nonlinearity of the system, its modeling error and uncertainties. The application of nonlinear robust control techniques is a necessity for successful Operation of electro-hydraulic systems. Among these techniques, sliding mode control have attracted considerable attention because it provides a systematic approach to the problem of maintaining stability and consistent performance in the face of modeling imprecision and disturbances**[14].**

3. Analysis

Consider the ship shown in **Fig. (1)**, where

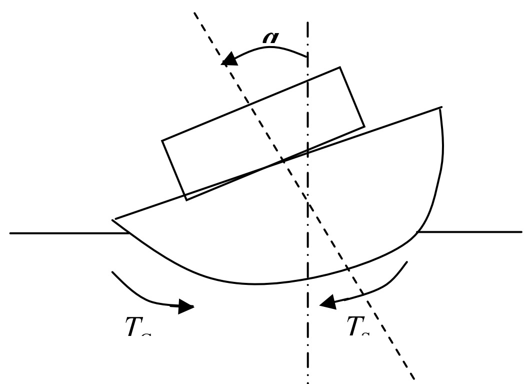

Fig. (1) Representation of the disturbed

T_C denotes the torque which tries to capsize the ship, while T_S denotes the torque required to stabilize the ship in the presence of the torque T_C. The torque T_S includes the torque caused by the buoyancy force, the torque caused by the damping effect of the water and the torque produced by the proposed stabilizer.

The torque required for the dynamic stability of a ship subjected to an external disturbance could be specified by a feedback control system such that the angle "α" tracks a zero angle (α=0) as shown in **Fig. (2).**

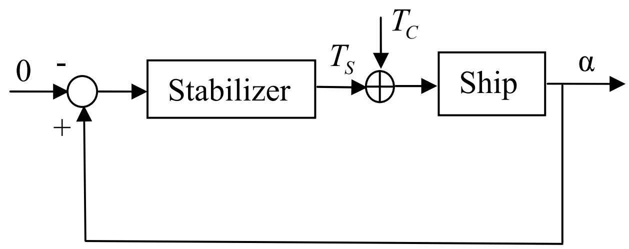

Fig. (2) Feedback control system for ship's dynamic stability.

4. The proposed active stabilizer

To produce the required torque, the proposed stabilizer consists of four unbalanced mass systems; each of them has an equal mass "***m***" and rotating with an angular velocity "***ω***", as shown in **Fig. (3),** where point "***c***" represents the mass center of the system which is eccentric from the center of rotation "***S***" with an eccentricity "***r***".

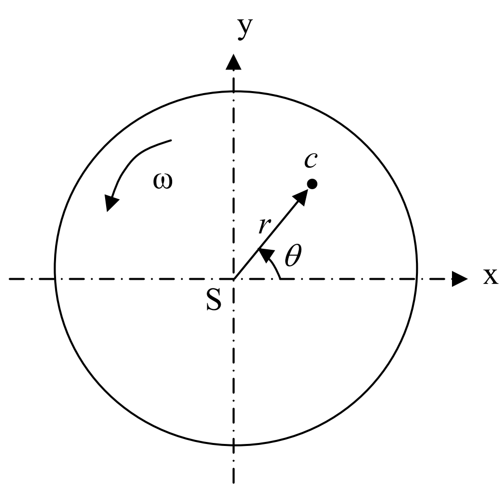

Fig. (3) Unbalanced mass system.

Figure (4) represents the total system for the proposed stabilizer. Point **"O"** is the origin of the stationary coordinate system.

Consider the first subsystem whose moving center of rotation is "S_1". The acceleration of point "c_1", the mass center of the subsystem, could be written as [**8**]**:**

$$\boldsymbol{a}_{C1} = \boldsymbol{a}_{S1} + \boldsymbol{a}_{C1S1} \qquad \textbf{(1)}$$

where: $$\boldsymbol{a}_{S1} = a_{S1} i \qquad \textbf{(2)}$$

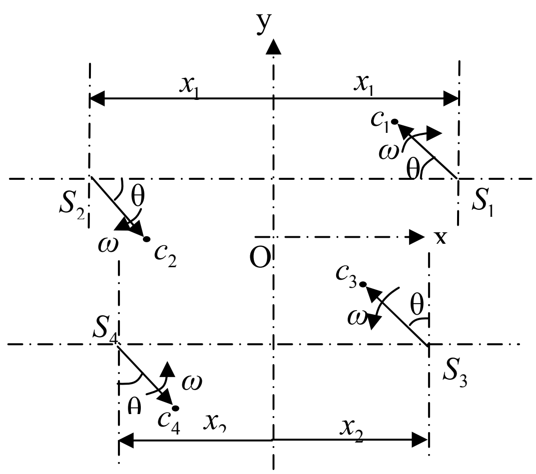

Fig. (4) Representation of the proposed stabilizer.

and :

$$\boldsymbol{a}_{C1S1} = (-\ddot{r}\cos\theta + 2\dot{r}\,\omega\sin\theta + r\omega^2\cos\theta)i + (\ddot{r}\sin\theta + 2\dot{r}\,\omega\cos\theta - r\omega^2\sin\theta)j \qquad \textbf{(3)}$$

where "ω" is assumed to be constant. If the radius "r" is chosen to be constant:

$$r = B \qquad \textbf{(4)}$$

then (3) will be:

$$\boldsymbol{a}_{C1S1} = (B\omega^2\cos\theta)i + (-B\omega^2\sin\theta)j \qquad \textbf{(5)}$$

Substituting (5) into (1), the y-component of $\boldsymbol{a}_{C1}$ will be:

$$\boldsymbol{a}_{C1y} = (-B\omega^2\sin\theta)j \qquad \textbf{(6)}$$

The reaction force induced due to a_{C1y} can be written as:

$$\boldsymbol{F}_{y1} = -(mB\omega^2 \sin\theta)\, j \qquad \textbf{(7)}$$

In a similar manner, another force F_{y2} can be obtained for the second subsystem to be:

$$\boldsymbol{F}_{y2} = (-mB\omega^2 \sin\theta)\, j \qquad \textbf{(8)}$$

The torque induced due to $\boldsymbol{F}_{y1}$ and $\boldsymbol{F}_{y2}$ can be expressed as:

$$T_1 = 2x_1 mB\omega^2 \sin\theta \qquad \textbf{(9)}$$

If the distance x_1 is chosen to obey the following relation:

$$x_1 = A\sin\theta \qquad \textbf{(10)}$$

where "*A*" is a design parameter which determines the amplitude of x_1, then **(9)** will take the form:

$$T_1 = 2mAB\omega^2 \sin^2\theta \qquad \textbf{(11)}$$

Another torque "T_2" can be obtained for the third and fourth subsystems in the form:

$$T_2 = 2mAB\omega^2 \cos^2\theta \qquad \textbf{(12)}$$

Then a total torque "*T*" is obtained in the following form:

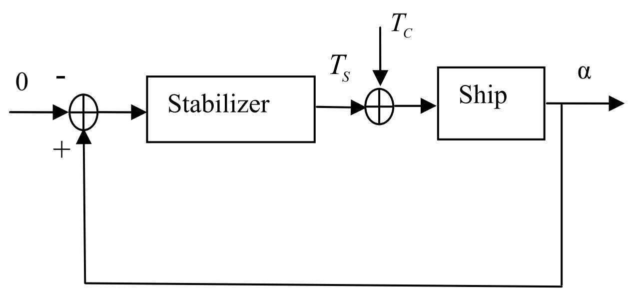

Fig. (6) Feedback control system for ship's dynamic stability.

$$T = T_1 + T_2 = 2mAB\omega^2 \qquad \textbf{(13)}$$

The values of the parameters **"*A*"** and **"*B*"** are restricted by space limitation, while the selection of ***ω*** will determine the value of the required torque **"*T*".** The direction of **"*T*"** is determined by the signs of **"*A*"** and **"*B*".**

5. Dynamic modeling and control design

Several forms of the equation of motion have been deduced from experimental studies based on different hull types **[5, 6].** In this case study, a simplest equation will be considered in the following form:

$$\ddot{\alpha}+\beta\dot{\alpha}+\alpha-\alpha^2=F\sin(\Omega t)+u \qquad \textbf{(14)}$$

where β is a damping constant, F is the amplitude of the external disturbing torque (the size of the waves), Ω is the frequency of the waves and u is the torque provided by the stabilizer.

In this paper, the following form is proposed for the control input u which is proven here to be valid to stabilize the disturbed ship described by **(14):**

$$u=-F\sin(\Omega t)-k_1\dot{\alpha}-\alpha^2-k_2\alpha \qquad \textbf{(15)}$$

where k_1 and k_2 are design parameters. To prove stability of the system described by **(14)** by using the control law (**15**), substitute **(15)** into (**14)** to get:

$$\ddot{\alpha}+(\beta+k_1)\dot{\alpha}+(1+k_2)\alpha=0 \qquad \textbf{(16)}$$

In term of Laplace parameter "*s*" with zero initial conditions, (16) can be written as:

$$s^2+(\beta+k_1)s+(1+k_2)=0 \qquad \textbf{(17)}$$

To achieve exponentially stable equilibrium state ($\dot{\alpha}=\alpha=0$), the parameters k_1 and k_2 are chosen so that (17) has all its roots strictly in the left-half complex plane **[7].**

By utilizing the proposed stabilizer, the control variable u can be written as:

$$u=2mAB\omega^2 \qquad \textbf{(18)}$$

The design parameter B is selected to have a constant positive value. The magnitude of the parameter A is chosen to be constant while its sign is governed by the following relation:

$$sgn(A)=sgn\{-F\sin(\Omega t)-k_1\dot{\alpha}-\alpha^2-k_2\alpha\}$$

Then the parameter A can be expressed as:

$$A=sgn\{-F\sin(\Omega t)-k_1\dot{\alpha}-\alpha^2-k_2\alpha\}|A| \qquad \textbf{(19)}$$

From (15), (18) and (19), the angular velocity ω can be calculated by the equation:

$$\omega=\sqrt{\frac{\{-F\sin(\Omega t)-k_1\dot{\alpha}-\alpha^2-k_2\alpha\}}{2mB\,sgn\{-F\sin(\Omega t)-k_1\dot{\alpha}-\alpha^2-k_2\alpha\}|A|}} \qquad \textbf{(20)}$$

6. Simulation

In this section, three cases are considered for the ship described by (14). In each case we consider different values for the damping coefficient β and waves frequency Ω as shown in the table below.

Case No.	β	Ω (Hz)
1	0.5	20
2	1	15
3	1.5	10

In all these cases, the designed controller (15) is used to obtain the results shown in **figures (7)** to (9). It is clear from these figures that the designed controller (15) is valid to achieve system's stability and ensures dynamic stability of the ship by using the proposed unbalanced mass system, where we use *m=15 kg , A=3 m,, B=1 m* and angular velocity described by (20) and shown in the figures below.

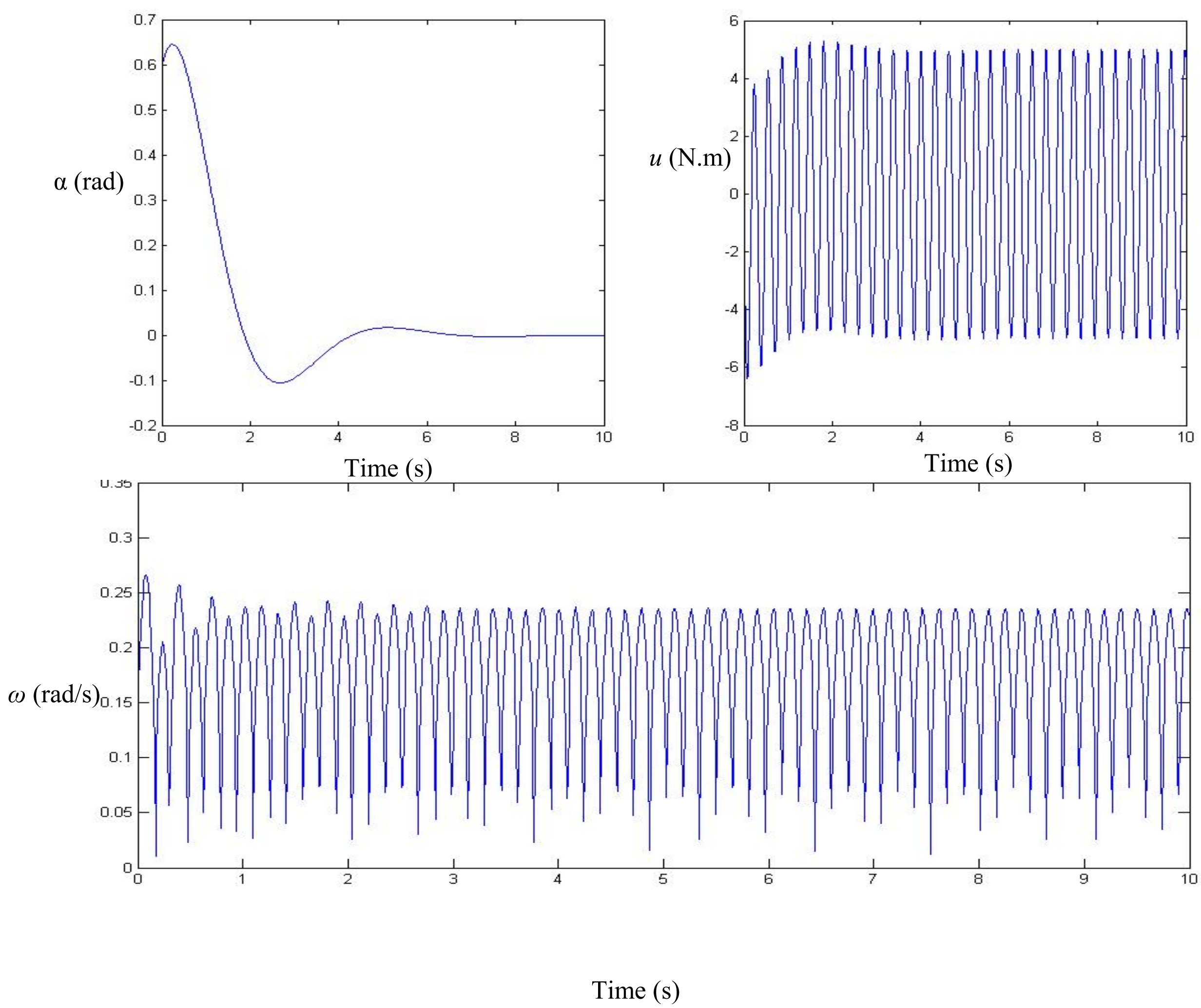

Figure (7). System's response using control input (15) with β=0.5 & Ω=20 Hz.

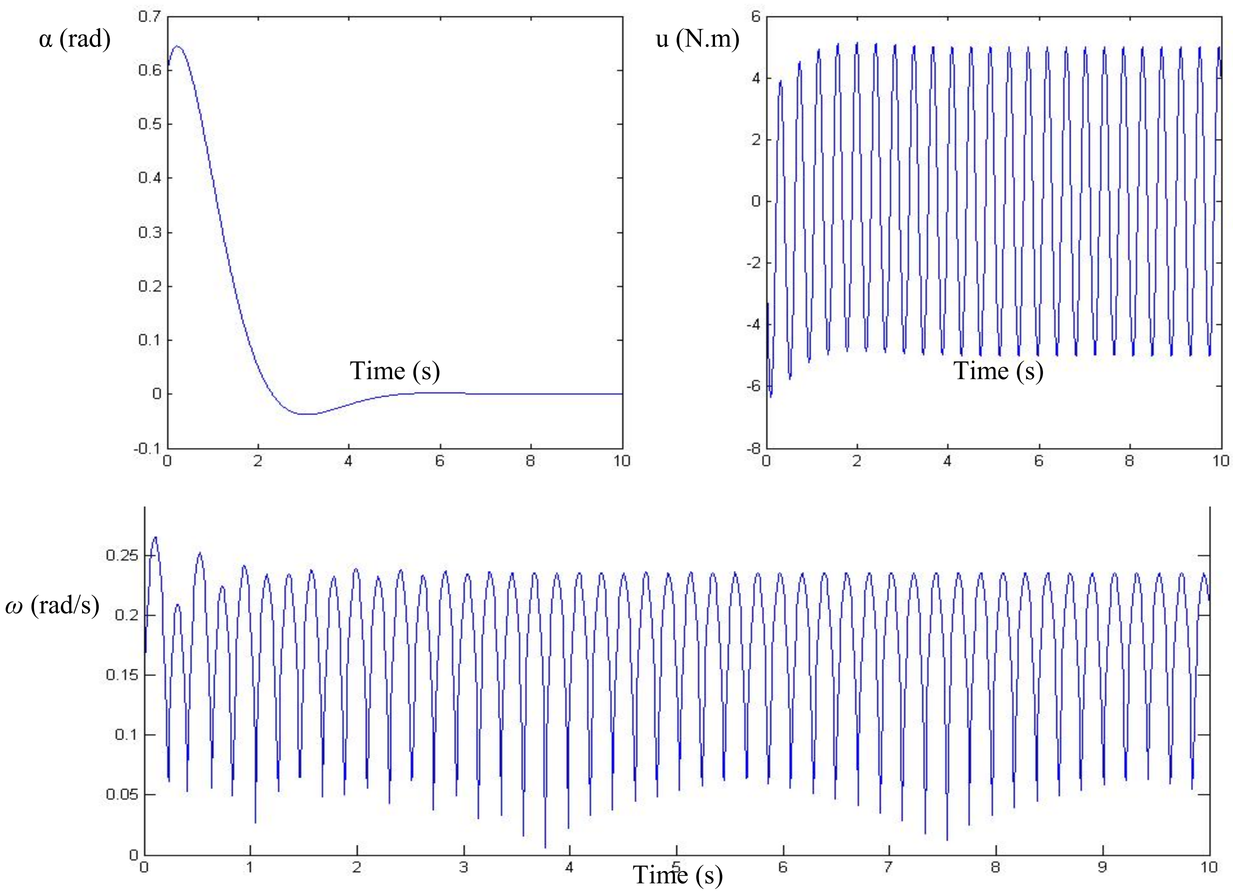

Figure (8). System's response using control input (15) with β=1 & Ω=15 Hz.

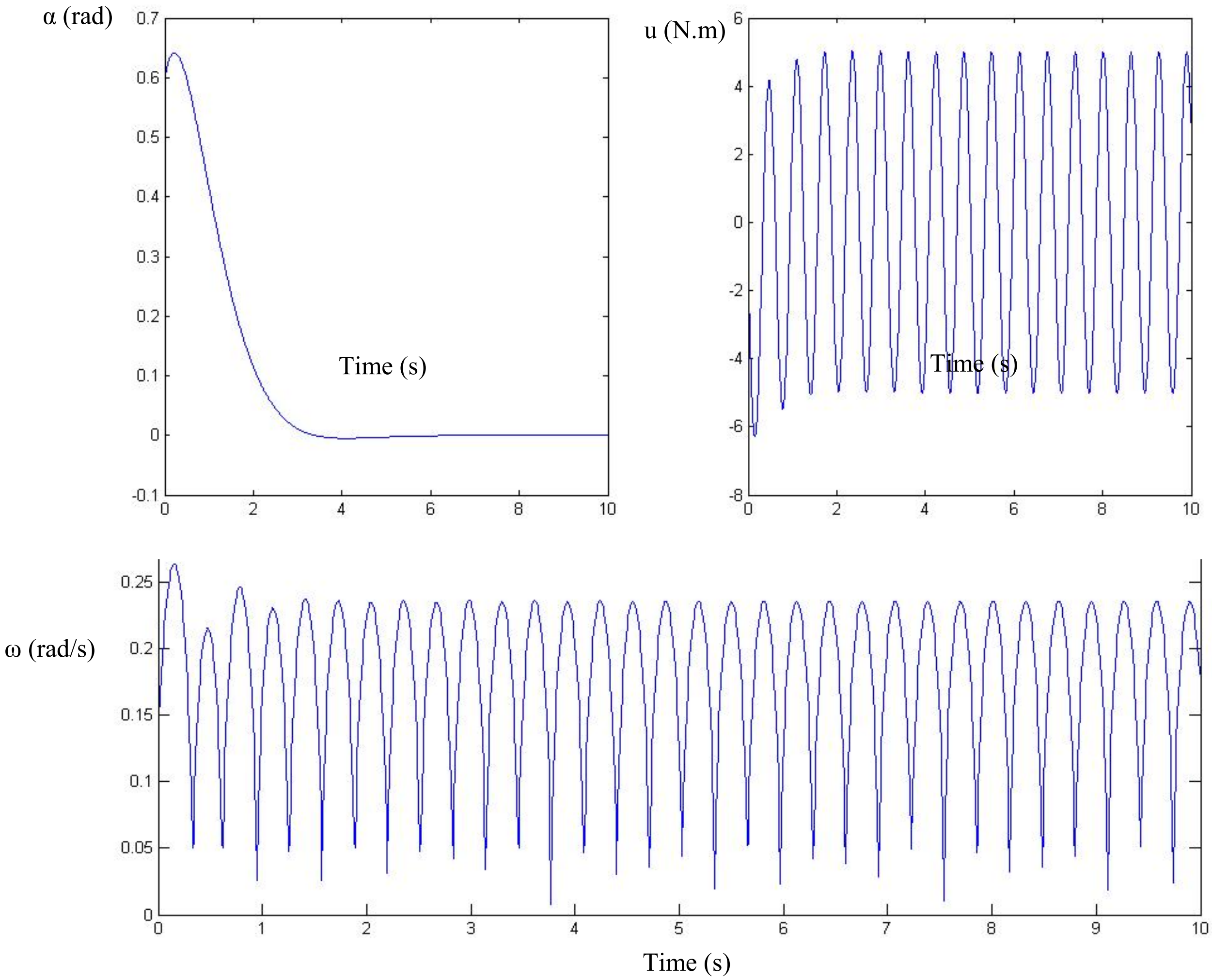

Figure (9). System's response using control input (15) with β=1.5 & Ω=10 Hz.

7. Conclusions

An active stabilizer for ship is considered based on employing inertia forces induced from unbalanced mass systems. The basic idea of this proposed stabilizer can be employed in attitude control of space-vehicles, antirollover systems in automobiles and other different applications. Together with this proposed stabilizer, a control systems is also designed to determine the torque required to be produced from the active stabilizer to achieve dynamic stability of the ship. Three different cases are considered for simulation, and the results obtained from these cases demonstrate the validity of the proposed controller and active stabilizer to make the ship track a zero angle.

The proposed control system is capable of mitigating the control of the rolling angle of a ship when an unknown disturbance produced by the waves.Also we examine the stability by assuming that the raudom term of the restoring moment in the our motion equation caused by the irreqular waves is a periodie motion. The calculated results and conclusion obtained with present methods coincide with the relevant research works of the other investigators about 100% Especially with regard to making the ship track close to zero angle.

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