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Dynamics modeling of the MoorMaster unit and investigate the interaction between the moored ship and the MoorMaster

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ABSTRACT

Developed mooring unit, the MoorMaster, which replaces conventional mooring lines is addressed here. The hydraulics of the system have a strong deducting effects on the motions of the moored ship. MoorMaster act in two different states. In first state; mechanism controls transfer mechanism to suitable position and joint with ship. Second state is passive mechanism state that lock in last position and the controller is passive so that springs and dampers appliance in mechanism carry passively apply forces from ship to mechanism. First; we defined state variables and According to the Lagrange equations, dynamics model of MoorMaster is extracted using Matlab Toolboxes and dynamics numerical simulations will be done. Then design a Controller to control the mechanism to stick to the vessel's body. Second state; investigate the interaction forces/moments in between the moored ship and the mechanism. have considered the simplest case, where the ship is located just under the MoorMaster force. Ship motion equations solved using Lagrange equations. And then design a controller that gives the ability to MoorMaster which exert forces and torques suitable in the freedom direction, per ship behavior. The results are given in a series of figures.

1. Introduction

Container ships should only make very small horizontal movements at the berth for efficient (off) loading of containers. This is especially a concern in ports directly facing the open ocean, where high swells at sea can cause harbor oscillations and low-frequency surge motions of the ship. On the other hand when a ship is moored at a quay wall or jetty, certain problems can occur:

- Mooring lines can break, which has resulted in (lethal) accidents in the past.
- Large motions of moored ships can result in inefficient handling of cargo by the cranes at the quay wall or jetty, especially in case of container handling.

The surge motion of a moored container ship is very critical. The surge amplitude should be smaller than 0.5 meter for efficient container handling (PIANC, 1995). Measurements at a container terminal port have shown that the surge motion of container ships was reduced from an amplitude of 1 meter to an amplitude in the order of 5 centimeters, while using MoorMaster™ units. MoorMaster units can offer a solution for both these problems. MoorMaster units consist of a vacuum pad which is attached to the ship hull. Hydraulic cylinders, connected to the vacuum pad, generate forces in the horizontal plane to control the horizontal motions of the moored ship. Four to twelve units are required to moor a ship depending on size of the ship, the cargo handling requirements and the local environmental conditions. Measurements have shown that ships moored with MoorMaster units move much less than ships moored with conventional mooring lines [1]. In 1999 Cavotec installed the first MoorMaster units at a ferry terminal in New Zeeland. Currently the units have been installed at about 10 locations in the world, mainly ferry terminals. The main advantage of MoorMaster units for a ferry terminal is quick mooring and instant release of the ship, without use of mooring lines [1].

Apart from a quick fastening of the vessel using vacuum pads, the hydraulics of the system showed to have a strong reducing effect on the motions of the moored ship. Therewith, MoorMaster™ units include a method to reduce (large) vessel motions and reduce operational downtime, which makes them suitable for mooring large container ships. MoorMaster units control horizontal motions of moored ship better than conventional mooring lines, because:

- MoorMaster units are stiff and generate efficient forces in magnitude and direction to control ship motions. Forces generated by mooring lines only respond to (relatively large) displacements of the moored ship.
- The MoorMaster force is being generated for 100% in the horizontal plane. Only a percentage of the force generated by a mooring line (40%-80%, depending on the angle of the mooring line) acts in the horizontal plane. The feasibility of MoorMaster units mainly depends on environmental conditions and operational requirements in a port and is eventually an economic consideration.

Possible economic advantages of MoorMaster units compared to conventional mooring lines are:

- Increasing efficiency of cargo handling and extending the operational period of cargo handling, because of higher reduction of ship motions.

MoorMaster units can allow higher waves in the harbor basin, while still keeping the ship motions within the motion criteria for efficient cargo handling. This can result in considerable savings on breakwaters.

Possible disadvantages of using MoorMaster units, compared to using conventional mooring lines are:

- Higher capital costs (of the units only, not considering possible cost savings of more efficient operations and reduced length of breakwaters).
- High maintenance level, especially in a saline environment of a sea port.
- Higher power consumption.

In here studied on the operation mechanism of MoorMaster units. With attend to a MoorMaster unit can say that mechanism action in two states, here in two step explained the operation mechanism of MoorMaster units. In first step dynamics model of MoorMaster is extracted. And in second step Obtain applied forces and moments on one MoorMaster from ship.

Modeling the operating mechanism is an important tool for port engineers to make a port design, which provides acceptable conditions to handle the cargo efficiently.

Step1: explain the operation mechanism of MoorMaster and dynamics simulation

Dynamics modeling of the mechanism it was shown in fig1 is addressed here. Defined state variables and According to the Lagrange equations, dynamics model of MoorMaster is extracted using Matlab Toolboxes and dynamics numerical simulations will be done. Then design a Controller to control the mechanism to stick to the vessel's body.

Extracted dynamics modeling of this mechanism is shown in fig2. Its characteristic is represent in table1.

Table1- Extracted dynamics modeling characteristic

m_1	100kg	l_6	0.3m
m_2	100kg	l_7	0.2m
m_3	40kg	a	0.3m
l_0	1.5m	b	0.1m
l_1	1.5m	c	0.3m
l_2	1.3m	k	500N/m
l_3	0.4m	I	$m_1 {l_2}^2/_2$
l_4	0.35m	x-final	1m
l_5	0.7m	θ_1-final	$\pi/_2$ rad

Figure1 -Moormaster unit, a commercial type [1]

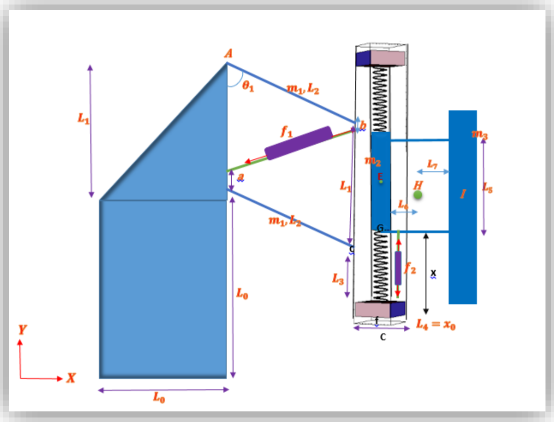


Figure2- Extracted dynamics modeling of MoorMaster

Angular motion θ_1 and vertical displacement x are to be considered as state variables for actuating the MoorMaster mechanism and the other depicted parameters are constant values in the mechanism. These two input variables are actuated via two hydraulic jacks which can exert jack forces (f_1 andf_2). f_1 Is the actuating force to derive $\theta_1$and f_2 is similarly for x.

According to the fig2 kinetic energy of the system and potential energy of the system are:

$$T = \frac{1}{2}m_1{V_{CG_1}}^2 + \frac{1}{2}m_1{V_D}^2 + \frac{1}{2}\,I\,\dot{\theta}_1 + \frac{1}{2}\,I\,{\dot{\theta}_1}^2 + \frac{1}{2}m_2{V_E}^2 + \frac{1}{2}m_3{V_H}^2 \qquad (1)$$

$$V = m_1 g V_{CG_1}(2) + m_1 g V_D(2) + m_1 g V_E(2) + m_1 g V_H(2) + \frac{1}{2}\,Kx^2 + \frac{1}{2}\,Kx^2 \qquad (2)$$

Now dynamics analysis the mechanism by using matrix Lagrange equations [2].

$$\frac{d}{dt}\left(\frac{\partial L}{\partial\{\dot{q}_i\}}\right) - \frac{\partial L}{\delta\{q_i\}} = \{Q_i\} \qquad (3)$$

q is Generalized coordinates and L is the Lagrangian and Q is matrix of forces and torques.

According to the Lagrange equations, dynamics model of MoorMaster is extracted using Toolboxes Matlab2013 software. Dynamics numerical simulations to verify equations. Fig3 is shown dynamics energy at time after numerical simulations (while the mechanism not stick to the vessel's body and no force and moment apply to the MoorMaster). According to fig3 E is in acceptable range, therefore Extracted dynamics is suitable. Because the total energy remained conservative.

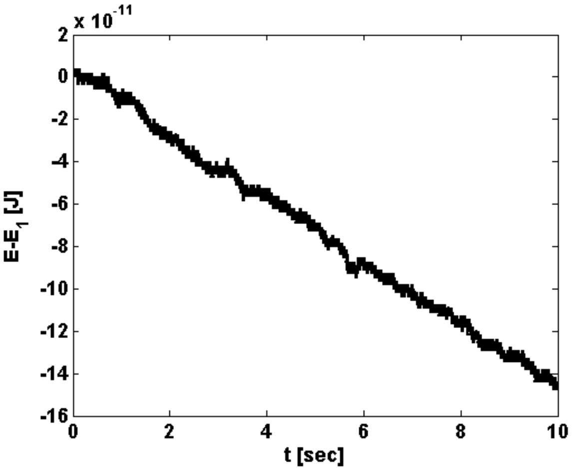


Figure3 - dynamics energy at time

Results and discussions

Now it is needed to control the mechanism of MoorMaster to stick to the vessel's body. This is a nonlinear dynamic system with two control input u_1 and $u_2$in each of the above mentioned jacks which were shown with f_1 andf_2. The adopted method for dynamic control is based on 'input-output Linearization' [3].

Applied control law is:

$$\ddot{q} = u = \ddot{q}_d - 2\lambda\dot{\tilde{q}} - \lambda^2\tilde{q} \qquad (4)$$

$$that\ \ \tilde{q} = q - q_d\ ,\dot{q} = \dot{q} - \dot{q}_d$$

In this system we have:

$$[M_L]\{\ddot{q}\} + \{B_L\} = \{Q\} \quad \Rightarrow \quad \{Q\} = [C]\{u\} \qquad (5)$$

$$\{Q\} - \{B_L\} = [M_L](\{V\}) \ \Rightarrow \{Q\} = \{B_L\} + [M_L](\{V\}) \ \Rightarrow \{V\} = \{\ddot{q}\} \qquad (6)$$

With apply I/O law:

$$\{V\} = \{\ddot{q}_d\} - 2\begin{Bmatrix} \lambda_1\dot{\tilde{q}}_1 \\ . \\ : \\ \lambda_m\dot{\tilde{q}}_m \end{Bmatrix} - \begin{Bmatrix} {\lambda_1}^2\tilde{q}_1 \\ . \\ : \\ {\lambda_m}^2\tilde{q}_m \end{Bmatrix}$$

$$\Rightarrow \begin{cases} \ddot{\tilde{q}}_1 + 2\lambda_1\dot{\tilde{q}}_1 + {\lambda_1}^2\tilde{q}_1 = 0 \\ \qquad : \\ \qquad . \\ \ddot{\tilde{q}}_m + 2\lambda_m\dot{\tilde{q}}_m + {\lambda_m}^2\tilde{q}_m = 0 \end{cases} \qquad (7)$$

From (5) and (7);

$$\{u\} = [C]^{-1}\{Q\} = [C]^{-1}\big(\{B_L\} + [M_L](\{V\})\big) \qquad (8)$$

By substituting numerical values of system parameters according to Table1, and initial condition $x = 1.5 - 0.1$ (m), and $\theta_1 = {}^{\pi}/_{3}$ (rad), the controller outputs and Tracking error of staste variables will be derived. That are shown in fig4 and fig5.

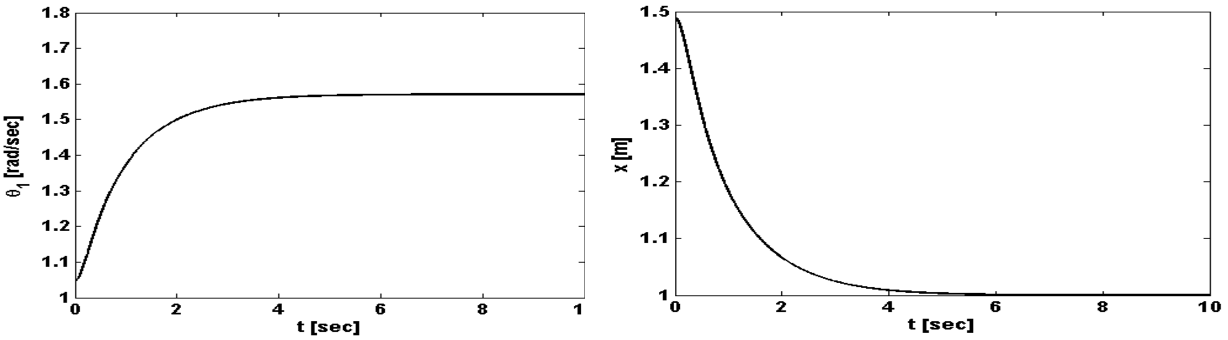


Figure 4 - staste variables

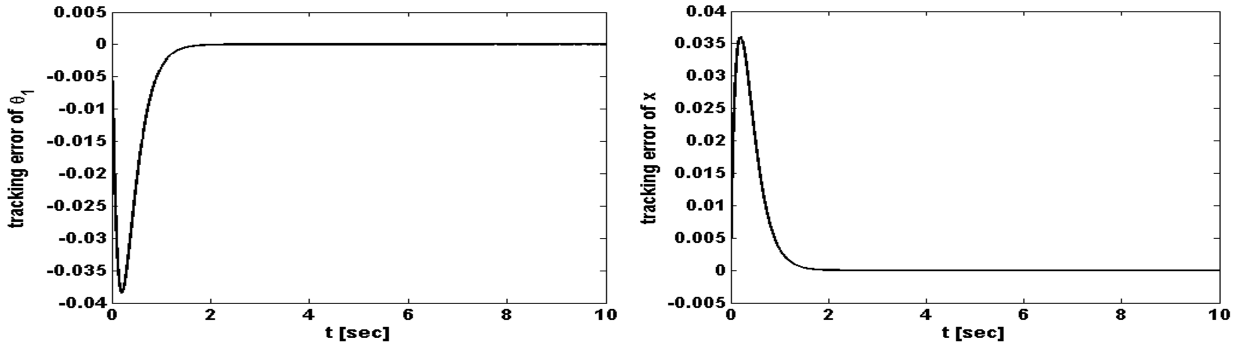


Figure 5 - Tracking error of staste variables

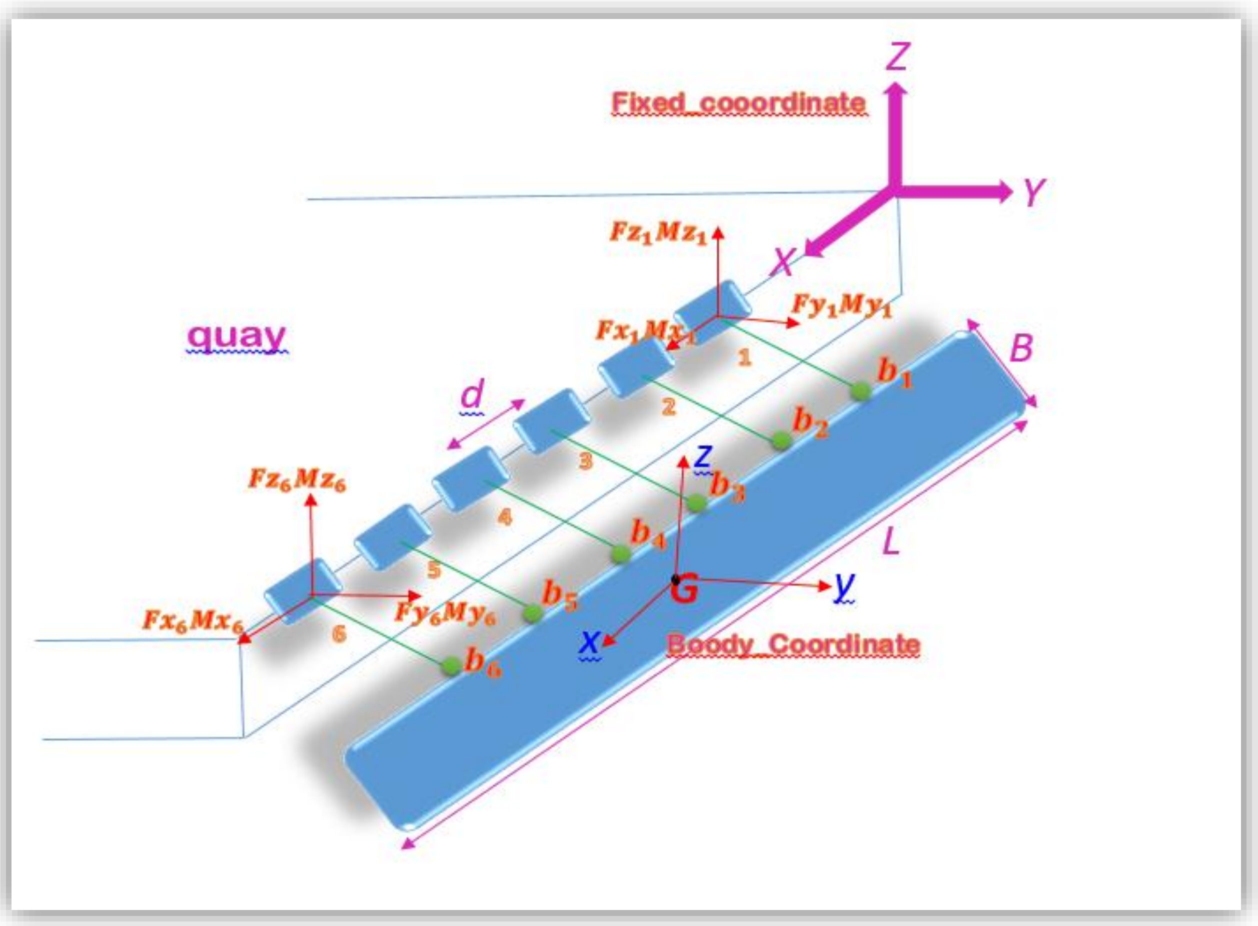


Figure 6 - A schematic of the moored ship connected to 6 MoorMaster units

Table2- Ship characteristics under review

(length) L	100m	g	9.81
B)width(	30	I_{XX}	225000
d)MoorMasters longitudinal distance from each other(	14	I_{YY}	22500000
a)Vertical distance of the center of mass to the connection point MoorMasters(	5	I_{ZZ}	22500
H)Height(	20	Δ	1096087.3

According to fig4 and fig5 numerical simulations results show that control law used up was acceptable, because in less than one second achieve to perfect tracking error. And system state variables smoothly achieved to the final value.

Step2: explain the investigate the interaction between the moored ship and the MoorMaster

It is needed to investigate the interaction forces/moments in between the moored ship and the mechanism. First, we have considered the simplest case, where the ship is isolated and located just under the MoorMaster force. Ship motion equations solved using Lagrange equations. And then design a controller that gives the ability to MoorMaster which exert forces and torques suitable in the freedom direction of the floating to ship, per ship behavior. 6 arbitrarily MoorMaster units for typical ship is intended for modeling. As can be seen in the below figure (fig6). In fig6 is shown a schematic of the moored ship connected to 6 MoorMaster units. That Ship characteristics under review is represent in table2.

To describe the locations of system components is need to introduce two coordinate systems, which is a fixed coordinate system, on the edge of the quay is considered (X,Y,Z) and the other is Moving coordinate systems (body coordinate) that is located in the center of gravity of ships(x, y, z). With follow of rotatory Euler angles pattern, coordinate system (x, y, z) can be level to coordinate system (X, Y, Z). rotatory pattern, respectively consist of; the first rotation (precession) The amount of angle ψ around axis z , the second rotation (Nutation) The amount of angle θ around axis new y, The third rotation (Spin) The amount of angle ϕ around axis new z. Which combines three rotation pattern, gives converting coordinates system (x, y, z) to (X, Y, Z) [2].

For this ship with 6 degree of freedom, 6 generalized coordinates have to be defined, according to Euler angles [2] and definition coordinate systems. That respectively consist of;

$$q_1 = X, q_2 = Y, q_3 = Z, q_4 = \psi, q_5 = \theta, q_6 = \phi \qquad (9)$$

To solve equations need to use the Lagrange equations in the matrix form (equation 3).

Due to the symmetry plane of the draft on ships and to simplify problems, consider inertia matrix (I) polarity. now can kinetic and potential energy values calculated as a function of generalized coordinates;

$$\begin{aligned} T = \frac{1}{2} M\left(\dot{q_1}^2 + \dot{q_2}^2 + \dot{q_3}^2\right) \\ + \frac{1}{2} I_{xx}\left(\dot{q_4}^2 (\sin q_5)^2 (\cos q_6)^2 \right. \\ \left. + \dot{q_5}^2 (\sin q_6)^2\right) \\ + \frac{1}{2} I_{yy}\left(\dot{q_4}^2 (\sin q_5)^2 (\sin q_6)^2 \right. \\ \left. + \dot{q_5}^2 (\cos q_6)^2\right) \\ + \frac{1}{2} I_{zz}\left(\dot{q_4}^2 (\cos q_5)^2 \right. \\ \left. + \dot{q_6}^2\right) \qquad (10) \end{aligned}$$

$$V = -Mgq_3 \qquad (11)$$

That Lagrangian equation form used for this system are as follows:

$$(M\_L)\ddot{q} + (B\_L) = Q = C * F \qquad (12)$$

That M_L , B_L are Lagrangian matrix. Q is matrix of forces and torques are applied to MoorMasters and as unknowns, C is constant coefficient, F is applied forces and moments on the MoorMaster matrix. F can be expressed as follows:

$$F = \left[F_{x_1}, F_{y_1}, F_{z_1}, F_{x_2}, F_{y_2}, F_{z_2}, F_{x_3}, F_{y_3}, F_{z_3}, F_{x_4}, F_{y_4}, F_{z_4}, F_{x_5}, F_{y_5}, F_{z_5}, F_{x_6}, F_{y_6}, F_{z_6}, M_{x_1}, M_{y_1}, M_{z_1}, M_{x_2}, M_{y_2}, M_{z_2}, M_{x_3}, M_{y_3}, M_{z_3}, M_{x_4}, M_{y_4}, M_{z_4}, M_{x_5}, M_{y_5}, M_{z_5}, M_{x_6}, M_{y_6}, M_{z_6}\right]^T \qquad (13)$$

Due to the dynamic floating and connection MoorMaster to the ship, from any MoorMaster three forces and three moments is applied, in three direction of coordinate system attached to the center of mass (fig6).

$$\begin{cases} F_{y_i} \approx \text{ Sawy motion} \\ F_{z_i} \approx \text{heave motion} \\ F_{x_i} \approx \text{Surge motion} \end{cases}, \begin{cases} M_{y_i} \approx \text{ Pitch motion} \\ M_{z_i} \approx \text{Yaw motion} \\ M_{x_i} \approx \text{Roll motion} \end{cases}$$

All components must be transmitted to the coordinate system fixed with using transmission matrix [2].

To understand that how much forces and torque should be carried MoorMasters for each movement of the ship. To this purpose should be using a proportional control law to this system, Here has been

used the linearization control law in put _ Out put based on the tracking error [3].
In this system we have:

$$(M\_L)\ddot{q} + (B\_L) = C * F \quad \Longrightarrow (M_L)\ddot{q} = (B_L) + C * F = Mv \qquad (14)$$

Applied control law is:

$$\ddot{q} = v = \ddot{q}_d - P\dot{\tilde{q}} - Q\tilde{q} \qquad (15)$$

To predict the forces and torques acting on the MoorMaster units, applied to the system any desired movement of the ship as $q_d = q\ desired$ then Obtains Proportional forces and torques based on. Here for the first step a linear frequency has been considered as follows.

$$q_{1_d} = 0.1\ \sin t \qquad (16)$$

To simplify the problem, the frequency moving ship in other directions is zero, [except the coordinates q_5 that due $\cos(q_5)$ in the denominator of one the term of the equation of motion appeared; should not to be 0 and π, which arbitrary $dq_5 = \frac{\pi}{3}$ is considered]. Initial condition of the system, also expressed based on the q_d .

Results and discussions

Calculate equations using numerical solution, for numerical solution can use matlab2013 numerical solvers, as “Ode45”. Equation is solved for a ship with the specifications Table2, and the results of simulations and tracking error diagrams of state variables have been extracted in fig7.

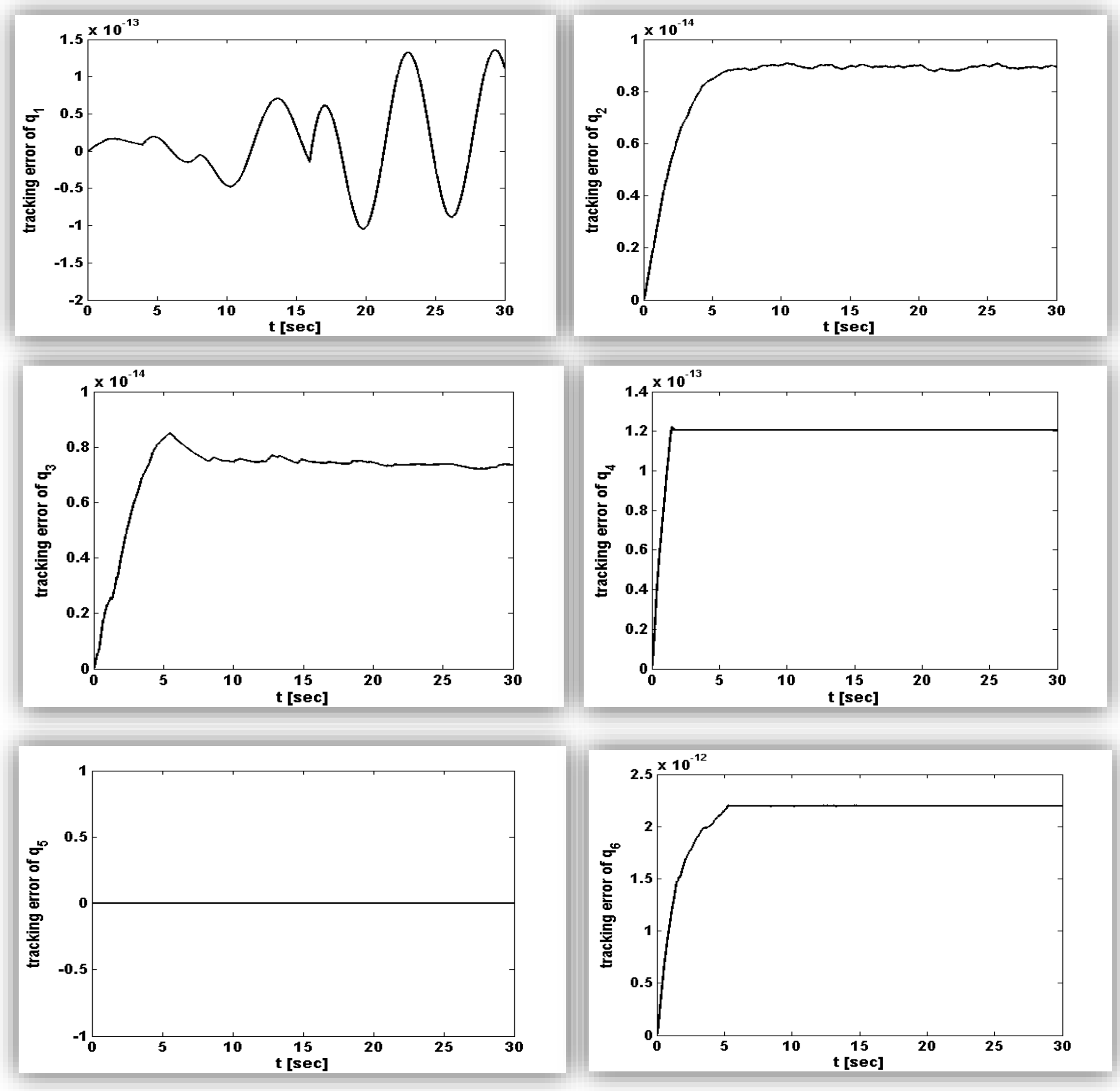
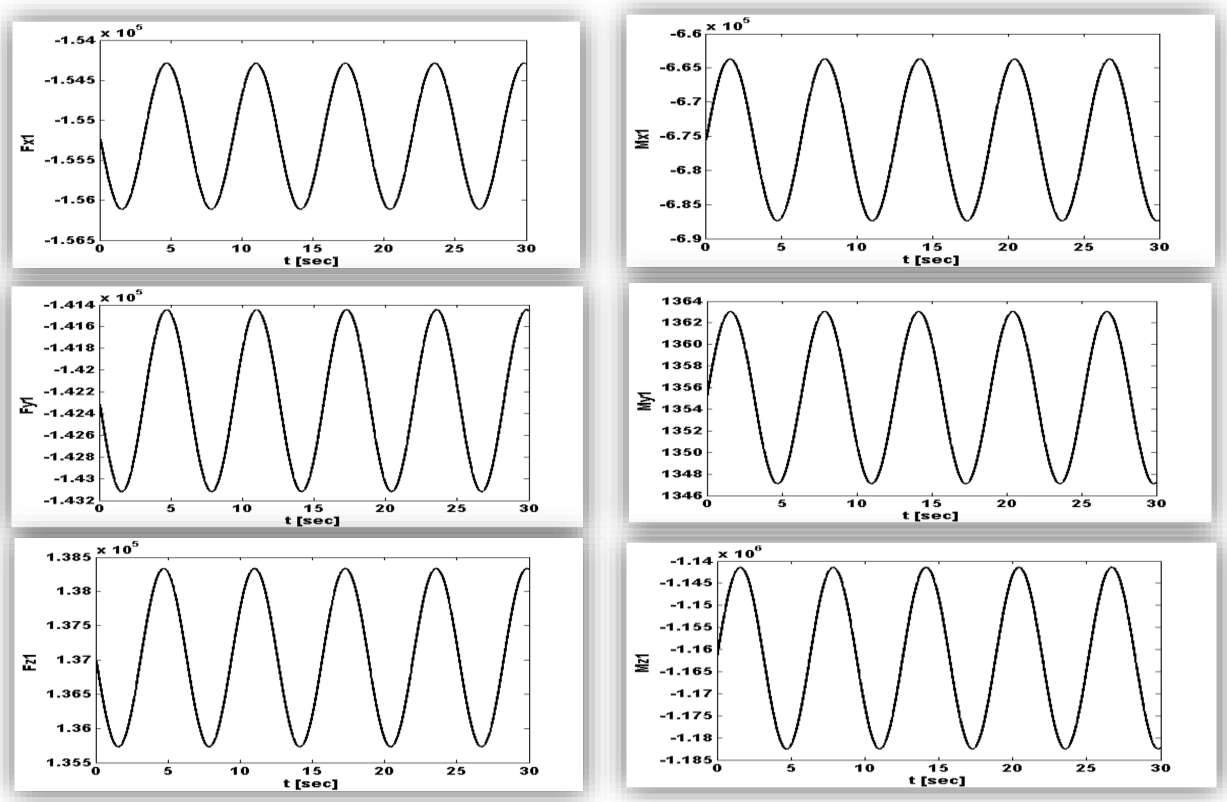


Figure 7 - tracking error diagrams of state variables

Graphs in fig7 Show that in the second state also in less than a second perfect tracking is smoothly achieved. It means that the Extracted forces and torques are applied forces and torques to MoorMasters.

Based on simulation results, we see that the proposed control scheme shows Perfect tracking behavior. And the error is in the proper range, so can say that if the ship do a longitudinal frequency as $0.1\ \sin t$, for example first MoorMaster unit must bear the below forces and torques. (fig8)



1Figure8- first MoorMaster unit forces and torques

Conclusions

In this paper Considered two state for MoorMaster operation. In first state; mechanism controls transfer mechanism to suitable position and joint with ship, results shown in less than a second perfect tracking is smoothly achieved, It is a well extraction system dynamics. Second state is passive mechanism state that lock in last position and the controller is passive so that springs and dampers appliance in mechanism carry passively apply forces from ship to mechanism. In fact, Obtain applied forces and moments is the aim of the second state. Which enables the design engineers performing better design with the correct prediction of the MoorMaster behavior for the different of ships when loading and unloading at the quay.

One can also consider the different frequency motion of ship as desired trajectory, then extract the forces and torques.

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