Dynamical model of cargo offshore operations, vessel-crane-cargo.

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Abstract. *Different kind of offshore operations are considered activities with high impact in the economy; container cargo ships, offshore petroleum platforms or wind farms, are some examples of possible scenarios where the offshore operations has an important role. This offshore operations has a specific process called load and unload cargo operations.*
The cargo operations, especially in the area of oil and gas require high levels of accuracy and security in various stages of exploration and exploitation. Nowadays a big portion of cargo operations are controlled by human operators, unfortunately, this operators are not prepared to handled several wind or wave conditions.
In order to improve this cargo operations, is necessary to define and study the problem of the processes. Consequently to develop these technologies is mandatory to know the dynamical behavior of these cargo operations, therefore, in this work, the authors present the study carried through on the dynamics of a suspended load that is connected to a vessel's cargo manipulator.
The paper presents the complete dynamic model of the vessel-crane-cargo systems. Moreover some simulations under specific sea conditions were presented and show the complex response motion of the load due the visibly nonlinear behavior of the ship and the crane motions.

Keywords: *Offshore operations; Dynamic models; Multibody System.*

1. INTRODUCTION

Different kind of offshore operations are considered activities with high impact in the economy; container cargo ships, offshore petroleum platforms or wind farms, are some examples of possible scenarios where the offshore operations has an important role. This offshore operations has a specific process called load and unload cargo operations.

In order to improve this cargo operations, is necessary to define and study the problem of the processes. This work is a study carried through on the dynamics of a suspended load that is connected to a vessel's cargo manipulator.

The paper presents the complete dynamic model of the vessel-crane-cargo systems. Besides, the authors shows the structure and the methodology to handled with the large systems of equations in order define the complete dynamical model of the problem. Moreover some simulations under specific sea conditions were presented and show the complex response motion of the load due the visibly nonlinear behavior of the ship and the crane motions.

2. MATHEMATICAL MODEL

In order to construct the mathematical model was necessary to define three systems of reference, the first one was the inertial frame defined by X_I,Y_I and Z_I, the system of reference of the ship X_S,Y_S and Z_S is the ship's system of reference and finally the system of reference of the crane is defined by X_C,Y_C and Z_C. All these systems of reference can be seen in the Fig 1.

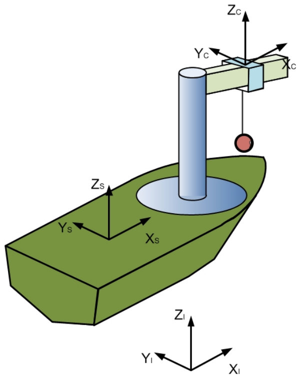


Figura 1. Systems of references

2.1 Ship's frame

The first step is the definition of degrees of freedom of the ship as done by Schaub (2008) and recommended by Amerongen and Breedveld (2003). For the ship has six degrees of freedom, three translational named *sway*(yn), *heave*(zn) and *surge*(xn) and three rotational degrees of freedom called *pitch*(θ_{yn}), *yaw*(θ_{zn}) and *roll*(θ_{xn})Journée (2003). Figure 2 shows the degrees of freedom of the ship.

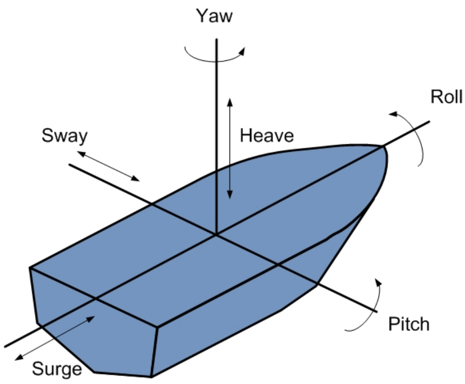


Figura 2. Ship Degrees of freedom

For further simplicity in reading and interpretation, the degrees of freedom of the ship are expressed as vector components of the vector Dof_N as presented in equation (1).

$$\mathbf{Dof_N} = \begin{bmatrix} xn \\ yn \\ zn \\ \theta_{xn} \\ \theta_{yn} \\ \theta_{zn} \end{bmatrix} \quad (1)$$

In order to representation and calculation of the different references used are implemented corresponding transformation matrices, that is based on homogeneous transformation matrices Barrientos (2007) .

Multiplication of matrices, in the order presented in Equ. (2) where T_x and R_x means translation and rotation on x respectively, allows to transform the inertial reference frame in the local frame of the ship.

$$\mathbf{Ref_2} = \mathbf{T_x} * \mathbf{T_y} * \mathbf{T_z} * \mathbf{R_x} * \mathbf{R_y} * \mathbf{R_z} \quad (2)$$

The elements in matrix Ref_2 are presented at Equ. (3).

$$\mathbf{Ref_2} = \begin{bmatrix} C_{\theta_{yn}} * C_{\theta_{zn}} & -C_{\theta_{yn}} * S_{\theta_{zn}} & S_{\theta_{yn}} & xn \\ C_{\theta_{xn}} * S_{\theta_{zn}} + C_{\theta_{zn}} * S_{\theta_{xn}} * S_{\theta_{yn}} & C_{\theta_{xn}} * C_{\theta_{zn}} - S_{\theta_{xn}} * S_{\theta_{yn}} * S_{\theta_{zn}} & -C_{\theta_{yn}} * S_{\theta_{xn}} & yn \\ S_{\theta_{xn}} * S_{\theta_{zn}} - C_{\theta_{xn}} * C_{\theta_{zn}} * S_{\theta_{yn}} & C_{\theta_{zn}} * S_{\theta_{xn}} + C_{\theta_{xn}} * S_{\theta_{yn}} * S_{\theta_{zn}} & C_{\theta_{xn}} * C_{\theta_{yn}} & zn \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

2.2 Crane's Frame.

The second reference system is defined by the spatial position of the shaft of the crane, (xp,yp,zp), for the rotation of the rope in x axis and y axis $((\theta_1,\theta_2))$ and for the length of the rope (L_c). The vector representation of the degrees of freedom of the crane (Dof_{gc}) are presented in Equ. (4).

$$\mathbf{Dof_{gc}} = \begin{bmatrix} xp \\ yp \\ zp \\ \theta_1 \\ \theta_2 \\ L_c \end{bmatrix} \quad (4)$$

Multiplication of the matrices in the order presented in Equ (5) allows to transform the inertial reference system in the local coordinate system of the ship.

$$\mathbf{Ref_3} = \mathbf{T_{x2}} * \mathbf{T_{y2}} * \mathbf{T_{z2}} * \mathbf{R_{x2}} * \mathbf{R_{y2}} * \mathbf{T_{z3}} \quad (5)$$

The elements of the matrix Ref_3 are presented in Equ. (6).

$$\mathbf{Ref_3} = \begin{bmatrix} C_{\theta_2} & 0 & S_{\theta_2} & xp - L_c * S_{\theta_2} \\ S_{\theta_1} * S_{\theta_2} & C_{\theta_1} & -C_{\theta_2} * S_{\theta_1} & yp + L_c * C_{\theta_2} * S_{\theta_1} \\ -C_{\theta_1} * S_{\theta_2} & S_{\theta_1} & C_{\theta_1} * C_{\theta_2} & zp - L_c * C_{\theta_1} * C_{\theta_2} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6)$$

Finally the transformation matrix that takes the reference from Ref_3 to the inertial frame is defined by Equ. (7).

$$\mathbf{Ref_4} = \mathbf{Ref_2} * \mathbf{Ref_3} \quad (7)$$

$$\mathbf{Ref_4} = \begin{bmatrix} c_{11} & c_{12} & c_{13} & c_{14} \\ c_{21} & c_{22} & c_{23} & c_{24} \\ c_{31} & c_{32} & c_{33} & c_{34} \\ c_{41} & c_{42} & c_{43} & c_{44} \end{bmatrix} \quad (8)$$

The elements of the matrix Ref_4 are presented in Equ. (9) until Equ. (24).

$$c_{11} = C_{\theta_{yn}} * C_{\theta_{zn}} * C_{\theta_2} - C_{\theta_1} * S_{\theta_{yn}} * S_{\theta_2} - C_{\theta_{yn}} * S_{\theta_{zn}} * S_{\theta_1} * S_{\theta_2} \quad (9)$$
$$c_{12} = S_{\theta_{yn}} * S_{\theta_1} - C_{\theta_{yn}} * C_{\theta_1} * S_{\theta_{zn}} \quad (10)$$
$$c_{13} = C_{\theta_{yn}} * C_{\theta_{zn}} * S_{\theta_2} + C_{\theta_1} * C_{\theta_2} * S_{\theta_{yn}} + C_{\theta_{yn}} * C_{\theta_2} * S_{\theta_{zn}} * S_{\theta_1} \quad (11)$$
$$c_{14} = xn + S_{\theta_{yn}} * (b_{34}) + C_{\theta_{yn}} * C_{\theta_{zn}} * (b_{14}) - C_{\theta_{yn}} * S_{\theta_{zn}} * (b_{24}) \quad (12)$$
$$c_{21} = C_{\theta_2} * (a_{21}) + S_{\theta_1} * S_{\theta_2} * (a_{22}) + C_{\theta_{yn}} * C_{\theta_1} * S_{\theta_{xn}} * S_{\theta_2} \quad (13)$$
$$c_{22} = C_{\theta_1} * (a_{22}) - C_{\theta_{yn}} * S_{\theta_{xn}} * S_{\theta_1} \quad (14)$$
$$c_{23} = S_{\theta_2} * (a_{21}) - C_{\theta_2} * S_{\theta_1} * (a_{22} - C_{\theta_{yn}} * C_{\theta_1} * C_{\theta_2} * S_{\theta_{xn}} \quad (15)$$
$$c_{24} = yn + (b_{24}) * (a_{22}) + (b_{14}) * (a_{21}) - C_{\theta_{yn}} * S_{\theta_{xn}} * (b_{34}) \quad (16)$$

$$c_{31} = C_{\theta_2} * (a_{31}) + S_{\theta_1} * S_{\theta_2} * (a_{31}) - C_{\theta_{xn}} * C_{\theta_{yn}} * C_{\theta_1} * S_{\theta_2} \quad (17)$$
$$c_{32} = C_{\theta_1} * (a_{31}) + C_{\theta_{xn}} * C_{\theta_{yn}} * S_{\theta_1} \quad (18)$$
$$c_{33} = S_{\theta_2} * (a_{31}) - C_{\theta_2} * S_{\theta_1} * (a_{31}) + C_{\theta_{xn}} * C_{\theta_{yn}} * C_{\theta_1} * C_{\theta_2} \quad (19)$$
$$c_{34} = zn + (b_{24}) * (a_{31}) + (b_{14}) * (a_{31}) + C_{\theta_{xn}} * C_{\theta_{yn}} * (b_{34}) \quad (20)$$
$$c_{41} = 0 \quad (21)$$
$$c_{42} = 0 \quad (22)$$
$$c_{43} = 0 \quad (23)$$
$$b_{44} = 1 \quad (24)$$

The position of center of mass of the load is defined by the vector p^* defined in Equ. (25).

$$\mathbf{p}^* = [c_{14}, c_{24}, c_{34}] \quad (25)$$

Parameter	Value
Simulation time	10 s
Mass	10 kg
Dof_N	[0 0 20 0 0 0]'
$\dot{Dof}_N$	[0 0 0 0 0 0]'
Dof_{gc}	[0 0 10 θ_1 θ_2 10]'
$\dot{Dof}_{gc}$	[0 0 0 $\dot{\theta}_1$ $\dot{\theta}_2$ 0]'

Cuadro 1. Simulations condition's

After calculated the vector p^* is possible to find the values of kinetic and potential energy of the system. The kinetic energy of the body (K^C) can be calculated by the Equ. (26) Tenenbaum (2006) where v^* is the velocity of the center body mass, **I** the inertia tensor of the body and w^c the angular velocity of the body.

Likewise, the potential energy can be calculated using Equ. (27) where g represents the acceleration of gravity and h the distance from the inertial coordinate system to the body.

$$K^C = \frac{1}{2}m\mathbf{v}^* \cdot \mathbf{v}^+ \frac{1}{2}\mathbf{w}^c \cdot \mathbf{I} \cdot \mathbf{w}^c \tag{26}$$

$$\Phi^C = mgh \tag{27}$$

After calculated the kinetic and potential energy of the body is calculated the Lagrangian (La). It is described by Equ. (28)Meirovithc (1970) where K^S represents Kinetic energyof the system and Φ^S is the Potential energy .

$$La = K^S - \Phi^S \tag{28}$$

Finally the Lagrangian of the load hanging on the crane which is installed on a ship is represented by the Equ. (29).

$$La_c = Bk_{19}/2 - Bk_{31}/2 - Bk_{34}/2 - Bk_{37}/2 - g * m * Bk_{22} \tag{29}$$

Where La_c represents the Lagrangian of the load hanging on a Cartesian manipulator installed on a ship.

2.2.1 Model Validation

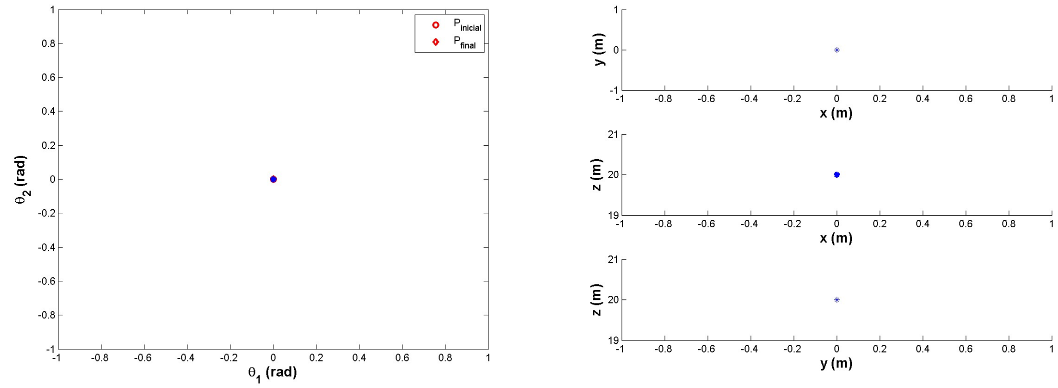
The model presented in the previous section, the system for ship-loading crane, can be evaluated using a model previously known and studied bye Baier (2008). In this case it is possible, imposing some restrictions, to compare the dynamics of the model with the dynamics of a spherical pendulum. The comparison can be made when fixing the degrees of freedom of the ship and the crane, so the only dynamics involved in proposed model is corresponding to the load.

Table 1 present the initial condition of the simulation used to study the model, in the same way, Tab. 2 present the initial values of θ_1 and θ_2 for the various tests for evaluating the model.

Number of test	Initial condition	
	θ_1(Degree)	θ_2 (Degree)
1	0	0
2	0	80
3	0	180
4	80	80

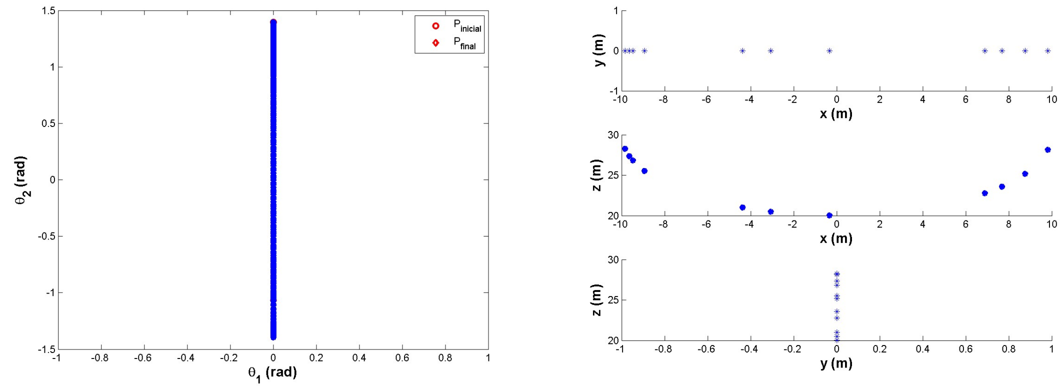
Cuadro 2. Test specification

One way to condense the simulations is to perform the phase diagram, this diagram one can observe the behavior of the charge degrees of freedom as well as the speeds of the same. Figure 7 presents simulations to



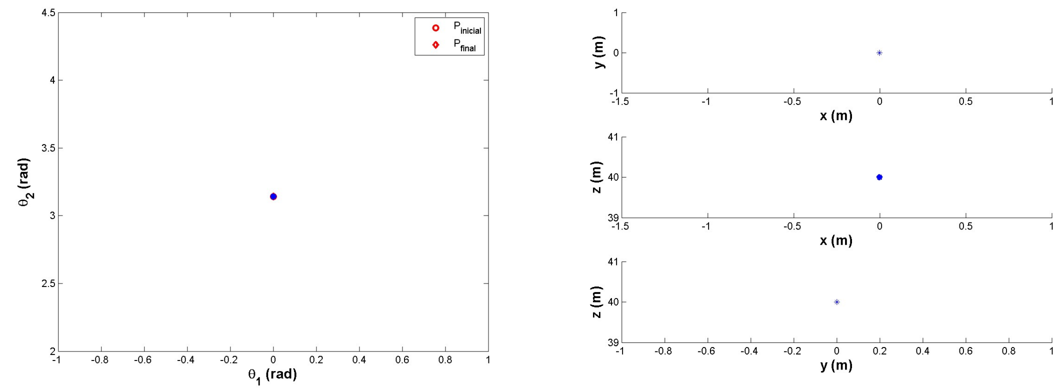
(a) θ_1 vs θ_2 (b) Cargo Handling

Figura 3. Cargo handling test 1



(a) θ_1 vs θ_2 (b) Cargo Handling

Figura 4. Cargo handling test 2



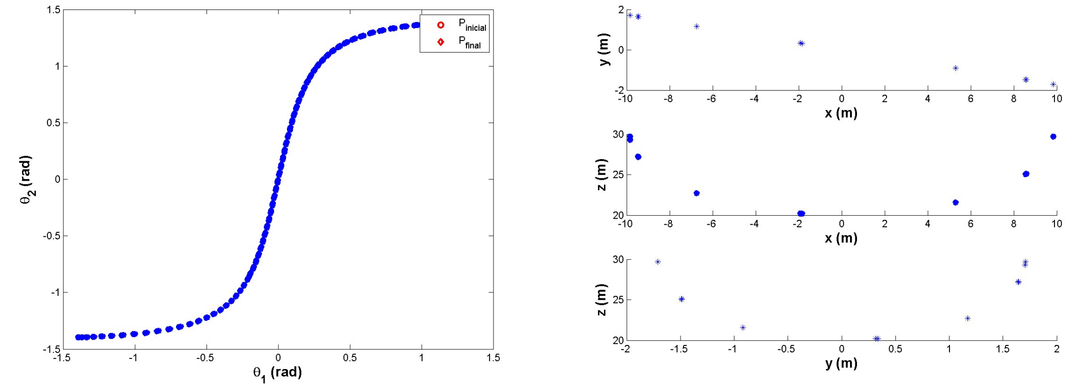
(a) θ_1 vs θ_2 (b) Cargo Handling

Figura 5. Cargo handling test 3

initial θ_1 equal to zero and variations of initial θ_2 in from 20 to 20 degrees. Figure 8 presents simulations to initial θ_2 equal to zero and variations of initial θ_1 from 20 to 20 degrees.

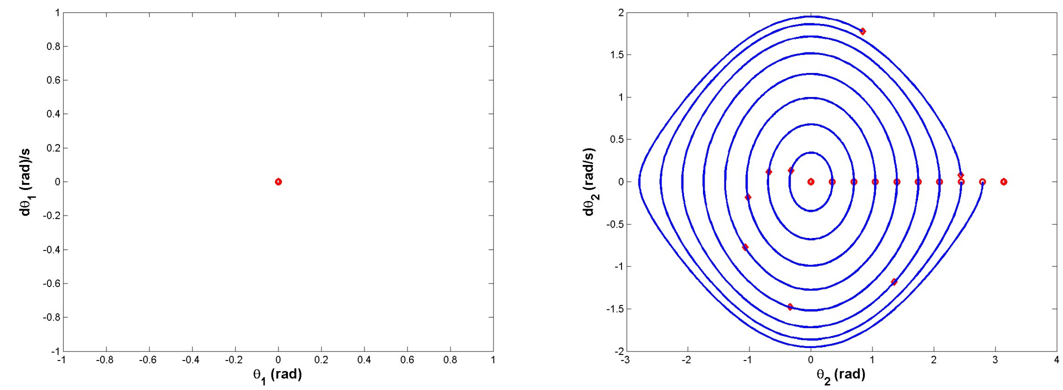
Finally are presented, in Fig. 9, phase diagrams for initial conditions of θ_1 equal to 10 degrees and variations of θ_2 from 20 em 20 degrees.

Was performed a second comparison of the model presented in this section against a model of spherical pendulum. For this evaluation the spherical pendulum model was developed in SimMechanics. The comparison



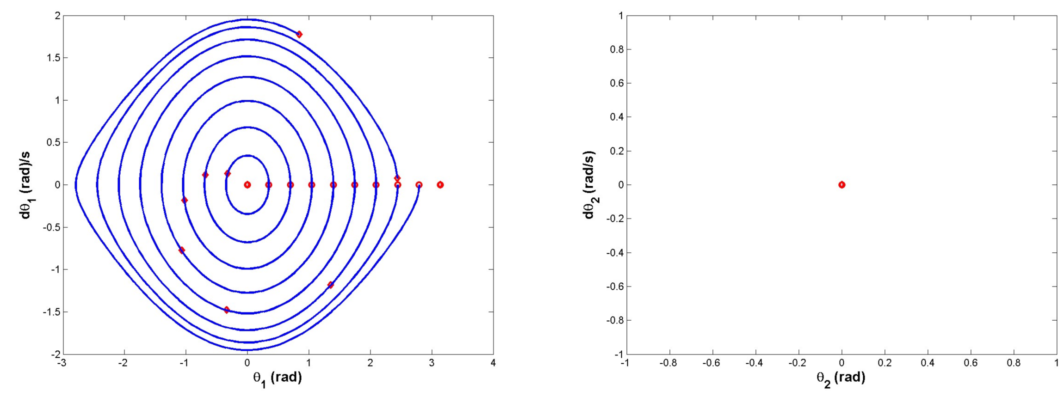
(a) θ_1 vs θ_2 (b) Cargo Handling

Figura 6. Cargo handling test 4



(a) θ_1 vs $\dot{\theta_1}$ (b) θ_2 vs $\dot{\theta_2}$

Figura 7. Phase diagram 1

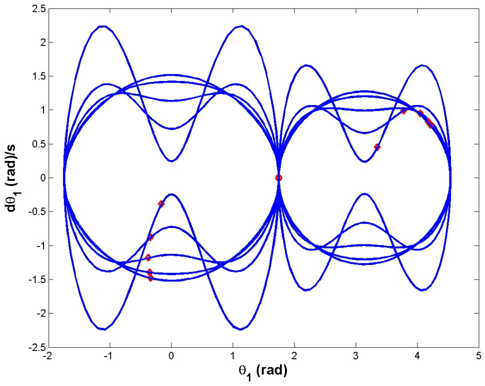


(a) θ_1 vs $\dot{\theta_1}$ (b) θ_2 vs $\dot{\theta_2}$

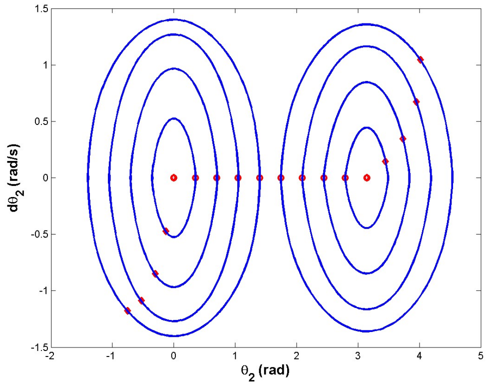
Figura 8. Phase diagram 2

of the dynamics of the two models is done through simulations with equal conditions. The conditions of simulation for the comparison were the same ones used in Tab. 2 The simulation result, with the conditions of test 4, are presented in Fig. 10.

To evaluate the influence of degrees of freedom of the ship ($\mathbf{Dof_N}$) was implemented a new simulation. For this simulation the rotational degree of vessel θ_{zn} was set at 10 degrees. Figure 11 presents the diagram of phase and is possible to see the displacement of the equilibrium point to 10 degrees, confirming the effect of changing value of θ_{zn} in the dynamics of the load hanging.



(a) θ_1 vs $\dot{\theta_1}$



(b) θ_2 vs $\dot{\theta_2}$

Figura 9. Phase diagram 3

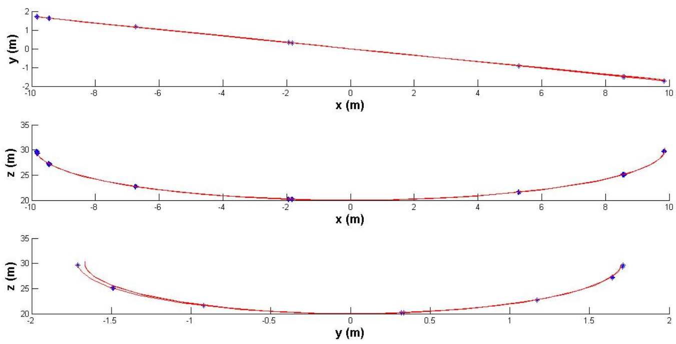
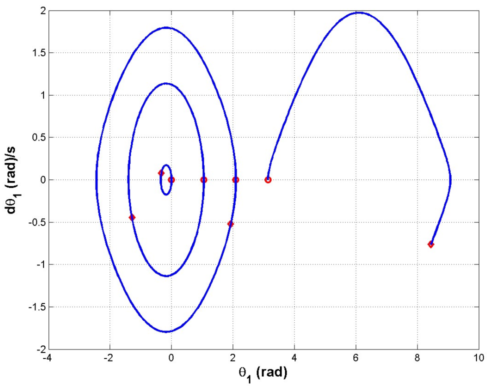
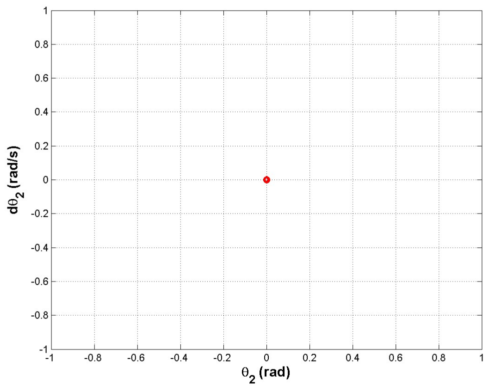


Figura 10. Model comparition



(a) θ_1 vs $\dot{\theta_1}$



(b) θ_2 vs $\dot{\theta_2}$

Figura 11. Phase diagram

3. CONCLUSIONS

The paper presents the complete dynamic model of the vessel-crane-cargo systems using an Lagrangian approach. Additionally are presented simulations that validate the model using external softwares, like Sim-Mechanics, showing physical concordance.

The Model presented is used to generate different phase diagram that shows the influence of θ_1 in the equilibrium position of the cargo as is presented in Fig.11.

The authors shows the structure and the methodology to handled with the large systems of equations in order define the complete dynamical model of the problem. Moreover some simulations under specific sea conditions were presented and show the complex response motion of the load due the visibly nonlinear behavior of the ship and the crane motions.

For future works, the authors will implement different kinds of control algorithms in order to guarantee the stability during the process of load transfer.

4. ACKNOWLEDGEMENTS

The authors thank CNPq and FAPERJ for financial support.

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6. Responsibility notice