NONLINEAR BEHAVIOR OF OFFSHORE LOADS

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Abstract. *Currently 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 loads has an important role. Thus, the implementation of new technologies that make the manipulation of these products faster and easier becomes more necessary. In order to develop these technologies is mandatory to know and study the dynamical behavior of these offshore loads, 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 offshore load model that includes the influences of the vessel, cargo and load. Moreover some simulations under specific sea and wind conditions were presented and show the complex large-amplitude motion of the load due the visibly nonlinear behavior of the ship.*

Keywords*: Nonlinear behavior; Cargo load transfer; Offshore operations.*

1. INTRODUCTION.

Container ships account for most of the intercontinental load transports. This is the reason for the interest in the development of innovative alternatives that help to load and off-load cargo from and to ships. The offshore load operations are part of this new way to work with cargo, for this reason a diverse number of research projects and developments in innovative alternatives, which support this kind of operation to work in a variety of situations, are helping to establish a new way of performing load operations (Nottebom T, 2004; Diesel M, 2005).

The offshore operations are related to all transport, transfer and manipulation of any type of cargo carried on the seas, as the transfer of goods and raw materials from a ship to another, as well as the exchange of goods and equipment between ships and oil platforms.

The most important task of a load positioning system is tracking a possible path. The idea is track the motions of A-ship from a B-ship. The B-ship has a manipulator that helps with the load and unloads of containers, as show by Fig. 1.

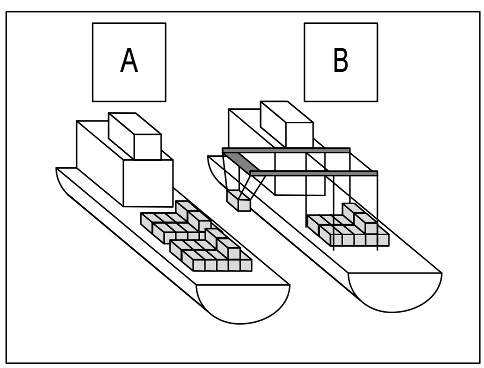

Figure 1 Offshore load operation.

This paper presents a study on the dynamics of a suspended load that is coupled with a mechanism of two prismatic DOF (Degrees Of Freedom). Due to the non-linear behavior of the ship, is possible to see a complex load dynamics that, emphasizing the necessity of using a control mechanism which allows for the reduction of oscillations and positioning the load on a particular point of interest. In order to carry out this task, a fuzzy logic controller was implemented. It generated interesting results which show that the combination of manipulator and the control strategy reduces the oscillations to small amplitudes increasing the range of allowable operating conditions.

The degrees of freedom of a ship (Silva R 2008) are presented by Fig. 2.

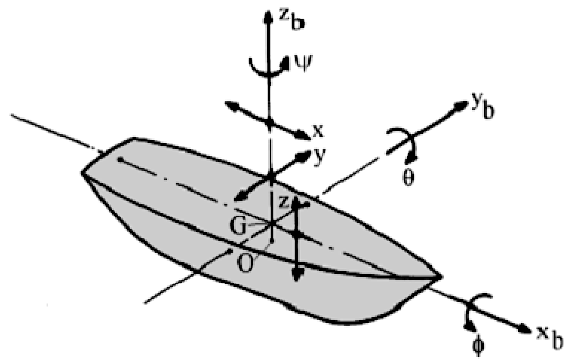

Figure 2 Degrees of freedom

2. CARGO MANIPULATOR.

A Cartesian model for the cargo manipulator was developed, which is positioned on the ship. In order to study its dynamics, it is mandatory to learn how the ship's motions affect the cargo manipulator behavior. The first step is to determine the degrees of freedom from ships. Generally, in order to identify or model the movement of the ship 6 degrees of freedom are used (Fossen T, 1994; Sphaier HS 2005). For that reason the final position of the ship is given by the combination of 6 degrees of freedom (3 rotations, roll, pitch and yaw; and 3 translations surge, sway, heave).

Defined the motions of the ship, the kinematics is calculated for each degree of freedom in a specific order. For this particular case, the first motions will be the rotations on each axis, then the displacements. Therefore, it is possible to see the matrix transformation for each axis. The rotation on X axis in equation (1), rotation on the Y axis in equation (2), and finally, we have a matrix of transformation to the rotation on its axis called Z in equation (3).

$$\mathbf{T}_0^1 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(\theta_{XN}) & -\sin(\theta_{XN}) & 0 \\ 0 & \sin(\theta_{XN}) & \cos(\theta_{XN}) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

$$\mathbf{T}_1^2 = \begin{bmatrix} \cos(\theta_{YN}) & 0 & \sin(\theta_{YN}) & 0 \\ 0 & 1 & 0 & 0 \\ -\sin(\theta_{YN}) & 0 & \cos(\theta_{YN}) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

$$\mathbf{T}_2^3 = \begin{bmatrix} \cos(\theta_{ZN}) & -\sin(\theta_{ZN}) & 0 & 0 \\ \sin(\theta_{ZN}) & \cos(\theta_{ZN}) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

The same procedure is performed for the displacements in the ship's axes, the displacement on axes X, Y and Z represented by matrices described in equation (4).

$$\mathbf{T}_3^6 = \begin{bmatrix} 1 & 0 & 0 & X_N \\ 0 & 1 & 0 & Y_N \\ 0 & 0 & 1 & Z_N \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4}$$

Finally is possible to find the actual position of the ship multiplying the previous matrices, as is shown in equation (5).

$$\mathbf{T}_0^{\,6} = \mathbf{T}_0^{\,1} * \mathbf{T}_1^{\,2} * \mathbf{T}_2^{\,3} * \mathbf{T}_3^{\,6} \tag{5}$$

The result of the multiplication is a matrix transforming the fixed frame to the moving ship frame, this matrix is called T_0^6 and is denoted as given in equation (6).

$$\mathbf{T}_0^6 = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix} \tag{6}$$

In order to describe the ship's final position, the elements needed are a_{14}, a_{24} and, a_{34}. These components are given in equations (7), (8), and (9).

$$\mathbf{a_{14}} = -\cos(\theta_{Y_N})\sin(\theta_{Z_N})\,Y_N + \cos(\theta_{Y_N})\cos(\theta_{Z_N})\,X_N + \sin(\theta_{Y_N})\,Z_N \tag{7}$$

$$\begin{aligned}\mathbf{a_{24}} &= (-\sin(\theta_{X_N})\sin(\theta_{Y_N})\sin(\theta_{Z_N}) + \cos(\theta_{X_N})\cos(\theta_{Z_N}))\,Y_N + \\ &(\sin(\theta_{X_N})\sin(\theta_{Y_N})\cos(\theta_{Z_N}) + \cos(\theta_{X_N})\sin(\theta_{Z_N}))\,X_N - \sin(\theta_{X_N})\cos(\theta_{Y_N})\,Z_N\end{aligned} \tag{8}$$

$$\begin{aligned}\mathbf{a_{34}} &= (\cos(\theta_{X_N})\sin(\theta_{Y_N})\sin(\theta_{Z_N}) + \sin(\theta_{X_N})\cos(\theta_{Z_N}))\,Y_N + \\ &(-\cos(\theta_{X_N})\sin(\theta_{Y_N})\cos(\theta_{Z_N}) + \sin(\theta_{X_N})\sin(\theta_{Z_N}))\,X_N + \cos(\theta_{X_N})\cos(\theta_{Y_N})\,Z_N\end{aligned} \tag{9}$$

The elements represent:

X ship position $= a_{14}$
Y ship position $= a_{24}$
Z ship position $= a_{34}$

2.1 Manipulator movements.

At the time the cargo leaves the ship's surface, it can be considered as a hung load, and if all the mass is concentrated in a one single point the system represents itself as a simple pendulum. In order to improve the dynamic model the next element to define is the handler. It is defined as a Cartesian handler that moves the hung cargo (simple pendulum). The simplified system cargo-manipulator can be seen in Fig. 3.

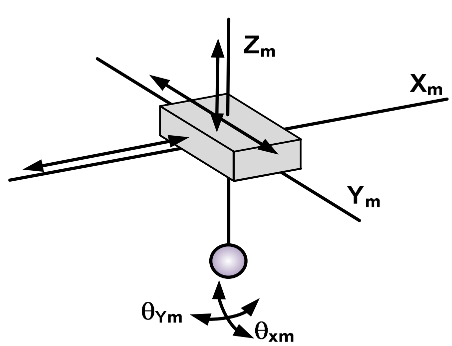

Figure 3 Cargo manipulator.

The position of the pendulum (cargo) in any moment of time in reference to the vessel by a set of transformation's matrices that start from the ship, passing by the manipulator, to the load.

$$\mathbf{T}_n^m = \begin{bmatrix} 1 & 0 & 0 & X_m \\ 0 & 1 & 0 & Y_m \\ 0 & 0 & 1 & Z_m \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{10}$$

$$\mathbf{T}_m^c = \begin{bmatrix} \cos(\theta_{Ym}) & 0 & \sin(\theta_{Ym}) & -\sin(\theta_{Ym})L_c \\ \sin(\theta_{Ym})\sin(\theta_{Xm}) & \cos(\theta_{Xm}) & -\sin(\theta_{Xm})\cos(\theta_{Ym}) & \sin(\theta_{Xm})\cos(\theta_{Ym})L_c \\ -\cos(\theta_{Xm})\sin(\theta_{Ym}) & \sin(\theta_{Xm}) & \cos(\theta_{Xm})\cos(\theta_{Ym}) & -\cos(\theta_{Xm})\cos(\theta_{Ym})L_c \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{11}$$

In this case the equation (10) represents the transformation matrix that takes the frame from the ship to the manipulator's frame taking into account the variables X_m, Y_m, which are the axial displacement of the manipulator. The equation (11) is the transformation matrix that change the manipulator frame to the load frame where L_c is the length of the cable that links the cargo and the manipulator; θ_{Xm} and θ_{Ym} represent the angles of rotation on the X and Y manipulator's axes which can define the position of cargo at any time.

In order to define the position of the load respect the fixed frame, the transformation matrices of the transformations T_0^6 , T_n^m and T_m^c are multiplied, generating the equation (12) which represents the conversion of fixed frame to the load.

$$\mathbf{T}_m^c = \begin{bmatrix} b_{11} & b_{12} & b_{13} & b_{14} \\ b_{21} & b_{22} & b_{23} & b_{24} \\ b_{31} & b_{32} & b_{33} & b_{34} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{12}$$

The result of equation (12) is a 4X4 matrix, for a second time the most important elements of this matrix, because permit to know the position of the load, are written on equation (13) for X, equation (14) for Y and equation (15) for Z.

$$\begin{aligned} \mathbf{b_{14}} &= \cos(\theta_{Y_N})\cos(\theta_{Z_N})\left(-\sin(\theta_{Ym})\,L_c + X_m\right) - \\ &\cos(\theta_{Y_N})\sin(\theta_{Z_N})\left(\sin(\theta_{Xm})\cos(\theta_{Ym})\,L_c + Y_m\right) \\ &+ \sin(\theta_{Y_N})\left(-\cos(\theta_{Xm})\cos(\theta_{Ym})\,L_c + Z_m\right) - \cos(\theta_{Y_N})\sin(\theta_{Z_N})\,Y_N + \\ &\cos(\theta_{Y_N})\cos(\theta_{Z_N})\,X_N + \sin(\theta_{Y_N})\,Z_N \end{aligned} \tag{13}$$

$$\begin{aligned} \mathbf{b_{24}} &= \left(\sin(\theta_{X_N})\sin(\theta_{Y_N})\cos(\theta_{Z_N}) + \cos(\theta_{X_N})\sin(\theta_{Z_N})\right)\left(-\sin(\theta_{Ym})\,L_c + X_m\right) + \\ &\left(-\sin(\theta_{X_N})\sin(\theta_{Y_N})\sin(\theta_{Z_N}) + \cos(\theta_{X_N})\cos(\theta_{Z_N})\right)\left(\sin(\theta_{Xm})\cos(\theta_{Ym})\,L_c + Y_m\right) - \\ &\sin(\theta_{X_N})\cos(\theta_{Y_N})\left(-\cos(\theta_{Xm})\cos(\theta_{Ym})\,L_c + Z_m\right) + \\ &\left(-\sin(\theta_{X_N})\sin(\theta_{Y_N})\sin(\theta_{Z_N}) + \cos(\theta_{X_N})\cos(\theta_{Z_N})\right)\,Y_N + \\ &\left(\sin(\theta_{X_N})\sin(\theta_{Y_N})\cos(\theta_{Z_N})\cos(\theta_{X_N})\sin(\theta_{Z_N})\right)\,X_N - \sin(\theta_{X_N})\cos(\theta_{Y_N})\,Z_N \end{aligned} \tag{14}$$

$$\begin{aligned} \mathbf{b_{34}} &= \left(-\cos(\theta_{X_N})\sin(\theta_{Y_N})\cos(\theta_{Z_N}) + \sin(\theta_{X_N})\sin(\theta_{Z_N})\right)\left(-\sin(\theta_{Ym})\,L_c + X_m\right) + \\ &\left(\cos(\theta_{X_N})\sin(\theta_{Y_N})\sin(\theta_{Z_N}) + \sin(\theta_{X_N})\cos(\theta_{Z_N})\right)\left(\sin(\theta_{Xm})\cos(\theta_{Ym})\,L_c + Y_m\right) + \\ &\cos(\theta_{X_N})\cos(\theta_{Y_N})\left(-\cos(\theta_{Xm})\cos(\theta_{Ym})\,L_c + Z_m\right) + \\ &\left(\cos(\theta_{X_N})\sin(\theta_{Y_N})\sin(\theta_{Z_N}) + \sin(\theta_{X_N})\cos(\theta_{Z_N})\right)\,Y_N + \\ &\left(-\cos(\theta_{X_N})\sin(\theta_{Y_N})\cos(\theta_{Z_N}) + \sin(\theta_{X_N})\sin(\theta_{Z_N})\right)\,X_N + \cos(\theta_{X_N})\cos(\theta_{Y_N})\,Z_N \end{aligned} \tag{15}$$

3. QUALITATIVE LOAD BEHAVIOR.

The crane manipulator model made so far does not take into account the effects of wind on the load, to do that it is necessary to add damping and external force; these elements do not permit the free oscillation of the system. The equation of motion is modified to add a damping constant V. It is possible to write the equation as follows.

$$ml\cos(\theta_{Ym})^2\ddot{\theta}_{Xm} - mr\cos(\theta_{Ym})\left(2r\sin(\theta_{Ym})\dot{\theta}_{Xm}\dot{\theta}_{Ym} - g\sin(\theta_{Xm})\right) + V\dot{\theta}_{Xm} = A\sin(wt) \quad (16)$$

$$ml\ddot{\theta}_{Ym} - mr\left(r\cos(\theta_{Ym})\sin(\theta_{Ym})\dot{\theta}_{Xm}^2 + g\sin(\theta_{Ym})\cos(\theta_{Xm})\right) = 0 \quad (17)$$

Writing the equations as space state notation:

$$x_1 = \theta_{Xm} \qquad x_2 = \dot{x}_1 \qquad x_3 = \theta_{Ym} \qquad x_4 = \dot{x}_3 \quad (18)$$

$$\dot{x}_1 = x_2 \quad (19)$$

$$\dot{x}_2 = \frac{mr\cos(x_3)\cdot\left(2r\sin(x_3)x_2x_4 - g\sin(x_1)\right) - Vx_2 + A\sin(wt)}{mr\cos(x_3)^2} \quad (20)$$

$$\dot{x}_3 = x_4 \quad (21)$$

$$x_4 = \frac{mr\left(r\cos(x_3)\sin(x_3)x_2^2 + g\cos(x_1)\sin(x_3)\right)}{mr^2} \quad (22)$$

In order to understand the load dynamics when wind effect is considered in the model, some simulations were done to validate the relevance of this force on the load behavior. Implementing the equation (20) and assuming that the oscillations at θ_{Ym} are neglected. With the last equation and working with oscillation wind force; several tests were made and are presented in Tab. 1.

Table 1 Test parameters.

Parameters	Value
V	0.01
g	9.8 (m/s^2)
Lc	10(m)
Initial conditions	0
Perturbation frequency	0.02(hz)
Excitations	50

The test consist of a study of the phase diagrams: The model is simulated for specific initial conditions, zero for all state variables. After the transient response ends, the data is sampled in phase with excitation period. This information is plotted in Fig. 4.

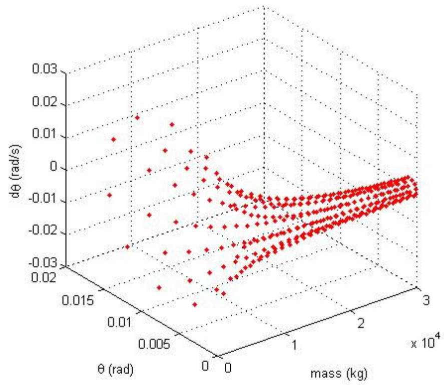

Figure 4 Mass phase diagram.

The Fig. 4. shows how the phase diagram changes while the mass of the container is increased. The next test shows how the phase diagram changes with the increase of period excitations and the variations of the damping V. The test parameters are presented in Tab. 2. and Tab. 3.

Table 2 Test parameters.

Period excitations (s)	Figure	Container mass	Rope Length
20	Figure 5	3000 kg	10 m
40	Figure 6		
60	Figure 7		
80	Figure 8		

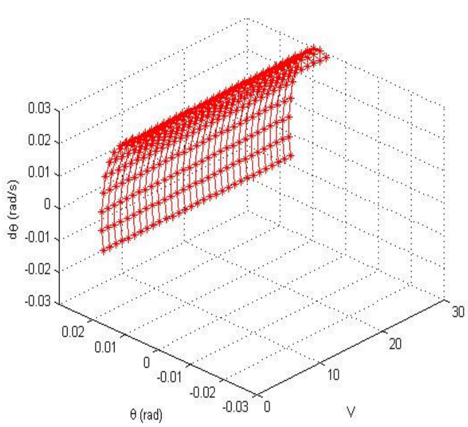

Figure 5 Period =20s mass 3000kg

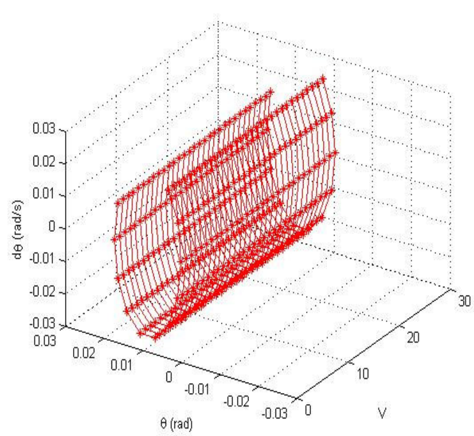

Figure 6 Period =40s mass 3000kg

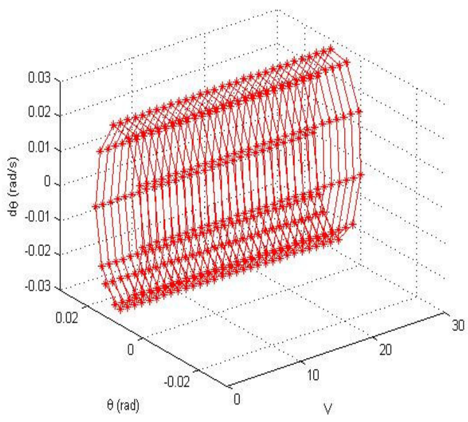

Figure 7 Period =60s mass 3000kg

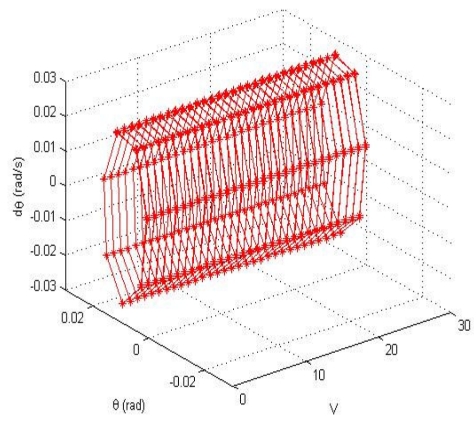

Figure 8 Period =80s mass 3000kg

Table 3 Test parameters.

Period excitations (s)	Container area	Container mass	Rope Length
20	Figure 9	30000kg	10 m
40	Figure 10		
60	Figure 11		
80	Figure 12		

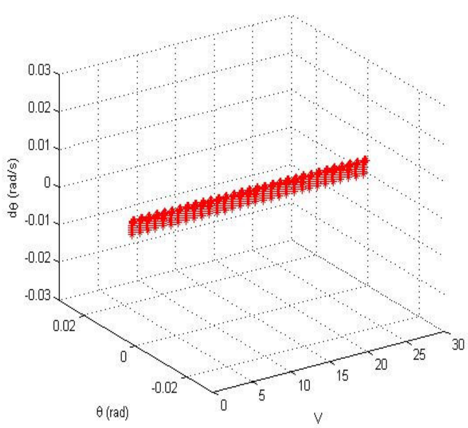

Figure 9 Period =20s mass 30000kg

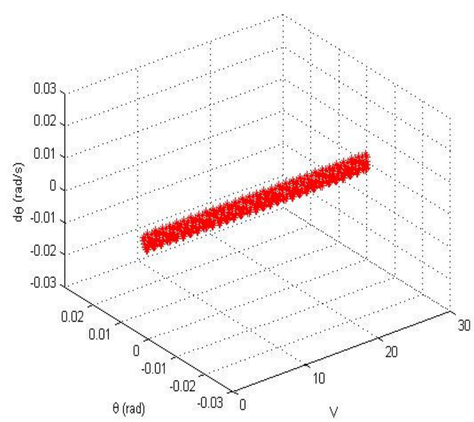

Figure 10 Period =40s mass 30000kg

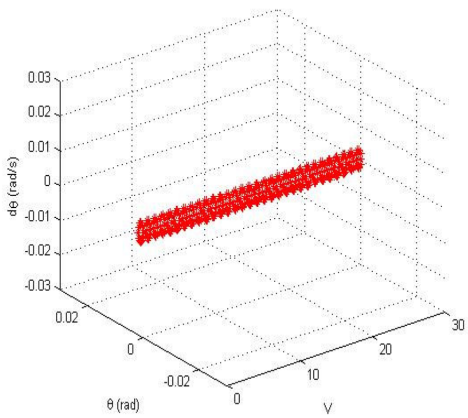

Figure 11 Period =60s mass 30000kg

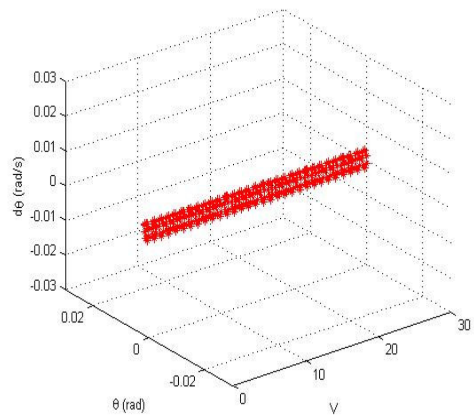

Figure 12 Period =20s mass 30000kg

3. CONCLUSION.

This paper shows the analysis of the dynamics during offshore operations loading transfers. The offshore operations have a large degree of complexity due to their dynamics that is non-linear. Because of that, is mandatory to implement a non-linear controller in order to achieve the setpoint.

The simulations show that heavy loads, like full capacity container, have not perturbation effects due the damping parameter, Fig. 9. to Fig. 12, in the other hand light loads, like empty container, have significative perturbation effects Fig. 5. to Fig. 8.

The effects of the ship on the cargo manipulator were neglected, nevertheless, some influences of the ship can be approximated as harmonic perturbation. Therefore, the model applied on this work can be used for simulated some ship influences in one of the two degrees of freedom of the cargo manipulator, these let study different cargo response for different kind of seas.

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