OFFSHORE LOAD CONTROL

Dutra, Max Suell, max@mecanica.coppe.ufrj.br
Lache, Ivanovich, ilache@ufrj.br
Federal University of Rio de Janeiro (UFRJ) – Laboratory of Machine Design and Robotics.

Ellermann, Katrin, ellermann@tu-harburg.de
Hamburg University of Technology (TUHH) – Deparment of Fluid Dynamics and Ship Theory.

Jesuz, Julio, juliojesuz@yahoo.com.br
Instruction center Almirante Graça Aranha - CIAGA

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. Hence, becomes more necessary the implementation of new technologies that makes the offshore load's manipulation, faster and easier. In order to develop these technologies is mandatory know and study diverse kinds of control techniques that carry out positional control and tracking trajectories. Therefore, in this work, the authors present the dynamical model of a suspended load that is coupled to a ship crane and is controlled by a Fuzzy logic based controller. The results of implementing this controller in specific sea conditions represented by the JONSWAP spectrum are presented, results that allow to conclude that this kind of controller achieves the minimum security standards for this kind of operations.*

***Keywords**:* Offshore *operations; Nonlinear Control; Load Manipulator; Cargo load transfer.*

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 researches and developments in innovative alternatives, that support this kind of operation to work in a variety 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.

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 behaviour 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.1.

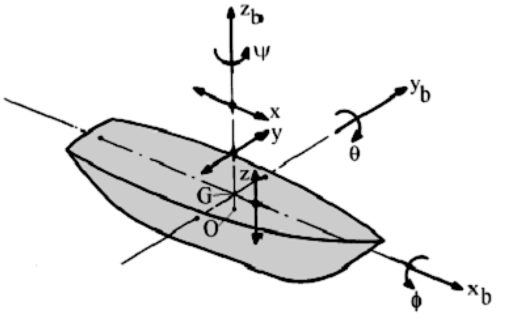


Figure 1 Degrees of freedom

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 movements affect the cargo manipulator behaviour. 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 movements (3 rotations, roll, pitch and yaw; and 3 translations surge, sway, heave).

Defined the movements of the ship, the kinematics is calculated for each degree of freedom in a specific order. For this particular case, the first movements 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. 2.

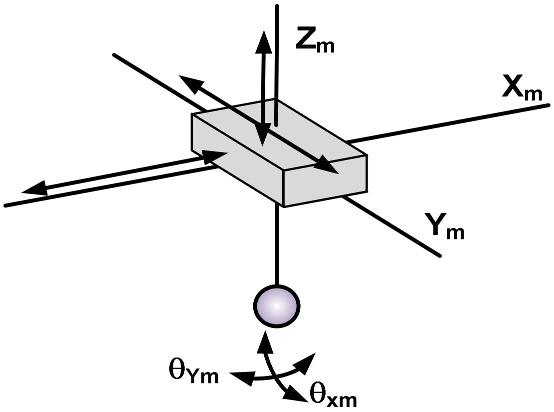


Figure 2 Cargo manipulator.

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.

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

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

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

3 FUZZY CONTROLLER.

The system presented in this article (ship-manipulator) is clearly a system with several non-linearities, which implies a big task when it is necessary to choose a correct controller. This type of problem is studied in many papers (Jie L, 2005; Dongbin z, 2004; Yang K, 2006), where different types of non-linear controllers are used for the control of cranes and cargo systems, especially those that work on container ships.

One of the techniques, that it is also implemented to control crane, is the fuzzy logic (Abbod M, 2000). It is a very intuitive way to put all the knowledge for the specialist in the controller behaviour. The process of designing a fuzzy control system is basically to take the knowledge of the procedure for the transfer of cargo and the type of cargo and then to follow the basic steps:

1. Define Input and output variables.
2. Define fuzzy sets.
3. Define fuzzy inference system.
4. Define fuzzy controller rules.
5. Test to improve the controller.

For an efficient control using fuzzy logic it is mandatory to allocate adequately the input variables, the range and the relevance of the rules that generates a correct output value, in this case the speed of the manipulator.

3.1 Input and outputs variables.

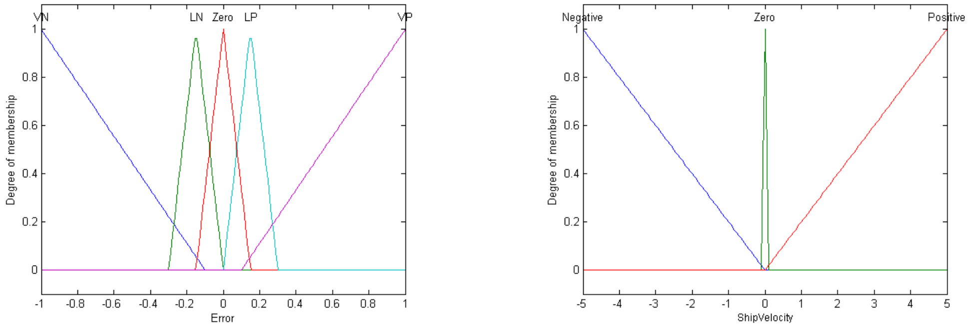
In any project based on a fuzzy logic controller it is required to determine the relevant variables for the problem that can be measured (inputs) and those that can be controlled. From the moment where those variables of input and output are defined, it is important to also determine a reasonable range of values that can occur (due the physical restrictions). For the presented problem the set of variables are.

- Error between the set point and the actual position
- Ship velocity.
- Manipulator velocity.

This project uses two independent fuzzy controllers, one for the Y-axis and other one for the Z-axis. Both have the same inputs, outputs, and rules.

3.2 Membership functions.

The fuzzy controller uses only triangular functions. For the pertinence function of the error, represented by the Fig. 3a., five triangular limited graduations of -1 to 1 were used. They are called *Very Negative, Negative, Zero, Positive, Very Positive*. For the pertinence function of the speed of the ship, represented by the Fig. 3b. three functions of triangular limited relevance from -5 to 5 were used: *Negative, Zero, Positive*.



a) b)

Figure 3 Fuzzy sets.

The Fig. 4. shows the output velocity of the triangular graduations for the manipulator, limited to -1.3 to 1.3 these values were selected based on the recommendations in literature on the speed found in devices of manipulation similar load, which recommends or requires a maximum of 2m / s. The sets used are called: Very Negative, Negative, Zero, Positive, Very Positive.

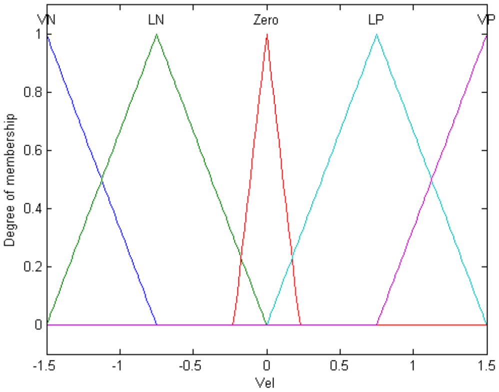


Figure 4 Output set.

3.3 Rules.

Setting the controller rules is one of the most important phase in order to achieve correctly the set point because any error can reproduce an undesired response. Table 1 show the rules used for the control of the proposed system.

Table 1 Controller rules.

		Position Error				
		Very Negative	Less Negative	ZERO	Less Positive	Very Positive
Ship's Velocity	Negative	Very Negative	Very Negative	Very Positive	Zero	Less Positive
	Zero	Very Negative	Less Negative	Zero	Less Positive	Very Positive
	Positive	Less Negative	Zero	Very Negative	Very Positive	Very Positive

At this point is important to mention that the set of rules presented on Tab. 1. is the result of a optimization design process; this process includes the technique called simulated annealing that shows its utility in diverse kinds of problems (Dutra M, 2008).

For a better view of the behavior of the rules, Fig. 5. shows the value of the output called "speed of the actuator" for the different levels of contributions from both linguistic variable called "error of position" as the so-called " ship speed".

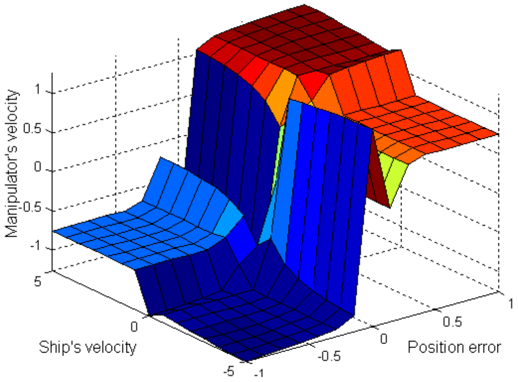


Figure 5 Output set.

The general characteristics of the controller can be implemented as given in Tab. 2.

Table 2 General characteristics.

Characteristic	Value
Inputs	2
Outputs	1
Rules	20
Fuzzy sets	Triangular
Or	Minimum
And	Maximum
Defuzzification	Centroid

1.4 Tracking trajectory.

The most important task of a load positioning system is tracking a possible path. The idea is track the movements 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. 6. Tracking a path is important because the system ship-manipulator-load should be able to compensate the oscillations of the final vessel and cancel the perturbations of the start vessel in order to be able to track the desired position.

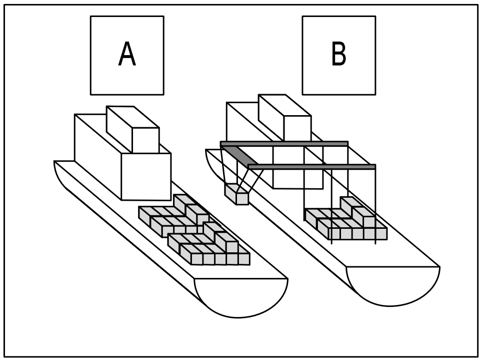


Figure 6 Offshore load operation.

The first implementation considers harmonic motion of the ship in each degree of freedom. Then the target is set-up with the same kind of perturbations. Finally the controller is used in order to track the trajectory. Table 3 give the perturbation parameters.

Table 3 Perturbation parameters

Target Frequency	0,6 Hz
Amplitude	3 m
Ship Frequency	0,25 Hz
Amplitude (Ship)	2m

The behavior of the relative trajectory (the trajectory from the start ship to the end ship) can be seen at Fig. 7. It shows the course of one point on the ship with the containers viewed from the ship with the crane in meters.

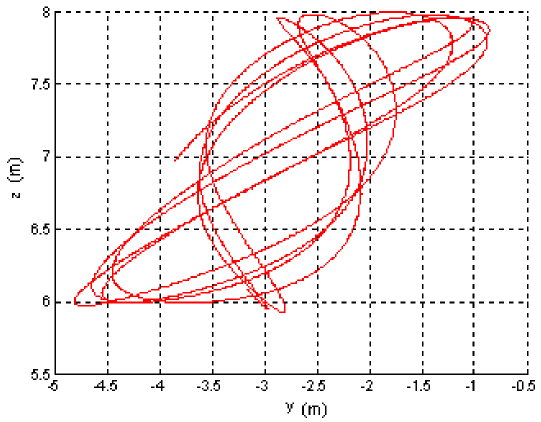


Figure 7 Relative trajectory.

The results for the excitement and set target can be observed in Fig. 8. which presents the movements of the load and the desired position at Y axis.

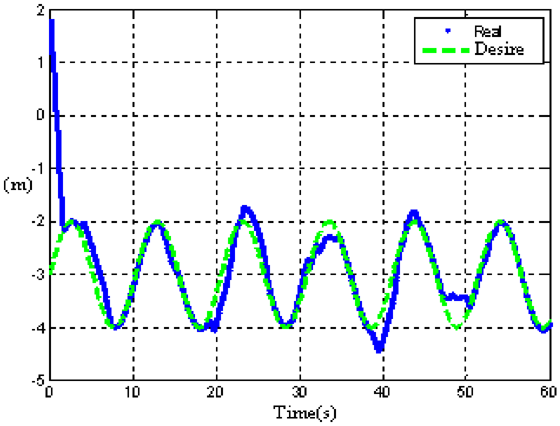


Figure 8 Desire position vs Real position (Y axis)

The Fig. 9. shows the load behavior and the desired position at the z axis.

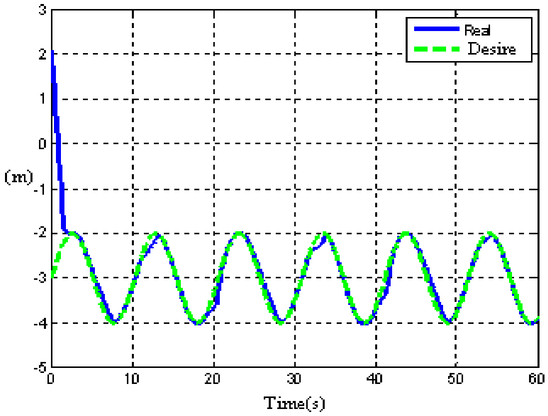


Figure 9 Desire position vs Real position (Z axis)

Finally, the behavior of error of the two movements can be seen in Fig. 10. which for the conditions presented, does not exceed the 20%.

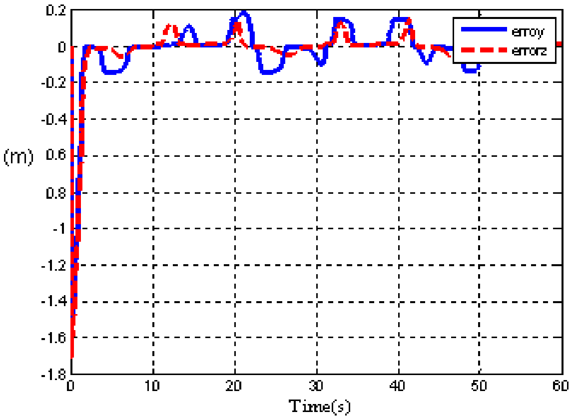


Figure 10 Error for Y and Z axis

3.5 Tracking trajectory. (II).

The following test shows the operation of the controller at real excitement, that are the movements of the ship obtained from wave spectrums applied to the transfer functions of the system. Fig. 11. shows one example for the movements of a ship using the JONSWAP spectrum for the excitement waves.

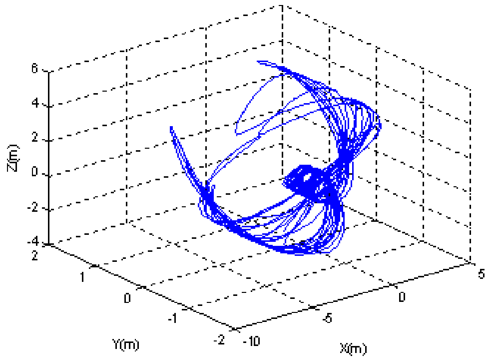
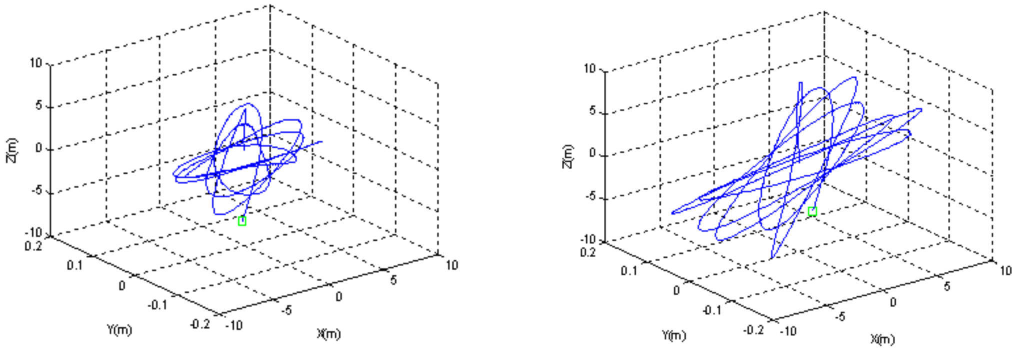


Figure 11 Ship trajectory.

The relative trajectory, that is required for the load, can be represented like the difference between the ships' movements. For this example, the same dynamic model was used for the two ships involved in the offshore operation. However, the motion is out of phase and thus gives a trajectory to be followed.

In order to generate more complex trajectories, it is important to introduce a phase between the movements of ships. In Fig. 12a. it is possible to see the trajectory between the two vessels with 1 second out off phase. In Fig. 12b. the trajectory between the two vessels are 10 second out off phase. This last trajectory is larger and will be used as the test tracking trajectory.



(a) (b)

Figure 12 Ship relatives trajectories.

After selecting the relative trajectory to be tracked, regardless the ship oscillations, the controller proposed is applied in order to study the load behavior. The result is plotted in Fig. 13. where is possible to see the load movement at Z axis.

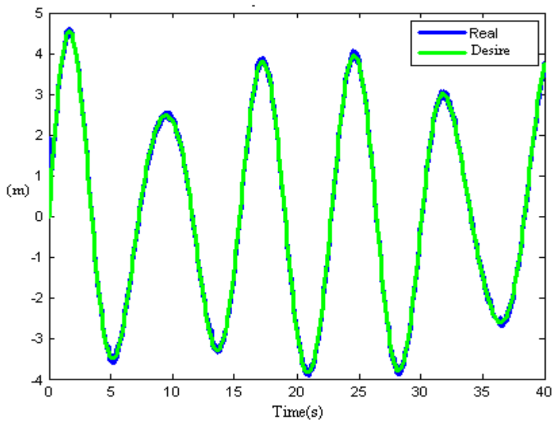


Figure 13 Load error position, Z axis.

4 CONCLUSIONS.

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, it was mandatory to implement a non-linear controller which is based on fuzzy logic.

The fuzzy controller stabilizes the load at the desired point relatively quick as the results presented in Section 4 indicate. The effectiveness of the control generates good expectations for practical implementations, even knowing that some disturbances in real conditions have not been considered.

For tracking trajectories, the controller carries out the task with some accuracy with less than 20cm between the desired and real trajectories; this means that for offshore applications, especially for container transfers, it is possible to use this kind of controller even with different lengths of the rope.

5 REFERENCES

Abbod M. F Mahfouf M, Kee C. H., 2000, “Fuzzy logic-based anti-sway control design for overhead cranes. Neural computing and applications”.

Dongbin Z Diantong L, Jianqiang Y., 2004, “Adaptive sliding mode fuzzy control for a two dimensional overhead crane.” Mechatronics.

Fossen T., 1994 “Guidance and Control of Ocean Vehicles. JohnWiley and Sons, New York.”

Groom N Robinnet D., 2002, “Pendulation control system and method for rotary boom crane. Patent No US 6,442,439 B1”.

Jie L Guangfu S, Kleeberger M., 2005, "Complete dynamic calculation of lattice mobile crane during hoisting motion. Mechanism and machine theory".
MAN BW DIESEL A/S., 2005, "Propulsion trends in container vessels. Man BW diesel a/s industrial manual reference".
Nottebom T., 2004, "Container shipping and ports: An overview." Review of Network Economics.
Silva R., 2008, "Análise hidrodinâmica e estrutural de um tanque de estabilização para controle de balanço transversal à bordo de uma plataforma FPSO". Universidade Federal do Rio de Janeiro.
Sphaier SH., 2005, "Hidrodinâmica." Universidade Federal do Rio de Janeiro.
Yang K S Yang J H., 2006 "Adaptive coupling control for overhead crane systems." Mechatronics.
Verschoof J., 2002 "Cranes - Design, Practice and Maintenance. Professional Engineering Publishing Limited." London and Bury St Edmunds UK.

5. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.