RELIABILITY-BASED DYNAMIC POSITIONING OF FLOATING VESSELS WITH RISER AND MOORING SYSTEM

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Abstract: To maintain safety of a floating vessel with associated slender components such as risers and mooring line, the vessel is normally kept within a limited region. To specify a safe position in that region, this paper suggests a new position chasing algorithm with the consideration of both riser angles and mooring line tensions. The riser angles were considered in an object function in [1] and the mooring line tension was considered in an object function in [2]. The contribution of this paper is to combine riser angle and mooring line tension together in one unified object function. A combination of scaled riser angles and structural reliability index is utilized to evaluate the "reserve capacity" relative to failure events. With this object function, the riser angles and mooring line tension are considered in a unified formulation, with higher weight added to the riser angles due to their criticality. An optimal position set-point is produced by minimization of the value of the cost function. Numerical simulations show the effectiveness of the proposed algorithm.

1 INTRODUCTION

The real time control structure of marine control systems can be divided into three levels: low level actuator control, high level plant control and local optimization[3]. The local optimization control provides the "set point" to be followed by the plant control system. At the plant level, the control system focuses on the positioning control objective and generates the necessary commanded forces and moments, hereafter called control forces. The thrust allocation calculates the commanded thrust of each actuator so as to obtain the desired control forces. The commanded thrust is the input to each individual thruster which is often associated with a local control system, referred to as thruster control, at the actuator control level. Fault diagnosis and fault tolerance are also essential issues for marine control systems. The fault tolerant level is added in this control architecture shown in Fig. 1. The fault tolerant level is to detect and isolate certain faults in the system[4]. In the case that a fault is detected, the plant control level may accommodate the effects of the fault[12]. The research topic in this paper is the local optimization and fault tolerant level.

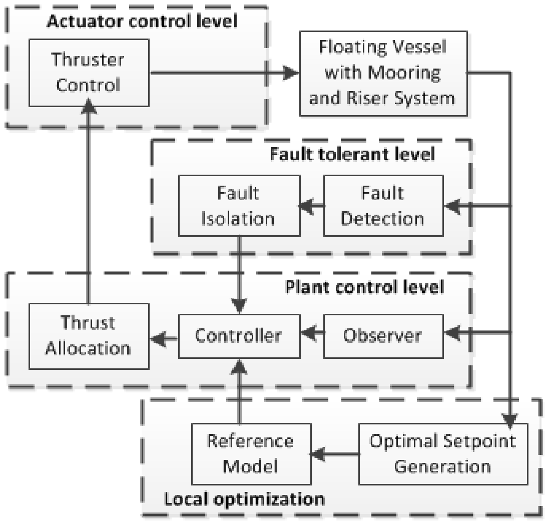

Figure 1: Control Structure of PM system (adapted from [3])

The local optimization level provides set points for the plant control system to follow. Set points are normally produced by the experienced operator. The main objective of the PM system operation is to keep the vessel at a certain position. The secondary target is to protect the system from hazards, e.g. mooring line breakage, riser buckling etc. Considering the safety of the riser system, a set point is recommended in order to keep the riser angles at safe levels[1]. This set point is further derived to protect the mooring system from line breakage[2]. This set-point chasing algorithm for the mooring system is first utilized to protect the line tension in the case that one line breaks accidentally[5]. The objective of this paper is to combine the set-point chasing algorithm in [1] and [2] in a unified manner. The application case for this unified algorithm corresponds to the breakage of one line of an FPSO system.

2 GENERAL FRAMEWORK OF FLOATING VESSEL ANALYSIS

2.1 Process Plant Model

In order to implement the unified set-point chasing algorithm within a dynamic positioning control loop, a description of the presently operating control scheme is first given. The three degree-of-freedom (DOF) nonlinear LF body-fixed coupled equation of motion in surge, sway and yaw of the DP vessel can be formulated as:

$$M\dot{v} + C_{RB}(v)v + C_A(v_r)v_r + D_{NL}(v_r,\gamma_r)v_r + D_L v_r + G(\eta) = \tau_{wi} + \tau_{wa2} + \tau_{thr} + \tau_{mo}$$

where M is the low-frequency mass matrix including added mass, v is the velocity vector, $C_{RB}(v)$ and $C_A(v_r)$ are the skew-symmetric Coriolis and centripetal matrices of the rigid body and added mass; $D_{NL}(v_r, \gamma_r)$ is the non-linear damping matrix and γ_r is the relative drag angle. D_L is a strictly positive linear damping matrix caused by linear wave drift damping and laminar skin friction. $G(\eta)$ is the generalized restoring vector caused by the buoyancy and gravitation. τ_{thr} is a vector of generalized control force provided by the thrust system, τ_{wi} is the mean wind load vector and τ_{wa2} is the second-order wave drift load vector. τ_{mo} is a vector of generalized mooring forces expressed as:

$$\tau_{mo} = [\sum_{k=1}^{q} T_{x,k} \quad \sum_{k=1}^{q} T_{y,k} \quad 0]^T$$

where $T_{x,k}$ denotes the k^{th} mooring line force in the surge direction, $T_{y,k}$ is that in the sway direction and the calculation of these forces was dealt with in [2]. The mooring system is assumed to consist of q mooring lines, attached to a turret.

The dynamic influence from the riser motion on the vessel itself is assumed to be negligible. This is due to its small mass and stiffness as compared to the surface vessel characteristics. However, the vessel motion is important for the riser dynamics.

With current present, the riser behaves like a tensioned beam. The entire riser is hence discretized into beam elements (i.e. a finite element representation). With hydrodynamic riser forces from current and waves, the riser low frequency model becomes:

$$M(r)\ddot{r} + C(r)\dot{r} + K(r)r = F_{vesselLF}(r) + F_{current}(v_c, r, \dot{r})$$

where r is the riser response, $M(r)$ is the total mass matrix, $C(r)$ is the total structural damping, $K(r)$ is the total stiffness matrix, $F_{vesselLF}$ is the contribution of the vessel's low frequency motion, $F_{current}$ is the load due to current and v_c is the current. A generally applied simplification is to neglect the two dynamic terms related to inertia and damping forces. The resulting model is said to be quasi-static, meaning that the response model is static, but external loads are calculated by taking the riser motions into account. This simplifies the analysis, and allows e.g. frequency domain analysis to be applied. However, linearization also implies loss of accuracy in the numerical model.

2.2 Design of Local Optimization

The local optimization provides the set point for the vessel to follow. In order to minimize the riser angles by vessel positioning, a riser angle response criterion was implemented as part of the control scheme to provide an optimal position[1]. Considering the strength of the mooring lines, the set point chasing algorithm is further extended to include the line tension[2]. Riser angles and mooring line tension are all important for the safety of the offshore structure.

However, the scale of these two terms is different. It is necessary to normalize them in order to combine the different criteria. The structural reliability index is a proper way to evaluate the criticality of these terms. It is denoted as [6]:

$$\delta = \frac{r_t - r_{ex}}{\sigma_t}$$

where r_t is a threshold for a certain response (i.e. the mean critical riser angle, mean breaking strength of the mooring line), r_{ex} is the on-line estimated short-term extreme value, σ_t is the standard deviation of that mean response process. In practice, σ_t, i.e. the standard deviation of the mean breaking strength, may be found from tests, alternatively from data sheets provided by the manufacturer. A lower bound for δ, denoted as δ_s, defines the critical value of the reliability index. The condition $\delta < \delta_s$ represents a situation where the failure probability is intolerably high.

A convenient way to estimate the extreme value is [7]:

$$r_{ex} = r_m + k\sigma_r$$

where r_m is the instantaneous mean value of the response, σ_r is its standard deviation. k is a factor to convert the standard deviation of the basic process into the extreme value. This value depends on many factors: response distribution, estimation method for the short term extreme value and even the number of local maxima etc. The wave-induced response process is normally a combined series with low and wave frequency component. A tri-modal process is also available, e.g. vortex induced vibration (VIV) for riser response. The objective of the control effort is to compensate the low frequency effect. In an ideal condition, only wave frequency or higher frequency response components will then remain. The wave frequency component is assumed to be a narrow-banded Gaussian process if nonlinear effects are neglected. For a Gaussian dynamic response process with a corresponding Gumbel extreme value distribution, the k value is calculated as [7]:

$$k = \sqrt{2\ln(n)} + \frac{\lambda}{\sqrt{2\ln(n)}}$$

where λ is the Euler-Mascheroni constant (0.57722), and n is the number of individual maxima that occurs during the considered time period.

This index above is a kind of normalized value which can be used to evaluate the safety level for different response process. A normalization of the response process itself would also be possible to apply, but comparatively the structural reliability index is more easily understood. The control target is to avoid that the value of this index will exceed a specified lower bound. This index is also a more conservative method to limit the response due to its representation of dynamic effects.

The relationship between the response process and the vessel motion is detailed in [1], [2] and [5]. It is written as:

$$\theta_t = \theta_{ot} + c_t \Delta r_v \quad \theta_b = \theta_{ob} + c_b \Delta r_v \quad T_{mi} = T_{oi} + c_i \Delta r_v \sin(\beta + \beta_{io})$$

where θ_t, θ_b is the top and bottom angle of the rigid riser, T_{mi} is the i^{th} mooring line tension. These three terms are denoted as r_m above. θ_{ot}, θ_{ob} are the angles at a certain working point, β_{io}, T_{oi} are the tension and angle of the i^{th} mooring line at that working point, Δr_v, β are the vessel displacement and direction, c_t, c_b, c_i are incremental coefficients for the riser angles and line tension. Note that the two riser angle components can also be combined[8]. There are also cases where the top and bottom angles have different signs[1]. This analysis is unified into a combination of riser angles and line tension. The structural reliability indices for the riser angle and line tension are:

$$\delta_t = \frac{\theta_t - \theta_{tex}}{\sigma_{tt}} \quad \delta_b = \frac{\theta_b - \theta_{bex}}{\sigma_{bt}} \quad \delta_i = \frac{T_{mi} - T_{exi}}{\sigma_{mti}}$$

where δ_t, δ_b is the structural index for the top and bottom angle, δ_i is the index for the i^{th} mooring line tension. $\theta_{tex}, \theta_{bex}, T_{exi}$ are the extreme values for these terms, $\sigma_{tt}, \sigma_{bt}, \sigma_{mti}$ are their standard deviation. The object function based on these structural reliability indices becomes:

$$L = w_t(\delta_{st} - \delta_t)^2 + w_b(\delta_{sb} - \delta_b)^2 + \sum_{i=1}^{p} w_i(\delta_{si} - \delta_i)^2$$

where w_t, w_b and w_i are respectively the weighting factors for the top -, bottom angle and mooring line tension, δ_{st}, δ_{st} and δ_{si} are respectively the lower bound of the structural reliability indices for the top -, bottom angle and mooring line tension. The riser is more critical than the mooring lines and larger weights are accordingly associated with the riser angles. In addition, the bottom angle is typically more critical than the top one and also has a larger weight.

Solution of the equations which are obtained when the partial derivatives of this expression with respect to the optimal increment of vessel position and direction are set to zero, identifies the minimum value of the object function. The optimal increments of the vessel position and direction are then expressed as:

$$\Delta r_v = \frac{K_{11}^m \sin\beta + K_{12}^m \cos\beta - K_{11}^r \cos\beta}{K_{21}^m \sin^2\beta + 2K_{22}^m \sin\beta\cos\beta + K_{23}^m \cos^2\beta + K_{21}^r \cos^2\beta}$$

$$\beta_{op} = \mathrm{tg}^{-1} \frac{K_{11}^m K_{23}^m - K_{12}^m K_{22}^m + K_{22}^m K_{11}^r + K_{11}^m K_{21}^r}{K_{12}^m K_{21}^m - K_{11}^m K_{22}^m - K_{21}^m K_{11}^r}$$

where K_{11}^m - K_{23}^m, K_{11}^r - K_{21}^r are constants that depend on geometry and riser angle as:

$$K_{11}^{m}=\frac{w_1c_1}{\sigma_{t1}}(\delta_{s1}-\frac{T_{t1}-T_{o1}-k_1\sigma_{r1}}{\sigma_{t1}})\cos\beta_{o1}+\frac{w_2c_2}{\sigma_{t2}}(\delta_{s2}-\frac{T_{t2}-T_{o2}-k_2\sigma_{r2}}{\sigma_{t2}})\cos\beta_{o2}+\cdots$$

$$+\frac{w_qc_q}{\sigma_{tq}}(\delta_{sq}-\frac{T_{tq}-T_{oq}-k_q\sigma_{rq}}{\sigma_{tq}})\cos\beta_{oq}$$

$$K_{12}^{m}=\frac{w_1c_1}{\sigma_{t1}}(\delta_{s1}-\frac{T_{t1}-T_{o1}-k_1\sigma_{r1}}{\sigma_{t1}})\sin\beta_{o1}+\frac{w_2c_2}{\sigma_{t2}}(\delta_{s2}-\frac{T_{t2}-T_{o2}-k_2\sigma_{r2}}{\sigma_{t2}})\sin\beta_{o2}+\cdots$$

$$+\frac{w_qc_q}{\sigma_{tq}}(\delta_{sq}-\frac{T_{tq}-T_{oq}-k_q\sigma_{rq}}{\sigma_{tq}})\sin\beta_{oq}$$

$$K_{21}^{m}=\frac{w_1c_1^2}{\sigma_{t1}^2}\cos^2\beta_{o1}+\frac{w_2c_2^2}{\sigma_{t2}^2}\cos^2\beta_{o2}+\cdots+\frac{w_qc_q^2}{\sigma_{tq}^2}\cos^2\beta_{oq}$$

$$K_{22}^{m}=\frac{w_1c_1^2}{\sigma_{t1}^2}\sin\beta_{o1}\cos\beta_{o1}+\frac{w_2c_2^2}{\sigma_{t2}^2}\sin\beta_{o1}\cos\beta_{o2}+\cdots+\frac{w_qc_q^2}{\sigma_{tq}^2}\sin\beta_{o1}\cos\beta_{oq}$$

$$K_{23}^{m}=\frac{w_1c_1^2}{\sigma_{t1}^2}\sin^2\beta_{o1}+\frac{w_2c_2^2}{\sigma_{t2}^2}\sin^2\beta_{o1}+\cdots+\frac{w_qc_q^2}{\sigma_{tq}^2}\sin^2\beta_{o1}$$

$$K_{11}^{r}=\frac{w_tc_t}{\sigma_{tt}}(\delta_{st}-\frac{r_t-r_{ot}-k_r\sigma_{rt}}{\sigma_{tt}})+\frac{w_bc_b}{\sigma_{tb}}(\delta_{sb}-\frac{r_b-r_{ob}-k_b\sigma_{rb}}{\sigma_{tb}})$$

$$K_{21}^{r}=\frac{w_tc_t^2}{\sigma_{tt}^2}+\frac{w_bc_b^2}{\sigma_{tb}^2}$$

Finally, the algorithm for updating the vessel position and heading vectors are expressed by:

$$\eta=\eta_o+\Delta r_v[\cos\beta_{op} \quad \sin\beta_{op} \quad 0]^T$$

where $\eta=[x \quad y \quad \varphi]^T$ is the reference position and heading set-point. For a 2-D case with surge and heading as the only degrees-of-freedom, the direction becomes simply $\beta_{op}=0$.

2.3 CONTROLLER DESIGN

The objective of the controller is to maintain the vessel position and prevent mooring and riser system from failing, e.g. line breakage or riser buckling. Furthermore, faults that may occur need to be detected and then isolated. This is handled by the fault tolerant level shown in Fig. 1. The fault detection and isolation algorithm for the mooring line breakage is found in [5]. The set-point chasing algorithm in Section 2.2 is used to keep the riser angle index and the line tension index within a safe domain. This is implemented by application of a multi-variable PID controller given by:

$$\tau_{thr} = -K_i R^T(\varphi)\int \hat{\eta}_e \partial t - K_p R^T(\varphi)\hat{\eta}_e - K_d \hat{v}_e$$

where $\hat{\eta}_e = \eta - \eta_d, \hat{v}_e = v - v_d; \eta_d, v_d$ are the desired position and velocity vectors; K_p, K_i, K_d are the non-negative P,I,D controller gain matrices; φ is the measured heading. The wind feed-forward, acceleration feedback, and roll-pitch damping can be used in addition. The functionality of different controllers was treated in [9].

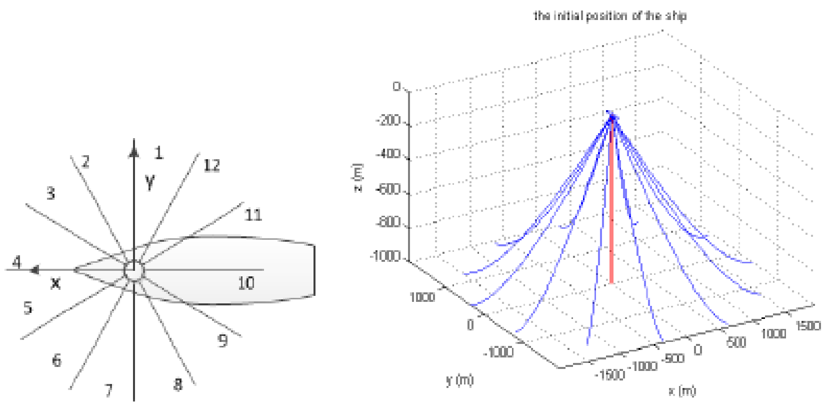

Figure 2: The setting of floating vessel with mooring and riser system

3 NUMERIAL SIMULATION RESULT

The simulation is carried out using the Marine System Simulator (MSS)[10]. A thruster-assisted PM system in MSS is used. The mooring system consists of 12 mooring lines connected to a turret. A rigid marine riser is also attached to the vessel, as shown in Fig. 2. The water depth is 1000 meters and twelve mooring lines are spread out, with approximately 1/3 of their total length lying on the sea bead. The mooring lines are described in more detail in [11]. The riser radius is 0.25m, its wall thickness is 0.025m and the modulus of elasticity is $E = 2.1\text{E}8\text{Pa}$. The top tension is 2500 Pa, and tension at the lower part is 1200 Pa. The current profile is characterized by 75% of the surface velocity at a depth of 500m, and 15% of the surface velocity at the bottom with a linear variation between these values.

The simulation was carried out using a JONSWAP model for wave energy distribution. The significant wave height is $H_s = 7\text{m}$ and the peak period is $T_p = 10\text{s}$. The wave direction is along the symmetry axis of the system. The surface current is 0.8 m/s. The wind speed is 8 m/s from a direction of 45deg. The simulation duration is 5000s and the breakage of one line (line 10) occurs at $t = 2500\text{s}$.

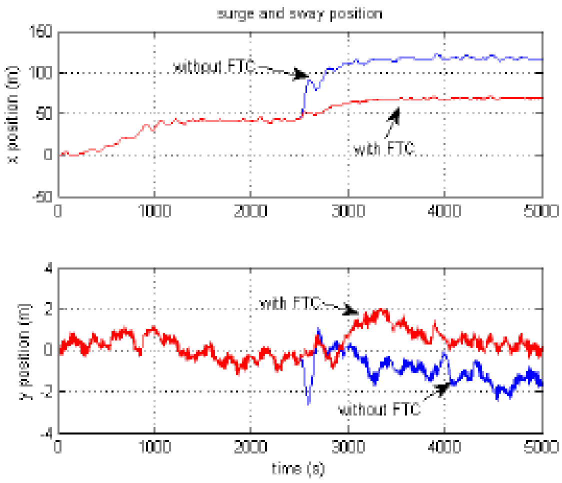

Figure 3: Position variation

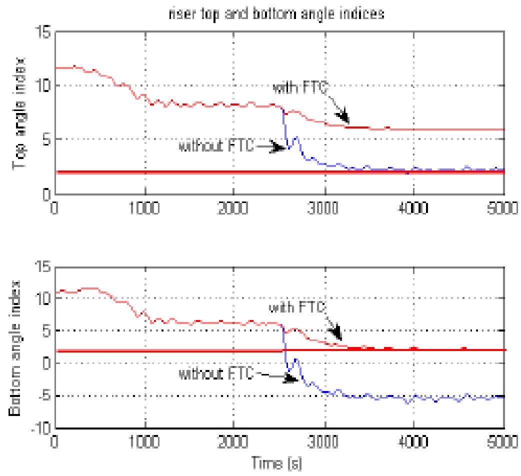

Figure 4: Riser angle indices

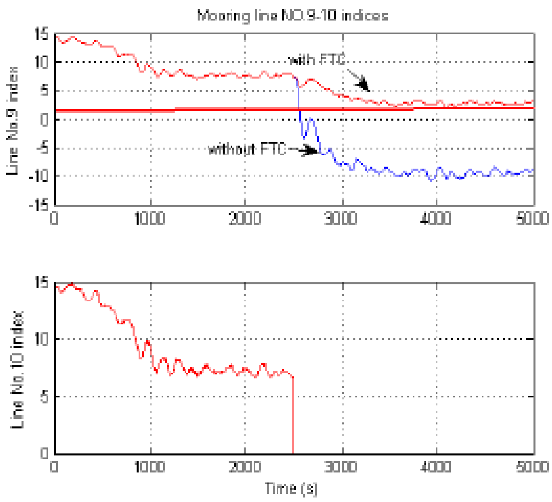

Figure 5: Indices for mooring lines 9-10.

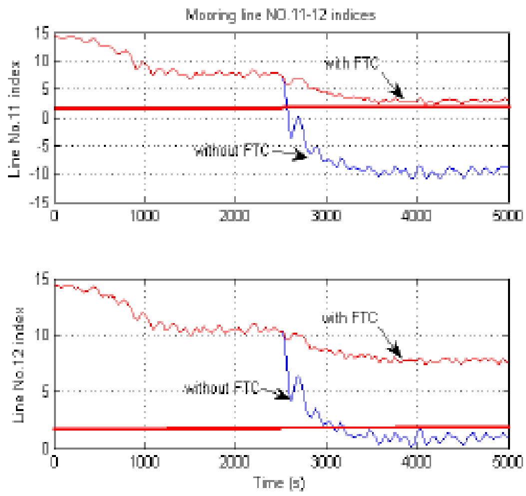

Figure 6: Indices for mooring lines 11-12.

Figures 4-6 show the reliability index variation based on the instantaneous mooring line tension and riser angles after line No.10 breaks at $t = 2500\text{s}$. Only information related to mooring-lines lines 9-12 are shown as these are the most critical. Other lines are far from the limits. The lower bound of the indices for mooring line and riser angle are defined to be the same, i.e. $\delta_s = 2$. The riser top and bottom angles, in addition to mooring lines 9 and 11 are the critical components. After the line breakage is detected at $t = 2500\text{s}$, the fault tolerant control is activated. With the optimal set-point chasing algorithm, the riser top and bottom angle indices are kept within safe limits. The same is the case for mooring lines 9 and 11.

4 CONCLUSIONS

An optimal set-point chasing algorithm was proposed for a floating vessel with riser and mooring system. A structural reliability index was employed to combine mooring line tension and riser angles in a single cost function. The algorithm was developed such that the associated reliability indices were prevented from falling below a critical value, which would represent an unacceptable risk of line and riser failure. Essential features of the new algorithm were shown to be the ability to protect several mooring lines and the riser simultaneously. In the industrial implementation, both automatic and operator-assisted decision support could be included.

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REFERENCES

[1] Leira, B. J., A. J. Sørensen, C. M. Larsen: A reliability-based control algorithm for dynamic positioning of floating vessels, Structural Safety, vol.26, 2004
[2] Fang, S., B. J. Leira, M. Blanke: Position mooring control with a structural reliability criterion, Structural Safety, submitted
[3] Sørensen, A. J.: Structural issues in the design and operation of marine control systems, IFAC Annual Reviews in Control, vol.29, no.1, pp125-149, 2005
[4] Blanke, M., M. Kinnaert, J. Lunze and M. Staroswiecki: Diagnosis and Fault-tolerant Control, 2nd ed., Springer, 2006
[5] Fang, S. and M. Blanke: Fault monitoring and fault recovery control for position moored tanker, International Journal of Applied Mathematics and Computer Science, vol. 21, 2011
[6] Berntsen P. I. B.: Structural reliability based position mooring, PhD thesis, Department of Marine Technology, NTNU, 2008
[7] Myrhaug D.: Statistics of narrow band processes and equivalent linearizing, Lecture notes, UK-2005-74, Department of Marine Technology, NTNU, Trondheim, Norway, 2005
[8] Sørensen, A. J., B. J. Leira, J. P. Strand and C. M. Larsen, Optimal set-point chasing in dynamic positioning of deep-water drilling and intervention vessels, International journal of robust and nonlinear control, vol.11, pp1187-120, 2001
[9] Nguyen T. D. and A. Sørensen, Set-point chasing for thruster-assisted position mooring, Control Engineering Practice, pp. 985-994, 2009
[10] MSS, Marine system simulator, http://www.marinecontrol.org, 2010
[11] Aamo O., T. I. Fossen: Finite element modeling of moored vessels, Mathematical and Computer Modelling of Dynamical Systems, pp 47-75, 2001
[12] Blanke, M.: A Structure-graph Approach to Diagnosis and Control Reconfiguration Design – Exemplified by Station-keeping Control. ASNE Reconfiguration and Survivability Symposium, Jacksonville, Florida, February 16-18, 2005. Plenary.