DYNAMIC POSITIONING CONFERENCE
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Control Systems I

A numerical DP MODULE to help design and operation for projects including DP components

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Dynamic Positioning (DP) is a rapidly maturing technology. Nowadays increasing demands for DP vessels not only for exploration and installation operations but for units in production, the designs of such vessels require meticulous analysis.

PRINCIPIA R.D. has developed DIODORE™ their general hydrodynamic software for over 20 years. It has recently enhanced this marine package with an extensive DP module.
Indeed, the need for DP tools to evaluate the feasibility of a marine operation or a long term station keeping concept with or without classical mooring systems is used at all the stages of offshore development projects from the concept analysis to the detailed installation study but also for basic design.
This paper includes a detailed description of the mechanical and DP model with some academic results for the case of tandem DP tanker offloading. It will show how the program can help in providing design criterion for the DP system as well as the design concept for related operation.

THE DYNAMIC POSITIONNING MODEL

Basically a DP system consists of three main components:

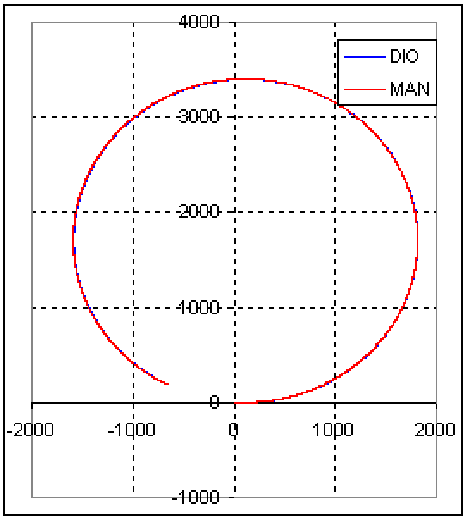
- Sensors (motions, wind, thruster feedback)
- Control system (PID, Thruster allocation, wind feed forward…)
- Thrusters

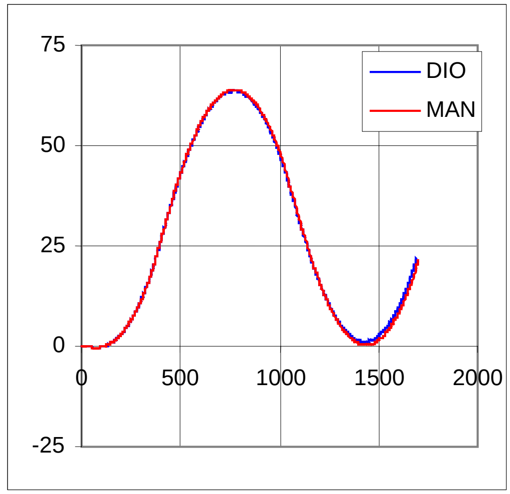
Therefore, a DP simulator must include the previous components in a mechanical simulator able to model the DP ship motions :

- Sensors are derived from the results of the simulation (motions, wind speed, thruster load)
- The control system includes a robust PID algorithm to derive the command load from the ship response, then an allocation process to define the command of each thruster from the command load.

The Ship Simulator

The time domain simulation model is based on a station-keeping simulation solver i.e. the ship motion is solved in a frame with its origin at the centre of gravity and its axis remaining parallel to the initial axis. This is not the usual approach that uses the local frame. Validation has shown equivalent results for classical maneuvers such as a turning circle or zigzag with a maneuvering solver such as Mandoline developed by PRINCIPIA.





DIO stands for DIODORE™ results
MAN for MANDOLINE maneuvering simulator

The hydrodynamic loads are computed from a sink-source diffraction-radiation method, accounting for multi-body interaction. Low-frequency wave loads can be derived from drift forces using the Newman approximation as well as computing the full QTF (Quadratic Transfer Function)matrix using HydroStar developed by Bureau Veritas. Using the later method to compute low frequency wave load can be crucial for modeling DP operation in shallow water. If the wave height is significant, the mechanical stiffness induced by the DP system (i.e. the proportional gain) is going to be high and 2nd order wave loads computed with the Newman approximation would be largely underestimated. Wind and current loads are computed using Morrison drag formulation. User input coefficients are extracted from the OCIMF database. Wave and current interaction can be taken into account by computing hydrodynamic loads using the Grekas formulation for the free surface condition.

Maneuvering Model

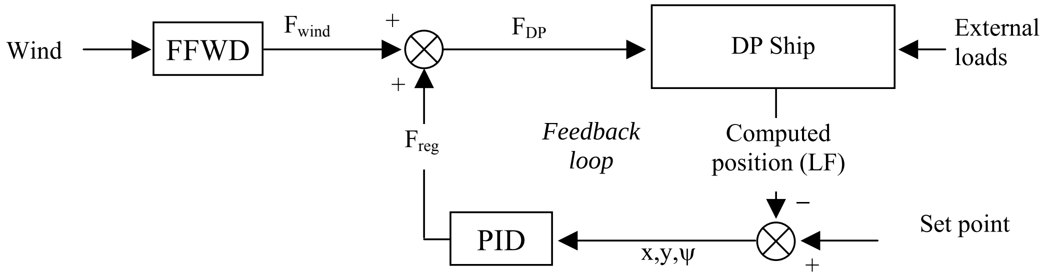
Contrary to diffraction-radiation loads that can be computed accurately using the sink-source method, maneuvering models remain based on empirical formulas. Two approaches have been considered: If the DP system is used as a mooring system, the classical mooring damping terms should be used. The surge and sway low frequency additional damping accounting for viscous phenomena, the Molin yaw moment, and wave drift damping following Arahna's formula are used. If the DP operation involves more maneuvering considerations, the Clarke model (see Lewis 1988) or linear equivalent model is applied.

PID Command Load

A robust PID algorithm is developed to define the command load vector F_{reg}:

$$\begin{vmatrix} F_x^{reg} \\ F_y^{reg} \\ M_z^{reg} \end{vmatrix} = -\begin{bmatrix} & G_P & \end{bmatrix} \begin{vmatrix} x \\ y \\ \psi \end{vmatrix} - \begin{bmatrix} & G_D & \end{bmatrix} \begin{vmatrix} x' \\ y' \\ \psi' \end{vmatrix} - \begin{bmatrix} & G_I & \end{bmatrix} \begin{vmatrix} \int x \\ \int y \\ \int \psi \end{vmatrix}$$

x, y and ψ are the low frequency set point error, i.e. the difference between the computed position and the set point. This error is computed at a set point defined by the user G_P, G_D and G_I are proportional, derivative and integral gain matrices.



A perfect wind feedforward is applied as the computed wind load and directly integrated in the correction. No Kalman filter has been developed as numerically the low frequency signal is computed without filtering and includes the correct phase lag. Anti-reset windup is implemented to prevent thruster saturation by limiting integral commands in case of durable drift.

Allocation Process

If the thruster loads of n azimuth thrusters are expressed according to their thrust f and azimuth α, the command load F_{reg} can be expressed as:

$$F_{Xreg} = \Sigma\, f_i \cos \alpha_i$$
$$F_{Yreg} = \Sigma\, f_i \sin \alpha_i$$
$$M_{Zreg} = \Sigma\, (x_i f_i \sin \alpha_i - y_i f_i \cos \alpha_i)$$

with (x_i,y_i) the position of the thrusters.

The allocation system can be written F = [B] U with:

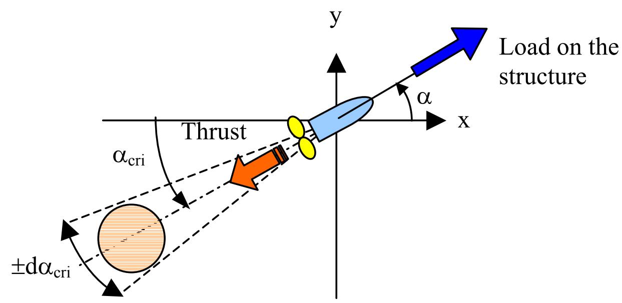
$$[B] = \begin{bmatrix} 1 & \ldots & 1 & 0 & \ldots & 0 \\ 0 & \ldots & 0 & 1 & \ldots & 1 \\ -y_1 & \ldots & -y_n & x_1 & \ldots & x_n \end{bmatrix}_{3\times 2n}, \quad F_{reg} = \begin{vmatrix} F_{Xreg} \\ F_{Yreg} \\ M_{Zreg} \end{vmatrix}$$

and $U = [\, f_1\cos\alpha_1 \ldots f_n\cos\alpha_n \;\; f_1\sin\alpha_1 \ldots f_n\sin\alpha_n \,]^T$

To solve the system, the Moore-Penrose pseudo-inverse matrix is applied to optimize the command by minimizing the energy (see Fossen 1994). This system can be derived if fixed thrusters are used.

Thrusters

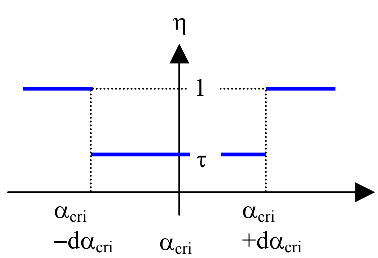
DP systems can be easily defined by mixing multiple types of units such as tunnel thrusters, azimuth pods or main propellers. Thrust and azimuth saturation, including range limiting and interference, are taken into account in the thrust allocation process. Special attention has been given to analyze the shielding effects that can be encountered when considering different modifications of the thrust efficiency due to an obstacle.



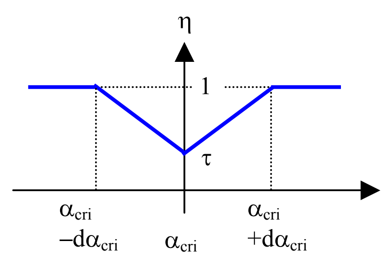
Four types of thrust efficiency modifications are available in the model:

- No transition: n=0
- Linear transition: n=1
- Circular transition: n=0.5
- Inverse transition: n=2

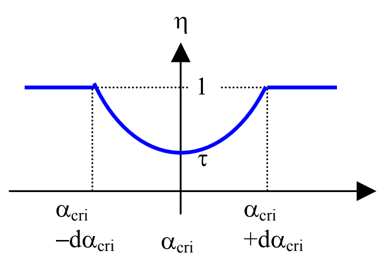
$n = 0$



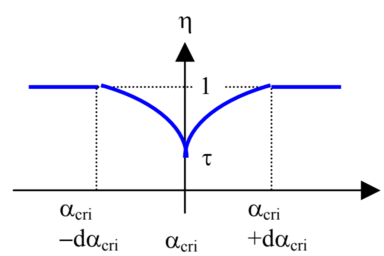
$n = 1$



$n = 0.5$



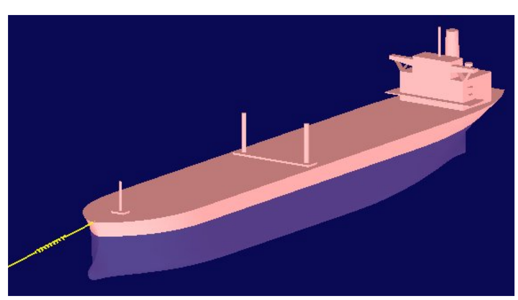
$n = 2$



FIRST CASE STUDY : DP TANKER – CALM BUOY OFFLOADING

Scenario

The case study is based on the academic analysis of the utility of a DP tanker to perform tandem offloading from a CALM buoy. The purpose of the DP system in such a configuration will be to permit offloading with large range of weather conditions. The criteria of offloading feasibility is to maintain the tanker in the vicinity of the buoy, for example at a target distance of 70m.



The CALM buoy has been considered fixed at this stage of the analysis.
The 110,000 DWT tanker (L=320m, B=55m, T=8.2m) is equipped with a dynamic positioning system composed of two tunnel thrusters (one bow and one stern) and two secondary azimuth thrusters positioned on each side (port/starboard). The tunnel thrusters are limited to 100kN and secondary thruster to 75kN.

Results presented here are for the most probable environment (headings are arbitraries). Environmental conditions combine 9.6 knots wind from 75°N with a long crested JONSWAP sea state: Hs=2.3m, Tp=12s. from 300°N and a 0.65m/s current to the 330°.

Wind and current loads are computed from the OCIMF database. Wave loads are computed using DIODORE™ diffraction radiation processor.

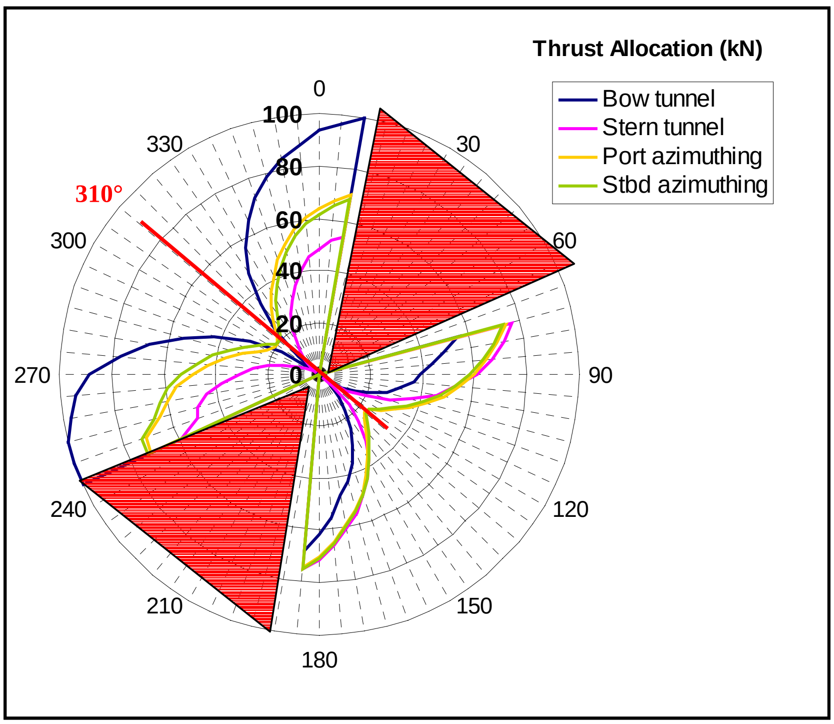
Capability Analysis

Capability plots can be drawn following IMCA (International Marine Contractors Association) or API (American Petroleum Institute) standards to obtain a fast and precise idea of the maximum environment that the vessel can sustain, or the allocation of the thrusters under given environmental conditions. For our case, a static Capability Analysis is performed to determine the optimal position of the tanker as regards thruster solicitation. Tunnel thrusters are limited to 100kN and secondary thrusters to 75 kN.

The API-standard Capability Plot represents the thrust allocated to each thruster of the DP system. Allocation is processed in two or three steps :

- the mean environmental loads are calculated to assess the restoring forces (here, exactly opposed to environmental loads)
- the global command is equally distributed to each thruster (linear allocation)
- when thrusters come to saturation, they are set to their maximum available contribution and the residual command is re-allocated to the other thrusters (compensation)

Linear allocation is performed by solving a non-square system [B]U=F, F being the restoring forces, U the generalized thrust command, and [B] an allocation matrix which depends only on thrusters' co-ordinates. The program automatically builds the allocation matrix for any DP system mixing directional and azimuth thrusters, as well as screw-rudder devices.



Minimum allocation is encountered for the tanker heading at 310°N and the two red triangles marks the saturation sector where the DP system is not able to sustain the environmental loads.

SECOND CASE STUDY : DP TANKER TANDEM OFFLOADING

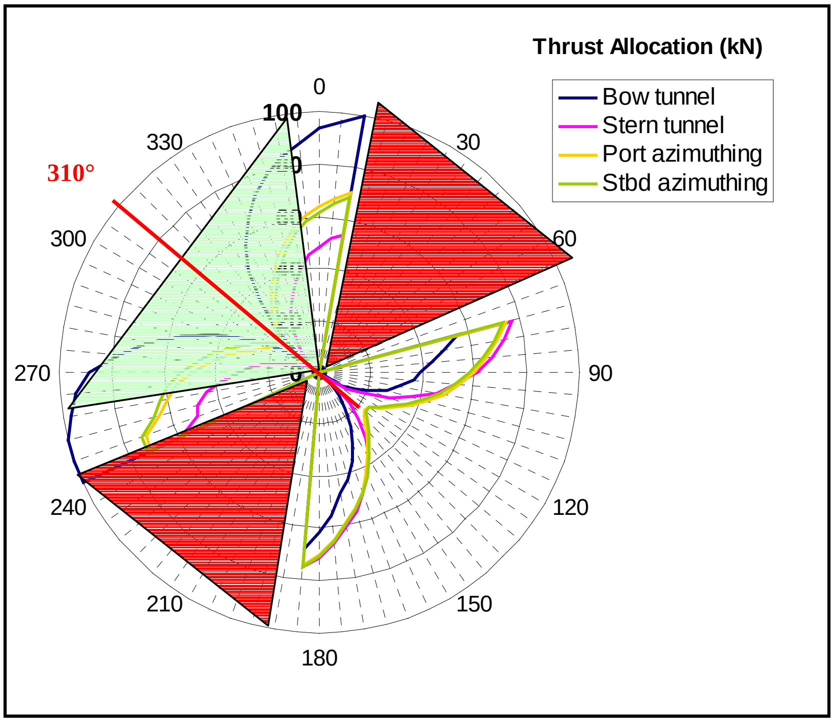
Scenario

Another case study is based on the academic analysis of the utility of a DP tanker to perform tandem offloading with a spread moored FPSO. The criteria of offloading feasibility is still to maintain the tanker at a target distance of 70m but the tanker should remain within the +/- 40° green angular area with respect to the FPSO axis.

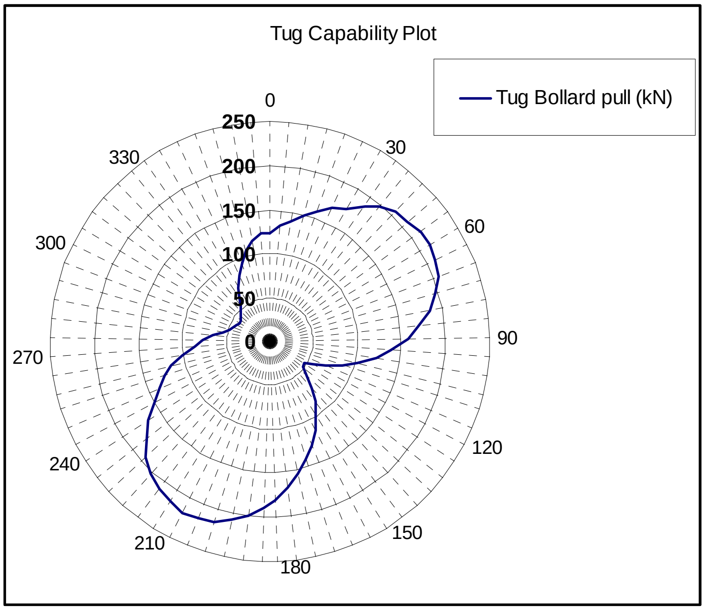
The spread moored FPSO has been considered fixed for this part of the analysis.
The 110,000 DWT tanker with the same DP system is used. The same environmental conditions are used. The FPSO is supposed to be heading to 310°CWN so that the ordered tanker position corresponds to the minimum thrust allocation.

Capability Plot

With unchanged environmental conditions and thruster limitations the same capability plot is obtained. Important considerations can be pinpointed with the help of this capability plot. Comparing the heading range where the DP system can sustain the set point, it can be seen that for the considered environmental conditions, there is no risk of disconnection as the DP operability sector is larger than the +/-40° safe area.(green triangle)



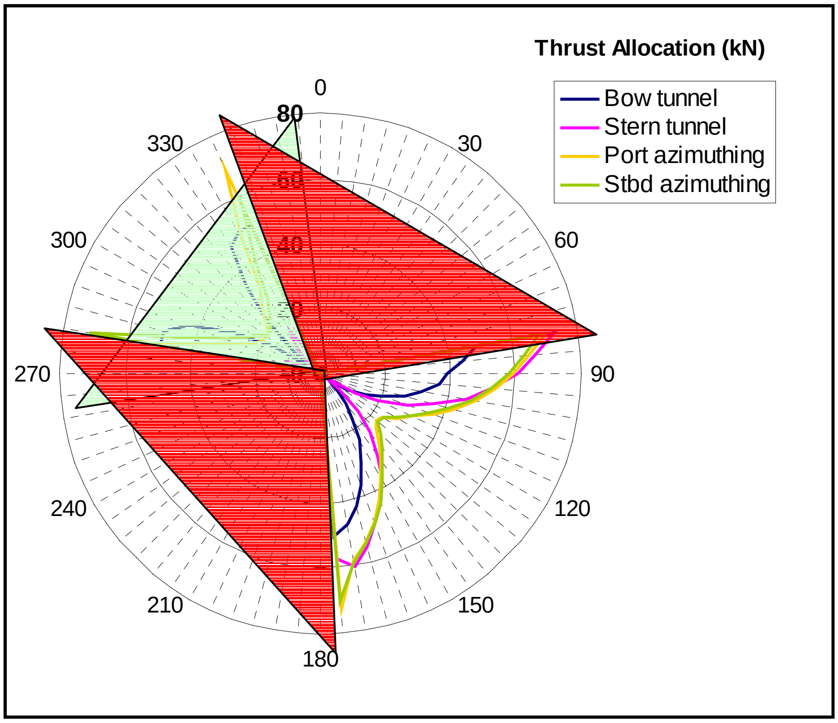
In comparison, one can consider a tug as a azimuth thruster for the tanker with a very slow angular speed variation. The capability plot below presents the bollard pull (BP) required for the same environmental conditions for a typical 50 tons BP tug.



There are no saturation sectors for a tanker and tug system but these capability calculations do not integrate the fact that a tug is a very slow "azimuth" thruster. It also leads to the conclusion that this tug is over-powered in the considered environment. It is not only able to maintain the tanker in the green sector (where the DP system is as efficient with less energy) but at any other headings.
From this point of view, it might be estimated then that the DP tanker is more suited to the tandem offloading specific needs than a tanker and tug system.

Failure Mode

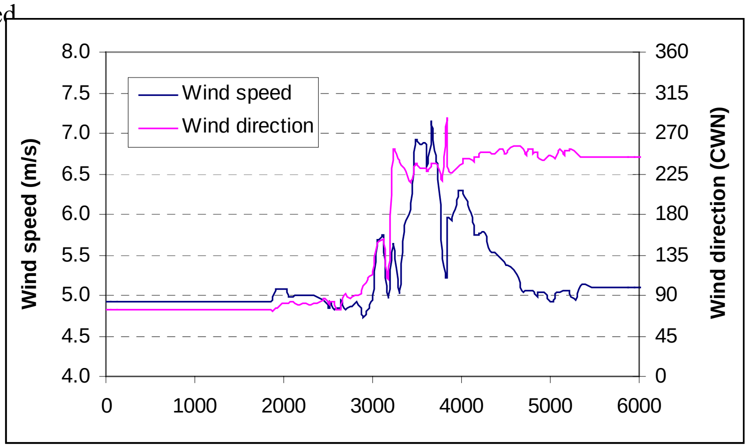
Failure mode analysis represents a large part of the design of a DP system with the purpose assess the required redundancies. If one of the bow tanker's thruster experienced a 50% thrust loss, the previous conclusions would no longer be valid. In this case the tanker is not able to maintain its position in the green sector as the saturation areas intersect the safe offloading area.



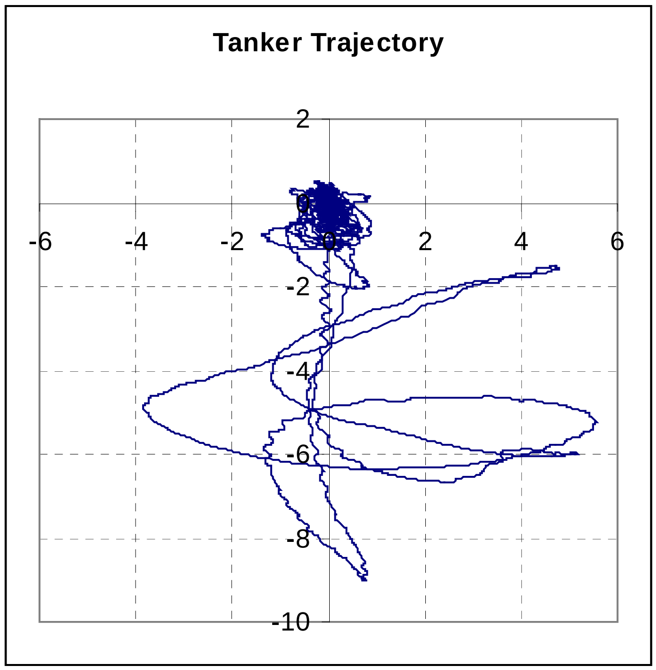
Time Domain Low Frequency Analysis

The global low-frequency response of the DP tanker is evaluated through time-domain simulation. Previously defined environmental conditions are applied to the vessel. The low-frequency wave effects are estimated using the Newman approximation. The tanker is connected to the FPSO with a double hawser and its DP is activated.

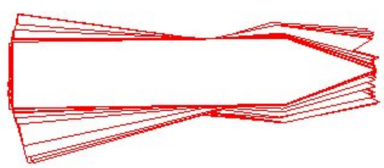
At a given time a squall wind is applied with restricted increase of speed but important change in direction (235°CWN at maximum speed 14 knots).



In the time-domain, the restoring forces allocated to the DP system are computed by a PID-pilot of gains 500 kN per m in both surge and sway, 8700 kN.m per degree in yaw. In the case of reset-windup, the integral thrust command is limited to the sum of the maximum available thrust.

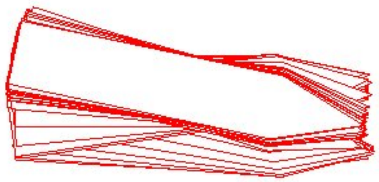


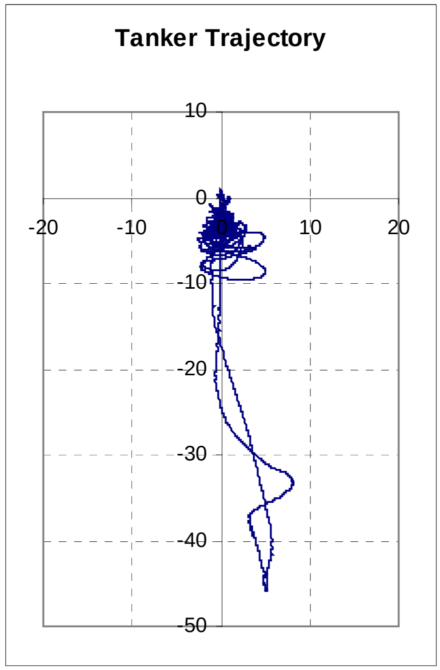
The response of the tanker is represented below :



Bow Thruster Failure

A 50%-loss of efficiency of the bow thruster is investigated. The response of the tanker is shown below :





In this case the offloading would not be interrupted as the DP target radius is maintained in spite of a significant drift to starboard.

CONCLUSION

The paper shows how a DP module can be integrated in a classical station-keeping and mooring model. Several points can be highlighted:

- The DP module is open, not a black box. The user has control of the model, this is particularly useful for verification of operational feasibility or DP design.
- Both capability plot and full time domain simulations are available with the same allocation model. It provides useful capability plots even for complex configurations including directional or azimuth thrusters, as well as screw-rudders.
- All the elements of the mooring and station-keeping model can be integrated in the DP model, therefore multi-structures cases can be assessed.

The calculations presented have allowed more interest in tandem offloading with a DP tanker rather than a tanker and tug system. They can pinpoint the necessity for redundancies in the DP system through the failure mode analysis or the extreme environmental cases analysis e.g. squall wind.

ACKNOWLEDGEMENT

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REFERENCES

Lewis, E. V. “Principles of Naval Architecture” volume III, Motion in waves and controllability, SNAME publication, 1988

Fossen, T.I. “Guidance and control of ocean vehicles”, Ed J. Whiley & sons, 1994

“Mooring Equipment Guidelines”, OCIMF, Ed. Witheby & Co. Ltd, 1997

“Technical Report Specification for DP Capability Plots”, IMCA, 2000

“Recommended Practice for Design and Analysis of Stationkeeping Systems for Floating Structures”, API