DYNAMIC POSITIONING CONFERENCE
September 28-30, 2004

Design and Control System

Wave Feed Forward DP and the Effect on Shuttle Tanker Operation

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Introduction

From 2000 through 2003 a Joint Industry Project (DP-JIP) was carried out, developing technology to improve dynamic positioning control by using wave drift force feed forward. It could be demonstrated from model tests and computational analysis that better positioning in harsh sea conditions can be achieved for the same or somewhat less power use.

In the present paper the impact of such an improvement on the actual operation of a shuttle tanker is investigated. The target case is the shuttle tanker operation on the Schiehallion Field, West of the Shetland Islands. The harsh weather and severe wave conditions in the area influence the regularity of the operation, especially in winter.

DP time domain simulations for a shuttle tanker in offloading mode have been carried out to assess the limiting conditions for safe operation. Two cases are considered: with wave feed forward and without (the conventional approach). The latter is compared with the actually used criteria. New criteria that would be applicable for the improved DP system have been assessed.
With these criteria, Monte Carlo type simulations were carried out using the program Safetrans (Ref 1). In this program offshore operations can be simulated as a series of tasks with given criteria and criticality. The Monte Carlo approach uses a Captain's Decision Mimic to decide on basis of weather forecast and actual conditions whether a next task can be started or continued or has to be postponed.

The simulations of offshore operations with DP vessels have shown the suitability of the method to investigate the economic benefit of system modifications, e.g. aimed to extend operational limits and/or to save fuel.

Wave feed forward Control

The estimation of wave drift forces, which cannot be directly measured, has to make use of physical relations between observables and these second order forces. It has been found from hydrodynamic research that the relative water motion at the bow, stern and sides of the ship is a good observable: it is a measurement with a good signal to noise ratio and it contains the physical information required to estimate the wave drift forces in various ways.

In the DP-JIP, this knowledge has been used to develop a robust wave feed forward method. DPMaster, the DP control and simulation program of MARIN has been extended with the capability to apply wave feed forward. A short introduction into wave feed forward and the program's validation as to that aspect is presented in the following.

DP Control

The external forces acting on a dynamically positioning vessel at sea are caused by:

- current
- waves
- wind
- thrusters
- hydrodynamic reaction forces

For some applications, e.g. DP assisted moored FPSO's and pipe laying vessels, additional external forces exist. These are not considered here but can be treated in a similar way.

When the ship stays on the same position the sum of all forces equals 0. So, the basic assumption is:

$$\overline{F_{thr}} = -\{\overline{F_{win}} + \overline{F_{wav}} + \overline{F_{cur}} + \overline{F_{reac}}\} \qquad (1)$$

In conventional DP control systems the current and wave forces (F_{cur} and F_{wav}) are not known. The required thruster force (F_{thr}) is known from the allocation algorithm and the wind force (F_{win}) can be estimated from the measured wind speed and direction (Wind Feed Forward). Therefore F_{cur} and F_{wav} are estimated jointly in the Kalman Filter as the so-called 'rest force':

$$\overline{F_{wav} + F_{cur}} = -\{\overline{F_{thr}} + \overline{F_{reac}} + \overline{F_{win}}\} \qquad (2)$$

The present wave drift force estimator gives a real time estimate of the quite strongly varying external force F_{wav}. Hence, the Kalman Filter only has to estimate the current force, which is very slowly varying and thus easier and more accurate to achieve:

$$\overline{F_{cur}} = -\{\overline{F_{wav}} + \overline{F_{thr}} + \overline{F_{reac}} + \overline{F_{win}}\} \qquad (3)$$

In the Feed Forward DP, the wave drift force estimate is used directly in the PID feed back loop by adding the forces F_x, F_y and M_z to the required positioning forces from the PID controller, see Fig .

Wave Feed Forward: the Real Time Environmental Force Estimator (RTEFE)

Two methods are used for the estimation process of the wave drift forces in real time. The basic assumption for both methods is that:

- The wave drift forces are dominated by the relative motion contribution
- The wave drift forces are in phase with the envelope of the wave groups

Hence, the wave drift forces are quantified through analysis of the relative motions along the hull. The first mentioned method is described by Pinkster (2) and requires many measurement locations around the hull of the vessel. The second approach is derived from the notion that a good estimate of the wave drift forces can be made if the wave direction with respect to the vessel is known. The method requires only three measurement locations on the bow and shoulders of the vessel (assuming that the vessel heading under DP will be with the bow into the waves). The method to estimate the dominant wave direction is first described by Aalbers and Nienhuis (3).

Method 1. Using full integration along the waterline.

The wave drift force is estimated by numerical integration of the low pass filtered pressure from the relative motion squared along the waterline:

$$-\frac{1}{2} r g \oint_{WL} S_r^{\,2}(x)\cdot n\cdot dx \approx F^{(2)}(t, a_{rel}) * C_f \qquad (4)$$

in which C_f is a correction factor to tune the magnitude of the total drift forces to that of the waterline integrated second order pressures.

Method 2. Based on wave direction measurement and using drift force transfer functions.

Measurement probes for the relative water motion at the side of the ship are located at the bow and at the shoulder on Port and Starboard side. The sensor at the bow is used to measure the average period T_{zs} and the "envelope squared" $A_s^2(t)$ of the relative motion at the bow. The sensors at the shoulders are used to derive the wave direction $\alpha_r(t)$ on basis of the difference between windward side and lee side.

All these values: T_{zs}, $A_s^2(t)$ and $\alpha_r(t)$ are the result of averaging or low pass filtering to be applicable in the time scale of wave groups instead of individual waves.

The theoretical basis of method 2 is that with standard numerical tools (diffraction theory) the mean wave drift force acting on a vessel in a given wave spectrum (with unit wave height) can be calculated as a function of the average (zero upcrossing) wave period and the wave direction. Using the wave envelope squared as modulation function, the wave drift force on the vessel can be evaluated.

The method is described in detail by Aalbers, Tap and Pinkster in Ref. 4 and makes an estimate of the instantaneous wave drift force, using the measurement of the relative motion at the bow as follows:

$$F_j^{(2)}(t) = \bar{F}_j^{(2)}(t)\frac{\left[s_{BOW}^{\;2}\right]_{LP}}{\overline{\left[s_{BOW}^{\;2}\right]}_{LP}} \text{ with} \tag{5}$$

$$\bar{F}^{(2)}(t) = m_{0s}\,\bar{F}_*^{(2)}(T_{zus}, a_{rel})\text{, and} \tag{6}$$

$$\bar{F}_*^{(2)}(T_{zus}) = 2\int_0^\infty \frac{\bar{F}^{(2)}(w)}{S_a^{\;2}} S_s^*(w, T_{zus})\,dw \text{ which can be evaluated for } T_{zus} \text{ and } \alpha_{rel} \tag{7}$$

Herein was used that $S_s(\omega) = m_{0s} \,.\, S_s^*$, where S_s^* is a unit relative motion spectrum depending on T_z (of the wave) and α_{rel}.

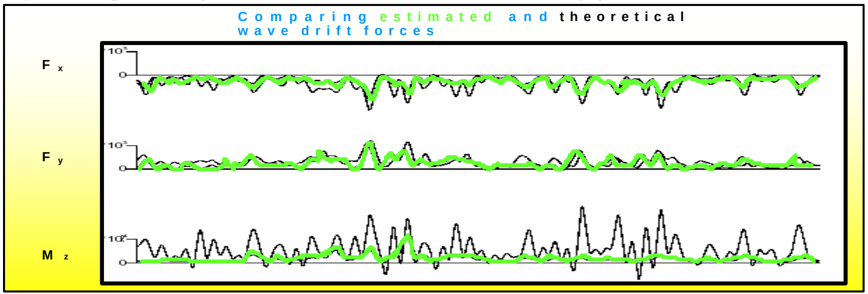
In Eq. (5) the low pass filtered value of the relative motions squared ($s_{bow}^2 |_{LP}$) is divided by its mean value (= $m_{0s(Actual)}$). Due to the difference in time period for which s_{bow}^2 is evaluated, the quotient is the 'modulator' giving the real time value of the varying drift force. The long term average (say 0.5 hour) of the 'modulator' is 1.

The subscript j = 1, 2 stands for the components in x and y direction with respect to the ship. For the yaw moment a simplified estimate is made. Thereto, for each combination of T_{zs} and α_r the wave drift moment is expressed in the point of application of F_y with respect to the midships, x_{Fy} , as follows:

$$M_z\,(t) \cong x_{Fy} \,.\, F_2 \tag{8}$$

The accuracy of the real time estimate of the wave drift forces is shown in Fig. 1. For the longitudinal (Fx) and transverse drift force (Fy) the agreement with the theoretical value is quite good, for the moment good accuracy was not achievable. But, further evaluation learns that the moment strongly fluctuates during passage of a wave group. This oscillation is of too high frequency for the ship inertia to follow, so that it is not relevant for DP control.

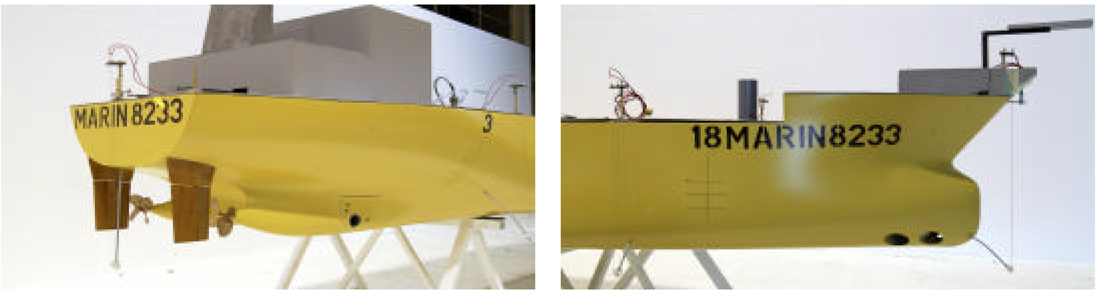
Fig. 1: Comparison of RTEFE result with theoretical wave drift forces



DP model test validation

The model tests were carried out using a model of the shuttle tanker at scale 1 to 42, equipped with two bow tunnels forward and twin propeller/rudders aft. In each shaft gondola a small tunnel truster was present, see Fig.2. The model DP system uses a Kalman filter and a PID feedback controller. It includes the RTEFE (Real Time Environmental Force Estimator- the software for wave drift force feed forward) as well as wind feed forward.

Fig.2: Stern and bow trhsuter arrangement on the shuttle tanker model



In Figures 3 and 4 is shown how the use of the RTEFE affects positioning. Positioning improvements in the order of 25% to 40% could be obtained, mainly because the large excursions were 'topped off'. This means that in harsh environment the vessel lies more stable and hence workability is improved.

To evaluate fuel saving, power consumption was estimated from the thrust measurement, using the relation P~ T $^{1.5}$. The following was concluded:

1. The test results showed a small power saving (upto 4%) for the higher sea states.
2. The improved positioning is worthwhile to use for increased efficiency of the vessel's operation, creating additional options to save fuel.

Fig. 3: Result of using RTEFE in a 4.5 m sea state (compared with conventional DP)

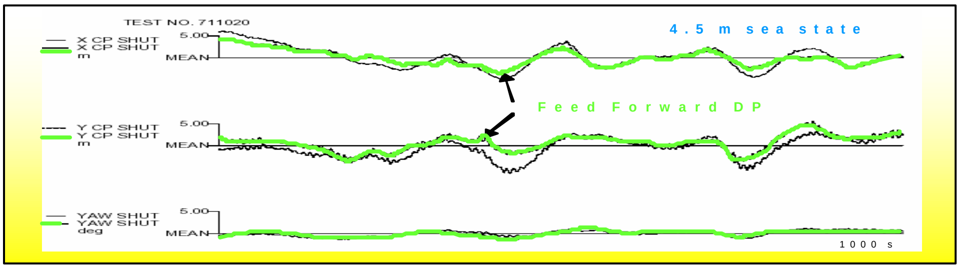
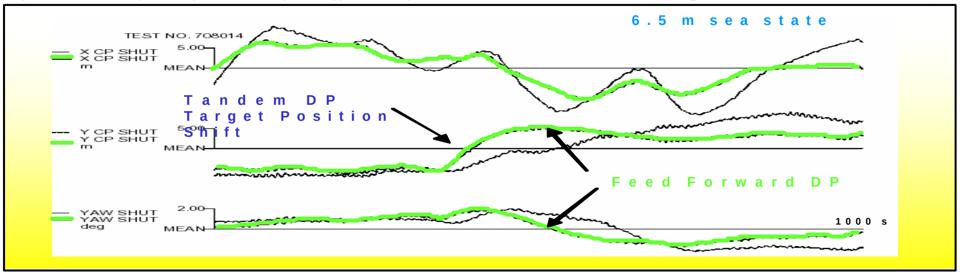


Fig.4: Result of using RTEFE for Offloading DP in a 6.5 m sea state (comp'd with conventional DP)

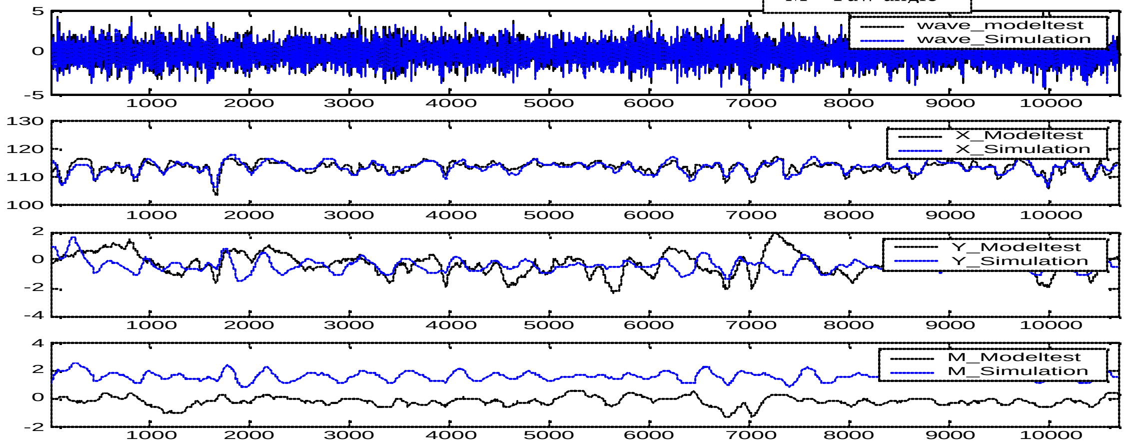


DP time domain simulation

Time domain simulations were carried out to validate the program DP-Master against the model tests. A typical example of the agreement is shown in Fig.5. Note: The simulations and tests are for collinear conditions. Heading setpoint in the test is 0 degr (bow into the waves) and for the simulation 1.5 degr. (a small offset for stability, which explains the differences in Y and M)

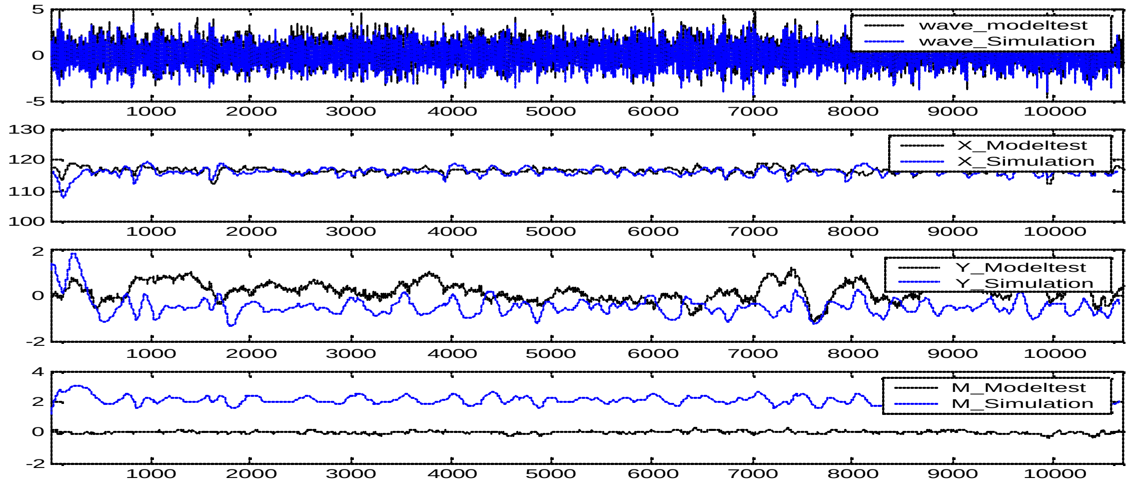
Fig.5: Comparison of DP model test with DP simulation

(Conventional DP)



M= Yaw angle

(RTEFE DP)



With the good correlation obtained, the simulation work was continued in tandem offloading mode, in which the FPSO stern motions were followed. To avoid that all FPSO motions are fed into the positioning system, a box size deadband is defined. This is an earth fixed box, nominaly 15 m by 15 m, of which the centre is updated if the FPSO stern goes out of its border. Its centre is the target position of the shuttle tanker, to which the bow control point has to keep a given distance. The shuttle tanker heading has a +/- 7.5 degree freedom with respect to that of the FPSO.

Results of DP simulations and tests

The results of the simulations and tests, comparing the DP capability with use of conventional (as is) DP control to that with use of the RTEFE are given in the tables and figures below.

In Table 1 the results are given for a 6.5 m sea state with 15 m/s wind, with the shuttle tanker in tandem offloading mode. Apparently, this is a limiting sea condition because the full scale operation was aborted. It may be concluded from the Y-motions and bow tunnel actions that the excursions trying to follow the FPSO were too large. In Fig. 4 on the previous page a part of the time trace from the model tests is given.

Table 1: Comparison of DP model test with full scale logging results

Sea State 4 Loading 19 feb 2002 condition			
Signals (Sig = St. Dev.^{n})	Full Scale measurement	Model test Conv.	 RTEFE
Sig_Rm	5.89	5.76	3.11
Sig_Psi	2.76	2.07	1.4
Sig_Y	10.72	6.22	4.69
Sig_BTs Corr	342	126	107
Mean BTs	-44	-24	-38
	(Aborted)		

From the model test results, the conclusion was drawn that the offloading operation might have been feasible, assuming the use of the default box size. In the DP simulations the conditions were varied around this sea state, in order to see if the use of the RTEFE would really make this sea state feasible for operation.
In Table 2 the results are shown for full DP with the shuttle tanker alone.

Table 2: Comparison of DP simulation with and without RTEFE (Wave Feed Forward)

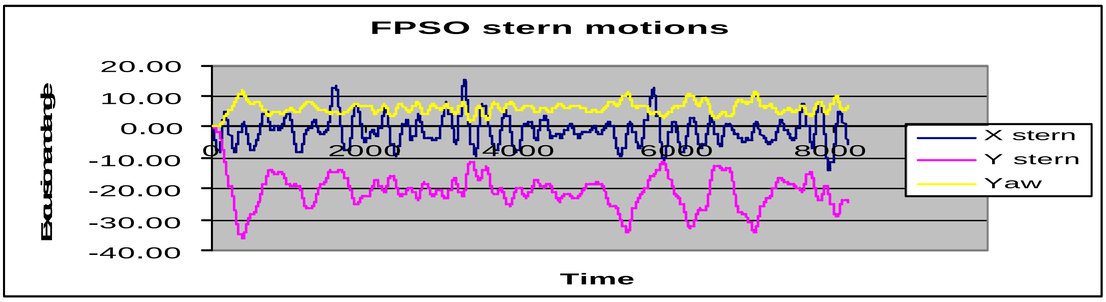
DP Shuttle tanker alone								
Ballast	Conv 6.5 // 18	RTEFE 6.5 // 18	Conv 6.5 < 18	RTEFE 6.5 < 18	Conv 6.5 // 30	RTEFE 6.5 // 30	Conv 7.0 // 18	RTEFE 7.0 // 18
Sig_X		1.96	2.12	1.4		1.88		1.56
Sig_Y		3.04	0.51	0.57		0.49		1.67
Sig_Psi		1.21	0.13	0.19		0.18		0.95
Heading S.P.		6.5	6	6		5		6.5
	Drift Off				Drift Off		Drift Off	
Sig_BTs		95	80	78		66		81
Mean BTs		-256	-84	-71		-236		-232
Sig_MP		379	322	325		559		314
Mean MP		580	532	530		811		523

// Parallel sea and wind
> Wind at 20 deg angle, cur. perp.
6.5 Significant wave height
18 Wind speed 1 hr mean
Heading setpoint w.r.t waves (deg)

DP shuttle tanker alone								
Loaded	Conv 6.5 // 18	RTEFE 6.5 // 18	Conv 6.5 // 30	RTEFE 6.5 // 30	Conv 7.0 // 18	RTEFE 7.0 // 18	Conv 7.0 // 18	RTEFE 7.0 // 18
Sig_X		1.51		2	Drift Off	2.12	Drift Off	2.1
Sig_Y		1.99		0.41		0.68		0.47
Sig_Psi		1.05		0.19		0.27		n.a.
Heading S.P.		6.5		5		5		weathervaning
	Drift Off		Drift Off					
Sig_BTs		133		79		90		81
Mean BTs		-231		-208		-224		-104
Sig_MP		412		570		399		340
Mean MP		592		825		669		677

Also a number of simulations were carried out in tandem DP mode. Thereto the Schiehallion FPSO stern motions were first computed. In Fig. 6the results of such simulation are given. The heading and stern surge (X) and sway (Y) motions, and an input value for the separation distance (60m) are used by the tandem DP system to compute the target position and heading of the Shuttle tanker.
The box size was set at 8 m surge and 6 m sway 'deadband' which are the mostly used values in the actual operation.

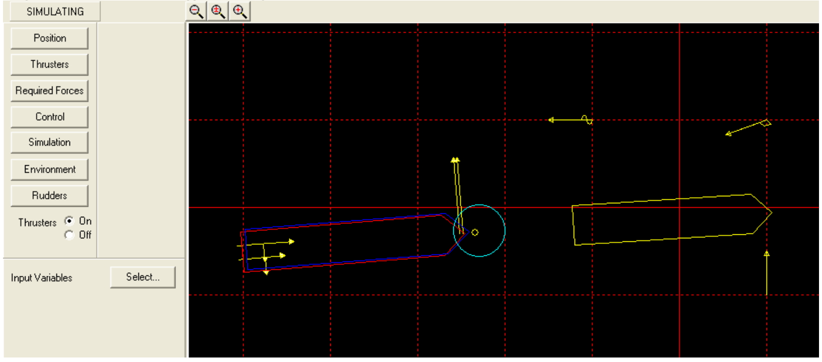
Fig. 6: Calculated FPSO stern motion



In Table 3 the results of the Tandem DP simulations are given for a 6.5 m sea, non-collinear (i.e. 18 m/s wind at 20 deg, perpendicular current), for which the FPSO stern motions of Figure 6 apply. In Figure 7 a snapshot of the tandem simulation is shown.

Additional simulations were carried out in a non-collinear sea with Hs= 6.5 m and 30 m/s wind. It appears that the average heading that the FPSO takes is quite optimum for the shuttle tanker as well, so that the simulations show a shuttle tanker holding position even upto a 7 m sea.

Fig.7: DP tandem offloading simulation in 6.5 m sea with 40 kn wind and 0.75 kn cross current



Thrusters ● On ○ Off

Table 3: Statistics of tandem DP simulation

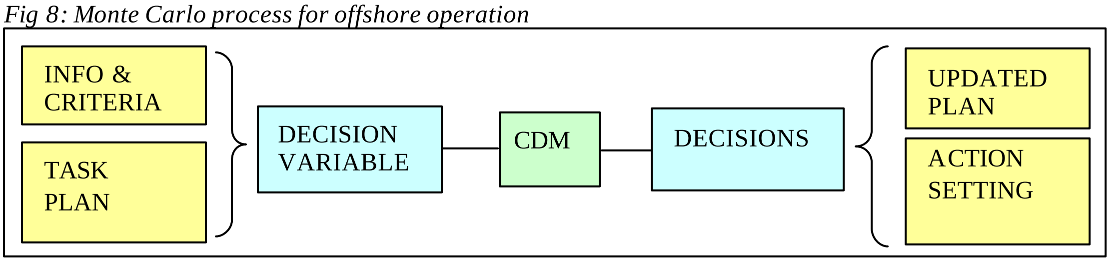
DP Shuttle tanker tandem offloading						
Ballast	Conv 6.5 < 18	RTEFE 6.5 < 18	Conv 6.5 < 30	RTEFE 6.5 < 30	Conv 7.0 < 30	RTEFE 7.0 < 30
Sig_X	3.29	3.22	3.52	3.33	3.6	3.61
Sig_Y	11.3	11.3	11.4	11.2	11.2	11.4
Sig_Psi	1.92	1.9	1.91	1.88	1.88	1.99
Heading S.P.	From FPSO		From FPSO		From FPSO	
Sig_BTs	152	152	162	158	170	170
Mean BTs	-49	-49	84	86	72	68
Sig_MP	450	452	552	564	608	609
Mean MP	540	539	818	817	875	876
Note: FPSO stern position updates dictate the shuttle tanker excursions and thruster use						

From these results is concluded that DP in tandem configuration, with the shuttle tanker following the heading and stern of the FPSO is less severe than keeping position in a sea state with a heading set point somewhat off the optimum. Therefore the simulations with the shuttle tanker alone are considered decisive in setting the offloading criteria.

Offshore operations simulations using Safetrans

The SafeTrans software system (see Ref.1) allows to carry out Monte Carlo type simulations of offshore operations. The operation is defined as a series of tasks with given criteria and criticality. The simulator uses the Captain's Decision Mimic (CDM) to decide on basis of weather forecast and actual conditions whether a task can be started or continued or has to be postponed. The simulation does not include a DP simulation, so that these were carried out sparately to provide the operational criteria for the CDM.

Fig 8: Monte Carlo process for offshore operation



For the application to the DP shuttle tanker at the Schiehallion Field the offshore operation comprised the following tasks, being a close representation of the actual operation at the field.

1. *Approach manoeuvre&connect: 3 hr critical task of preparation of loading operation*
2. *Loading first phase: 6 hr critical task with Shuttle tanker in light draft*
3. *Loading second phase: 6 hr critical task of Shuttle tanker in intermediate draft*
4. *Wait and de-ballast: 60 hr task*
5. *Approach manoeuvre&connect: 3 hr critical task of preparation of loading operation*
6. *Loading third phase: 6 hour critical task with Shuttle tanker in intermediate draft*
7. *Loading fourth phase: 6 hour critical task with Shuttle tanker in deep draft*

A critical task is a task which may not be interrupted, so the decision mimic decides to start such a task only if it can also be completed. Other operations may be interrupted if weather deteriorates.
The 10 hr voyage from Sullom Voe to the Schiehallion Field is not included in the operation simulation. Regularity of the operation requires a 6 day departure scheme from Sullom Voe.

Criteria development

The actual and new criteria for the offloading operation have been established on basis of the present operational experience and safety regime. The presently used criteria are listed below:

1. Approach criterion Hs 0 to 4.5m; W 0-40k; FPSO +/- 30deg. At the final stage of the approach prior to mooring we request the FPSO to have her heading control on when yaw is +/- 10deg.
2. Load criterion Hs 0-6m; W 0-60k; FPSO yaw +/- 10deg.
3. The 'deadband box' referred to is generally 8 x 6m. This is adjusted depending on sway and surge movements.
4. The maximum time for FPSO normally goes without loading is 2.5days +/- 6h. So from arrival 10 nmz to from one export to the next can be about 4d 15h.
5. Confirm FPSO stern thruster bollard pull are 2 x 25tonne and normal practice is to use these each offtake.
Master

On basis of the results of the computations, the criteria for the operations analysis were set as in Table 4. The criteria are *either-or* criteria, not *and-and* criteria.

Table 4: Criteria for DP offloading operation in MonteCarlo simulation

Task No.	Criteria as is				Criteria with RTEFE			
(see list above)	Hs	Vw	F_{BT}	F_X	Hs	Vw	F_{BT}	F_X
	(m)	(m/s)	(kN)	(kN)	(m)	(m/s)	(kN)	(kN)
1	4.5	20	340	450	4.5	20	340	550
2	6.0	30	340	550	6.5	30	340	650
3	6.0	30	340	550	6.5	30	340	650
4	No limits				No limits			
5	4.5	20	340	450	4.5	20	340	550
6	6.0	30	340	550	6.5	30	340	650
7	6.0	30	340	550	6.5	30	340	650

The criterion F_{BT} is derived from the bow tunnel capacity, allowing a 25% dynamic load variation to compensate for the low frequency part of the wave drift moment. The F_X criterion is the operational limit with respect to the wave drift forces, because these depend not only on the wave height, but also on wave period. Note that in the Offshore Operation simulations the vessel heading is kept into the wind.

Results

In Table 5 the results are given of the simulations in a historic weather database (1995 through 1998) with the SafeTrans Monte Carlo process. In total 250 operations were simulated in random distributed starting times, giving an average interval for a loading cycle of 6 days. Since the weather database is representative for the climate and persistence of the weather patterns, the random starting times (instead of incremental) make the results reasonably applicable to future planning.

Table 5: Results of DP offloading operation simulations with use f various criteria settings

REVIEW OF 250 SIMULATION RESULTS OFFLOADING OPERATION SCHIEHALLION FIELD							
	CRITERIA:	Actual	RTEFE	RTEFE++	Actual+	RTEFE+	+ means that the connect condition has been increased to Hs=5 m instead of Hs=4.5 m ++ means that the loading criterion has been increased to 40 m/s wind instead of 30m/s
RESULT							
90 -120 hrs	(no loss)	184	189	190	199	207	
121-150 hrs	(1 day loss)	23	19	19	15	14	
151-300 hrs	(1 cycle loss)	31	30	29	23	21	
> 301 hr	See Note	12	12	12	9	8	

Note: Two bad weather periods, i.e. 12-26 feb 1998 and 10-29 dec 1997 caused long non-workable periods

Since the whole loading cycle has some spare time, conclusion of the offloading within 120 hours is considered 'on time'. Completion in 121-150 hrs causes one day of production loss and so on. In the historic database there were two periods with prolonged bad weather with very little opportunity to do the connect operation.

The results show that using the improved positioning capabilities of the RTEFE leads to about 3% greater regularity and enables 10 to 16 days extra production in a 4 year period. It has to be noted that this improvement is largely obtained in the winter half year.
Although worthwhile in terms of oil revenue, this is still a relatively small effect because the connect condition is the same. It may be assumed that the connect condition can be defined a bit sharper if the vessel has (together with the RTEFE) a sea state measurement available. In such case the uncertainty in

the sea state assessment can be reduced and a slightly higher connect condition can be defined (RTEFE+). This leads to 10% greater regularity and about 70 extra production days in 4 years, again largely obtained in the winter half year.
Comparing the results of the simulations with the increased connect criterion only (actual+ and RTEFE+) shows about 4% increase in reguarity and 20-30 days extra production. This is better than in the original comparison because the connect condition is less dominant for the success of the operation.

Conclusions

The Real Time Environmental Force Estimator (RTEFE) provides wave drift force feed forward to DP control and sea state decision support to the DP operator. In the present paper it has been applied to a shuttle tanker operation in the West of Shetlands area. In the numerical study was shown that the regularity of the shuttle tanker operation can be improved by 3-4% if the connect condition is kept the same. If the sea state information from decision support may be used to decrease the uncertainty margin in the connect condition, a combined improvement upto 10% could be obtained. It has to be noted that the improvement is largely obtained in winter season.

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Ref. 4: **An Application of Dynamic Positioning Control using Wave feed Forward.** A.B. Aalbers, R.F. Tap and J.A. Pinkster, Int. Journal of Robust and Nonlinear Control, Vol 11, pp 1207-1237, 2001.