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DYNAMIC POSITIONING CONFERENCE
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Thrusters

Thrust Degradation in DP Operations

DP Model Test of an Aframaz Shuttle Tanker - Methods, Results, Operations

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Abstract

In the Spring of 2006, Dynamic Positioning (DP) model tests were conducted at Marintek's Ocean Basin Laboratory in Trondheim. The purpose was to study thrust degradation effects in DP operations and DP performance of an Aframax shuttle tanker operating in rough environmental conditions in the North Sea. The shuttle tanker was equipped according to the International Maritime Organization (IMO) DP Class 2.

The DP model tests were conducted for:

- ballasted draught
- loaded draught
- single-screw configuration
- twin-screw configuration

Results from the DP performance tests are presented.

Thrust degradation model tests were conducted for:

- tunnel thrusters
- azimuth thrusters
- main propellers with rudders

Results from the thrust degradation measurements are presented.

Software (SW) algorithms for thrust degradation estimates have been developed and incorporated into the DP capability analysis program StatCap. An example of how the calculations compare to the measured thrust degradations is presented.

The project was a joint effort between Teekay Corporation, Kongsberg Maritime and Marintek.

Brief company descriptions

Teekay Corporation

Teekay Corporation transports more than 10 percent of the world's seaborne oil, has expanded into the liquefied natural gas shipping sector and is also growing its operation in offshore production, storage and transportation. With a fleet of more than 190 vessel, offices in 17 countries and 6,300 seagoing and shore-based employees, Teekay provides a comprehensive set of marine services to the world's leading oil and gas companies, helping them seamlessly link their upstream energy production to their downstream processing operations. Teekay's reputation for safety, quality and innovation has earned us a position with our customers as the The Marine Midstream Company.

For more information, please visit us at *www.teekay.com*

Kongsberg Maritime

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Marintek

MARINTEK is a research company in the SINTEF Group, delivering marine technology research and development services. Our clients include leading national and international companies and authorities. MARINTEK operates a subsidiary in Houston, serving the oil and gas industry - MARINTEK (USA), Inc.

MARINTEK performs research and development for industry and public-sector bodies involved in marine activities. The company operates in an international market, developing new technologies in the fields of floating petroleum production, subsea pipelines for oil and gas transportation, vessel development, the shipbuilding and marine equipment industries, shipping and logistics.

MARINTEK, together with the Department of Marine Technology at the Norwegian University of science and Technology (NTNU), constitutes the Marine Technology Centre in Trondheim. The collaboration between the University and MARINTEK significantly enhances quality of commercial projects and teaching programs.

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Introduction

Teekay is the world's largest owner and operator of offshore loading DP shuttle tankers. Today, Teekay operates 41 shuttle tankers around the world. The fleet is expected to grow in the years to come, and four Aframax DP Class 2 (DP2) shuttle tankers are currently under construction for Teekay ownership.

Teekay has been the market leader for offshore loading, using DP controlled shuttle tankers, since the pioneer project for offshore loading, at the Statfjord field in the North Sea, in 1982.

The technology and operational procedures for offshore loading have been improved continuously over the years. The main drivers have always been to maintain the highest standards of safety for crew, environment and assets, and to improve the operational regularity and efficiency of the vessels.

Use of DP controlled shuttle tankers for offshore loading is recognized as a safe and reliable way of loading and transporting oil. One of the key success factors is that Teekay has always worked closely with customers and vendors to improve the technology further. The subject and result of this study is another example of improvement through cooperation.

Over the years different designs of propulsion systems for DP2 shuttle tankers have been developed. In general, a DP2 shuttle tanker could be a twin screw vessel equipped with tunnel thrusters, or with tunnel and azimuth thrusters in combination. A DP2 shuttle tanker might also be a single screw vessel equipped with azimuth thrusters, or tunnel and azimuth thrusters in combination. See examples in Figure 1.

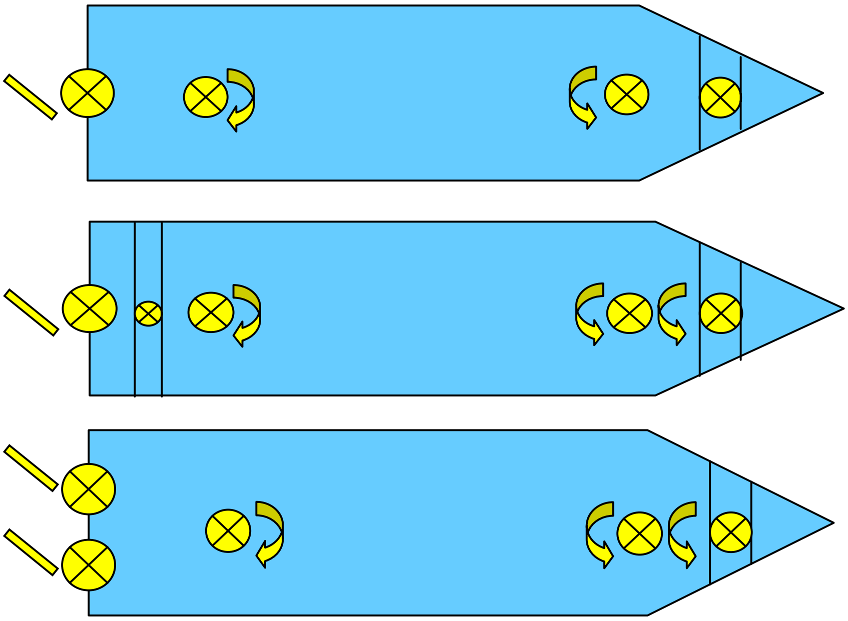

Figure 1 **Possible thruster configurations for DP2 Shuttle Tankers.**
Propulsion could be based on twin or single main propulsion in combination with tunnel and azimuth thrusters.

A DP shuttle tanker can experience significant environmental forces in harsh weather conditions, requiring large thruster forces to maintain its position. The station keeping ability of a single screw DP2 vessel relies on azimuth thrusters for longitudinal back up propulsion-force in case of failure of the main engine, or main propeller. Large retractable azimuth thrusters, over 2000 kW, have been commercially available since the late 90's.

Experience from operation of DP shuttle tankers in harsh weather conditions have shown indications of lower margins on the vessel's station keeping performance than calculated by theoretical analysis such as DP capability plots.

Also, lacks of industrial practices on how thrust loss or propulsion degradation effects are incorporated in DP capability analysis in general have been identified.

As a result of these observations Teekay together with Kongsberg Maritime and Marintek, performed an extensive DP model test for an IMO DP2 Aframax shuttle tanker at Marintek's laboratory in Trondheim in 2006. The study was carried out in an environment with conditions similar to the Haltenbanken area in the Norwegian Sea.

The objectives for the study were:

- To identify and measure thrust loss and propulsion degradation effects for tunnel- and azimuth thrusters as well as main propellers (single and twin screw) for the sea state corresponding to the tandem offshore loading design criterion.

- To document the station keeping performance by DP model test for an IMO DP2 Aframax shuttle tanker for the sea state corresponding to the tandem offshore loading design criterion.

The most commonly used thrust devices for DP are rotatable (azimuth) thrusters, tunnel thrusters and main propellers with rudders. Generally, the characteristics of these devices are known for the open-water situation, i.e. without the presence of the hull, and often limited to the bollard condition. When installed on a vessel, however, their characteristics are affected by:

- thruster-hull interactions
- thruster-thruster interactions
- current effects
- wave effects
- ship motions
- ventilation

These degradation effects have operational consequences as they can have a major impact on the station-keeping capability of the vessel and contribute to thruster wear-and-tear. It is therefore very important to consider these effects together with the environmental forces, both in the design phase and the operation of the vessel.

Figure 2 **DP Offshore Loading in Marintek's Ocean Basin Laboratory. The Teekay model is controlled by an "off the shelf" Kongsberg DP system.**

Figure 3 **DP Offshore Loading at Aasgard A field in the North Sea.**

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Environmental design criteria

The DP requirements for design of a shuttle tanker could be divided in two main groups; Redundancy requirements and Operational requirements.

Redundancy requirements define the requirements for system functions and system redundancy (e.g. number and type of thrusters). Redundancy requirements are defined by Class (e.g. DNV) and by International Regulations (e.g. IMO).

Operational requirements define the requirements for DP capability, or station keeping performance, of the vessel (e.g. size or capacity of thrusters). To evaluate a vessels DP performance the environmental design criteria has to be defined. Environmental limiting conditions for offshore loading are normally contracted by the vessel owner and the field operator. Requirements are often limited to, and defined by, significant wave height, wind and current speed.

However, not only are the environmental forces defined by wave height, wind and current speed are of importance, but so is the wave energy defined by the wave spectrum parameters. The energy, shape and steepness of the wave spectrum vary from area to area. Hence, an appropriate wave spectrum must be selected for each particular area of operation. Important factors like water depth and topographical conditions need to be considered.

Variation in wave length, for a given sea state, influence the driving forces acting on the vessel. In general, short waves give higher drift forces than longer waves.

Loop current, well known from the Gulf of Mexico, directions of the environmental forces, and the coincidence of directions, are also of significant importance for the evaluation of total environmental forces acting on DP vessels.

For offshore loading connection and disconnection, the following environmental design conditions (see table 1), representative for the Halten area in the North Sea, were used in the model tests:

Connection:
Significant wave height [Hs] = 4.5 m
Wind speed [U10] = 31 knots
Current speed [Cv] = 1 knot
Wave spectrum peak period [Tp] = 11 sec.
Wave spectrum: JONSWAP – peak enhancement factor [γ] = 1.8

Disconnection:
Significant wave height [Hs] = 5.5 m
Wind speed [U10] = 38 knots
Current speed [Cv] = 1 knot
Wave spectrum peak period [Tp] = 12 sec.
Wave spectrum: JONSWAP – peak enhancement factor [γ] = 1.8

Table 1 Environmental design conditions.

All environmental forces were considered to be coincident in directions.

Thrust Loss Model Tests

The thrust losses of the different thruster and propeller units were measured in the large towing tank of Marintek. The tank has the dimensions L by B by H of 260m, 10.5m and 10m. A double flap wave maker positioned in one end of the tank produces both regular and irregular long-crested waves, in the opposite end of the tank a parabolic beach is mounted for wave damping. On the tank sides, wave dampers are mounted in the area where the tests were performed.

Model tests introduce several challenges in order to find reliable full scale variables, in the case of thrust losses, the following forces are important regarding the flow characteristics:

Force	Physical variable, Force/unit volume
Viscous Force	$\nu U/D^2$
Inertial Force	$\rho U^2/D$
Gravitational Force	Pg
Pressure Force, ideal (inviscid) fluid	$\rho U^2/D$
Pressure Force, compressible fluid	p/D
Surface Tension	σD
Elastic Force	$\epsilon_v E_v D^2$

Here U represents the speed, D is the characteristic length, ν is the kinematic viscosity, ρ is the density, p is pressure, σ represents the surface tension, g is the gravitational constant, ϵ_v is the relative elongation and E_v is the elasticity number of the fluid.

The important parameters and scaling laws in this case can be summarised as:

Parameter	Symbol	Definition	Force Ratio (Comments)
Scale Factor	Λ	D_{ship}/D_{model}	(General comparison ship – model)
Froude number	F_n	$U/gL^{1/2}$	Inertial Force/Gravitational Force
Reynolds number	R_n	UL/ν	Inertial Force/Viscous Force
Euler number	E_n	$\rho U^2/p$	Pressure Force/Inertial Force
Weber number	W_n	$U/(\sigma/\rho L)^{1/2}$	Inertial Force/Surface Tension
Strouhal number	S_t	Df_v/U	(Nondimensional vortex shedding frequency)
KeuleganCarpenter number	KC	V_0T/D	(Nondimensional amplitude in dynamic oscillation)

The different scaling parameters were considered when initiating the thruster loss test and the DP-test of the Aframax tanker. On one hand, a very large model was required in order to have model propellers as large as possible. On the other hand a large model is more exposed to wall effects and blockage effects than a small model. By compromise, the selected model scale for the 245 m long vessel was 25.52, giving a 10 m long model and azimuth propeller diameters of approximately 120 mm.

Figure 4 **Forebody of model showing two azimuth thrusters and marking of bow tunnel thruster position.**

Figure 5 **Aftbody of single screw hull showing azimuth thruster, stern tunnel thruster, main propeller and rudder.**

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Figure 6 **Aftbody of twin screw tanker where skegs, propellers and rudders can be seen. The aft azimuth thruster is located at centre line between the skegs.**

As shown in the pictures, both single-screw and twin-screw variants were tested, the aftbody alternatives (see Figure 5 and 6) were interchangeable with one forebody alternative (see Figure 4) . Both hull variants were tested in loaded and in ballasted conditions.

The thrust loss model tests comprised the following:

- Thruster- thruster interactions
- Thruster- hull interactions
- Thruster - rudder interaction
- Tunnel thruster losses
- Thrust degradation due to current
- Thrust degradation due to waves
- Thrust degradation due to ventilation

Thruster in the above overview also refers to main propeller units. See Reference 7 for more details on ventilation phenomena.

The single screw ship has the following basic particulars:

Length overall, Loa (m):	249
Length between perpendiculars, Lpp (m):	238
Breadth in waterline, Bwl (m)	44
Design waterline, Dwl, (m)	12.19
Volume displacement at Dwl, Δ (tonnes):	104366
Block Coefficient (CB):	0.807
Prismatic Coefficient (CP):	0.809
LCB relative to Lpp/2 (+forward) (m)	8.21

The single screw tanker was equipped by two azimuth thrusters in the forebody, one 108 m from midship, one 116m from midship, both thrusters were placed in ships' centreline and propeller centre was 2.65m below baseline. One azimuth thruster was positioned in the aftbody, 80 m aft of midship, in centreline and 2.65 m below the baseline. The azimuth thrusters had a nominal force of 2,2 MW, a propeller diameter of 3.0 m, however the force range tested varied from 1.5 MW to 3.0 MW. A tunnel thruster with propeller diameter of 2.0 m was positioned in the skeg 15 m forward of aft perpendicular and with propeller centre 2.0 m above baseline. The main propeller had a diameter of 7.1 m, power of 13.5 MW in combination with a Schilling high lift rudder (see Figure 7).

The twin screw ship has the following particulars:

Length overall, Loa (m):	249
Length between perpendiculars, Lpp (m):	238
Breadth in waterline, Bwl (m)	44
Design waterline, Dwl, (m)	12.19
Volume displacement at Dwl, Δ (tonnes):	108750
Block Coefficient (CB):	0.831
Prismatic Coefficient (CP):	0.834
LCB relative to Lpp/2 (+forward) (m)	6.45

The twin screw tanker was equipped by two azimuth thrusters in the forebody, one 108 m from midship, one 116m from midship, both thrusters were placed in ships' centreline and propeller centre was 2.65m below baseline. One azimuth thruster was positioned in the aftbody, 80 m aft of midship, in centreline and 2.65 m below the baseline. The azimuth thrusters had a nominal force of 2,2 MW, a propeller diameter of 3.0 m, however the force range tested varied from 1.5 MW to 3.0 MW. The main propellers have a diameter of 5.45 m, the power on each propeller is 6.67 MW, and behind each propeller a Schilling high lift rudder is mounted (see Figure 7).

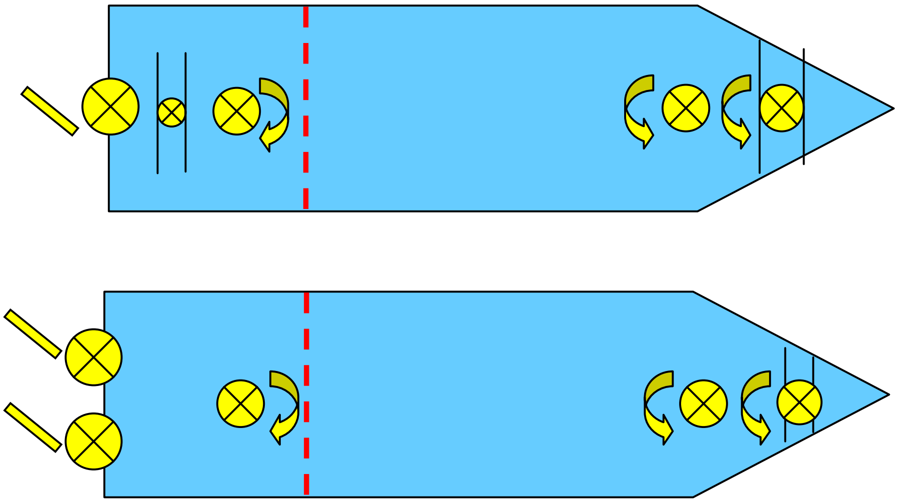

Figure 7 **Thruster configurations for vessel model - single and twin main propulsion. Two aftbodies, interchangeable forebody.**

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Altogether, the instrumentation and measurements performed under the thrust loss measurements consisted of 74 different channels. The measurements can be summarised as follows:

- Measurements of 6 degrees of freedom motions of ship model
- X-, Y- forces at bow and stern of the tanker model giving local and global longitudinal and transverse forces and yaw moments, angle and magnitude of resultant force
- X-, Y- forces of the azimuth thrusters, thrust, torque, rps, power, angle of attack, resultant force and corresponding angle, yaw moment on ship model
- Rate of revolutions (rps), torque and total force of stern tunnel thruster
- Thrust, torque, rps and power of the propeller(s)
- Angle and total force from rudder(s)
- Relative wave motions at 3 positions, forward azimuth, aft azimuth and stern tunnel thrusters
- Incoming wave
- Vertical accelerations at 3 positions, FP, LPP/2 and AP

During tests, the tanker model was suspended in a soft spring system and the spring characteristics were carefully selected to be well away from critical response periods.

In general, a right-handed co-ordinate system is used to define directions, motions, velocities, accelerations forces and moments. Performing the tests, the origin was defined to be at Lpp/2 and at ships centreline and at the design waterline, that is 12.19 m above baseline (see figure 8 below).

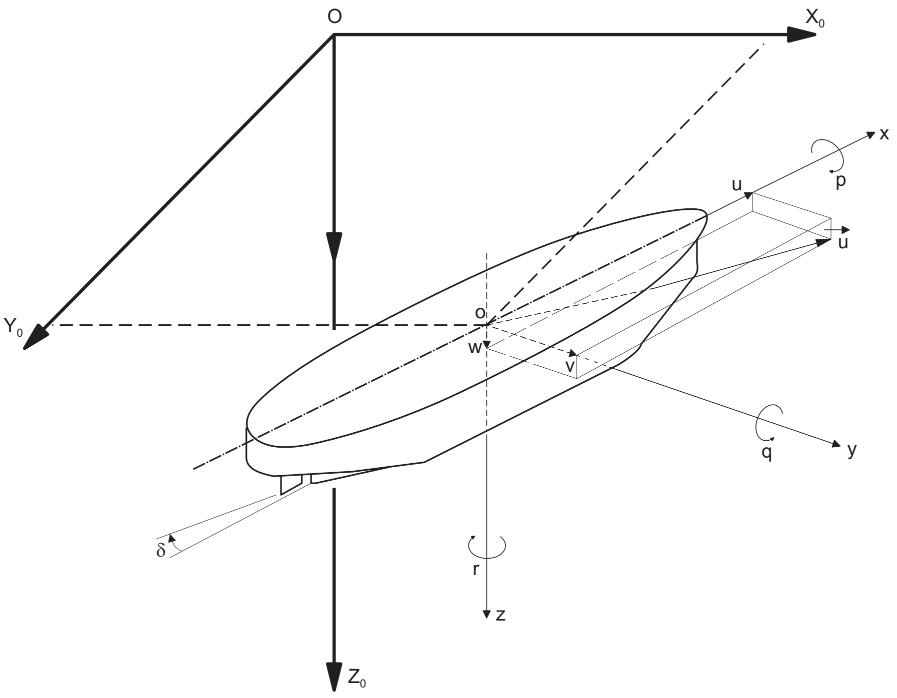

Figure 8 **Coordinate System.**

Thrusters and propellers were calibrated in a jig prior to tests in order to keep control of mechanical losses in drive systems. Open water characteristics were measured. For the main propeller(s) and the stern tunnel thruster both forward and backward modes were measured. For the azimuth thrusters only the forward propeller mode was measured (non reversible propeller direction for azimuth thrusters).

The idea behind the extensive test programme performed was to investigate all loss effects that may occur when operating different thruster units in calm water, in current, in waves and in combinations of current and waves. Interactions between thrusters or between group of thrusters, interactions between thruster(s) and hull, and loss effects from thrusters operating in a wave field, ventilation and out of water phenomena were looked into.

In principle, all the different systems interact with each other, with ships hull and environment. However, the bow units have relatively small influence on the stern units and vice versa. In this respect, the interaction between the forward azimuth thrusters give high loss factors and the interactions between stern azimuth thruster, stern tunnel thruster and main propeller(s)/rudder(s) are also considerable.

DP Model Tests

The DP model tests were performed in Marintek's Ocean Basin, a basin with the dimensions L by B by H of 80 m, 50m and 10 m. The basin is equipped with an adjustable bottom and a current generating system that circulate the water around the adjustable bottom. For the actual tests the water depth in model scale was 5 meter, corresponding to a full scale water depth of 128 m. The basin is equipped with a long-crested double flap wave generator on one side, (50 m long), a multi-flap wave generator of 80 m length on one side (long-crested and short-crested waves), and wind batteries. The wave generators can produce regular or irregular waves. The wind batteries can produce constant wind speed or irregular wind spectra. The two other sides of the basin have large parabolic beaches.

In the actual DP tests, irregular wave spectra, constant wind and constant current were used in a colinear way consistent with the present criteria for connection and disconnection for offshore loading.

The twin-screw shuttle tanker was tested in the Ocean Basin, however some tests were also performed in order to simulate the behaviour of a single-screw tanker. In addition to the instrumentation used in the tests of thrust losses, some extra instrumentation was used in the DP-tests:

- Wind sensor positioned in the forebody (on the BLS)
- "Nypos" position control system
- Gyro compass

The "Nypos" position control system used in the ocean basin gives the global coordinates of the tanker in the same way as the full scale system, thus the bow-to-base measurements are identical in model and full scale. The response time of all actuators and units were set and scaled according to real full scale values.

The LabBridge-system equalise data between model scale and full scale, and provide and receive data via a standardized National Marine Electronics Association (NMEA) protocol. It is always assumed that the control system operates in full-scale, but accelerated in time due to Froude scaling where the time acceleration factor is equal to the square root of the model scale. The time difference between model and full scale is taken care of by a powerful CPU. The NEMO system handles the low-level sensor and actuator communication. It receives set points and commands from LabBridge, and sends sensor feedback to LabBridge. The LabBridge application has been realized using existing software from MARINTEK's vessel simulator and library of associated tools.

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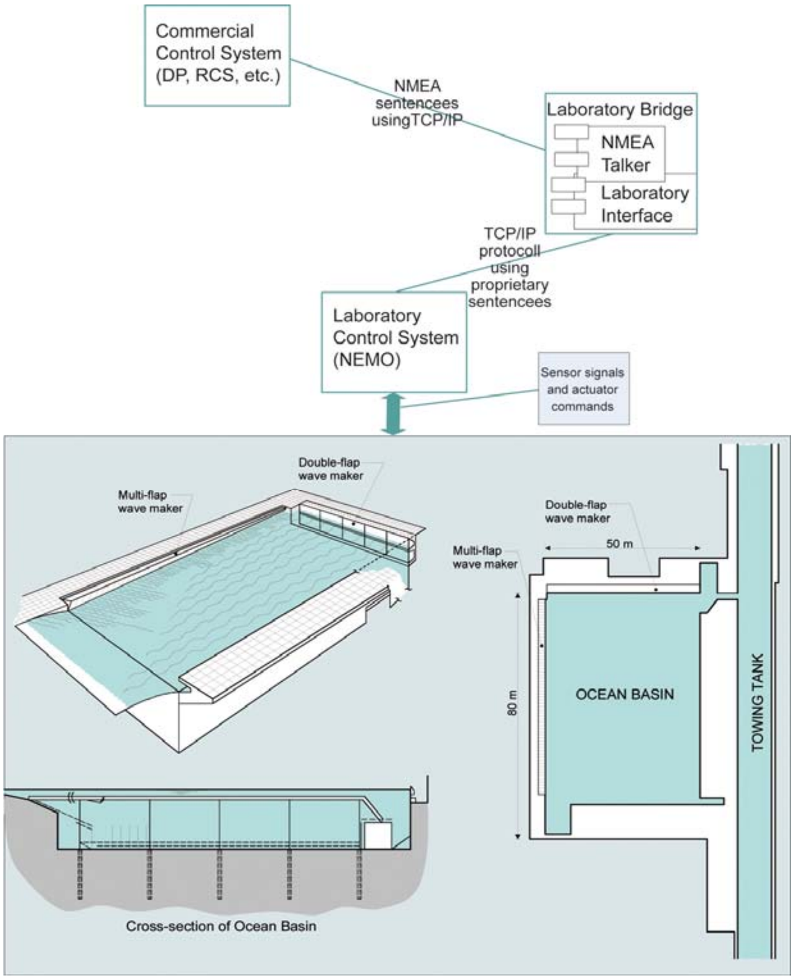

Figure 9 **The figure shows the logical flow of data between a commercial control system, LabBridge and the laboratory control and data acquisition system (NEMO).**

Teekay requested that the DP system to be used in the model tests should be identical to the systems installed on their “real-world” shuttle tankers. Prior to the tests, a standard Kongsberg DP system was taken “off-the-shelf”, configured and parameterized according to normal procedures. This means that all the standard sensors (compass, position measurements, motion references and wind sensor) and actuators (thrusters, main propellers and rudders) were interfaced, and that all the vessel size dependent quantities were entered into the system in full scale. From the viewpoint of the DP system it was in control of a “real” ship. All signals between the DP and the basin equipment were exchanged by means of a NMEA protocol on the network. All sensor and measured actuator signals from the laboratory system were fed to the Kongsberg DP system which returned the commanded actuator signals.

An important feature of this system is that the commercial company providing the DP software does not have to disclose proprietary routines and algorithms since the DP system is treated as a black box.

Prior to the model tests the DP system was used as a black box together with a MARINTEK vessel simulator for testing and tuning of the DP controller and the signal processing. An important advantage of both these simulations and model tests, is the possibility to efficiently study a wide range of wind, wave and current conditions. In addition various failure situations can easily be tested and analysed at low costs.

In addition to running the vessel simulator prior to testing, a dry test was performed on interface of all signals, communication, actuators and units in the ocean basin laboratory. This proved to be very useful for the tests themselves, and saved valuable test time in the ocean basin as well.

Figure 10 **The 10 meter long model ready for DP testing in Marintek's Ocean Basin. The model is controlled by an "off the shelf" Kongsberg DP system.**

The tests in the Ocean Basin comprised the following:

- Tuning of Kongsberg Controller
- DP- tests in Connection Mode
- DP- tests in Disconnection Mode

The tuning tests were performed in calm water with the same procedures as normally used in full scale by Kongsberg.

DP-tests were performed both for connection and disconnection worst case weather criteria as described above (Table 1). In these tests, different nominal power settings were used for the azimuth thruster units, thus the necessary power under different failure modes could be determined. Both ballast and loaded condition were tested thoroughly.

Each test was performed with a special startup procedure:

After the standard Marintek startup of wind, current and waves, which correspond to a certain time window, the model is released when Kongsberg has started the system in weather vane mode towards the buoy which is the fixed target. This will be interpreted by the DP- system as if the vessel is suddenly exposed to wind, current and wave forces. Due to this, the system is allowed to work for 30 minutes (full scale time) before proper measurements/analyses are started. It is assumed that the different transients that may occur has died away during this 30 minutes period. All analyses performed and reported in this paper refer to one hour full scale time, and this one hour period starts after the aforementioned 30 minute period.

Initially, in the test programme, some investigations were made regarding the effect of variation in the wave period. For the selected significant wave height $H_s = 5.5$ m (disconnection criteria), wave periods of 10, 12 and 14 seconds were investigated. The peak enhancement factor, γ, was kept constant. As the 10 second period gives the highest loads, most of the tests are run with spectrum wave peak period of 10 seconds.

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Thrust loss measurements results

The thrust reduction coefficient τ can be defined as:

$$\tau = \frac{T}{T_{nom}}$$

where T_{nom} is the nominal thrust and T the available thrust.

Figure 11 and Figure 12 shows the measured thrust reduction coefficients for a bow- and aft azimuth thruster operating in the disconnection condition (see *Table 1*). A thrust angle equal to 0 degrees corresponds to ahead thrust, whereas a thrust angle of 90 degrees corresponds to starboard thrust, see Figure 8. The waves and the current coincide in direction and attack the vessel head on, whereas the thruster is rotated about its vertical axis.

As can be seen from the measurements for the bow azimuth thruster, a dramatic degradation of thrust exists in the sector from 0 degrees up to approximately 30 degrees. The reason is that the thruster is blowing towards a neighbouring thruster, in this case forward thruster no.2. For thruster angles larger than 30 degrees the propeller slipstream has clearance to the second thruster and the loss becomes moderate. The same picture is established when thruster no. 2 is blowing with astern thrust. For thruster angles between 150 – 180 degrees the propeller slipstream hits thruster no 1. As a consequence, angles 0-30 degrees for thruster 1, and 150 -180 degrees for thruster 2 should be barred in a real operation.

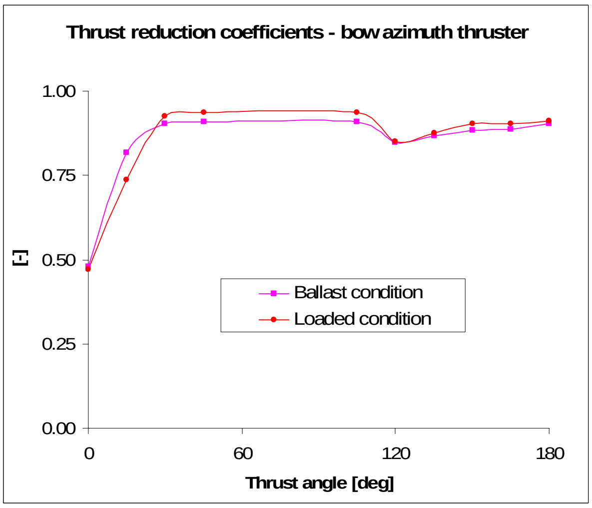

Figure 11 **Measured thrust reduction coefficients for a bow azimuth thruster.**

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The thrust degradation of the aft azimuth thruster is highly influenced by the skegs in the twin screw aftbody configuration. The variation in the Coanda effect is probably due to the fact that the propeller slipstream interacts with the skeg in different ways for different thruster azimuth angles. For small angles, less than 20 degrees, a "normal" Coanda effect is established along the hull between the skegs. For angles between 20 – 120 degrees the slipstream is deflected either along the skeg or across the skeg, for angles larger than 120 degrees the slipstream follows the flat bottom of the hull.

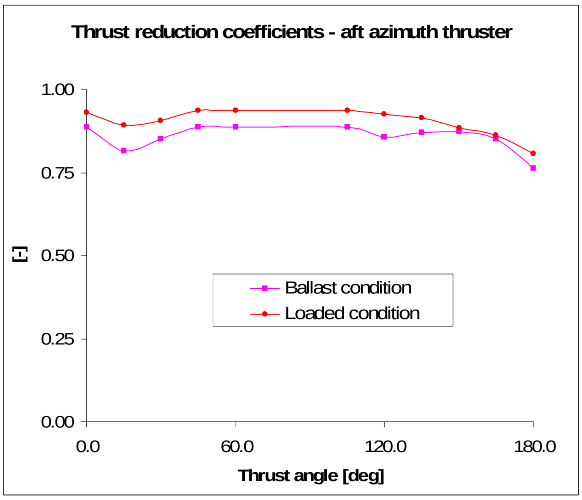

Figure 12 **Measured thrust reduction coefficients for an aft azimuth thruster.**

Table 2 shows the average reduction coefficients for main propellers and tunnel thrusters. The figures for main propellers are measured, whereas the tunnel thruster figures are estimated on the basis of relative motion measurements.

Thrust reduction coefficients		
	Ballast condition	*Loaded condition*
Main propeller[1] – single-screw	0.75	0.85
Main propeller[1] – twin-screw	0.75	0.87
Tunnel thruster – bow	0.65	0.80
Tunnel thruster – aft	0.65	0.80

Table 2 **Thrust reduction coefficients for main propellers and tunnel thrusters.**

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[1] Applicable to ahead thrust.

DP model test Results

An example of the DP model test results is given for the test run; #620 and #320, in Figure 13 below. The test represents failure mode in extreme weather conditions for offshore loading (Hs = 5.5 m). The bow-to-base distance (ordinate) is given as a function of time (abscissa). The desired bow-to-base distance is set to be 60 meters. The results show acceptable offset distances to base with failure on forward thruster and port main propeller. The power setting of azimuth thruster no. 2(forward) and no. 3(aft) were in this test run 2.2 MW nominal effect.

The time (abscissa) is displaced for the test runs represented by the two graphs shown below. The offset distance (ordinate) for bow-to-base is slightly higher for ballast condition. The vessel recovers its position after relative short time. Hence, the vessel's station keeping capability is regarded as good.

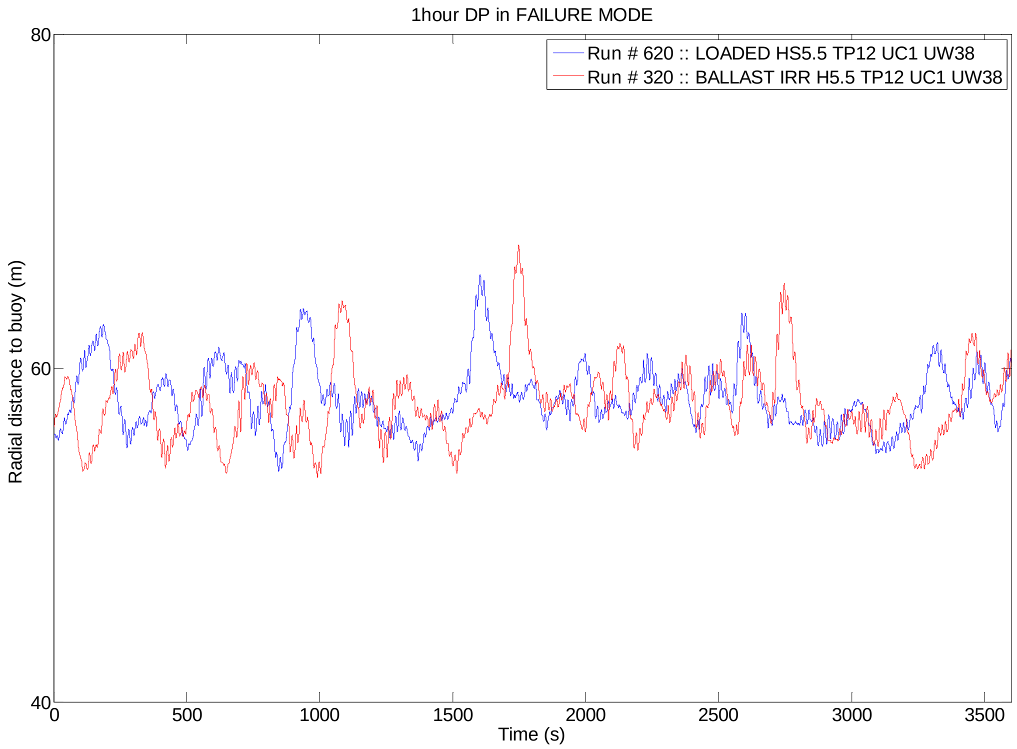

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Figure 13 **Bow-to-base distance for failure mode as a function of time for ballast and loaded condition in extreme offshore loading weather condition (H_S = 5,5 m, U_W = 38 knots, T_p =12 sec, U_C = 1 knot)**

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Scale Effects

The scale effects to be considered for the tests discussed herein are many; some of them are listed and briefly discussed in the following:

Scale effects on:

- motions of vessel
- wave and current forces
- wind forces
- rudder forces
- thrusters and thruster-interaction

Froudes' scaling law takes care of the potential forces, i.e. inertial-, gravitational- and pressure forces. Scale effect on potential damping is negligible in this case, while there will be some effects on the viscous part. The viscous effect is directly proportional to the drag-coefficient of an oscillating body, that is, the effect is related to the difference between model and full scale drag- coefficient. An advantage with the present test is that head seas are focused on, meaning that both model and full scale drag-coefficients are well defined. The major concern regarding effects on motions and subsequently the forces on the model are influence from the side walls in the towing tank. In order to reduce these effects wave damping devices were mounted on the side walls in the area where the testing took place. Normally, there are large scale effects connected to the roll damping for model and ship; however, with the actual headings, roll motions are insignificant.

The scale effects of wind generated in an open laboratory are large and modelling is very difficult; this has to do both with Reynolds number, boundary layer and the modelled above-water wind area. In the DP-tests only static wind was used, and the modelling was done by first calculating the wind forces and yaw moments for loaded and ballasted condition by CFD. A wind sensor was positioned on top of the forecastle deck. For the actual wind speeds, (U10 - 31 and 38 knots), the model was suspended in a force measuring system and the wind speeds were adjusted to give the correct force in the longitudinal direction. With correct longitudinal force it was assumed that for the limited range of headings also the transverse force and the yaw moment were correct.

Scale effects on rudder forces are highly dependent on Reynolds number, and on Euler and Weber numbers. The Reynolds number has influence on the maximum lift and the angle where separation occurs. The angle is less in model scale than in full scale. The fact that the rudder is working in the propeller slipstream and relatively close to the propeller reduces the scale effects. Other scale effects on rudder forces due to Euler and Weber numbers are cavitation and air suction, these effects are more pronounced in full scale than in model scale.

For the azimuth thrusters (model diameter 120mm), the Reynolds numbers used are low but acceptable, that is the propeller blades have turbulent flow. Good torque measurements are important in addition to having an acceptable flow, which was achieved under these tests. The interaction forces are also dependent upon scale effects, but as long as turbulent flow is achieved these effects are small both for thruster-thruster and thruster-hull effects.

Due to the actual scaling factor, the tunnel thruster in the aftbody of the single-screw vessel operates at too low Reynolds number. Besides, hydrodynamic effects also occur due to the flow in the tunnel, and the thruster-hull effects will be more uncertain.

The scale effects are acceptable for all the measurements, except for the aft tunnel thruster measurements of the single screw ship. Additional measurements, such as relative motions between ship/wave were used to evaluate the loss factors of tunnel thrusters.

Discussion

Thruster and propeller wear-and-tear

Experience from operation of DP shuttle tankers has shown that maintenance and repair costs for thruster failure due to wear and tear are significant. Ventilation, or suction of air, is believed to be the most important reason for thruster failure.

Tunnel thrusters located in the vessel's bow area are the most exposed thrusters for ventilation. Especially for a DP tanker with large difference in draught from ballast to loaded condition, the forward tunnel thruster will be exposed to ventilation when loading in harsh weather.

Ventilation, or air suction, reduces the available thrust and hence the vessel's DP performance. For a tunnel thruster, the thruster loss due to ventilation can be as much as 50%+ over a short period of time.

Ventilation of thrusters is often caused by harsh weather in combination with a big wave hitting the vessel. When a DP controlled thruster is exposed to ventilation, the thruster will have a drop in shaft torque. If the vessel starts losing position due to the driving environmental forces, the DP controller responds by giving command for more thrust. The thruster will then respond by increasing the propeller pitch or propeller RPM. Increased propeller pitch, or propeller RPM, will maintain the ventilation and have no contribution to increased thrust. When the thruster is again deeply submerged and free of ventilation, the shaft torque will peak due to high RPM or propeller pitch. This could damage the prime mover in the thruster.

The model test showed high probability for ventilation of forward tunnel thruster for an Aframax shuttle tanker. Even ventilation of the main propeller occasionally occurred for ballast operation in harsh weather conditions.

Increased ballast draft will increase submersion of thrusters, and therefore reduced the probability of ventilation.

An azimuth thruster located underneath the flat bottom of the vessel is unlikely to be exposed to ventilation.

DP Capability Analyses

The DP capability of a vessel can be defined as the capacity of the vessel's thrusters to counteract the forces exerted on the vessel by wind, waves and current. Hence, a static DP capability analysis is basically a force balance exercise, in which the environmental forces and turning moments acting upon the vessel are counteracted by the vessel's thrusters, propellers and rudders.

Investigating shuttle tanker designs by means of static DP capability analyses has become a common industry practice. These analyses are performed under the assumption that the vessel is operated in Auto Position mode which means that the position and heading control is fully automatic and held against a fixed reference. Since shuttle tankers are generally operated in Weather Vane mode, neither the position nor the heading reference of the vessel is fixed. As a consequence, when considering the results of shuttle tanker DP capability analyses the attention is focused on the thrust requirements in a sector around the bow, see Reference 6.

When a specific environmental design condition is given, the DP capability can be measured in terms of thrust utilisation envelopes. For these diagrams, the required thrust to hold position and heading is calculated and compared to the vessel's thrust capacity. The ratio between the two is plotted as a function of wind direction, see example in Figure 14.

In the below diagram, a thrust utilization less or equal to 100 % means that the vessel is able to hold position and heading in the specified design sea state. If the ratio exceeds 100 % the vessel will experience poor positioning performance or drift off position.

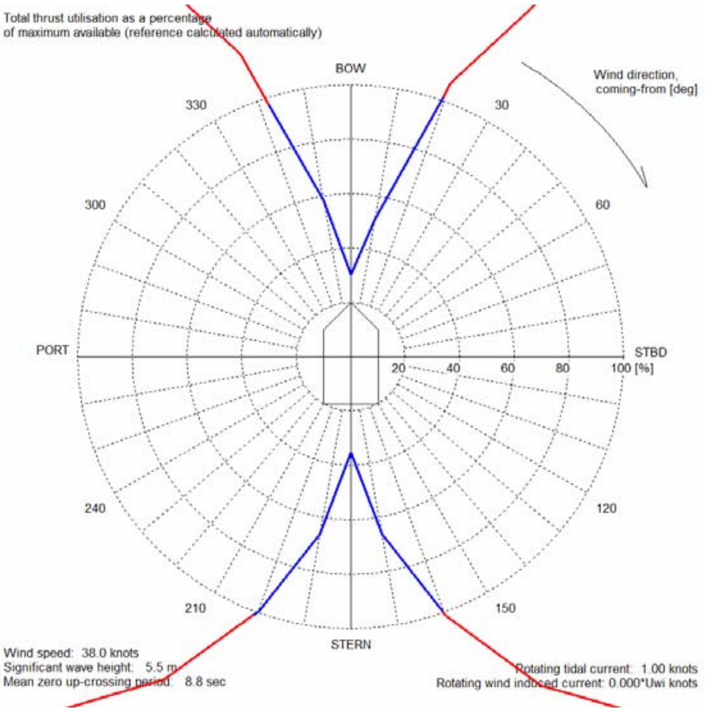

Figure 14 **Shuttle tanker DP capability analysis example.**

It is evident that the results of a DP capability analysis depend heavily on the expected net thrust in a given direction, and hence, thrust degradation assessments become very important. Thrust degradation effects are complex. Historically, in DP capability analyses they are either neglected entirely or they are taken into account by means of a fixed, in our opinion often optimistic, figure.

The model test results show that the thrust degradations are considerable for all the thrust devices on the shuttle tanker (see Table 2, and Figure 11 and 12). Kongsberg Maritime has therefore developed SW algorithms for thrust degradation estimates based on the model test results, see Reference 1, and the work put forward in Reference 2 through to Reference 5. This SW has been incorporated in the DP capability analysis computer program StatCap.

An engineering approach towards the complex problem of thrust degradation modelling has been taken, in order to estimate the effect of:

- axial current
- transverse current
- thruster-hull interactions and the Coanda effect
- waves

Additionally, for tunnel thrusters a similar approach was taken in order to be able to estimate the effect of:

- tunnel inlet shape
- tunnel grids
- the tunnel length

For each thruster, a thrust degradation coefficient is obtained for each particular effect. Subsequently the thrust degradation coefficients are combined to arrive at an estimate for the total thrust degradation for each thruster as:

$$\tau_{tot} = \prod \tau_i$$

where the counter *i* refers to the degradation effects mentioned above. The degradation varies with:

- the thruster submergence
- the thruster orientation
- the thruster load
- the wave condition and direction
- the sea current amplitude and direction

An example of a thrust degradation calculation, and how it compares to the model test results, is shown in Figure 15. In a DP system, thruster-thruster interactions are dealt with by means of barred azimuth sectors. The StatCap program contains a simple algorithm for the calculation of barred azimuth sectors, based on the diameter of the propeller disc and its location relative to neighbouring thrusters. The result of such a calculation is indicated on Figure 15 as an orange, bold line. When the barred azimuth sector is considered, the thrust degradation calculations agree reasonably well with the model test results.

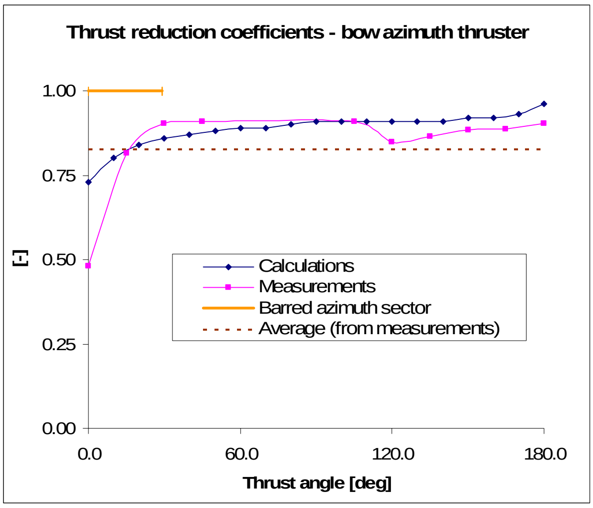

Figure 15 **Measured and calculated thrust reduction coefficients for a bow azimuth thruster. The data are valid for ballasted condition.**

Practical design consequences

The results and observations from the DP Model test have been used in initial design of four new Teekay shuttle tankers under construction at Samsung (Hull no. 1749/50 and 1827/28). These vessels will be Classed as IMO DP2 Aframax ,109 DWT, shuttle tankers, where propulsion is based on redundant twin screw main propellers, two high lift rudders, two retractable azimuth thrusters forward, and one retractable azimuth thruster aft. The vessels are designed for offshore loading year round operation at Haltenbanken, Norwegian Sea.

Kongsberg Maritime has developed thrust loss calculations in their software program StatCap. The modified software, including thrust degradations, is now used by Teekay for analysis of the vessels DP capability.

Conclusions

The results from the model tests show that thrust loss effects or thrust degradation due to thruster-thruster and thruster-hull interference and dynamics effects are of significant importance for a DP vessel. The effect of thrust degradation needs to be considered in:

- design phase
- DP capability analyses
- planning of new operations

The model test described was performed with focus on shuttle tanker operation in the North Sea. However, thrust degradation effects are applicable for all types of DP vessels. The magnitude of thrust degradation depends on vessel type, design, operation and environmental forces.

The following thrust degradation coefficients are recommended to be used in DP capability analysis for an Aframax shuttle tanker operating in the northern part of the North Sea:

Thrust reduction coefficients		
	Ballast condition	*Loaded condition*
Main propeller[1] – single-screw	0.75	0.85
Main propeller[1] – twin-screw	0.75	0.87
Tunnel thruster – bow	0.65	0.80
Tunnel thruster – aft	0.65	0.80
Azimuth thruster[2] – bow	0.825	0.825
Azimuth thruster[2] – aft	0.85	0.85

[1] Applicable to ahead thrust
[2] Dependent on azimuth angle

The Software algorithms, developed by Kongsberg Maritime, for thrust degradation estimates in DP capability analyses compare reasonably well with the thrust degradation measurements given in the table above. Hence, DP capability analyses are valuable in the early stages of new design and for the verification of minor design changes. However, since thrust degradation effects are complex physical phenomena, new concept designs should be verified by other methods as well, e.g. by DP model tests.

This project has been a joint effort where each company have contributed with expert knowledge. The combined effort utilizing the Ship Simulator, Model tests and commercial DP system has provided a better understanding for the design and operation of shuttle tankers.

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