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Application of an Alternative Concept in Dynamic Positioning to a Tanker Floating Production System

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ABSTRACT

This paper describes the development of a cost-effective floating production system, comprising a conventional tanker fitted with a dynamic positioning (DP) system to maintain the riser connection to the well head.

Reduced costs in the DP system are achieved by using a control strategy based on thrusters at the forward end of the vessel thus allowing the vessel to rotate freely, i.e. weathervane, to the environment. A description of the principles of this control strategy is given.

Application of this DP system to a conventional tanker is briefly outlined. Special attention was required in the location of the thrusters in the forward cargo tank and a description is given of the numerical studies and model tests used to optimise thruster location.

In order to gain insight into vessel behaviour under such a DP system, simulation studies were carried out and the results correlated with model tests in a wind, wave and current environment. These results indicated the need for a thruster at the aft end of the vessel under certain environmental conditions.

The paper concludes with an economic assessment of the operational costs of such a DP system, which together with reduced thruster and power plant costs presents an attractive solution to production from marginal fields.

References and illustrations at end of paper.

INTRODUCTION

There is a growing need for more cost effective solutions to development of marginal oil fields particularly in the light of the current depressed oil prices and the uncertainty attached to them. Floating production systems can provide such a solution using existing technology which is evidenced by the growing trend of units being put into operation during the past decade. A tanker based system is ideally suited to this role since it has the capability for in-built storage of the produced crude oil combined with a high deck load capability. The ability of the tanker to weathervane to ambient environmental conditions provides a relatively stable platform, which is comparable with the motion performance of a semi-submersible, for the process plant to function.

Large tankers are subject to large drift forces from the waves which place substantial demands on mooring systems. Common practice is to provide a catenary anchored buoy or tower to which the tanker is linked by a yoke structure. The vessel is permanently on station and discharges produced oil in reasonable weather conditions to shuttle tankers in a tandem mode.

The moored system is suitable for many applications but the costs can rise significantly with increasing water depth and in areas with severe environmental conditions.

An alternative solution for location of the vessel is use dynamic positioning (DP). This offers a large degree of flexibility. Risers can be disconnected quickly and the vessel moved off station in the event of environmental hazards, such as typhoons or ice. In certain circumstances where discharge ports are nearby the vessel can transport the cargo alleviating the need for shuttle tankers.

Dynamic positioning is generally not dependent on water depth. Recent developments in satellite navigation, such as GPS, will soon provide position measurement accuracy comparable with existing position reference systems. This opens up an area for the development of deep water reservoirs in remote locations.

The operating costs of DP systems can be greatly reduced by using off gas as fuel to generate electrical power, see References (1) and (2).

Thus there is a strong case for considering DP vessels for certain field developments. The capital and operating costs need careful analysis over the field life when comparing alternative systems and the environment in which the field is located. In the past the capital costs of DP have been considered to be high. The following paper describes the work that has been undertaken in developing a lower cost option, the Dynamically Positioned Tanker (DPT) which was designed by BP Shipping Limited and utilised an alternative concept in DP previously researched by MARIN.

DESCRIPTION OF AN ALTERNATIVE CONCEPT IN DP

Conventional DP vessels employ a so-called three axis control system where surge, sway and heading axes are controlled by means of thrusters near the bow and stern. This thruster arrangement is a result of the heading control requirement - a yaw moment is generated most effectively by applying opposing transverse forces at each end of the vessel. The DP system attempts to keep a point near midships stationary with respect to the earth. Typically such vessels are fitted with moonpools near amidships for deployment of diving bells, drilling and production risers. The amidships location is desirable to minimise vessel wave frequency motions.

Thus the requirement for heading control is an important factor in the DP system configuration. However, if the heading requirement could be neglected altogether then the considerable thrust used in producing yaw moments could be saved and also it would then not be necessary to install thrusters at both ends of the vessel.

This could result in a significant reduction in power consumption and simplification of the thruster layout which in turn will reduce the capital and operational costs of the DP vessel. Hence the concept of a two-axis DP system, with no heading control, was born, see Reference (3) and (4).

The heading the vessel assumes is dictated by the environment and thruster location and can be explained below.

If the thrusters are all located at a point xt from the centre of gravity of the vessel, then examining the equilibrium of mean forces and moments gives the following:

$$\overline{F}xt = - \overline{F}xe\ (\alpha) \quad \dots\dots\dots\dots \quad (1)$$

$$\overline{F}yt = - \overline{F}ye\ (\alpha) \quad \dots\dots\dots\dots \quad (2)$$

$$\overline{F}yt.xt = - \overline{N}e\ (\alpha) \quad \dots\dots\dots\dots \quad (3)$$

The equilibrium mean heading is then given by α, such that:

$$\overline{F}ye(\alpha).xt = \overline{N}e(\alpha) \quad \dots\dots\dots\dots \quad (4)$$

i.e. where the point of application of the environmental forces coincides with the location of the thrusters (xt).

This condition will usually only be met for one stable equilibrium heading of the vessel. If the thrusters are at the forward end of the vessel then the stable heading will be bow on to the environment, such that the mean environmental forces acting on the vessel are a minimum. This heading is often referred to as the 'minimum power' heading, but this term is rather misleading. The environment forces, predominantly due to waves, consist of both mean and peak components which can lead to different 'minimum power' headings.

The choice of reference point - the point on the vessel which is attempted to keep stationary, therefore does not dictate the stable equilibrium heading. It can be shown that there is most DP control stability if the reference point is also at the forward end of the vessel, but in principle any point forward of midships can be chosen.

One of the main problems in stationing a large monohull vessel is that when the vessel adopts an angle to the waves, it can be subject to very large varying transverse wave drift forces, which can strain the DP system (or mooring system) and it can also be prone to high wave frequency roll motion. Figure (10) shows typical wind and wave forces on the DPT at the 'minimum power' heading.

On a conventional 3-axis DP system, the 'minimum power' heading can be easily determined by the DP control system, which will often have a 'minimum power' mode of operation. Hence the possibility of problems will arise (using either 2 or 3 axis DP control) when the minimum power heading does not correspond to the wave heading.

These conditions will occur when the directions of wind wave and current are not colinear. In many sea areas these conditions will occur frequently. It may be wondered, therefore, what effect this would have on the behaviour of a vessel with 2-axis DP control. This is one of the items discussed in this paper.

With the two axis DP system the riser has to be deployed forward in the vessel to achieve maximum benefit from the method of control. The design of the riser has to be amenable to the less rigid heading control of the vessel together with the increased vertical motions occuring away from the centre of gravity - this will generally be acceptable if a flexible riser is used.

Positioning the reference point and thrusters at the bow of the vessel has some benefits, since no complex alterations are required in the aft engine room and all structural modifications are confined to a forward cargo tank area. The open structure of such a tank enables an array of azimuthing thrusters to be fitted. It is also of benefit to position the riser forward of the thrusters to avoid thruster downwash against the riser and to keep it clear of the hazardous areas over the oil storage tanks and around the process plant.

APPLICATION TO THE DYNAMICALLY POSITIONED TANKER

The Dynamic Positioned Tanker (DPT) was conceived by BP Shipping Limited as a low-cost floating production system utilising the two-axis DP control.

Design criteria were initially formulated as folllows:

1. Storage of 500,000 barrels of crude oil.
2. DP performance capability up to a significant wave height of 7 metres based on N.Sea (Forties) environmental data.
3. Flexible risers deployed over the bow.
4. Maximum DP watch circle radius of 12% of water depth (ie 15 metres for Forties Field) based on riser characteristics.
5. Low-cost conversion of an existing tanker with segregated ballast.
6. Process plant to be mounted on the upper deck.
7. Flexibility of operations constraints would enable vessel to discharge at port after disconnection of the riser or offload to a shuttle tanker with the riser connected.
8. Draught of vessel to be maintained for entry to port in full load condition i.e. thrusters to be retractable.

An existing BP 109,000 tonne deadweight tanker was selected for the DPT to meet the production storage demands of 500,000 barrels. A modern tanker with segregated ballast tanks was seen as an advantage since very little conversion work would then be necessary to meet current rules and regulations worldwide.

Figure (1) gives a general arrangement of the vessel with identification of the additional modules required to transform the vessel into a floating production system. These modules are listed as follows:

1. Flexible riser handling system at the bow.
2. Flare tower on the main deck forward.
3. Process and fiscal metering modules near amidships.
4. Power generation module above the poop deck aft of the existing engine casing.
5. Helideck over the power generation module.

In addition to storage of the produced oil, produced water tanks are provided within the existing slop tanks together with separators in the process modules.

The forward thrusters are located in a new machinery space created in No. 1 centre cargo tank. The size of these thrusters is dictated by the required operating environment. A stern thruster, if fitted would be situated in the vessel's main engine room. In the early stages it was considered possible that the vessel's main engine could be used to assist the forward thrusters in higher sea states.

Power generation for the new thrusters is provided by three diesel alternators located on the poop deck machinery module. Process system, power and vessel services would be provided from the vessel's existing boilers.

Discharge of the produced oil was seen as very much dependent on the location of the well and the field production rate. The following options were considered:

1. Vessel disconnects risers when fully loaded and steams to port.
2. Shuttle tanker offloading from the stern of the DPT in a tandem configuration.

TIME DOMAIN COMPUTER SIMULATION STUDY

It was required that a method be devised to analyse the DPT vessel under 2-axis dynamic positioning control, in order to:

1) Select the final forward thruster sizes and layout.
2) Identify the sea state operating limits under DP.
3) Investigate the effect of varying environmental headings on vessel behaviour.
4) Decide whether a stern thruster should be fitted, how it would best be used, and what size it should be.

It was thought that this could best be carried out by using a time domain computer simulation program. A program was thus developed and implemented on an IBM PC compatible microcomputer by BP Shipping Limited.

Varying environmental forces, thruster forces, including interactions and a simple control system, together with a low frequency 3 axis vessel model were incorporated in the program.

It is possible to simulate 6 degrees of freedom with high (wave frequency) and low frequency motions, in which case a more complex DP control algorithm is required. A low frequency model would give sufficient initial information and would also produce a program with an acceptable run time.

Environmental forces are precalculated before the simulation starts to minimise simulation run time. It was considered important to model these as accurately as possible, particularly the wave drift forces which were known to dominate behaviour of a large monohull vessel under DP.

Wave drift forces are synthesised from the mean drift force transfer functions, see Reference (5), which were scaled from the results for a similar vessel using the following non-dimensionalisation for frequency:

$$\omega' = \omega \left(\frac{\nabla^{\frac{1}{3}}}{g}\right)^{\frac{1}{2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

and for forces:

$$\overline{F}_2(\omega,\alpha) = \overline{F}_1(\omega,\alpha)\left(\frac{\nabla_2}{\nabla_1}\right)^{\frac{1}{3}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

and for moment:

$$\overline{N}_2(\omega,\alpha) = \overline{N}_1(\omega,\alpha)\left(\frac{\nabla_2}{\nabla_1}\right)^{\frac{2}{3}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

The wave force time trace is produced using a sum of sines approach:

$$\overline{F}(t,\alpha) = \sum_{i=1}^{N}\sum_{j=1}^{N} \overline{F}(\omega_i, \omega_j, \alpha).$$

$$ai.aj.\cos[(\omega_i-\omega_j).t+(\varepsilon_i-\varepsilon_j)] \quad (9)$$

with phase angles (ε) picked up at random between 0-2π and using the approximation:

$$\overline{F}(\omega_i, \omega_j) = \overline{F}\left(\frac{\omega_i+\omega_j}{2}, \frac{\omega_i+\omega_j}{2}\right) \ldots . \quad (10)$$

which is reasonably valid for deep water and where:

$$a_i = (2.S(\omega_i).dw)^{\frac{1}{2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (11)$$

Wind forces were produced by scaling force coefficients from a similar vessel and then again using a sum of sines approach with the Harris gust spectrum formulation.

Current forces were also obtained by scaling force coefficients from a similar vessel.

The vessel model uses equations of motion of the form:

$$a_x.\ddot{x} + b_{x1}.\dot{x} + b_{x2}.\dot{x}.\,|\dot{x}| - ay.\dot{y}.\dot{\theta}$$

$$= \overline{F}_{xe} + \overline{F}_{xt} \quad (12)$$

, for each axis, which is integrated numerically using a fixed interval fourth order Runge-Kutta method.

The thrust demands are produced by a controller in response to estimated position offsets, Δ x. The controller is a PID device with a constant term - one controller is provided for each axis of the form:

$$F_{xt}(\text{demand}) = c_x.\ \Delta x + b_x.V_x$$

$$+\ d_x \ {}_0\!\int^t \Delta x dt + Xaver \quad (13)$$

The thruster interaction factors were precalculated using empirical techniques and then applied to a single 'superthruster' at the forward end of the vessel, which represented a group of actual thrusters.

The required thrust and azimuth from the superthruster is given by:

$$T_t = (F_{xt}{}^2 + F_{yt}{}^2)^{\frac{1}{2}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (14)$$

$$\alpha_t = \tan^{-1}\left(\frac{Fyt}{Fxt}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (15)$$

Some time lags were introduced to simulate thruster pitch and azimuth hydraulic system actuation delays and hydrodynamic lag.

Two sizes of thruster were considered, 3 and 4.5MW The initial layout of 3 forward azimuthing thrusters was chosen as the maximum number for operation without severe interaction difficulties and also fitted in neatly with the chosen vessel's structural arrangement.

Approximate thrust/power relationships for the selected thrusters were included to estimate power consumption, eg for the 4.5MW units:

$$\text{Power (KW)} = n\{\, 530 + 0.0584 \left(\frac{Tt}{n}\right)^{1.66} \} \quad .....(16)$$

per thruster in the positive pitch direction.

A series of runs of the program was carried out over a range of significant wave heights from 2-7 metres, using wave height-period and wave height-wind speed correlation figures for the Forties field.

DISCUSSION OF SIMULATION RESULTS

The angle that the vessel adopts to the waves is of considerable importance to the behaviour of the vessel. When the stern thruster is not used this angle is given by the relative direction of wind, waves and current.

The angle that the vessel naturally adopts is the so called 'minimum power' heading. However as described earlier, this may not be the optimum heading, because as heading to waves increases in higher sea states, the vessel is susceptible to very large wave drift force peaks which may cause large position excursions and power surges. There is also the possibility of large wave frequency roll motions occurring. In low sea states, the current might dictate the ships heading which otherwise could be quite variable.

With the stern thruster used transversely, then it is possible to alter the ships equilibrium heading. This takes the vessel away from the 'minimum power' situation, but may be necessary to avoid those problems described above. In fact, some form of heading control is introduced, therefore approaching the conventional 3-axis DP control system.

The forward thrusters tend to act within an arc of plus or minus 45° from the vessel centreline. This gives minimal thruster interaction and no possibility of a thruster downwashing against the riser. When the stern thruster is used longitudinally, the forward thrusters act over plus or minus 180°.

In higher sea states there is very little improvement in performance. This indicates that any thrust shortfall is confined mainly to the transverse direction rather than to the longitudinal, which is really only to be expected in non-colinear environmental conditions. The use of longitudinal thrust at the aft end is really only justified in a colinear or nearly colinear environment.

The activity of the forward thruster could be reduced by controlling the stern thruster within the DP system when it is used longitudinally.

It is, of course, feasible to use the ships main propeller to provide longitudinal thrust at the aft of the vessel. However, it would have to be capable of running at low load for considerable lengths of time, ie it really has to be a controllable pitch propeller powered by geared medium speed diesels. For this particular vessel, which has a slow speed diesel and fixed pitch propeller, it was not feasible.

The vessel did exhibit some low frequency 'fishtailing motion'. This tended to decrease with increasing wave height and was not considered serious.

It was possible to meet the operating targets of Hs = 7m with 3 x 4.5MW thrusters provided the relative wind, wave and current angles were not unfavourable. A more realistic operating limit of Hs = 6 metres was chosen.

With 3 x 3MW forward thrusters an operating limit of Hs = 4.5 to 5 metres was anticipated.

In conditions below about Hs = 2m, it would be possible to operate on just one 4.5MW thruster and remain on station - this represents a high proportion of the time in the Forties location. In practice, it is unlikely that the vessel would operate on just one thruster, for redundancy reasons.

It was decided to proceed with the 3 x 4.5MW thruster option and to include a 3MW stern thruster at the aft of the vessel. The principal reason for including the stern thruster was for use transversely in unfavourable environmental headings to point the vessel into the waves, but it could also be used longitudinally as a back up to the forward thrusters in colinear environmental conditions. This thruster could be under either DP or manual control if used athwartships, but should be under DP control if used longitudinally.

The arrangement of thrusters in the forward group was considered satisfactory as the performance was predicted to be acceptable, even allowing for interaction losses.

The present control algorithim does not ~~not~~ allow for the inclusion of barred azimuth zones for thrusters as interaction was found not to be serious.

Examples of the output of the simulation are shown in Figure (9).

THRUSTER-INTERACTION STUDIES AND MODEL TESTS

The adequacy of the forward thruster arrangement was predicted by thruster-thruster interaction calculations. The calculations were performed with a computer program developed at MARIN and are based on the assumption that the propeller slipstream behaves as a turbulent jet. A semi-empirical model of the slipstream allows the determination of the velocity field at a certain thruster induced by another thruster. The velocity field thus found may be averaged to yield the average inflow of the thruster which then leads to the thrust and torque by an open-water diagram. More details of the calculation procedure may be found in Reference (9).

Results of the calculations for the present case are shown in Figure (2) which depicts the total thrust of the three thrusters in the longitudinal direction.

Subsequently a calm water test program was carried out in the shallow water laboratory of MARIN at a scale of 1 to 40 to verify the above results and to quantify thruster-hull and thruster-riser interaction.

The model was fitted with three azimuthing thrusters, each having a full scale diameter of 4.0 m. These thrusters allow the simultaneous measurement of propeller thrust, nozzle thrust, thrust of the pod and torque.

Provisions were also made to measure the total forces on the tanker in the horizontal plane. A part of the riser was modelled which extended well below the keel and which allowed the measurement of the horizontal forces on the riser. A sketch of the situation showing the measured quantities and the sign conventions is shown in Figure (3).

Tests were carried out to determine the thruster-thruster interaction, the thruster-hull interaction and the thruster-riser interaction. As a reference the open-water performance of the thruster was also measured.

Figure (2) shows some results of the thruster-thruster interaction. The results compare satisfactorily with the calculations, if the influence of the vicinity of the keel plating on the bollard pull is allowed for: the presence of the hull reduces the thrust of a thruster compared to the open-water value.

The calm water tests showed that the present thruster arrangement is satisfactory from the point of view of DP (acceptable thrust degradation). Further it was shown that the forces on the riser caused by the thruster slipstream have an acceptable level. The thruster-hull interaction was small for all considered cases.

DP CONTROL MODEL TESTS

The DP tests were carried out in the wave and current laboratory of MARIN at a scale of 1 to 60. The model was fitted with one 6m diameter azimuthing thruster which represented the arrangement of three 4m diameter azimuthing thrusters. In some cases two of the three 4 m thrusters were operational in which case the super thruster represented only these two thrusters.

A detailed copy was made of the superstructures such as the flare, the process plant and deckhouse. A flexible riser was laid out in the direction of the basin's x-axis, see Figure (5), and observations made of movement relative to the vessel's bow.

The azimuthing thruster was of the variable RPM-type and could be adjusted in azimuthing angle. The nozzle thrust, propeller thrust and the pod thrust as well as the torque could be measured continuously.

One smaller size (3 MW) azimuthing unit was mounted at the stern of the vessel.

This thruster served two purposes:

- to reduce the heading of the DPT with respect to the waves to limit roll motions;
- to assist the forward thrusters for cases where roll is not significant.

As this thruster will normally operate with a fixed azimuth angle, the azimuthing angle could be adjusted prior to each test. The RPM could be varied continuously.

For the DP tests a shore-based computer was used for the real time control. A schematic set-up is shown in Figure (4). Provisions were made to measure the position of the vessel in 6 degrees of freedom. The position of the control point was calculated on the basis of this information and was low-pass filtered to remove components with wave frequencies. The position information was also filtered to obtain the low frequency velocity. The filtering was performed with a causal filter, i.e. a linear filter derived prior to the tests from a least squares fit between a perfectly filtered and an unfiltered motion time trace.

The resulting filtered position was compared with the required position. Any deviations in surge or sway direction were related to a required thrust by a PD controller extended with an average term.

$$X_{req} = c_x \quad \Delta x + b_x v_x + X_{aver} \text{ .... (17)}$$

$$Y_{req} = c_y \quad \Delta y + b_y v_y + Y_{aver} \text{ .... (18)}$$

The average term in the controller prevents the ship from having a significant average position error. In full scale operation integral terms will be used for this purpose as the average environmental forces are hardly ever known.

The spring and damping coefficients for the PD controller were derived from optimum control theory, see Reference (6).

Three different control strategies were possible:

1. Forward thruster operational only.
2. Forward thruster operational, aft thruster transversely directed.
3. Forward thruster operational, aft thruster longitudinally directed.

In the first case the thruster angle and the required thrust were determined as detailed in section 4.

The thruster RPM was derived from the required thrust, which was corrected for thruster-thruster interaction found for the original arrangement in section 6, as follows:

$$n_{req} = C \quad \sqrt{T_{req}} \text{ .... (19)}$$

with C a factor derived from still water thrust-RPM measurements.

If the super thruster represented the case where only thrusters Nos. 2 and 3 were operational, see Figure (3), no interaction was taken into account.

In the second case (forward thruster and transversely directed aft thruster) the RPM of the aft thruster was constant and adjusted prior to the tests. The control of the forward thruster is analogous to the first case.

In the third case the required longitudinal force is distributed over the foward and aft thruster as follows:

$$X_{req}\text{, (fore)} = 3/4 \ X_{req} \text{ .... (20)}$$

$$X_{req}\text{, (aft)} = 1/4 \ X_{req} \text{ .... (21)}$$

with resulting values for RPM and thruster ngle.

The RPM and thruster angle were then

A number of tests was carried out for several operating conditions. The reference point was situated at the top of the flexible riser. Waves, wind and current were generated in the Wave and Current Laboratory of MARIN. This basin measures 60m X 40 m with a maximum water depth of 1 m. Irregular waves can be generated independently from two sides thus allowing cross-seas to be investigated. Current is generated over the length of the basin by large capacity axial pumps situated in current ducts external to the basin. Wind is generated by batteries of portable fans. Figure (5) shows the test set-up in the basin along with the position of the fans and the initial position of the vessel. This figure also included the co-ordinate system and sign conventions which were used.

Five environmental conditions were considered in the model tests. They range from a limiting operational condition Hs = 6.0 m to light-weather conditions: Hs = 2.0 m. In all cases current was running in a direction perpendicular to the waves.

The adjusted wind velocities corresponded to the wave heights: 18.8 m/s for the most severe conditions, 10.0 m/s for the lightest conditions. The wind direction with respect to the waves was either 0° or 40°.

DISCUSSION OF MODEL TEST RESULTS

The results were statistically and spectrally analysed and plots were made of the vessel motion in the horizontal plane. Plots of the time traces of the relevant quantities were also generated.

The main results of the statistical analysis for all ten test conditions are listed in Table (2). The time traces for Test No. 3 of Table (2) are shown in Figure (6). This figure shows on a basis of time the wave train, the motions of the riser attachment points, (see also Figure (7c)), the heading, the roll angle and the measured thrust vector of the super thruster (magnitude and direction). The latter quantities are low-pass filtered to remove wave-frequency components which arise on account of the first order motions. It is more realistic to remove these as in reality the control of pitch or RPM of the thruster will be softer and the wave-frequency components will therefore be much smaller compared to the test results.

Figures (7) and (8) show the position plots of the majority of the tests. In all cases the weathervaning property of the DP system is obvious: the vessel seems to rotate more or less around the riser.

Comparing the results of test No. 1 and 2 an improvement is observed if the aft thruster assists the forward thrusters in surge direction. This improvement is small, however, which partly originates from the fact that in the case of aft thruster assistance the forward thruster will have to rotate more as it still has to deliver the total transverse force. As the rotation of the thrusters is relatively slow this will introduce a phase lag in the system which partly offsets the improvement gained by the aft thruster operation.

Test Nos. 1 and 2 suffered somewhat from hunting: the combination of the phase lag introduced by the position filters and sub-optional setting of the gain factors causes an instability in the control leading to larger position overshoots and consumed power levels. The results for these tests are therefore somewhat on the pessimistic side as reduced values of the control coefficient will largely eliminate this problem. The instability associated with the hunting phenomenon may be observed in Figures (7a) and (7b) which show that in this case it occurred most significantly for the sway motion.

The use of the aft thruster to rotate the vessel bow into the waves proves to be an efficient way to reduce roll motions. Comparing the results of test Nos. 8 and 9 it can be seen that the roll motion level is reduced by approximately 50% at the cost of a higher power consumption. This is to be expected since the action of the aft thruster introduces a non 'minimum power' heading to the environment.

The aft thruster power appears to be sufficient to obtain a large enough change of the heading in a more severe 2 knot current condition so that the roll motion level is again significantly reduced, see results of Test No. 10.

A comparison of Test Nos. 4 and 5, and 6 and 7 reveal a dramatic difference in power consumption and position accuracy. In both cases a smaller heading with respect to the waves is more favourable as this reduces the large variations in wave drift forces for the yaw and sway motions. The difference, however, will be smaller in reality due to the contribution of the hunting instability present in Test Nos. 4 and 6.

Finally, it may be remarked that the visual observations made during the tests indicated that the distance of the riser to the hull was sufficient to avoid collisions between the hull and the riser with the riser laid out in the direction of wave propagation, see Figure (1).

COMPARISON OF MODEL TEST AND SIMULATION RESULTS

One of the main purposes in carrying out the model test programme was to investigate whether the simulation program described in section 4 gave results that were reasonably comparable. This was necessary because it was required to investigate the behaviour of the vessel in a wide range of conditions and it is considerably quicker to do this on the computer than in the model basis.

There are a number of difficulties with making comparisons, the wave history on the model tests cannot be reproduced using the techniques of section 4 (Reference (7) describes a method to solve this particular problem). Because of this, maxima and some statistical properties cannot be truly compared.

A further problem with some of these particular model tests is due to the phase lags inherent to real time filtering and the gain settings used to provide the signals to the DP control system. This resulted in unstable motions in some conditions which would not be present on the full scale vessel if a better filtering method was used.

Taking these points into account then good agreement was found between the simulations and the model tests. A number of items are worthy of note, however:

1) The vessel mean ('minimum power') heading found in simulations did not at first agree with the model tets. This was corrected by adjusting the wave drift moment coefficients used in the simulations. This is important as the drift moment has a considerable impact on determining the 'minimum power' heading which is of importance in determining vessel behaviour. Wave drift moment is difficult to calculate with accuracy using radiation-diffraction techniques, see Reference (2).

2) The heading variations of the vessel in the model tests were considerably less than in the simulation except where unstable motions occurred. This could be due to inadequate estimates of vessel damping coefficients.

3) Most of the model tests confirmed that the foward thrusters would act over a limited arc. The inclusion of an integral term in the controller would help in this respect.

4) Position excursions and power usage gave good agreement except in the cases of instability associated with the hunting phenomenum.

DPT CONCEPT FEASIBILITY

The main advantages of the DPT with 2-axis positioning control compared to the conventional DP vessel can be summarised as follows:

1) Fewer numbers of thrusters need to be installed for a given sea state operating limit and consequently the electrical generating plant can be smaller and therefore capital cost is lower.

2) Power consumption in operation is lower and consequently fuel consumption and operating costs are reduced.

3) Vessel adapts to fast changes in direction of the environment - for instance abrupt changes in wind direction, see Reference (3).

The power used in a particular sea state is generally low with occasional large peaks. An example is given in figure (11) which shows that in those particular conditions the power consumption is mainly in the range 2-3 MW.

The estimated fuel consumption of the DPT with varying environmental conditions is shown in figure (12). This is based on the assumptions that 2 thrusters will be used in Hs=2m and 3 thrusters in higher wave heights. The generating plant is assumed to be entirely diesel electric operating on heavy fuel oil. Base load refers to the vessel's auxiliary load and excludes any services to the oil production facilities.

In practice, depending on the oil field characteristics, produced gas would be used as a fuel, and the requirement for fuel oil would be minimal.

It should be noted that at the Forties field location, 60% of the time is spent in environments of below 2m significant wave height. Thus for 60% of the time the fuel consumption is below 25 tonnes per day.

It has been shown by model test and simulation that the vessel can remain within 15m of its desired location in sea states of at least 6 metres significant wave height. By utilising a flexible riser and a stern thruster to alter the vessels heading relative to waves, if required, then downtime due to inability to maintain position or excessive wave frequency motion, will be low.

In those areas where a floating production and storage system is required it has been shown to be feasible to use a tanker with dynamic positioning control. This type of system can be viewed as a viable alternative to a moored system in certain situations, particularly due to its ability to move independently of external support.

The capital cost of such a system need not be high due to the adoption of the 2-axis control system where fewer thrusters and smaller generating plant can be used. The running costs, particularly fuel costs, are thus considerably lower.

NOMENCLATURE

$\bar{F}_{xe}$, $\bar{F}_{ye}$, $\bar{N}_e$ - Mean longitudinal force, transverse force and yaw moment due to the environment depending on the mean heading,

$\bar{F}_{xt}$, $\bar{F}_{yt}$, $\bar{T}_t$ - Mean longitudinal and transverse force and total force produced by the thruster.

α_t - Azimuth angle of thruster.

x_t - longitudinal position of thruster forward of centre of gravity.

$\bar{F}(\omega,\alpha)$, $\bar{N}(\omega,\alpha)$ - Mean wave drift force and moment coefficients at given frequency, ω, and heading angle α .

∇ - Vessel Displacement (m^3).

g - Acceleration due to gravity (9.81 ms^{-2}).

ω - Circular frequency (rads/sec)

ω' - Non-dimensional frequency.

$F(t,\alpha)$ - Wave drift force varying with time, t, and heading, α .

a_i, ω_i, ε_i - Amplitude, frequency and phase angle of spectral wave component, i.

$F(\omega_i, \omega_j, \alpha)$ - Quadratic drift force transfer function for wave frequencies ωi and ωj and heading, ω .

$S(\omega_i)$ - Wave spectral ordinate at frequency, ωi.

a_x, a_y - Mass plus added mass in x and y axis.

b_{x1}, b_{x2} - Linear and quadratic damping coefficients, x axis.

$\dot{X}$, $\dot{Y}$, $\dot{\theta}$ - Surge sway and yaw velocities.

c_x, c_y - Proportional gain coefficients.

d_x, d_y - Integral gain coefficient.

b_x, b_y - Derivitive gain coefficient.

X_{aver}, Y_{aver} - Constant gain coefficient.

Δx, Δy - Estimated position errors from control point.

V_x, V_y - Estimated vessel velocity.

n - Number of thrusters in operation in forward group.

Hs - Significant wave height ($4\sqrt{m_0}$)

T_{req} - Required total thrust from thruster.

X_{req} - Required longitudinal component of thrust from thruster.

N_{req} - Required RPM of thruster.

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TABLE 1—MAIN PARTICULARS OF THE DPT

Ship model No. 4872A
Model scale 1 to 60

Designation	Symbol	Unit	Loading condition
Length between perpendiculars	L_{pp}	m	254.40
Breadth	B	m	38.70
Depth	D	m	21.80
Draft	T	m	12.00
Displacement weight	∇	t	99,187
Centre of buoyancy from St. 10	LCB	m	8.76
Centre of gravity above base	$\overline{KG}$	m	10.92
Metacentric height	$\overline{GM}$	m	5.16
Longitudinal radius of gyration	k_{yy}	m	63.00
Transverse radius of gyration	k_{xx}	m	13.55
Roll period	T_ϕ	s	13.10

TABLE 2—RESULTS OF DPT MODEL TESTS

Test No.	Waves			Wind		Current		Thrusters		Max. excursion (m)	Max power (kW)	Mean heading (deg)	Heave		Pitch		Roll		Vertical motion at riser		Vertical acceleration at riser	
	H_s (m)	T_z (s)	Dir. (deg)	V_w (m/s)	Dir. (deg)	V_c (m/s)	Dir. (deg)	Nos.	Aft thruster angle				Sign. (m)	Peak (m)	Sign. (deg)	Peak (deg)	Sign. (deg)	Peak (deg)	Sign. (m)	Peak (m)	Sign. (m/s^2)	Peak (m/s^2)
1	6	8.3	180	18.8	140	0.5	90	123	-	13.1	16,500	37	1.44	2.54	1.54	2.30	3.67	5.16	2.92	4.56	0.94	1.38
2	6	8.3	180	18.8	140	0.5	90	1234	0	13.9	19,640	36	1.51	2.16	1.51	2.22	3.16	4.58	3.03	4.93	0.88	1.28
3	6	8.3	180	18.8	180	0.5	90	123	-	4.7	6,560	22	1.04	1.69	1.20	2.05	2.07	2.93	2.73	5.03	0.80	1.22
4	4.5	7.2	180	18.8	140	0.5	90	123	-	11.6	15,580	39	0.82	1.20	0.88	1.48	1.73	3.24	1.83	3.26	0.64	0.96
5	4.5	7.2	180	18.8	180	0.5	90	123	-	4.7	4,370	22	0.68	1.17	0.72	1.36	1.01	1.71	1.51	2.63	0.51	0.86
6	4.5	6.5	180	18.8	140	0.5	90	123	-	10.4	15,110	34	0.63	0.98	0.55	0.47	1.08	1.78	1.31	2.07	0.51	0.92
7	4.5	6.5	180	18.8	140	0.5	90	1234	90	2.6	6,960	13	0.53	0.88	0.45	0.74	0.82	1.16	1.19	1.85	0.48	0.83
8	2	6.5	180	10.0	140	0.5	90	123	-	3.3	1,990	49	0.40	0.72	0.41	0.64	0.81	1.37	1.01	1.42	0.40	0.59
9	2	6.5	180	10.0	140	0.5	90	1234	90	2.1	3,570	24	0.31	0.53	0.19	0.49	0.41	0.72	0.56	1.05	0.24	0.39
10	2	6.5	180	10.0	140	0.5 2.0	90	1234	90	3.1	1,030	20	0.80	1.03	0.32	0.56	0.42	1.02	1.01	1.31	0.30	0.45

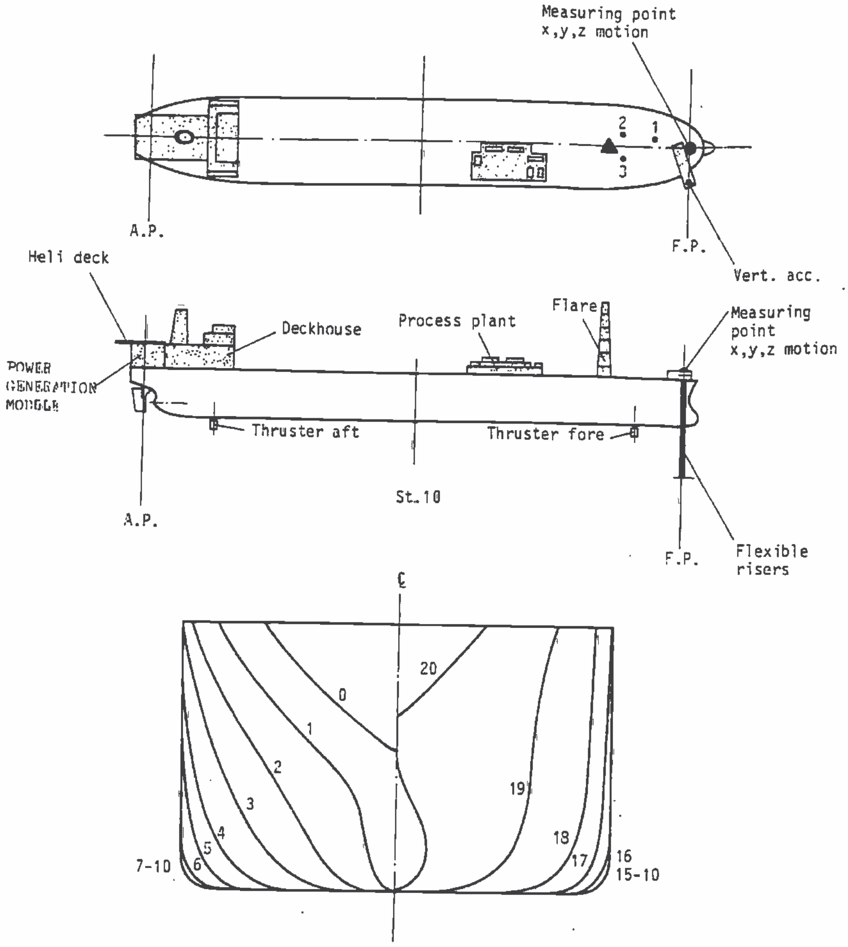
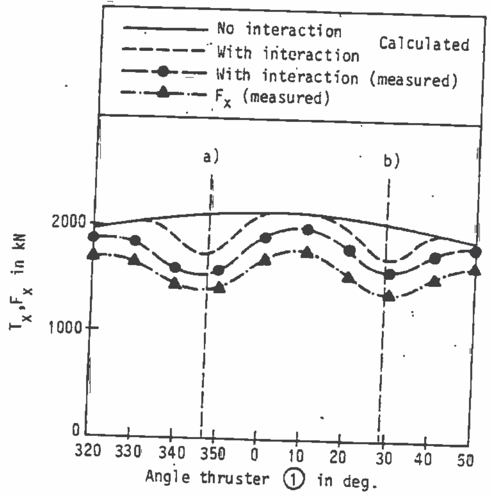


Fig. 1—General arrangement and body plan of DPT model.



a) Thruster ① directed towards No. ③
b) Thruster ① directed towards No. ②

Fig. 2—Results of thruster interaction computation and model tests.

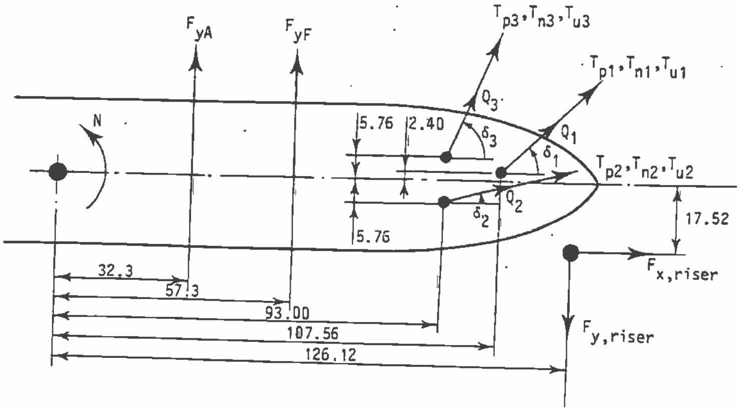


Fig. 3—Sign convention for forces and thruster angles.

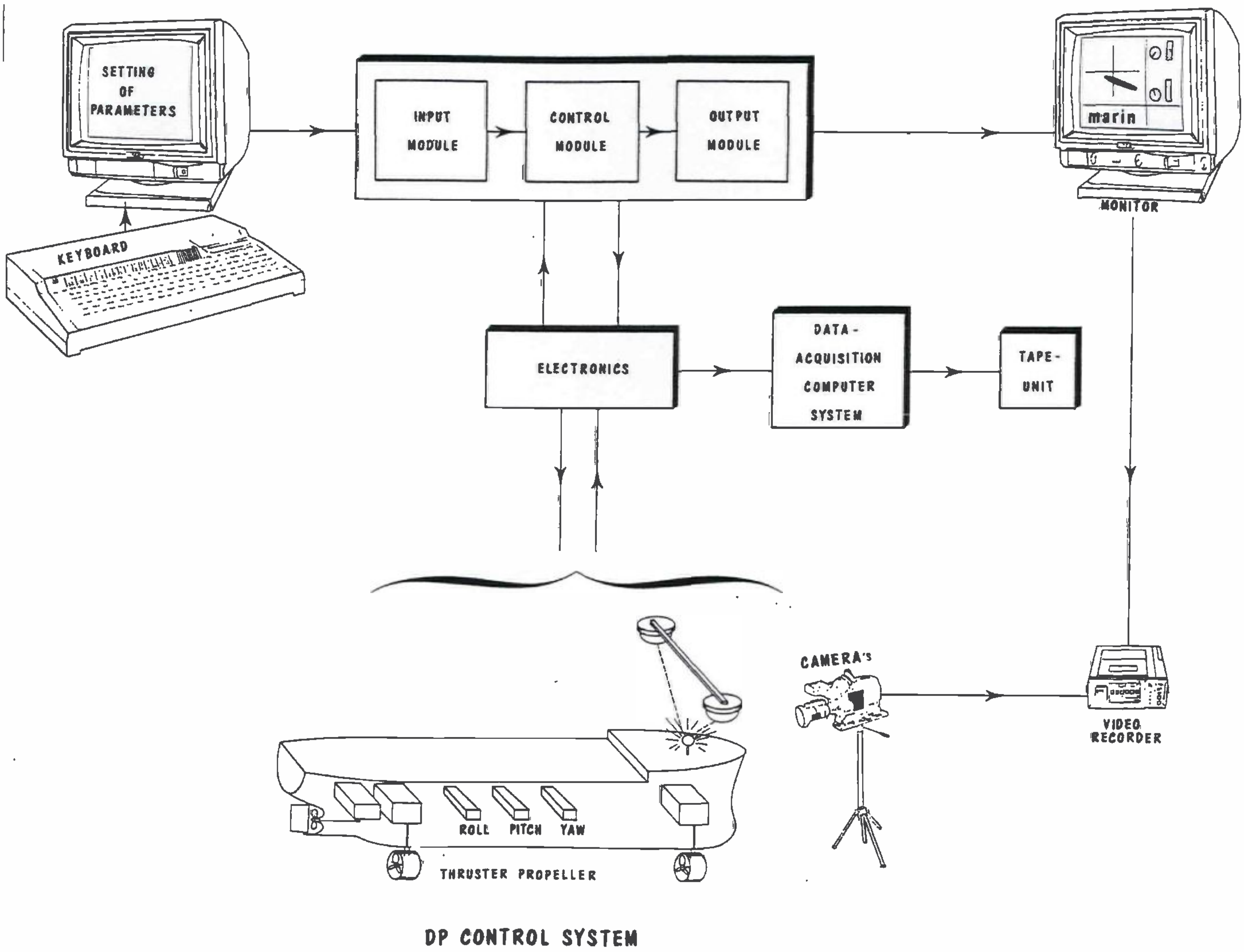


Fig. 4—DP control system.

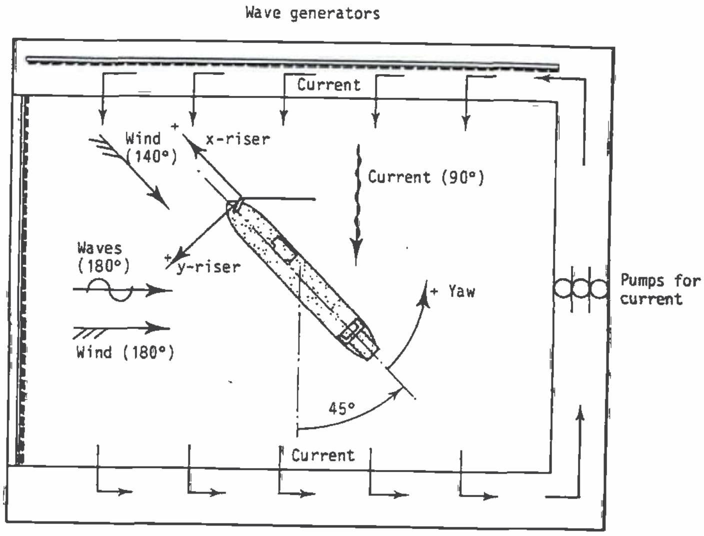


Fig. 5—Test setup in wave and current basin.

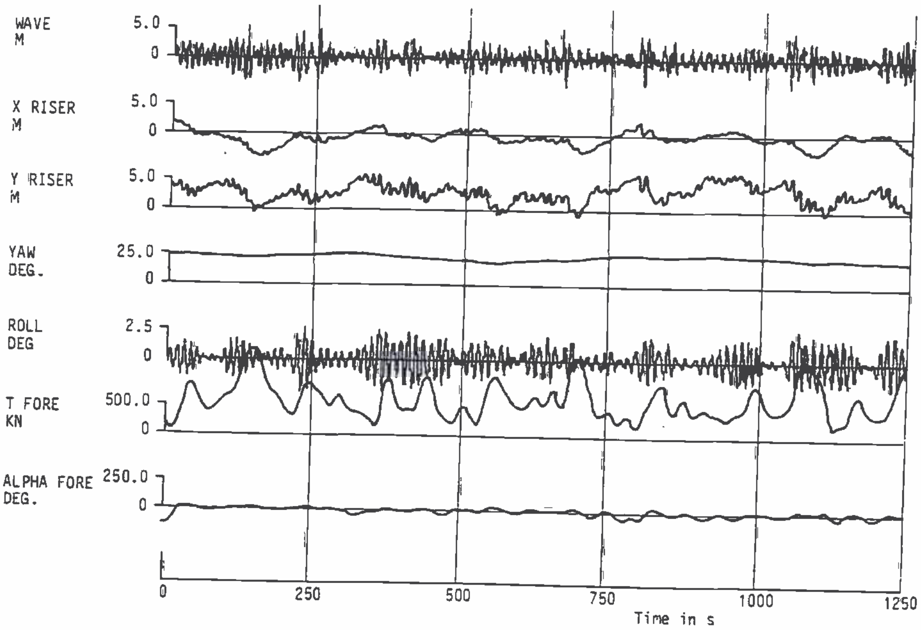


Fig. 6—Time traces of motions and forces measured during Test No. 6763 (Test No. 3).

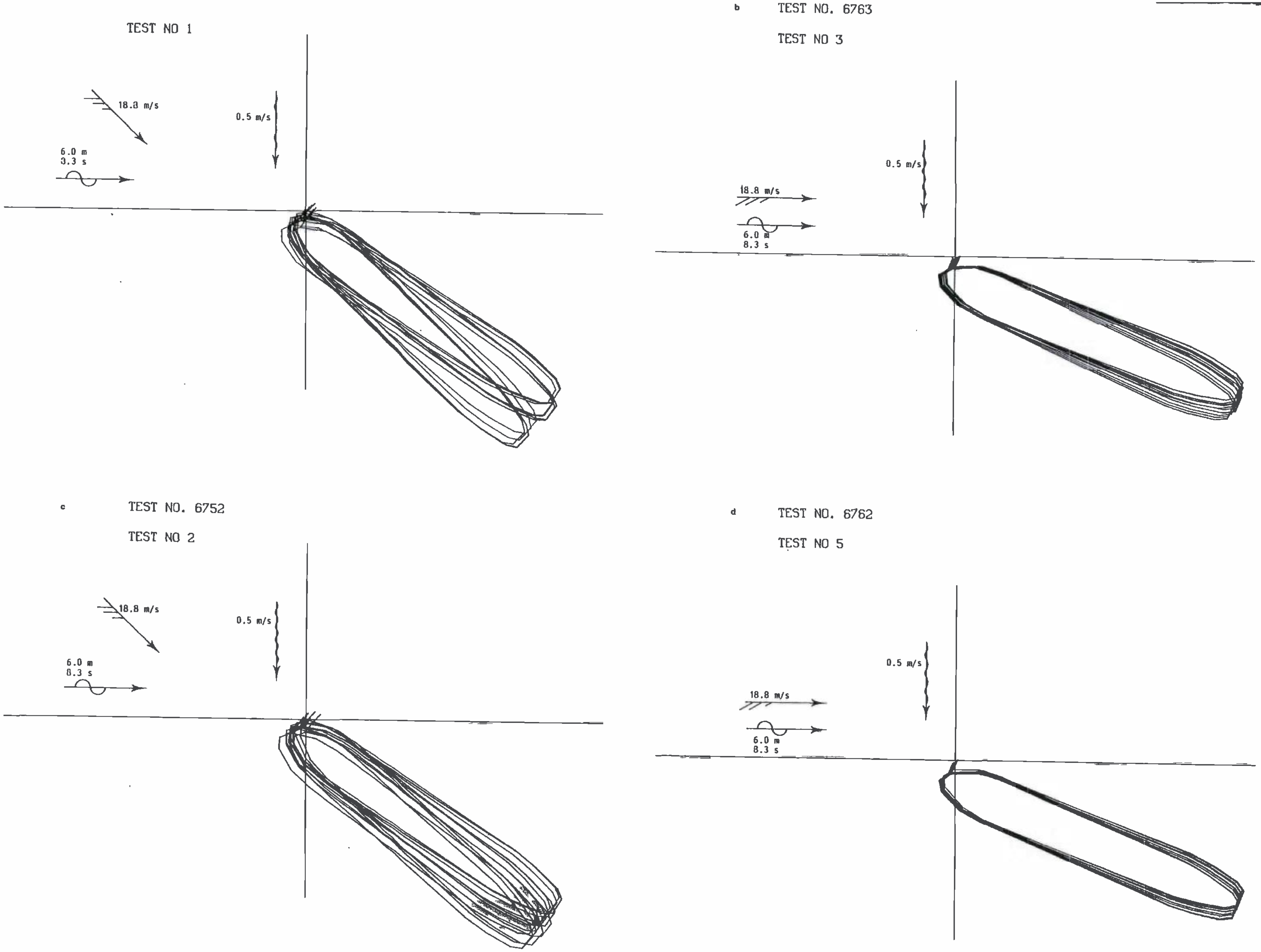


Fig. 7—Contour plots of DPT motions from model tests.

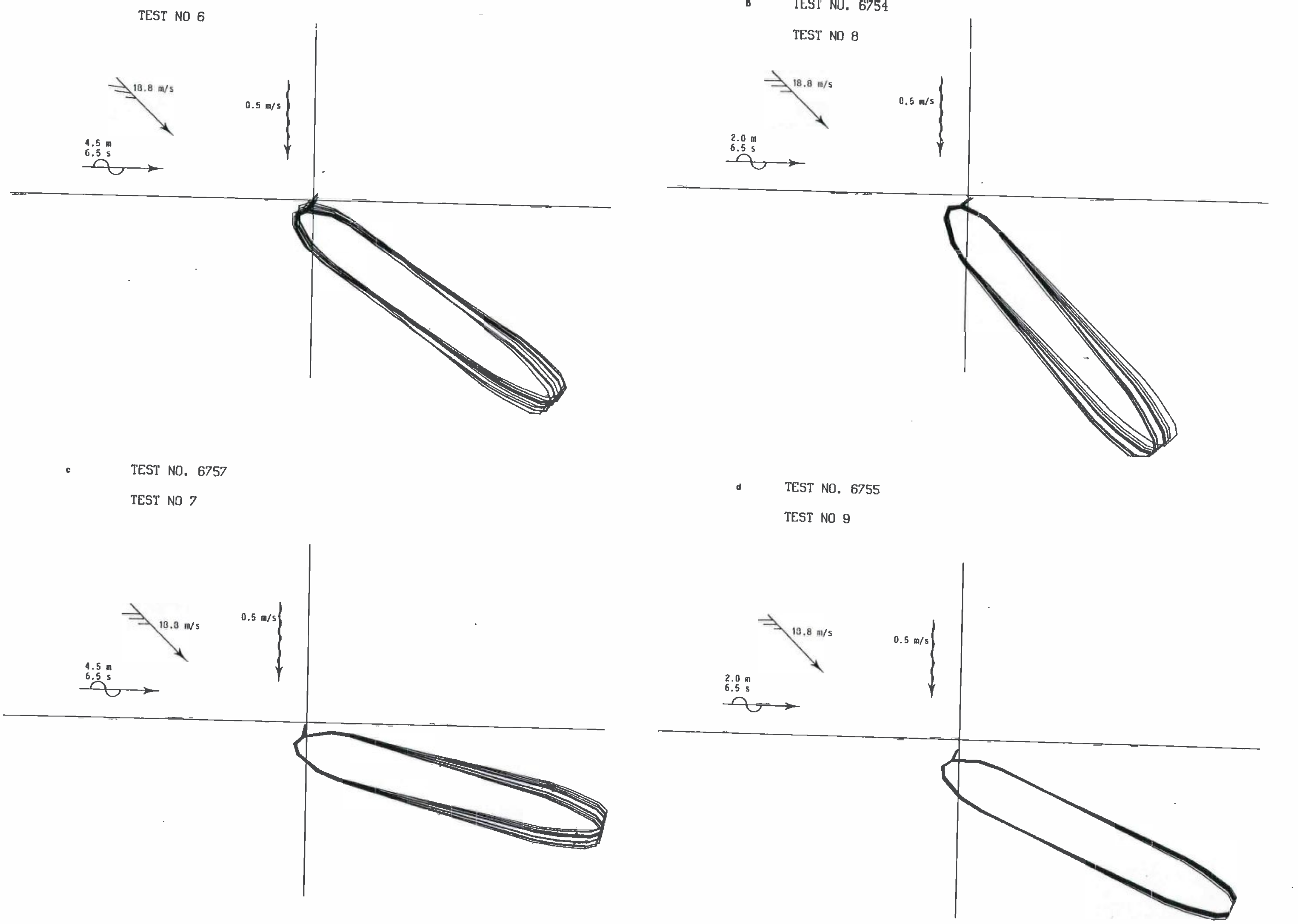


Fig. 8—Contour plots of DPT motions from model tests.

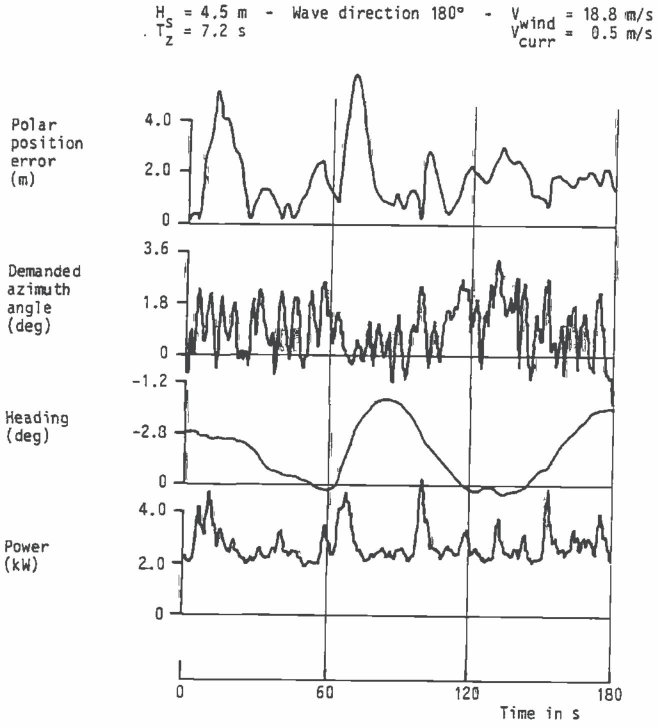


Fig. 9—Vessel motions and thruster power from time domain simulation computations.

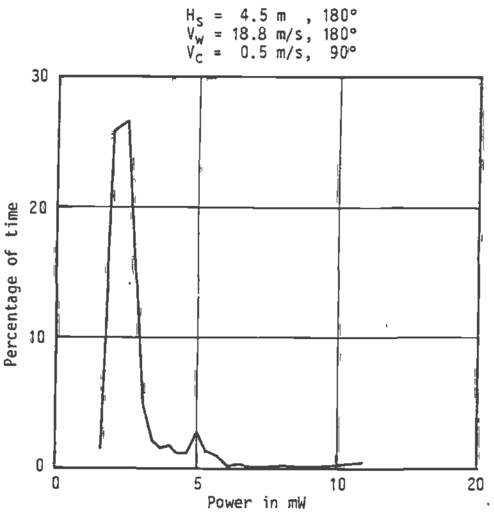


Fig. 11—Calculated DP power distribution.

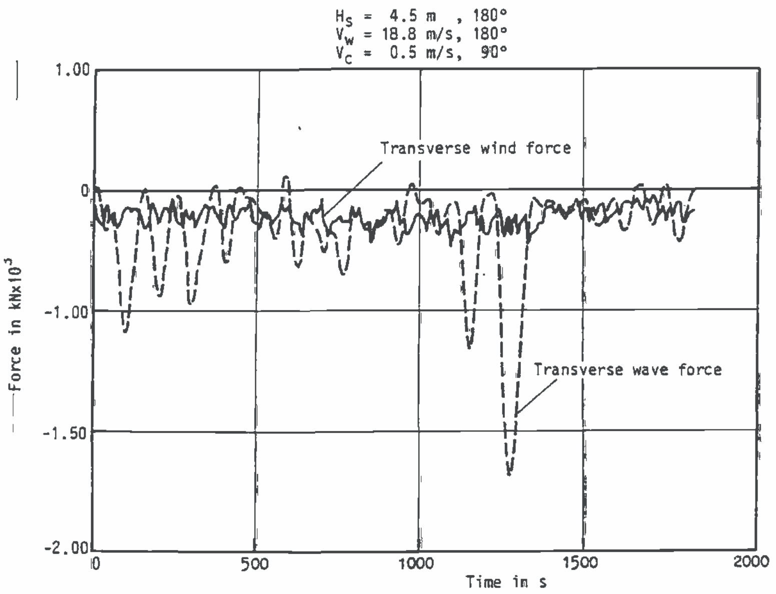


Fig. 10—Computed wave and wind forces at minimum power heading.

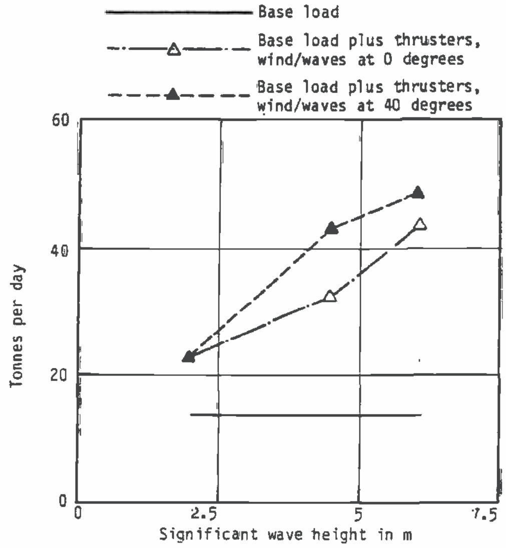


Fig. 12—Calculated fuel consumption.