Maneuvering Trials of a 278 000-DWT Tanker in Shallow and Deep Waters

C. Lincoln Crane, Jr., 1 Member

Maneuvering trials of the 278 000-dwt Esso Osaka were made in two shallow-water and one deep-water site in the Gulf of Mexico during July/August 1977 as a cooperative effort of the U. S. Maritime Administration, the U. S. Coast Guard, and the American Institute of Merchant Shipping. A principal objective of these trials was to develop data for improving the quality of computer simulations of shiphandling for training shiphandlers and for research and design. Other objectives were to provide data needed for the development of deepwater port safety zones and to aid in the development of maneuvering information for mariners aboard ship. The trials satisfied all of the objectives and demonstrated additionally that a typical VLCC can maneuver reliably and predictably under the realistic-type conditions that were tested. They also showed that industry and government, working together, can produce fruitful results toward improving navigational safety and protecting the environment.

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Introduction

Background

Interest in ship controllability has increased sharply in the past few years. While laymen mainly question the size and controllability of large tankers, experienced operators are equally concerned with the unique features affecting controllability of large containerships, liquefied gas ships and other vessels.

During the same few years, special facilities for analyzing and predicting ship controllability have been developed which apply to all sizes and sizes of vessels. Improvements of mathematical ship maneuvering models have resulted from accelerated work on maneuvering theory, captive model tests and calculation capabilities. Taking advantage of these developments, real-time shiphandling simulators, such as at Wageningen and Delft in The Netherlands, the Swedish State Shipbuilding Experimental Tank (SSPA) and CAORF, have been built, permitting research studies of the interactions among the key parts of overall ship/waterway control systems, including human factors. However, most simulators are now dedicated to use as training devices for ships' officers and pilots. In other work, hydraulic models of segments of particular waterways have been built which incorporate manned self-propelled ship models. These also are used in both shiphandler training and in controllability studies such as at Grenoble, France; The Netherlands Ship Model Basin (NSMB); the University of Michigan, and Vicksburg. With these tools available, the complex relationships existing between vessel, waterway, environment, aids-to-navigation, shipboard navigation aids, operating rules and the shiphandler are now subject to study and better understanding.

Maneuvering mathematical models are based on Newton's equations of motion, and incorporate such physical factors as ship's mass and fluid forces acting on hull, propeller and rudder, together with wind forces and the influences of shallow water, channel sides and water currents ([1-4] and similar sources). Because several of the complex factors affecting maneuvers are represented using scale-model data and theories containing assumptions, it is essential that mathematical models be validated through comparison of predicted results with carefully planned and executed full-scale maneuvering trials.

Unfortunately, in the case of shallow-water maneuvering, few data are available for this purpose [5, 6]. In view of this, and with the knowledge that the most important maneuvers of large ships such as tankers occur in shallow water, the U. S. Maritime Administration (MarAd), the U. S. Coast Guard and the American Institute of Merchant Shipping joined together to sponsor a comprehensive shallow-water maneuvering trial program in the Gulf of Mexico off Freeport, Texas. Appendix 1 lists contributing organizations. The trials were conducted under the management of Exxon International Company Tanker Department in late July and early August 1977, using the 278 000-dwt turbine tanker Esso Osaka. Other organizations assisting in the planning, execution and data processing are also listed in Appendix 1.

Objectives

The objectives of the trials were:
1. To develop full-scale ship trial data which will provide a major improvement in the quality of simulations of ship maneuvering behavior, particularly in shallow water.
2. To develop information leading to a better under-

Standing of model scale effects on ship maneuvering predictions.
3. To improve the data upon which the size and configuration of deepwater port safety zones are based.
4. To provide data upon which to base shiphandling maneuvering information for ships' watchkeeping officers and pilots.

Summary

The trials were conducted in shallow and deep waters providing 20, 50 and 320 percent bottom clearance, and showed the following main results: With 20 percent bottom clearance, turning-circle tactical diameter increased as much as 75 percent over the deepwater result. With 50 percent clearance, the increase was less than 20 percent, directionally confirming earlier model predictions. The ship's checking and countering ability was reduced in intermediate water depth, but was increased in shallow water.

The main shallow-water effect on stopping from slow speed was an increase in yaw rotation to the right as the ship came to a halt (increasing to almost 90 deg, with 20 percent bottom clearance). As expected, rudder control was eventually lost during stopping with sustained astern rpm, although heading could be controlled to some extent by early rudder action. In the "controlled" stop, where desired heading had priority over stopping distance, and rpm was controlled, the heading could be maintained almost constant, although this was at the expense of significantly increased stopping distance.

Perhaps the principal finding of the trials, in terms of maneuvering safety, was that steering control could be maintained in all three water depths at speeds as low as 1.5 knots, even with the engine stopped. This was demonstrated by the coasting turns and coasting Z-maneuvers; that is, checking and countering ability was preserved down to this slow speed in the coasting Z-maneuver. Accelerating turns quantified the advantage of "kicking ahead" with the engine to expedite a turn from stopped condition. The coasting maneuvers and the accelerating turns, taken together, confirmed what is already known by good shiphandlers, that is, that maneuverability is improved when rpm is quickly increased, and reduced when rpm is rapidly decreased. Because of this, a prudent shiphandler will navigate in tight quarters at the slowest safe speed. Then, if required to increase speed he will gain control, rather than risk losing it if required to slow down.

Other trial data covered the effects of speed of approach, propeller asymmetry and water currents. Very precise readings selected additional maneuvers were also made for use in researching "systems identification" methods for determining hydrodynamic coefficients of the mathematical maneuvering model.

Trial preparations

Ship selection

A very large crude carrier (VLCC) was selected for the maneuvering trials, recognizing the expected important model-to-ship scale effects due to large differences in Reynolds numbers (reflecting large differences in ratios of fluid inertial to viscous forces) and the modern and extensive navigation equipment found aboard VLCCs, often including double-axis Doppler sonar speed sensors. The latter was useful as part of the trial instrumentation. Other points in favor of selecting a VLCC were the anticipated construction of deepwater ports in the coastal waters of the United States, the large worldwide population of VLCCs, and the concern within some segments of the public over the ability of large single-screw VLCCs to...
maneuver reliably and predictably, especially in shallow water.

*Esso Osaka* satisfied all these requirements, and had the additional advantage of being scheduled for a lightering-type discharge in the Gulf of Mexico. It also had a hull cleaning and painting only three months before the trials. Principal characteristics and sketches are presented in Appendix 2.

**Trial agenda**

The trial agenda given in Table 1 was designed to efficiently obtain information on normal operating requirements, ship response in the event of propulsion breakdown, and model-ship scale effects in the linear and nonlinear motion ranges.

Planning discussions were held among project sponsors and hydrodynamic and ship control experts coordinated through SNAME Panels H-10 and H-5. The water depths that were chosen provided water depth-to-draft ratios of 1.2 (shallow), 1.5 (medium) and greater than 4.2 (deep). The appearance of the *Esso Osaka*’s cross section in these depths is sketched in Fig. 1.

**Trial site selection**

Factors entering the selection of the shallow- and medium-depth maneuvering trial sites included the needs for acceptable water depths, depth gradients and bottom smoothness. In addition, low water currents and high probability of good weather with low winds, waves and swell were sought, as were low vessel traffic, fishing effort and naval activity. Finally, a satisfactory location for trial vessel availability and logistical support was required.

The selection process was in two phases, covering a literature search of documented information from government, industry and academic sources, followed by a field confirmation of water depth, current and sea-floor bathymetry by precision survey. This work, described more fully in Appendix 3, resulted in selection of very satisfactory shallow, medium and deepwater trial sites in the Galveston area of the western Gulf of Mexico. The area is depicted on chart segments in Appendix Figs. 23 and 24.

**Measurements**

Ship instrumentation design, installation and monitoring were provided by the Full Scale Trials Branch of the David W. Taylor Naval Ship Research and Development Center (DTNSRDC). AMETEK, Straza Division, modified the ship’s existing double-axis sonar Doppler docking and navigation system to obtain precision bottom clearance information. Decca Survey Systems, Inc. separately provided ship position information.

Most trial measurements taken by DTNSRDC were from existing ship’s systems in the wheelhouse with careful calibrations, as described in Appendix 4. Test instrumentation installation commenced six days prior to the trials while the *Esso Osaka* was discharging Persian Gulf crude oil into smaller lightering vessels at a position about 50 miles south of Galveston, Texas.

Water current meters were fixed to their moorings by Sippican oceanographer/divers as soon as possible after arrival of the *Esso Osaka* in each trial area and they were removed shortly afterwards.

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**Table 1 Trial agenda**

<table>
<thead>
<tr>
<th>TYPE OF MANEUVER OR CALIBRATION RUN</th>
<th>SPEED OF APPROACH TO MANEUVERS, KNOTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth/ Draft</td>
<td>Speed/ rpm, taken during runs prior to</td>
</tr>
<tr>
<td>1. Maneuvers</td>
<td>chosen maneuvers</td>
</tr>
<tr>
<td>Turn, port, 35-deg L rudder</td>
<td>3.5, 6, 5, 7, 5, 7, 10</td>
</tr>
<tr>
<td>Turn, stbd, 35-deg R rudder</td>
<td></td>
</tr>
<tr>
<td>Turn, accelerating, 35-deg R rudder</td>
<td></td>
</tr>
<tr>
<td>Turn, coasting, 35-deg R rudder</td>
<td></td>
</tr>
<tr>
<td>Z-maneuver, 20/20</td>
<td></td>
</tr>
<tr>
<td>Z-maneuver, 20/20 coasting</td>
<td></td>
</tr>
<tr>
<td>Z-maneuver 10/10</td>
<td></td>
</tr>
<tr>
<td>Biased Z-maneuver</td>
<td></td>
</tr>
<tr>
<td>Spiral</td>
<td></td>
</tr>
<tr>
<td>Stop, 35-deg L rudder</td>
<td></td>
</tr>
<tr>
<td>Stop, 35-deg R rudder</td>
<td></td>
</tr>
<tr>
<td>Stop, controlled heading</td>
<td></td>
</tr>
<tr>
<td>Stop, steering for constant heading</td>
<td></td>
</tr>
<tr>
<td>Total runs</td>
<td>17, 12, 15</td>
</tr>
</tbody>
</table>

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**Fig. 1** Cross-sectional sketch of *Esso Osaka* relative to the three water depths of the trials
before departure. Current speed and direction were automatically recorded at 9.1-m (30 ft) and 21.3-m (70 ft) depths at each mooring location marked on Appendix Fig. 23. The measurement system and recorded data are presented in Appendix 5, which is paraphrased from Sippican’s report [9]. In addition, a portable profiling current meter was used to obtain local current and temperature profiles versus depth at several locations, as also reported in Appendix 5.

The following quantities were measured:

Automatically recorded:
- Position, by Decca Survey Systems (antennae on radar mast).
- Ship’s heading and rate of turn.
- Ship’s longitudinal and lateral speed components, at bow and stern locations of sonar Doppler transducers.
- Bottom clearance at location of stern sonar Doppler transducer.
- Wind direction and speed.
- Rudder angle.
- Propeller rpm.
- Water current direction and speed at two depths at two different locations adjacent to each trial site (Sippican’s moored current meters).
- Time.

Measured and recorded by Ship’s engineers (on file with Exxon International Co., R&D):
- High- and low-pressure turbine steam pressure and temperature.
- Condenser vacuum and seawater temperature.
- Propeller shaft torque, horsepower and rpm.
- Time.

Measured and recorded by oceanographer/divers:
- Water current speed, direction and temperature vertical profiles by a hand-operated profiling current meter—periodically at given stations.

Periodically measured and recorded by trial director and ship’s crew:
- Vessel drafts, forward, amidships and aft, and heel angle.
- Wave height, period and direction (estimated).
- Visibility.
- Visual observations of waterfall, wavemaking, etc.

U. S. Coast Guard support

Coast Guard support was received through Headquarters staff, Commander Eighth Coast Guard District staff, and from officers and crews of the USCG cutters Durable (210-ft medium-endurance cutter), Point Monroe (82-ft patrol boat), and Blackthorn (180-ft buoy tender). Support included publication of a “Notice to Mariners,” special notices to fishermen and contacts with fisheries experts. Immediately prior to trials, the Blackthorn assisted in establishing the Sippican-prepared current meter moorings at two stations bordering each trial site. The cutters Durable and Point Monroe alternated patrol duties throughout the trial, and assisted the oceanographer/divers in locating and successfully guiding moorings and current meters against theft or damage. Bird’s-eye view photographs of the maneuvering Esso Osaka were taken by a USCG patrol aircraft from Air Station Corpus Christi on the first day of trials.

Trial procedures

Preliminary

Prior to entering the trial areas, the Esso Osaka discharged cargo and ballasted to a draft of 21.79 m (71.5 ft), fore and aft. Decca Hi-Fix receivers were carried to the ship by launch, tracking the launch’s position from a known location to preserve lane counts. A Coast Guard patrol cutter preceded the Esso Osaka into the shallow-water sites, warning away fishing boats and providing safety assistance to the oceanographer/divers as they fixed current meters to previously set moorings. The 2 by 5-mile (3.2 by 8 km) shallow-water trial site was entered via a surveyed access lane. The Osaka then made a slow run along the shallowest side while the master verified minimum surveyed water depths.

Calibration runs

A series of speed-versus-rpm calibration runs were completed prior to conducting the maneuvering trials at each site. These were required to allow equilibrium ship speed and propeller speed to be set quickly on approach runs within limited trial area dimensions. Each calibration point required three straight trial runs at the given rpm in alternating directions.

As expected, the resulting speed/rpm calibrations differed according to water depth under the ship. For example, at 35 rpm the Esso Osaka attained a water speed of 6.55 knots at the deepwater site, 6.25 knots at the medium-water depth site and 5.90 knots at the shallow-water depth site. Calibration curves developed from these runs are shown in Fig. 2.

Trial runs

Most of the maneuvering runs were preceded by a minimum of two minutes steady approach during which baseline data were obtained. When the executive command was passed to the helmsman, a mark was entered on the recording medium to indicate the precise time of execution. Data collection then continued at two-second intervals until the end of run.

Several of the data channels, such as rpm and rudder angle, were continuously monitored via digital displays in order to facilitate the approach and execute procedure. The progress of each test was monitored by the printout of all data channels at 40-sec intervals.

Because of the limited site dimensions, it was necessary to maximize acceleration to achieve desired speed and rpm approach conditions. This was usually done by accelerating at
maximum maneuvering power on a parallel and reciprocal course from the desired approach, turning 180 deg near the end of the area and continuing the acceleration until approach speed was reached. The equilibrium rpm was then set using the feedback control and the "steady" approach commenced. Speed through the water was estimated by correcting measured speed-over-ground for longitudinal drift using whatever local water current data were available at that moment.

The sequence of maneuvering runs was chosen for maximum efficiency by linking runs together with the help of prettrial simulations. These prettrial studies were made by Hydronautics Inc., and sponsored by SNAME. Other steps taken to avoid delays included making accelerating turns from dead in the water as the first trial in the morning after drafts were read and the anchor heaved in. Stopping trials usually were made when coming to anchor at night. Except on a few occasions, the ship was not otherwise stopped.

Conventional turning circle, stopping and Z-maneuver trials followed well established procedures [10, 11] and will not be described in detail here. Definition diagrams of trial maneuvers are provided in Figs. 3 and 4. However, the accelerating turn, coasting turn, stopping while steering for constant heading, stopping with controlled heading, coasting Z-maneuver, spiral test and biased Z-maneuver all require some comment.

**Accelerating turn**—This trial begins from dead in the water. The rudder is set to 35 deg and the engine simultaneously ordered to 55 rpm ahead. The result is a turning path tighter than with the conventional turn.

**Coasting turn**—The coasting turn is similar to a conventional turning circle, except that the engine is ordered stopped at the instant the initial rudder execute command is given. Due to the initially slow approach speed and ship slowdown in the maneuver, it was not practical to continue this maneuver through a partial turn. Modified performance measures used are discussed under "Results."

**Stopping while steering for constant heading.** This is a conventional stopping maneuver with given astern rpm, except that the helmsman is ordered to hold course as closely as possible with rudder alone. In general, he will be unsuccessful after an interval as slower speed is reached. This speed depends upon the astern rpm that is ordered.

**Stopping with controlled heading**—In this trial, holding the original ship's heading has priority over minimizing stopping distance. To do this the shiphandler is given freedom to control both rudder angle and engine rpm as he sees fit. It is a subjective trial depending upon the skill and training of the shiphandler. In the absence of external disturbances, rudder angle alone will not suffice for heading control as the ship loses speed with constant astern rpm. Therefore, the engine will have to be periodically stopped or even run ahead for short intervals for heading control.

**Coasting Z-maneuver**—This trial is similar to the conventional Z-maneuver except that the engine is ordered stopped at the instant the first rudder execute command is given. The Z-maneuver is continued until the ship's heading no longer responds to rudder. In the present trials only two or three rudder commands were made before control was lost at very slow speed. Therefore, modified performance indices were used, such as maximum lateral deviation and corresponding advance at maximum lateral deviation. These are in addition to first yaw angle overshoot.

**Spiral test**—This is a specialized maneuvering trial which provides information on dynamic stability (that is, yaw and sway stability with controls fixed) in a small rudder angle range about amidships [2, 10, 12]. Only those special considerations required for the present trials are discussed here. For example, a compromise between a direct spiral and the reversed spiral was used.

In the direct spiral test, the rudder is consecutively fixed at predetermined angles, and after sufficient time to achieve steady turning, the turning rate and ship speed are recorded. To expedite the trial, which may take three hours, the reverse spiral is sometimes substituted. A skilled helmsman then steers using smallest possible rudder angle changes to achieve predetermined turning rates (degrees per second). In the present trial, preliminary rudder commands were given by the trial director to approach the desired turning rate, after which a constant rudder angle was ordered. When turning rate and ship speed appeared constant, data were recorded. This modified procedure was used because most helmsmen are not experienced at steering ordered turning rates, and because long steadying periods would cause the limited dimensions of the

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**Fig. 3** Definition diagrams of turning circle and stopping maneuvers

**Fig. 4** Definition diagram of Z-maneuver

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2 by 5-mile trial sites to be exceeded. Even with this procedure, it was not possible to do the spiral in a continuous run in the shallow-water site.

**Biased Z-maneuvers**—These maneuvers were made at MarAd’s request to provide transient data in the nonlinear turning range as required for systems identification work being done at Massachusetts Institute of Technology (MIT). MIT provided steering procedures in a sequence of rudder angles and ordered time durations. Path traces approached as circles with somewhat flattened segments on perimeters. Data were provided directly to MIT by DTNSRDC and are not reported here.

## Results

### General

Trial results address the effects of shallow water, engine maneuvers, approach speed, propeller asymmetry, and water currents, in that order.

Although detailed time-history and path plots of most maneuvers were prepared and are included in reference [17], only one pair is shown in Appendix 6 due to paper length limitations.

Time histories were prepared for all trial maneuvers except the biased Z-maneuver, which was performed and recorded in detail as previously described. Time-history variables include rpm, forward speed, lateral speed at center of gravity (CG), rudder angle, rate of turn, change of heading and bottom clearance. Ship speed components were corrected to "through the water," by methods described in Appendix 5, together with the water current measurements.

Plots showing swept paths of the vessel were also prepared for all maneuvers except the Z-maneuvers, spiral tests and biased Z-maneuvers. Path plots were initially made as measured relative to ground. They were then corrected for set and drift to a nominal stillwater condition. Winds and seas were very mild throughout the trials and their effects are assumed negligible. See Appendix 7 for weather data.

Trial data were printed at 2-sec intervals and are retained by Exxon International. Original magnetic flexible disk records are retained by the DTNSRDC Full Scale Trials Branch, and those records will be transferred to 8-track magnetic tape during 1979.

### Shallow-water effects

**Conventional Turning Circles**—The large effect of water depth on the *Esso Osaka* entering a turn is shown in Fig. 5.\(^4\) Turning circles were in most cases made through 540 deg, always corrected for set and drift to a nominal stillwater condition. The data were used for the analysis of the effects of shallow water, engine maneuvers, approach speed, and propeller asymmetry.

![Fig. 5 Water depth effect on turning circle path.](image)

![Fig. 6 Changes in turning circle indices with water depth](image)

#### Table 2  Turning circle results versus water depth, expressed using conventional indices

<table>
<thead>
<tr>
<th>Rudder Angle</th>
<th>Depth/draft</th>
<th>Advance Speed</th>
<th>Δ*</th>
<th>Transfer Speed</th>
<th>Δ*</th>
<th>Change of Heading</th>
<th>Δ*</th>
<th>Bottom Clearance</th>
<th>Δ*</th>
</tr>
</thead>
<tbody>
<tr>
<td>35-deg left</td>
<td>1.2</td>
<td>925</td>
<td>3.2</td>
<td>895</td>
<td>3.5</td>
<td>32%</td>
<td>56%</td>
<td>2%</td>
<td>50%</td>
</tr>
<tr>
<td>35-deg left</td>
<td>1.5</td>
<td>1120</td>
<td>3.7</td>
<td>1075</td>
<td>3.3</td>
<td>38%</td>
<td>50%</td>
<td>2%</td>
<td>40%</td>
</tr>
<tr>
<td>35-deg right</td>
<td>1.5</td>
<td>990</td>
<td>3.1</td>
<td>925</td>
<td>2.8</td>
<td>27%</td>
<td>40%</td>
<td>2%</td>
<td>35%</td>
</tr>
</tbody>
</table>

**NOTES:**
- Approach speed 7 knots.
- Corrected for set and drift.
- Percentage change from deepwater results.

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though not indicated in path plots. Table 2 and Fig. 6 report conventional measures of turning circles and indicate that, at 35-deg left rudder, advance was reduced an average of 6 percent in the medium water depth compared with deep water, and in shallow water increased by about 17 percent.

Perhaps most significant to tanker operations are the extreme paths swept by the ship’s hull. In this report, swept-path indices are measured from the extension of the approach path of the ship’s center of gravity to the point on the hull which sweeps the widest path during the maneuver. Table 3 relates maximum sweep advance and maximum swept diameter to water depth.

These data show that swept advance was reduced by an average of 8 percent in medium depth and increased by about 13 percent in shallow water, both relative to results in deep water. Maximum swept diameter increased by about 16 percent in medium depth and 61 percent in shallow water.

Transfer at 90-deg heading change increased an average of 19 percent in medium depth and by 88 percent in shallow water. Probably the most obvious water depth effect is on tactical diameter which, at 180-deg heading change, increased by 18 percent in medium depth and 74 percent in shallow water.

Taken together, these results show that normal modest course-changing maneuvers of a VLCC are not greatly affected by water depth, although the infrequent 180-deg course reversal maneuver is affected substantially.

Table 2 also shows that there is much less reduction of speed in a turn in shallow water than in medium or deep depths. At 180-deg heading change, speed loss from approach speed in deep water was roughly 17 percent. In the medium depth the speed was reduced by 48 percent and in shallow water by 40 percent.

Coasting turns—An interesting characteristic of shallow-water maneuvering is seen in the coasting turn. Results for the coasting turn to the right with 35-deg rudder are presented in Fig. 7, which also shows for comparison the conventional deepwater 35-deg rudder turn. Notice that initial turning is greatest in the medium water depth and least in deep water. In the shallow and deep cases, turning is consistently to the right, whereas in medium deep there is a slight reversal toward the end. As a performance measure for the coasting turn, we compare in Fig. 7 advance at 90-deg heading change to increase by only 15 percent, and in shallow water it increased by 37 percent.

Accelerating turns—Accelerating turns were made in both medium and shallow water depths by building up from zero rpm to about 56 ahead, beginning with the ship dead in the water with rudder angle at 35 deg right. As shown in Fig. 8, the main water depth effect is seen in the changes in the tactical and maximum swept diameters. In shallow water the tactical diameter increased by 31 percent and the maximum swept diameter by 26 percent relative to medium-depth water.

Stopping maneuvers—Water depth effects on stopping from slow speed are most apparent in trials made with 35-deg right rudder and engine ordered to 45 rpm astern. Figures 9 and 10 show that headreach is roughly the same in the deep, medium and shallow water depths at 520, 575 and 550 m (1705, 1886 and 1804 ft), respectively. And as shown in the table on Fig. 9, had the approach speed of the deepwater maneuver been exactly the 3.8 knots of the medium and shallow maneuvers, instead of 3.5 knots, even closer results would have been obtained. The water depth effect is most strongly seen in the large heading change as the ship comes to a halt. Heading change varied from 18 deg in deep water to 50 deg in medium depth to 88 deg in shallow water, all to the right.

Lateral deviation of the ship’s CG from the extended track-

Table 3 Turning circle results versus water depth, expressed using maximum swept-path indices

<table>
<thead>
<tr>
<th>Rudder Angle</th>
<th>Depth + Draft</th>
<th>Maximum Sweep Advance</th>
<th></th>
<th></th>
<th>Maximum Swept Tactical Diameter</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>+ L</td>
<td>m</td>
<td>+ L</td>
<td>Δ</td>
<td>+ L</td>
<td>Δ</td>
<td></td>
</tr>
<tr>
<td>--------------</td>
<td>--------------</td>
<td>-----------------------</td>
<td>---</td>
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<td>-----------------------</td>
<td>---</td>
</tr>
<tr>
<td>35-deg left</td>
<td>4.2</td>
<td>1160</td>
<td>3.6</td>
<td>-15%</td>
<td>1040</td>
<td>3.2</td>
</tr>
<tr>
<td>35-deg left</td>
<td>1.5</td>
<td>990</td>
<td>3.1</td>
<td>+10%</td>
<td>1190</td>
<td>3.7</td>
</tr>
<tr>
<td>35-deg right</td>
<td>1.2</td>
<td>1270</td>
<td>3.9</td>
<td>-2%</td>
<td>1690</td>
<td>5.2</td>
</tr>
<tr>
<td>35-deg right</td>
<td>4.2</td>
<td>1100</td>
<td>3.4</td>
<td></td>
<td>1025</td>
<td>3.2</td>
</tr>
<tr>
<td>35-deg right</td>
<td>1.5</td>
<td>1080</td>
<td>3.3</td>
<td></td>
<td>1200</td>
<td>3.7</td>
</tr>
<tr>
<td>35-deg right</td>
<td>1.2</td>
<td>1280</td>
<td>3.9</td>
<td>+16%</td>
<td>1620</td>
<td>5.0</td>
</tr>
</tbody>
</table>

NOTES:
- Approach speed 7 knots.
- Corrected for set and drift.
- Percentage change from deepwater results.
line was small, varying from 20 m (65.6 ft) starboard to 50 m (164 ft) port to 35 m (115 ft) port for deep, medium and shallow depths, respectively. Obviously, maximum swept-path deviations are more pronounced, with the bow 90 m (295 ft) to starboard in deep water, and the stern 200 m (656 ft) to port in medium depth and 205 m (672 ft) to port in shallow depth.

Z-maneuvers—Z-maneuvers describe relative checking and counterturning ability in maneuvers about an initial heading. Table 4 and Fig. 11 provide values in the three water depths for the 20/20-deg Z-maneuver with initial 7-knot speed.

For port entry-type maneuvers, the first yaw angle overshoot and the resulting maximum lateral deviation (swept path away from original trackline) are significant. First yaw angle overshoots in the 20/20-deg maneuver varied from 9.5 deg in deep water to 11.2 deg in medium depth to 7.8 deg in shallow water. The maximum swept-path lateral deviation from trackline varied from 460 m (1509 ft) deep to 590 m (1985 ft) medium to 505 m (1656 ft) shallow.

In the 10-deg/deg Z-maneuvers the first yaw angle overshoots varied from 3.6 deg in deep water to 7.9 deg in medium depth to 6.2 deg in shallow water; there was some drift of rudder angles, however, as apparent from the time histories in Appendix 6.

Coasting Z-maneuvers—The effect of water depth on a ship’s ability to continue maneuvering without propulsion power is shown by the coasting Z-maneuver. It is also useful

<table>
<thead>
<tr>
<th>DEPTH (DRAFT)</th>
<th>DISTANCE FROM V</th>
<th>HEAD REACH</th>
<th>LATERAL DEVIATION</th>
<th>FINAL</th>
<th>HEAD REACH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>METERS</td>
<td>KNOTS</td>
<td>CORRECTED TO 3.8 KTS</td>
<td>AT CO</td>
<td>MAX. LOC. ON SHIP</td>
</tr>
<tr>
<td>4.2</td>
<td>520</td>
<td>3.5</td>
<td>582</td>
<td>20 STB</td>
<td>905 BOW</td>
</tr>
<tr>
<td>1.5</td>
<td>575</td>
<td>3.8</td>
<td>575</td>
<td>50 PORT</td>
<td>200P STERN</td>
</tr>
<tr>
<td>1.2</td>
<td>550</td>
<td>3.8</td>
<td>550</td>
<td>35 PORT</td>
<td>205P STERN</td>
</tr>
</tbody>
</table>

Fig. 8 Water depth effect on the accelerating turn; shallow-water versus medium-water depth conditions

Fig. 9 Water depth effect on stopping path, with approach speed 3.8 knots, 35-deg right rudder and 45 rpm astern (about 50 percent of available astern power)
for determining a rough minimum maneuvering speed with engine stopped.

Again, first yaw angle overshoots, maximum lateral deviation and advance to that point are all informative. Figure 12 shows the effect of shallow water on the coasting Z-manuever.

Spiral test—Spiral test results provide certain technical information on steady-state turning characteristics at small fixed rudder angles, that is, in the absence of active steering. However, they provide no direct information on maneuvering or coursekeeping ability with active steering; at least not in the case of large slow vessels such as VLCCs. In fact, spiral tests are not meaningful to the VLCC shiphandler unless unusual results are also obtained from the Z-manuever, such as abnormally large overshoots.

A main purpose of the spiral test is to determine whether the resulting turning rate versus rudder angle curve contains a "hysteresis loop," which would be associated with "dynamic instability." It is important to understand, however, that the technical term "dynamically unstable," as used in these paragraphs, relates to controls-fixed stability. It does not directly relate to acceptable "directional stability," with use of the rudder, which is a required characteristic of every vessel.

The present spiral tests show interesting characteristics. From the records of turning rate in degrees per second (example segment in Fig. 30 of Appendix 8) together with working summary plots, Appendix 8 Figs. 31–33, smoothed summary dimensionless plots were prepared. These are shown compositely in Fig. 13. Comments are as follows:

- Deepwater spiral test: Turning rate versus rudder angle results of Fig. 13 and Appendix 8 suggest that the Esso Osaka is marginally dynamically stable in deep water; that is, no definite "loop" resulted, even though a very minor loop might have appeared if this particular trial was prolonged beyond the 2 hr-30 min used.

- Medium-depth spiral test: Results in Fig. 13 and Appendix 8 suggest that a narrow loop of perhaps 1-deg width exists, with a dimensionless height of about 0.4.

- Shallow-water spiral test: Results in Fig. 13 and Appendix 8 suggest that the vessel is probably dynamically stable, and probably has no loop. This interpretation ignores some of the plotted points and is based upon

  (a) Suspicion of points just to the left of the origin in Appendix 8 Fig. 33 because of the limited time they could be held for steady results. This was because of the restricted size of the 2 by 5-mile surveyed "safe" trial area.

  (b) Problems incurred in obtaining the points near the origin in piecewise fashion for the same reason as just given.

  (c) The tendency suggested by all points except those just to the upper left of the origin. A dashed line for the expected actual curve has been added to Fig. 33.

Taken together, the spiral test data in the three water depths suggest marginal dynamic stability in deep water, probable small instability in the medium depth, and stability in the shallow depth. Consistency of these results with the turning circle and Z-manuever data are considered under "Discussion of results."

### Table 4 20/20-deg Z-manuever indices versus water depth (approach speed 7 knots)

<table>
<thead>
<tr>
<th></th>
<th>Deep</th>
<th>Medium</th>
<th>Change*</th>
<th>Shallow Change*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st yaw angle overshoot, deg</td>
<td>9.5</td>
<td>11.2</td>
<td>+18%</td>
<td>7.8 -18%</td>
</tr>
<tr>
<td>Maximum lateral deviation, m</td>
<td>460</td>
<td>590</td>
<td>+28%</td>
<td>505 +10%</td>
</tr>
<tr>
<td>Advance, at maximum lateral deviation, m</td>
<td>1540</td>
<td>1650</td>
<td>+7%</td>
<td>1400 -9%</td>
</tr>
</tbody>
</table>

* Relative to deepwater result.

Propeller rpm effects on heading control

The effects of the use of propeller rpm on maneuvering are shown by certain turning, stopping and Z-manuever trials.

Rpm effects on turning—Turning of a single-screw single-rudder ship is strongly affected by use of propeller rpm.

**Fig. 10** Stopped position of ship as affected by water depth, with approach speed 3.8 knots, 35-deg right rudder and 45 rpm astern

**Fig. 11** 20/20-deg Z-manuever indices versus water depth

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This is clearly shown in Fig. 14 for the case of water-depth-to-draft ratio 1.2. The conventional turning maneuver shown in Path A is diminished when the vessel coasts with propulsion power cut off, as in Path B. The accelerating turn, Path C, has a different approach condition, beginning from dead in the water and building up propeller speed to about 56 rpm from the moment the rudder is deflected to 35-deg right.

Similar rpm effect results were obtained in medium-depth water, as seen in Fig. 15.

Coasting versus conventional Z-maneuvers—The relative ability to maneuver while “coasting” is seen in Table 5, which compares the coasting condition with the conventional Z-maneuvers of Table 4. Figure 16 shows the variations of Z-maneuver paths, coasting versus powered, for the three water depths. Figures 17 and 18 show how water depth changes the effects of coasting on Z-maneuver overshoot, maximum deviation and advance.

Effect of rudder and rpm control on stopping

Rudder angle effect—The stopping results reported under “Water depth effect” were for the 35-deg right-rudder case. The effects of applying instead 35-deg left rudder in the deep- and shallow-water cases can be seen in the combined Fig. 19, with paired left- and right-rudder stopping maneuvers. The tendency of the astern propeller rotation to move the stern to port is clearly preponderant in shallow water, whereas rudder angle was the controlling factor in deep water.
Table 5  Effect of coasting on 20/20-deg Z-maneuver in three water depths

<table>
<thead>
<tr>
<th></th>
<th>Deep</th>
<th>Medium</th>
<th>Shallow</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Conventional</td>
<td>Coasting</td>
<td>Conventional</td>
</tr>
<tr>
<td>1st yaw angle overshoot, deg</td>
<td>9.5</td>
<td>10</td>
<td>11.2</td>
</tr>
<tr>
<td>Maximum lateral deviation, m</td>
<td>460</td>
<td>615</td>
<td>590</td>
</tr>
<tr>
<td>Advance, at maximum lateral deviation, m</td>
<td>1540</td>
<td>1795</td>
<td>1650</td>
</tr>
<tr>
<td>Speed on approach, knots</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Speed when maneuver discontinued, knots</td>
<td>4.5</td>
<td>1.7</td>
<td>4.8</td>
</tr>
</tbody>
</table>
ESSO OSAKA, 278 k DWT

CONVENTIONAL Z-MANEUVER

COASTING Z-MANEUVER

SHALLOW, h/T = 1.2

1 km

1 km

1 km

MEDIUM, h/T = 1.5

DEEP, h/T = 4.2

Fig. 16 Coasting effect on 20/20-deg Z-maneuver path in three water depths

In deep water, special trials were made to show the value of steering and rpm maneuvers for maintaining constant heading while stopping. Results are shown in Fig. 20. The base case was a simple stopping maneuver with engine-ordered 45 rpm astern and rudder-ordered 35-deg right (top of Fig. 20), from an approach speed of 3.5 knots. Next, steering for constant heading was attempted, with engine ordered to a constant 45 rpm astern. The result, shown in the middle of the Fig. 20, indicates little change. Finally, the master was asked to stop the vessel using both rudder and engine speed as he thought best to maintain the original heading, with stopping distance being a secondary objective. The resulting maneuver is shown at the bottom of Fig. 20, with a headreach of about three times that of the simple stop or the steering stop. Examination of the time history of the controlled stop showed that when 35-deg left rudder was found insufficient to hold the heading steady (at about 140 sec into the maneuver) the master alternately used rpm astern, ahead, and stopped to control the heading. Table 6 shows that, although the heading was held virtually constant, the vessel gradually drifted to the left a distance even greater than the maximum deviation of the stern swinging to port in the 35-deg right-rudder case.

A similar trial run was made in shallow water (h/T = 1.2) without quite as much attention to maintaining heading. In that case, stopping distance, relative to the simple stop with 35-deg right rudder and no engine maneuvering, increased by about 80 percent (when normalized to 3.8-knots approach speed). However, ship's heading diverged as much as 17 deg to starboard and ended at 7 deg starboard when forward motion had stopped.

Additional results

Ship speed effects on rudder maneuvers with constant rpm—The effect of ship speed on the path geometry of a large tanker is usually considered to be small. This is because tankers normally operate at relatively low Froude number, meaning that wavemaking and heeling are small. For this reason the hull, propeller and rudder hydrodynamic forces all vary roughly proportionally to the square of ship's speed through the water, and produce geometrically similar maneuvering paths.

Two trial runs of the present series were scheduled in an attempt to verify this. The first was a turning circle with 35-deg
left rudder from 5.0 knots in shallow water. This is compared with another run which is the same except for the approach speed of 7.0 knots. Unfortunately, the 5-knots approach speed (and slower in the turn) allowed significant path distortion due to water current set and drift. Also, the measured rudder angle in the 7.0-knot trial was 36° instead of 35°-deg left. Nevertheless, the results show nothing that strongly contests the assumption that path geometry is independent of speed. Turning indices are summarized in Table 7.

The second comparison was made in a deepwater turn with 35-deg right rudder, Table 8. One run was from an approach speed of 7.8 knots, a comparison run from 10.0 knots. Again the water current (0.73 knots in the 7.8-knot approach case) casts some doubt on the validity of the comparison, but the results do not seriously contest the assumption of path independence of ship speed. In fact, the tendencies are in the opposite direction from those of the previous comparison.

Water current effects—Although path plots of all maneuvers were "corrected" to a nominal stillwater condition, as described in Appendix 5, set and drift are a fact of life in slow-speed maneuvers. Ship handlers must be skilled in adapting to nonuniform and time-varying currents for the same reason that current corrections cannot be accurately made even in controlled experiments such as these. The degree of water current nonuniformity in these trials is discussed in Appendix 5. Here
Suits in Table 9 should be kept in mind when asking shipmasters. Current speed is about 10 percent of the 7.8-knot approach speed to the maneuver. Approach heading was 272 deg, T. Unless ship speeds are correspondingly faster, current drift errors will be exaggerated in stronger currents. Accelerating from zero ship speed with engine rpm rapidly increased from zero to 56. Rudder 35-deg right, $h/t = 1.5$

**Table 9** Example of current effect on turning indices

<table>
<thead>
<tr>
<th>Condition</th>
<th>Advance, m, at 90 deg</th>
<th>Transfer, m, at 90 deg</th>
<th>Tactical Diameter, m, at 180 deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncorrected</td>
<td>880</td>
<td>420</td>
<td>1007</td>
</tr>
<tr>
<td>Corrected for set toward 66.5</td>
<td>1017</td>
<td>361</td>
<td>924</td>
</tr>
<tr>
<td>Error, relative to corrected</td>
<td>-14%</td>
<td>+16%</td>
<td>+9%</td>
</tr>
</tbody>
</table>

**Table 10** Propeller asymmetry effects on turning circles

<table>
<thead>
<tr>
<th>Water Depth</th>
<th>Rudder Angle</th>
<th>Advance, m, at 90-deg Heading</th>
<th>Transfer, m, at 90-deg Heading</th>
<th>Tactical Diameter, m, at 180 deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shallow</td>
<td>36-deg L</td>
<td>1189</td>
<td>555</td>
<td>1664</td>
</tr>
<tr>
<td>Shallow</td>
<td>34-deg R</td>
<td>1182</td>
<td>707</td>
<td>1501</td>
</tr>
<tr>
<td>Difference</td>
<td>-1%</td>
<td>+27%</td>
<td>+3%</td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td>33-deg L</td>
<td>916</td>
<td>384</td>
<td>1073</td>
</tr>
<tr>
<td>Medium</td>
<td>36-deg R</td>
<td>990</td>
<td>407</td>
<td>1074</td>
</tr>
<tr>
<td>Difference</td>
<td>+8%</td>
<td>+6%</td>
<td>0%</td>
<td></td>
</tr>
<tr>
<td>Deep</td>
<td>35-deg L</td>
<td>1006</td>
<td>309</td>
<td>894</td>
</tr>
<tr>
<td>Deep</td>
<td>36-deg R</td>
<td>1017</td>
<td>361</td>
<td>924</td>
</tr>
<tr>
<td>Difference</td>
<td>+1%</td>
<td>+17%</td>
<td>+3%</td>
<td></td>
</tr>
</tbody>
</table>

we need only point out that the importance of current effects can, if desired, be assessed by comparing "as measured" and corrected path plots which can be found in reference [17].

A particular example is a deepwater turning circle where current speed is about 10 percent of the 7.8-knot approach speed to the maneuver. Approach heading was 272 deg, T. Had path results not been corrected for set and drift, the turning indices would have been affected as seen in Table 9. The results in Table 9 should be kept in mind when asking shipmasters to perform ad hoc maneuvering trials at sea. Of course, water current drift errors will be exaggerated in stronger currents unless ship speeds are correspondingly faster.

**Table 10** Propeller asymmetry effects on turning circles

**Fig. 21** Propeller asymmetry effect on accelerating turn in medium water depth. Accelerating from zero ship speed with engine rpm rapidly increased from zero to 56. Rudder 35-deg right, $h/t = 1.5$

**Propeller asymmetry effects**—The effects of propeller asymmetry of a single-screw ship were already seen in the data on water depth effects on turning and stopping maneuvers. The comparisons of Table 10 only summarize asymmetry effects on turning maneuvers made in different water depths. The degree by which the dimensions of right turns exceed those of left turns is shown below each pair.

Although the exact rudder angles desired for good comparisons were not always achieved, it is apparent that turning circles to the left required somewhat smaller areas than those to the right.

The accelerating turn shows a larger effect of propeller asymmetry, as seen in Fig. 21.

**Visual observations during maneuvers**

- **Heel in turning**: Limited bottom clearance in the shallow-water site caused particular attention to be paid to any dynamic heeling that might have brought the bilge closer to the bottom. However, no measurable heel was detected with the ship's existing pendulum inclinometer. Sightings were therefore made from a central point in the wheelhouse, using wheelhouse side window edges and the clear horizon as guides. This rough check, made in the medium-depth area, indicated that heel due to turning at 7 knots, with 35-deg rudder, did not exceed one-half degree. Also, heel was toward the center of the turn and not outboard as anticipated. This may have resulted from a higher dynamic water level on the outboard side of the ship which would have more than corrected the opposing inertial heeling moment.
- **Sinkage and trim**: Vessel sinkage and trim were not measured in the trials, although pneumatic draft gages installed in the *Esso Osaka* were observed several times during maneuvers. On no occasion was more than 15-cm (6 in.) trim aft indicated, including during a 35-deg rudder angle turn from a 7-knot approach speed with 4-m (13 ft) bottom clearance. These indications are not taken as reliable, as we do not know the characteristics of pneumatic draft gage readings as a function of ship speed or local drift angle. Regarding sinkage, according to a preliminary calculation, a total change of about 15 cm was expected with 4-m bottom clearance. However, even with good echo-sounding measurements it was not believed that the generally flat sea bottom was sufficiently uniform to measure sinkage.
- **Silt in wake**: Hard-packed gray clay was observed by divers on the sea bottom and was collected from the anchor chain on deck. In addition, there was evidence of a bottom layer of fine silt or sand. The ship's wake was observed during turning maneuvers, and showed a bright yellow path in the otherwise blue water. In fact the ship was observed to retrace its own path after completing more than 360 deg of 540-deg turning circles in the medium- and shallow-water sites. Coast Guardsmen on patrol cutters also reported observing the wake from straight course running some distance behind the ship, although this was not evident from onboard. Divers reported reduced visibility near the sea bottom, also suggesting a finely silted bottom.

**Discussion of results**

**General**

The trial results show clearly that distortions of flow about a ship's hull in shallow water significantly affect maneuvering motions. The sketches of Fig. 1 show why the cross-flow passing under a ship's bottom when maneuvering in deep water must, in very shallow water, be mainly constrained to pass around the ship's sides. In consequence, the combined effects of shallow water on side drift and turning in maneuvers greatly exaggerate the hydrodynamic side forces acting on a ship, and
Turning, Z-maneuver and spiral test results

Changes in turning circle characteristics and Z-maneuver indices with water depth are loosely related to the changes in dynamic stability that are indicated by spiral test results. According to theory [12-16] and the present trials, the dynamic stability of a ship's hull (that is, with controls fixed) first decreases when moving from deep to medium water depths and then increases again as water depth becomes very shallow. We therefore look for relationships between dynamic stability and maneuvering in terms of turning ability and quickness of response, such as in checking a turn. In general, these appeared in the present trial results as follows.

The hull, with controls fixed, as interpreted from spiral test results, appeared to be marginally dynamically stable in deep water, slightly unstable in medium depth and stable in shallow water. Although dynamic (controls fixed) stability is not directly related to directional stability, it has some relationship to Z-maneuver and turning-circle behavior. For example, the first yaw angle overshoot in the Z-maneuver increased from 9.5 deg in deep water to 11.2 deg in medium depth, and then reduced to 7.8 deg in shallow water. Maximum lateral deviations, and advance at maximum lateral deviations also, changed consistently with yaw overshoots. This suggests that the minimum dynamic stability in medium water depth is associated with the maximum Z-maneuver overshoot in the medium water depth. Also, the maximum swept turning diameter increased only modestly in medium depth (14 percent), but greatly in shallow water (63 percent) compared with deep water.

Of course, not too much should be read into the relationship between dynamic stability and maximum turning ability, since dynamic stability indications from the spiral test refer mainly to steady turning motions with small rudder angles, while maximum turning with large rudder angle is highly nonlinear.

On the other hand, Z-maneuver results relate more closely to quickness of response as indicated by the spiral test results. And, in fact, the Z-maneuver results reflect the reversal trend of the spiral results much more faithfully than do the changes in maximum turning diameters.

Propeller rpm effects on heading control

The accelerating turns made in the medium and shallow water depths confirm facts well known to ship handlers, that is, that advance and tactical diameter can be reduced by "kicking ahead" with the propeller in a slow-speed turn. The reason is that water flow past the rudder is quickly increased, while the hull hydrodynamic forces aiding or resisting the turn are not.

On the other hand, the coasting turns showed a directionally predictable decrease in turning ability when the propeller discharge flow was removed from the rudder. Much of the rudder area then put in a separated flow region behind the idling propeller. But perhaps of greatest significance is that the single-screw VLCC, once predicted to be virtually unmanagable in slow-speed maneuvers, was able to turn reliably at slow speeds, even with the engine stopped.

Taken together, the foregoing trial results emphasize that maneuverability is improved when rpm is increased and degraded when rpm is reduced. Knowing this, the prudent ship handler will look for the slowest safe speed in certain critical maneuvering areas. If then required to speed up, maneuverability will increase instead of being degraded if unexpectedly required to slow down.

The coasting Z-maneuver gave further evidence that the trial vessel could maneuver reliably and predictably with engine stopped, even at speeds as low as 1.4 knots. In all cases it appeared that the ship was still responding to rudder commands when the maneuver was terminated.

The trends of response to the coasting 20/20-deg Z-maneuver closely followed those of the conventional 20/20-deg Z-maneuver, as shown in Table 4. Both follow the trends expected from the spiral tests based on what has been learned about dynamic stability in different water depths. The results with engine stopped were actually better than expected, since the water flow about the ship's rudder must have been greatly reduced with the propeller dragging.

Rudder and rpm effects on stopping

In general the strongest observed effect of shallow water on stopping was the much greater tendency for the ship's stern to swing to port as it comes to a halt. A possible explanation is that the sea bottom tends to restrict the forward-directed propeller outflow (when stopping), causing more flow around the sides of the vessel, and therefore exaggerating the usual propeller asymmetry side-force effects.

Although subjective, one of the more interesting trials was the controlled stopping maneuver, that is, holding the heading constant throughout. It had been assumed that success would show a clear benefit of the controlled stop over simple stopping with constant astern rpm. Instead, the results showed that from a prudent slow approach speed, as is normally used in approaching a single-point mooring (SPM), the simple stop developed smaller lateral deviation, and a much shorter headreach. This suggests that the only advantage of the controlled stop from a slow approach is that the desired heading is maintained. However, if the trial maneuver had been designed to maintain a desired straight trackline instead of heading, the trackline probably could have been achieved with substantially less lateral deviation than that of the simple stop.

The controlled trackline also corresponds more closely to actual operations in a channel or approaching an SPM. The gradual drift of the ship to the left during the controlled stop may be explained by the following considerations:

(a) With reversed propeller rotation, a side force to port develops, causing the stern to drift to port. To counter this, left rudder is used.
(b) If the sum of the side forces due to reversed propeller and left rudder are equal in magnitude, and have the same center of pressure, no lateral drift will result.
(c) Lateral drift to port did occur, however, even though no heading drift occurred. Therefore, although the yaw moments due to astern rpm and left rudder angle cancelled each other, their side force contributions apparently did not. A possible explanation is that the center of pressure of rudder force is further aft than the center of pressure due to astern propeller rpm. The rudder force acting to starboard could then be smaller than the propeller side force acting to port, and this would result in a small drift to port, as observed.

Ship speed and water current effects

The corrected turning circle results from tests at different approach speeds show quite similar paths. This verifies that

7 With controls fixed. See discussion under "Spiral test" in the section on results.
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Table 11 Comparison of Esso Osaka data with previous shallow-water results

<table>
<thead>
<tr>
<th>SHIP</th>
<th>Depth/Draft</th>
<th>Turning-Circle Tactical Diameter (ship lengths)</th>
<th>Z-Maneuver 1st Yaw Overshoot (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Esso Osaka (Present trials)</td>
<td>1.2</td>
<td>4.9</td>
<td>7.8</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>3.3</td>
<td>11.2</td>
</tr>
<tr>
<td></td>
<td>deep</td>
<td></td>
<td>9.5</td>
</tr>
<tr>
<td>Magdala (Ref. [6])</td>
<td>1.2</td>
<td>3.5</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>1.6</td>
<td></td>
<td>17</td>
</tr>
<tr>
<td>Esso Bernicia (Ref. [5]*)</td>
<td>1.2</td>
<td>4.2</td>
<td>2.5</td>
</tr>
<tr>
<td>(HY-A PMM model)</td>
<td></td>
<td></td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>deep</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Speed of approach 14.7 knots.

As indicated in the Introduction, previous model and full-scale maneuvering trial data in shallow water were not always satisfactory. To illustrate this, Table 11 provides comparative data from available shallow-water maneuvering trials of other VLCCs: Esso Bernicia [5] and Magdala [6]; and from predictions made of Esso Bernicia maneuvers by Hy-A Laboratory in Lyngby, Denmark (using planar motion mechanism model tests for hydrodynamic coefficients and computer calculations; unpublished).

The comparisons show that while the model-based predictions of tactical diameters do not differ greatly from the Esso Osaka or other full-scale results, the Hy-A Z-maneuver first yaw angle overshoot predictions for Esso Bernicia are much smaller than the results from the Osaka. Also Bernicia model and ship results do not compare very well, at least for the Z-maneuver in medium water depth.

Results of Hy-A model-based computer calculations of Bernicia spiral tests in different water depths predicted no loop in any of the depth-to-draft ratios tested: 1.2, 1.7 and 2.0. On the other hand, the Bernicia trials [5] show almost identical loops in spiral tests in shallow water (depth/draft = 1.4) and deep water. Although some differences should be expected due to somewhat different hull and rudder configurations, these comparisons support the original contention that insufficient shallow water maneuvering trial data existed at the outset of this program.

Conclusions

1. The present trials provided a quantity of new information regarding the maneuvering characteristics of a ship in shallow water. Both research- and operational-type maneuvers keyed to large tankers were made. In the process it was found that the single-screw Esso Osaka, a 278 000-dwt tanker, was able to maneuver reliably and predictably in all tested water depths, even with engine stopped as when simulating maneuvers after a propulsion failure.

2. Distortions of the flow about the hull of a ship in shallow water were found to have an important effect on maneuvering motions. For example, trial measurements indicated that:
   - In shallow water, turning circle tactical diameters will increase by as much as 75 percent with 20 percent underkeel clearance, while drift angle and related speed loss will reduce relative to turning in deep water. With 50 percent bottom clearance, the changes from deepwater turning are much less. The effects on turning circle diameter are significantly greater than expected, based on previous model predictions and full-scale trials.
   - Checking and counterturning ability are reduced as water depth decreases to an intermediate depth (50 percent bottom clearance in the trials) and then, with 20 percent bottom clearance, these qualities increase to better than in the deepwater case. This is closely related to the apparent reversal in maneuvering dynamic stability (with controls fixed), as is suggested by the present spiral test results. Again, previous model and full-scale trials in shallow water failed to disclose this.
   - The greatest effect of decreasing water depth on the stopping of a single-screw tanker, from slow speed, appears to be an increase in yaw rotation to the right as it comes to a halt. In the present trials the heading change increased from 18 to 50 to 88 deg in deep, medium and shallow water, respectively.
   - Accelerating turns increased in diameter in shallow water, but to a lesser extent than did the conventional turns. On the other hand, coasting turns suffered a trend reversal. The widest coasting turn path was in the medium water depth and the least was in deep water.

3. Trials to show the effects of a shiphandler’s control of propeller rpm during maneuvers provided useful insights. For example:
   - Accelerating turns confirmed that “kicking” ahead the rpm when moving at reduced speed significantly increases turning ability.
   - The coasting Z-maneuver demonstrated conclusively that the subject VLCC could continue maneuvering in response to rudder actions even with the engine stopped. It also showed that this very large vessel could continue maneuvering while coasting down to speeds less than 1.5 knots. This result should be encouraging to those concerned with the maneuvering safety of tankers. The magnitudes of yaw angle overshoots, although different from those with engine operating, showed directionally similar tendencies with respect to effect of water depth.
   - As expected, rudder control of the single-screw vessel was eventually lost during stopping maneuvers with constant astern rpm, although the vessel’s final orientation was to some extent affected by early rudder action. Although the ship’s heading could be maintained constant during a “controlled” stop by using various engine orders, it was at the expense of increased stopping distance and greater lateral drift.

Taken together, the points of Conclusion 3 emphasize that maneuverability is improved when rpm is increased and degraded when reduced. Knowing this, the prudent shiphandler will usually look for the slowest safe speed in a critical maneuv-

there is little speed effect on turning geometry at low Froude numbers (below 0.10 in these trials). With water current present, however, the slow-speed maneuvers suffer much greater distortion than high-speed maneuvers because of the translation of the current. Wind, if strong enough to be important, would also affect maneuvers at slow speed much more than those at high speed. For a given ship configuration and draft, the ratio of wind speed to ship speed is important. These facts are well understood by shiphandlers as they judge minimum safe maneuvering speeds. For further discussion of variable water current effects, see Appendix 9.

Comparison with previous model and ship data

As indicated in the Introduction, previous model and full-scale maneuvering trial data in shallow water were not always satisfactory. To illustrate this, Table 11 provides comparative data from available shallow-water maneuvering trials of other VLCCs: Esso Bernicia [5] and Magdala [6]; and from predictions made of Esso Bernicia maneuvers by Hy-A Laboratory in Lyngby, Denmark (using planar motion mechanism model tests for hydrodynamic coefficients and computer calculations; unpublished).

The comparisons show that while the model-based predictions of tactical diameters do not differ greatly from the Esso Osaka or other full-scale results, the Hy-A Z-maneuver first yaw angle overshoot predictions for Esso Bernicia are much smaller than the results from the Osaka. Also Bernicia model and ship results do not compare very well, at least for the Z-maneuver in medium water depth.

Results of Hy-A model-based computer calculations of Bernicia spiral tests in different water depths predicted no loop in any of the depth-to-draft ratios tested: 1.2, 1.7 and 2.0. On the other hand, the Bernicia trials [5] show almost identical loops in spiral tests in shallow water (depth/draft = 1.4) and deep water. Although some differences should be expected due to somewhat different hull and rudder configurations, these comparisons support the original contention that insufficient shallow water maneuvering trial data existed at the outset of this program.
vering area. If then required to speed up, maneuverability will increase instead of being degraded if unexpectedly required to slow down.

4. Other technical conclusions, which are mainly confirmatory, are

   • Speed of approach has a minor effect on the geometry of the conventional turning circle of a large tanker within the maneuvering speed range (5 to 10 knots).
   • Asymmetry of maneuvers to the left and right hand, caused by single-screw propeller rotation, is greatest when rpm ahead or astern is large relative to ship speed. This is the case in slow-speed stopping and in accelerating turns. It is minor in the case of conventional turns.
   • Technical data from the present trials should be adequate for validating model and analytical methods for predicting ship maneuvering in deep and shallow water under operational-type conditions at slow speeds, and for meeting all of the other objectives of the program.

Recommendations

After comparing the results and conclusions of the present trials against the objectives, it is recommended that the sponsors encourage and support efforts to:

1. Validate present-day procedures for developing mathematical models by performing experiments with captive models, making computer predictions, comparing these with the present full-scale trial data and then, if necessary, improving the prediction techniques.
2. Establish the validity of large hydraulic models in applicable areas. These models, which include large self-propelled model ships, are being used under conditions where irregular side and bottom boundaries and water currents are believed important.
3. Determine to what extent full-scale trial data can be useful for developing maneuvering information for posting in the wheelhouse of vessels, as is recommended by IMCO and required by U. S. Coast Guard.

Acknowledgments

The trial program reported here is the product of extensive industry/Government cooperation among the sponsoring organizations, advisory groups, and trial participants listed in Appendix 1. Contributing individuals most directly involved were W. O. Gray of Exxon Corporation who, after realizing the need, drew together the sponsors; P. M. Kimion, who had overall Exxon responsibility for the program; Dr. P. D. Fitzgerald, who shared in the onboard direction of the trials; and Captain G. Gomez, who acted as supernumerary captain. Outside of Exxon, grateful acknowledgement is given to Mr. R. Falls, Maritime Administration's technical representative, and CDR W. D. Snider, the Coast Guard's project monitor. Both gentlemen were closely associated with the trials from planning through execution.

Key persons among the subcontractors were Mr. L. L. Hundley, who headed the DTNSRDC Full Scale Trials Branch team, and Messrs. J. W. Feeney, W. E. Walsh, and R. Eustis of Sippican Corporation, who provided all oceanographic services, and personally carried out many long days of diving and carrying out many long days of diving and current measurements from a small inflatable boat, with enduring support.

We acknowledge also the services of R. Boehme of AMETEK, Straza, who modified the ship's Doppler sonar for precision depth sounding and otherwise assisted, and Messrs. J. Carpenter and J. Webb of Decca Survey for their competent position-fixing services.

We acknowledge the excellent cooperation and skills of the master of the Esso Osaka, Captain I. Basterrechea, and his crew, all of whom carried out their duties and our requests throughout the trials with good humor and with traditional good seamanship. Finally, the captains and crews of the assisting Coast Guard units are gratefully acknowledged.

References


Appendix 1

Sponsors, subcontractors, and participants

Sponsors

U. S. Government agencies:

U. S. Coast Guard, Department of Transportation
Maritime Administration, Department of Commerce
American Institute of Merchant Shipping, contributing members:

Amoco Shipping Company
Chevron Shipping Company
Appendix 2

Esso Osaka particulars (Fig. 22)

Hull

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length overall</td>
<td>343.00 m (1125.3 ft)</td>
<td></td>
</tr>
<tr>
<td>Length between</td>
<td>325.00 m (1066.3 ft)</td>
<td></td>
</tr>
<tr>
<td>perpendicuIars</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Breadth molded</td>
<td>53.00 m (173.9 ft)</td>
<td></td>
</tr>
<tr>
<td>Depth, molded</td>
<td>28.30 m (92.8 ft)</td>
<td></td>
</tr>
<tr>
<td>Designed load draft,</td>
<td>22.05 m (72.3 ft)</td>
<td></td>
</tr>
<tr>
<td>molded</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Assigned summer freeboard</td>
<td>22.09 m (72.5 ft)</td>
<td></td>
</tr>
<tr>
<td>draft</td>
<td></td>
<td></td>
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<tr>
<td>Full load displacement</td>
<td>328 880 mt (323 740 LT)</td>
<td></td>
</tr>
<tr>
<td>at assigned summer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>freeboard draft</td>
<td></td>
<td></td>
</tr>
<tr>
<td>draft, extreme</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Block coefficient,</td>
<td>0.831 (0.831)</td>
<td></td>
</tr>
<tr>
<td>summer freeboard draft</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bow</td>
<td>bulbous type</td>
<td></td>
</tr>
<tr>
<td>Stern</td>
<td>transom type</td>
<td></td>
</tr>
<tr>
<td>Number of rudders</td>
<td>one</td>
<td></td>
</tr>
<tr>
<td>Rudder area</td>
<td>119.817 m² (1289.67 ft²)</td>
<td></td>
</tr>
</tbody>
</table>

The trials were made at a slightly reduced draft, altering draft related figures as follows:

Draft, molded, at trials: 21.73 m (71.3 ft)
Draft, extreme, at trials: 21.79 m (71.5 ft)
Trim in still water, at trials: 0 m
Displacement at trials: 319 400 mt (314 410 LT)

Longitudinal CG at trials; forward of amidship: 10.30 m (33.8 ft)

Engine

Propulsion Machinery

Hitachi Impulse 2-Cylinder Cross-Compound Main Steam Turbine:
- continuous full output, hp: 36 000 at 82 rpm
- service output, hp: 35 000 at 81 rpm

Main Turbine Controls (Bridge Telegraph)

<table>
<thead>
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<th>Operation</th>
<th>Program control</th>
<th>Revolution Feedback</th>
<th>Notes</th>
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<tr>
<td>ahead</td>
<td>yes</td>
<td>yes, below 60 rpm</td>
<td>rpm indicator</td>
</tr>
<tr>
<td></td>
<td>above</td>
<td>no, 60 rpm and above</td>
<td>read rpm indicator</td>
</tr>
<tr>
<td>astern</td>
<td>yes</td>
<td>yes</td>
<td>read rpm indicator</td>
</tr>
<tr>
<td>crash astern</td>
<td>no</td>
<td>no</td>
<td>astern full revolutions</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>quickly attainable</td>
</tr>
</tbody>
</table>

Propeller

Single, right-handed, 5 blades
- Diameter: 9.10 m (29.86 ft)
- Propeller pitch: 6.507 (21.35 ft)
- Expanded area: 44.33 (477.15 ft²)
- Projected area: 37.22 (400.62 ft²)
- Disk area: 65.0 (699.64 ft²)
- Pitch ratio: 0.71505
- Expanded area ratio: 0.682
- Projected area ratio: 0.572
- Rake angle: 4 deg 24 min

Notes:
- Indicates rpm indicator inaccurate
- Indicates read rpm indicator

Fig. 22 Sketches of Esso Osaka rudder, propeller, hull end profiles, and body lines
Appendix 3

Trial site selection

Selection and surveys of sites for the shallow-, medium and deepwater trials that would satisfy all requirements listed in the main text were made in two phases:

Phase I was a literature search of documented National Ocean Surveys and other bathymetry, oceanographic and meteorological data. This included discussions with university and oil company oceanographers, fisheries experts, and fishermen. The search centered on the Galveston, Mobile, Panama City, and Suwanee areas of the Gulf of Mexico and an ocean area off Georgia. This work and later survey and trial oceanographic measurements were done by oceanographers and divers of Sippican Corporation.

Phase I resulted in the preliminary selection of shallow- and medium-depth trial sites in the Galveston area within the limits of the planned Seadock deepwater port survey area, as shown in Figs. 23 and 24.

Phase II was a field confirmation of water depth, current, and sea floor topography by a precision survey of the shallow- and medium-depth sites [8]. Soundings and side-scanning sonar continuously mapped the sea floor and assured that no bottom obstruction existed. This was done just three weeks before the trials to minimize the possibility of a new obstruction arising in the interim.

These data also gave the ship's master confidence when maneuvering in shallow water in an area not usually visited by large tankers. Reference [8] also describes and illustrates the construction and deployment of 12 expendable Sippican current drifters used to check water current drifts at two depths during the bottom survey.

The criteria for the deepwater trial site were the same except that the water depth criterion was to exceed only four times the ship's draft, but be within reach for water current meter moorings. The area used was about 20 miles (32 km) south of the medium water depth area. References [7] and [8] report details of the site selection process.

Details of site selection Phases I and II were reported in detail by Sippican, and can be made available [7, 8].

Appendix 4

Trial instrumentation

Ship's heading was obtained from the gyro repeater circuit normally used to drive the starboard wing heading indicator. This circuit was connected to a step motor brought onboard for the trials. This motor receives 70-V pulses from the gyrocompass in response to heading changes in increments of 1/6 of a deg. The shaft of the step motor was coupled to an ac synchro which controlled a solid-state synchro converter to provide a dc signal proportional to ship's course.

Rudder angle was obtained by paralleling the ship's rudder angle indicator on the bridge. This ac synchro signal was input to a solid-state synchro converter, producing a dc voltage proportional to rudder angle. A rudder angle calibration was performed using the ship's quadrant as a reference. This calibration, plus checks made during the course of the trials, indicated that the data recorded were within ±0.4 deg relative to the quadrant position.

Propeller rpm was obtained from the output of a tach generator geared to the main shaft. The rpm signal, equal to 0.1 V per rpm, was input to a high-impedance operational amplifier to avoid affecting the ship's indicating system. Calibration of the rpm signal was accomplished by counting shaft revolutions for one-minute intervals while on a steady course. Repeated checks on this signal indicated an rpm accuracy of better than ±0.2 rpm.

Ship's ground speed components were obtained from the ship's MRQ2036C sonar Doppler speed indicator. The 0.25-V-per-knot signal was coupled to the recording system via an operational amplifier to avoid changing the normal operation of the Doppler system. Bow and stern lateral speeds were also obtained from the Doppler instrument. Since the lateral speed data are present only in digital form and each speed reading consists of three digits and a polarity indication, a total of 27 data lines was required to obtain these two signals. Additionally, three control lines were necessary to insure that valid data were available when the Doppler was sampled. The recording system initiated a "handshake" procedure when speed data were requested. A gate signal was transmitted to the Doppler that caused the Doppler to complete its current update cycle and hold. When the current update was completed, a flag signal was generated causing the data to be transferred to the recording system. The Doppler system was then allowed to return to its own sample rate. The gate/flag handshake cycle required less than one millisecond (ms) for completion.

Depth under the keel was obtained by modifying the Doppler sonar. The modification, accomplished by an Ametek-Straza engineer, resulted in the repetitive generation of an additional electrical pulse at the aft Doppler transducer. The time difference between this pulse and its echo was indicative of the time required for the pulse to traverse to and from the sea bottom. The recording system automatically converted each interval measured to depth in feet by allowing for the 30-deg angle of pulse travel made with the vertical and the speed of the pulse through the water on its round trip. A period of 5.47 ms, for example, would be converted to a depth of 12 ft (3.6 m). The Doppler modification performed quite well, with a valid return signal being obtained about 98 percent of the time. A larger percentage of false returns occurred during parts of the shallow-water trials when the water was clouded by large amounts of silt stirred up from the ocean floor, such as with astern rpm at very slow ship speeds.

The output of the ship's turning rate indicator was recorded, in addition to the output of a rate gyro purchased specifically for these trials. Rate gyro No. 2, with a range of ±3 deg per second, was purchased from Condor Pacific Industries as a backup for the ship unit because of the importance placed on this measurement. Measurements obtained during the trial indicated larger turning rates by the carefully calibrated Condor unit. The rate of turn, checked by calculation from the time rate of change of heading signal, indicated that the ship's turning rate indicator is in error, reading too low.

Wind velocity was measured using a DTNSRDC anemometer installed on the ship's radar mast. It was not deemed feasible to obtain wind velocity from the ship's wind measurement system since the ship's wind transmitter is a dc selsyn motor. These motors are somewhat rare in the United States and attempts to locate one were futile.

Ship position was obtained by a Decca Hi-Fix tracking system. Two Decca Survey Systems engineers operated their own equipment. Due to problems encountered attempting to interface to the Decca system, the position data were recorded on a different medium than the data obtained by the main recording system. The update rate of the tracking system was, however, controlled by the main recording system, thus providing a common time base.

Recording instrumentation

The recording speed and the number of data channels specified for these trials resulted in selection of the Hewlett-
Fig. 23 Shallow, medium, and deepwater trial sites, and moored current meter locations
Packard 9825A Desktop Computer as the controller for the recording system. The various analog and digital signals were coupled to the controller via the Hewlett-Packard 6940B Multi-programmer. The multiprogrammer was wired to collect the required data in addition to controlling the input devices via the “handshake” procedure previously described.

The permanent recording medium was a flexible disk drive. The disk drive is a random-access mass storage device with a capacity of up to 58,560 data points per diskette. With a sampling rate of once every two seconds, each diskette could contain over two hours of data.

In order to spot check the validity of all data channels during the trials, a sample of the data being recorded was printed every 40 sec on a high-speed thermal printer. This output provided a quick look at the response of the ship for the various maneuvers. By this means any suspect data channels could be quickly spotted. At the conclusion of a run additional data could be printed by accessing a special data output program.

In addition to the previously discussed data channels, time of day (hours, minutes, seconds), an event marker, and a scan interval count were also recorded during each run. The event marker provides a method of locating precise execution points of the run, such as Start Run, Execute, or End Run. The data scan number allows immediate determination of the number of times each data channel was sampled.

Installation of all equipment went smoothly with the exception of the Decca interface problem previously mentioned. No ship system malfunctions were noted as a result of the external test connections. The additional equipment and personnel in the wheelhouse did, however, cause the ambient temperature to become unbearable. This problem was solved prior to the start of the trial with the installation of a household-type window air-conditioning unit on each side of the wheelhouse. The addition of these units created a comfortable working environment for the wheelhouse personnel, and in all probability prevented instrumentation breakdowns.

Appendix 5

Water current measurements, and set and drift corrections

General

Water current measurements are difficult to make and to describe when variabilities or incoherencies in water motion...
Fig. 25  Endeco Type 105 current meter being leveled by a Sippican diver

exist and measurements are limited in space and time. The problem, difficult even in open ocean where currents are influenced primarily by winds and sloping density surfaces, is compounded in shallow water by such influences as transient winds, tidal phenomena, boundary currents and rapidly changing bottom topography.

Because of this, the physical oceanography of the continental shelves region adjacent to the major land masses out to a water depth of approximately 600 ft (183 m) has been largely neglected in favor of the deep ocean regions and the resolution of basic problems in general circulation.

Based on the high variability of currents encountered during the brief Phase II drifting buoy survey of the present program, it was decided to continuously monitor currents during the maneuvering trials of the Esso Osaka. Evaluations were made of the type and number of current measurements, the locations of current meter moorings and the logistics of the current measurement operation. The complete report by Sippican Corporation [9] discusses these considerations in detail. All decisions were made with an eye toward maximizing useful information while minimizing cost.

Instrumentation and procedures

Current meters and mooring system—Currents were measured using Eulerian current meters fixed to mooring systems. This was done because of the time variability, and the difficulty of continuously plotting drifting buoy tracks.

Endeco Type 105 current meters were chosen (Fig. 25). The meters are approximately 2.5 ft (0.76 m) in length, and the ducted impeller (fan-shaped section) is approximately 1.5 ft (0.45 m) in diameter. The meters translate impeller revolution into current speed and record the data on photographic film at half-hour intervals. Current direction is obtained from an internal magnetic compass and is recorded on photographic film at the same time as the speed data. As recorded, the current speeds constitute cumulative averages over the half-hour measurement cycle, while the directions are instantaneous and correspond to the exact time that the data are recorded on the film. The manufacturer’s stated speed accuracy is ±3 percent of full scale or approximately 0.1 knots for the speed range used during the maneuvering trials. Directional accuracy is stated as being on the order of 10 deg of the compass.

The mooring configuration used is fairly standard for shallow-water current installations and incorporates several important features. The current meters were tethered to the stainless steel mooring cable at depths of 30 and 70 ft (9 and 21 m).

The current meters used had no provision for on-scene data readout. To obtain the data record, the photographic film was processed and decoded by the manufacturer. In order to provide for some real-time current input to the maneuvering trials, an Endeco Type 110 remote reading profiling current meter was also employed. Although less accurate than the permanently moored meters, it is useful when immediate knowledge of the currents is necessary. It is also a useful device for testing point-to-point variability across an area. The profiling meter contains a pressure/depth sensor and a temperature sensor in addition to the current speed and direction sensors. To obtain a data record from the profiling meter, it is lowered from an anchored vessel using an electromechanical cable connected to an on-deck instrument panel. Readings of ocean temperature, current speed and current direction are then taken at the desired depths.

During the trials the profiling current meter was employed in both the shallow and the medium-depth areas where it was practical to anchor a small boat. The profiling meter proved a valuable supplement to the permanently moored meters and enabled collection of temperature profiles. The temperature profiles were useful in the water current data analysis because of the stratification displayed.

Mooring locations—One of the disadvantages of dealing with fixed-point measurement devices is the difficulty of relating measurements at the fixed point to the mean motion, especially in shallow-water areas. Knowledge of the currents over an area of approximately 10 mile2 (26 km2) was of interest in both the shallow and the medium-depth sites and over a somewhat larger area at the deep site.

Precise knowledge of the currents over the areas in question would have required many moorings of several current meters each. As a compromise, moorings were located as shown in Fig. 23. Two moorings per area were located one-quarter mile (0.4 km) from the area boundaries in both the shallow and the medium-depth areas. Adjacent to the deep area the two moorings were located on the 50-fathom (91.44 m) curve and separated by approximately five nautical miles.

The current meters were deployed and recovered by Sippican divers, who took the meters to the appropriate depth and attached them to the stainless steel mooring cables using the manufacturer’s clamp-and-swivel arrangement.

After maneuvering trials were completed in a given area, the meters were recovered and moved to the next area. Because of the time required for recovery and redeployment, it was often impossible to have all four current meters in place by the time maneuvering trials recommenced in a new area, but monitoring time missed was minimal.

A small, 14-ft inflatable rubber boat with a 20-hp (14.9 kW) motor was used as a diving platform. However, nearly constant support in locating the moorings and in protecting the moorings from shipping traffic was provided by Coast Guard vessels assigned to the maneuvering trials.

During the maneuvering trials two of the original moorings were lost completely and two others were at least tampered with, probably by fishing vessels. Spare mooring material was carried and jury-rig replacement mooring systems were made. No mooring with current meters attached was lost, due to the diligent efforts of the cutters Durable and Point Monroe, which maintained a continuous watch on the moorings when outfitted with current meters.
All current meters were recovered, and 100 percent data recovery was achieved for the emplacement period.

Data presentation and analysis

Profiling data—Figure 26 shows an example of profiling data collected during the maneuvering trials. Because the small boat had to be anchored when using the profiler, no profiling data were collected in the deepwater area. A total of 21 current and temperature profiles were collected from the shallow and medium-depth areas. During the trials real-time data were radioed to the tanker bridge as they became available. The following general comments can be made concerning the profiling data:

- Changes in the current structure usually corresponded well with changes in the thermal structure.
- Current speeds usually decreased with depth; however, this was not universally true.
- The shallow-water area was generally stratified into two thermal layers, the transition point occurring at 50 to 70 ft.
- The medium-depth area was generally stratified into three thermal layers, the transition points occurring at 20 to 50 ft and 60 to 80 ft.
- On a given day, correlation of current speeds and directions across the areas was good, particularly in the upper layer.

The use of the profiling current meter proved valuable in providing real-time data and allowing for thermal analysis of the areas. Based on the spatial variability revealed by the profiling data, interpolation between current meter moorings for estimates of the currents at other points in the areas is reasonable.

Moored current meter data—The most reliable current data gathered during the maneuvering trials were the moored data, because of the method of collection, that is, continuous sampling by the moored current meter system.

Digital records as decoded by the instrument manufacturer are contained in reference [9]. Data were also inspected in other formats for ease in data interpretation. Figure 27 is an example of bar graphs keyed to 45-deg sectors of the compass. This approach was used as one method of examining cross-area and shallow/deep directional correlations among current meters. The bar graphs are plots of data from the shallow MSS versus the deep M3D meters on Mooring M3, showing the generally poor directional correlation that was typical with depth.

In the Phase I site selection an analysis was made of the expected currents, using data reported in a NOAA report on the South Texas Outer Continental Shelf. In that report a comparison was made between currents measured in the Shell Oil Company Buccaneer field and currents measured at the Seadock site. Both the shallow and medium trial areas were within the Seadock site boundaries, while the Buccaneer platform was some 30 miles (48 km) distant. As reported in reference [9], similar scales of variability were observed in speed, while directional variability is more marked at the Buccaneer platform.

In reference [9] and [17] the current meter data are presented in various formats, both graphical and tabular.

Current speed and direction estimates—In order to apply the current meter data to the tanker maneuvering data, a need existed for estimates of current speed and direction, not at the current meter locations, but at the location of the tanker within the maneuvering areas. Sippican was asked to provide their best estimates of current conditions at 32 positions and times corresponding to average tanker positions during 32 maneuvering runs. The estimates provided are included with those by other methods in Table 12.

The water current estimates are essentially interpolations among current meter moorings or profiling data, or both, where appropriate. Subjective confidence estimates have been given based upon current meter accuracies, number of current meters operating, spatial coherence, distances from the moorings, etc. Estimates were not possible for all runs, because some took place before current meters were in the water.

Diver's observations—During the deployment and retrieval of the current meters and moorings, the oceanographer/divers frequently entered the water for diving operations. They observed the following:

- Thermoclines measured with the profiler were physically sensed.
- Visibility was excellent, often on the order of 50 to 75 ft except within 10 ft of the bottom, where visibility was reduced to 10 ft.
- The bottom material in both the shallow and medium-depth areas was a hard-packed gray clay.

Set and drift corrections

Three methods were used to estimate set and drift caused by water currents during the trial maneuvers. These were:

![Fig. 26 Example current velocity and temperature profiles at one location and time during the trials. Medium-depth area, 29 July, 1040 hr](image)

![Fig. 27 Shallow and deep current meter data at Mooring Location M3, showing variation with time at deep (M3D) and shallow (M3S) depths](image)

Maneuvering Trials of 278 000-DWT Tanker 273
The circular path is swept by the ship after turning 180°. The current should provide a reasonably accurate estimate of set and drift. A different effect on the unbalanced hydrodynamic force and is that at each different heading the speed gradient might have proximate set and drift. This is the case in the present trials.

In the presence of a spatially varying current, this method provides only an approximate set and drift. The reason had been the speed in the boundary-layer gradient near the seabed. Even with no other disturbances, in the case of a temporally and spatially varying current, it could cause a nonuniform set and drift. The reason is that at each different heading the speed gradient might have a different effect on the unbalanced hydrodynamic force and moment components acting on the ship.

Taking due regard of the foregoing, it is believed that if the current variations are not extreme, the estimated average current should provide a reasonably accurate estimate of set and drift.

### Doppler ground speed versus speed/rpm calibration

- **Conventional turning-circle method**—Comparisons of measured longitudinal and lateral ship’s ground speed components against the speeds derived by rpm calibration (in the same water depth) can provide components of set and drift. This determination requires an accurate speed/rpm calibration as well as steady ship motion conditions on straight path, with negligible lateral drift due to other factors (wind, propeller asymmetry, etc.). The longitudinal component of drift equals the difference between forward speed over ground measured by the Doppler log and ground speed components against the speeds derived by rpm calibration (in the same water depth) can provide components of set and drift. This determination requires an accurate speed/rpm calibration as well as steady ship motion conditions on straight path, with negligible lateral drift due to other factors (wind, propeller asymmetry, etc.).

- **Current meter method**—This method assumes that the resultant set and drift of the ship are identical to the water current speed and direction. This is exact only in the ideal case of a uniform current with respect to both time and space, and with no other disturbances. In the case of a temporally and spatially varying current, this method provides only an approximate set and drift. This is the case in the present trials. Furthermore, it is expected that even if the only nonuniformity had been the speed in the boundary-layer gradient near the seabed, it could cause a nonuniform set and drift. The reason is that at each different heading the speed gradient might have a different effect on the unbalanced hydrodynamic force and moment components acting on the ship.

- **Doppler ground speed versus speed/rpm calibration**

### Table 12: Set and drift values estimated by three methods

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Maneuver (See Note)</th>
<th>Water Depth</th>
<th>Approach Sheet (Normal)</th>
<th>Sippican Meters</th>
<th>DTNSRDC</th>
<th>Doppler Data</th>
<th>Correction Data</th>
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<tbody>
<tr>
<td></td>
<td>Shallow</td>
<td>Deep</td>
<td>Circle Data</td>
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**Selected Direction**

- **CS** = controlled stop
- **SS** = steered stop
- **L** = left
- **R** = right

**Maneuver code:**

- **T** = turn
- **AT** = accelerating turn
- **CT** = coasting turn

**Z20 = 20/20 Z-maneuver**

**Z10 = 10/10 Z-maneuver**

---

1. **Conventional turning-circle method**—This method was applied to turning circles made through 540 deg. It requires the assumption that an almost circular path is swept by the ship after turning 180 deg. The estimated set and drift values are those which must be assumed to provide a corrected path which is a continuation of the circular path defined between the headings of 180 and 360 deg.

2. **Current meter method**—This method assumes that the resultant set and drift of the ship are identical to the water current speed and direction. This is exact only in the ideal case of a uniform current with respect to both time and space, and with no other disturbances. In the case of a temporally and spatially varying current, this method provides only an approximate set and drift. This is the case in the present trials. Furthermore, it is expected that even if the only nonuniformity had been the speed in the boundary-layer gradient near the seabed, it could cause a nonuniform set and drift. The reason is that at each different heading the speed gradient might have a different effect on the unbalanced hydrodynamic force and moment components acting on the ship.

Taking due regard of the foregoing, it is believed that if the current variations are not extreme, the estimated average current should provide a reasonably accurate estimate of set and drift.

3. **Doppler ground speed versus speed/rpm calibration**

---

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Maneuvering Trials of 278 000-DWT Tanker
Appendix 6

Example time-history and path plots of *Esso Osaka* maneuvers

<table>
<thead>
<tr>
<th>Run Number 3722</th>
<th>Date: 29 July 1977</th>
<th>Time at Start: 18:12:03</th>
<th>Water Depth/Draft: 1.2</th>
<th>Wind from 015° at 11.9 knots</th>
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<tbody>
<tr>
<td><strong>SHALLOW WATER DEPTH TURNING CIRCLE</strong></td>
<td><strong>(Rudder 34°R, CONSTANT RPM)</strong></td>
<td><strong>Approach Speed = 7.2 knots</strong></td>
<td><strong>Approach RPM = 39.0</strong></td>
<td><strong>Approach Heading = 246°</strong></td>
</tr>
<tr>
<td><strong>A</strong>- Advance = 1182 m (1293 yds)</td>
<td><strong>B</strong>- Transfer = 707 m (773 yds)</td>
<td><strong>C</strong>- Tactical Diameter = 1591 m (1740 yds)</td>
<td><strong>D</strong>- Ship CG</td>
<td><strong>E</strong>- Execute Position</td>
</tr>
</tbody>
</table>

**LEGEND**

- **Ship CG**
- **Execute Position**
- **90° Change of Heading**
- **180° Change of Heading**
- **Approximately 1 min CG Points**

---

**Fig. 28** Shallow water depth turning circle

**Fig. 29** Shallow water depth turning circle

---

Appendix 7

Weather and other trial conditions

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<tr>
<td>Days out of dock</td>
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</tr>
<tr>
<td>Average water temp.</td>
<td>86 (30)</td>
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<tr>
<td>Average air temp.</td>
<td>88 (31)</td>
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Wind Conditions

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<th>Wind Direction</th>
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<td>7.3</td>
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<td>shallow</td>
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(continued)
Appendix 8

Spiral test record plots

Fig. 30 Example segment of a spiral test record in shallow water, showing time histories of rudder angle, turning rate, and depth under keel.

Fig. 31 Spiral test data in the deepwater site (h/T = 4.2), showing turning rate, \( r \), versus rudder angle.

Fig. 32 Spiral test data in the medium-depth site (h/T = 1.5), showing turning rate, \( r \), versus rudder angle.

Fig. 33 Spiral test data in the shallow-water site (h/T = 1.2), showing turning rate, \( r \), versus rudder angle.

Appendix 9

Water current effects on maneuvering

Effects of a uniform water current on ship maneuvers are not difficult to determine. A more difficult problem is to understand the effects of water currents that vary in time and space, such as generally exist in waters restricted in depth and width. As described in Appendix 5, water current surveys were made before and during the present trials, and these showed both time and space variability. In normal maneuvering, time variability is not usually a problem for a shiphandler because of the relatively short time required for individual maneuvers. But space variability can be very difficult to assess even if current diagrams are available, as they are for several waterways along U. S. coasts.

Appendix 5 shows that variability of both water current speed and direction existed with respect to depth in the present trials. How this affected ship maneuvering motions is not fully understood, and further analysis of the present trial results may be desirable. However, the corrections made in this report appear adequate for the purpose of showing the effects of main parameters.

For examples of variability, consider the water current and temperature profiles of the medium depth area shown in Fig. 26 for 29 July at 10:40 a.m. At 3-m depth (10 ft) the current direction was toward 198 deg true and the speed was 0.60 knots. But at a depth about equal to ship's draft of 21.8 m (71.5 ft) current direction was 238 deg and the speed was 0.53 knots. This means that the vessel's speed and direction relative to water
were somewhat different at different depths.

Rigorous predictions of the effects of variable water current on maneuvering are outside the present state of the art. If current speeds are weak relative to ship speed, however, an estimated “average” water current value should suffice, as was used for correcting the present trial data. A more difficult problem in maneuvering is to predict the effects of a sudden shear current of large magnitude on a vessel moving slowly ahead in a constraint waterway.

In the present trials, an excessive number of current meters would have been required to provide a good understanding of the current environment. Both the cost and the interference they would have caused with trial maneuvering were considered unacceptable.

Discussion

David Clarke, Visitor

The author is to be congratulated on the overall presentation of this paper, where he has compressed an enormous amount of valuable information into a relatively small space and still managed to keep his treatment of the subject lucid and comprehensible.

The enormous number of maneuvers performed and the great wealth of data recorded will undoubtedly make this ship and these trials into the mathematical modeler’s test piece for years to come, probably taking over the role of the Compass Island. Although a great deal of information is made available here, the author will agree that the actual time-histories of the various system states, yaw rate, sway velocity, rudder angle, and so on are what the mathematical modeler would require to be able to make the best use of all the trial data. While I realize that space precludes such data being included here, I would ask if this detailed information may be made available to other interested agencies at a later stage, as well as to those quoted in the paper, for modeling and system identification purposes. That this full-scale input to mathematical modeling is required is shown in Table 11, where the PMM model prediction shows the Esso Bernicia to have its smallest turning circle at a depth/draft ratio of 1.7. This is at variance with the three full-scale trial results cited in Table 11.

I was particularly impressed with the data acquisition system installed on board the ship for these trials. Having performed many maneuvering trials myself and having progressed, over the years, from a paper-and-pencil system through paper tape and magnetic tape and eventually to a floppy disk system, I know only too well from bitter experience the pitfalls of this type of exercise. Success can be ensured only by painstaking detailed planning, and I cannot stress firmly enough how much I appreciate the efforts of the author and his many colleagues in this area.

I was reassured, however, to find that the method which I favor myself for tidal drift correction, and which I used in the analysis of the Esso Bernicia turning circles [5], was found here to be still the most reliable technique. While performing several of the turning circles on Esso Bernicia in the shallow-water location, we also observed seabed sand or silt being drawn to the surface and marking the wake very clearly indeed. The publication of this wealth of detailed data is extremely desirable.

The 'enormous number of maneuvers performed and the great wealth of data recorded will undoubtedly make this ship and these trials into the mathematical modeler's test piece for years to come, probably taking over the role of the Compass Island. Although a great deal of information is made available here, the author will agree that the actual time-histories of the various system states, yaw rate, sway velocity, rudder angle, and so on are what the mathematical modeler would require to be able to make the best use of all the trial data. While I realize that space precludes such data being included here, I would ask if this detailed information may be made available to other interested agencies at a later stage, as well as to those quoted in the paper, for modeling and system identification purposes. That this full-scale input to mathematical modeling is required is shown in Table 11, where the PMM model prediction shows the Esso Bernicia to have its smallest turning circle at a depth/draft ratio of 1.7. This is at variance with the three full-scale trial results cited in Table 11.

1. The program of trials carried out with the Esso Osaka forms part of an intensive and continuous study effort in recent years aimed at characterizing the ability of large ships to perform harbor approach maneuvers. The contribution made by these trials is original in two respects: First, numerous trial runs were effected in particularly shallow water (h/T = 1.2), and second, the trial maneuvers were designed specifically to relate to harbor maneuvering conditions. The results obtained will be beneficial both in improving the reliability of mathematical simulation models in shallow water and in providing seamen with information directly applicable to the handling of their ships.

2. In the latter respect we note that a new factor, of great importance for the shiphandler, was taken into account in these tests, namely, the propeller bias effect with engine astern. The stopping tests underlined both the importance of the turning moment thus applied to the ship and the fact that this moment is significantly increased in shallow water. Of course the shiphandler must bear in mind that this effect can be attenuated or even reversed by the configuration of the seabed (slight slope, shoal, etc.). It is common practice to use the propeller bias effect to turn a single-propeller ship on the spot, by successive maneuvers of the engine full ahead (with rudder completely to starboard) and full astern (about 50 rpm), the ship having practically no headway. It would be interesting to define the optimum procedure for such a maneuver, as well as its duration and the dimensions of the turning area concerned.

3. Another very important aspect of the tests is that they confirm the peculiarity of behavior of a ship over depths of around h/T = 1.5. This means that the VLCC pilot must not be surprised if rudder response differs from that in deep water for depths of this order. Such depths are encountered especially in the approaches to shallow-water channels, in areas where the destabilizing effect of waves on the stern can combine with the shallow-water effect to increase the difficulty of maintaining the heading.

4. With regard to low-speed stopping distances, the trials did not confirm the tendency which seemed to be revealed by the Magdala tests, that is, a reduction of stopping distances over medium depth. With the Esso Osaka, the variation of stopping distance with depth was insignificant, and we can agree on the range of 1.8 to 2.5 ship lengths for a VLCC stopping from 4 knots.

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J. Sommel, Visitor

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5. I would like to lend my support to Mr. Cranes’s suggestion that verification tests be carried out in the large ship model


testing stations under conditions similar to those of the *Esso Osaka* tests.

Finally, we must show our gratitude to Exxon for having made available the results of this very important trial program in the shortest possible time.

John H. Lancaster, Member

[The views expressed herein are the opinions of the discusser and not necessarily those of the U. S. Coast Guard.]

I should like to commend Mr. Crane not only for the excellence and timeliness of this paper but also for the competence of his efforts and those of his company in directing the development and accomplishment of these trials, carrying out the objectives which the American Institute of Merchant Shipping, the Maritime Administration, and the Coast Guard had agreed upon. Success in a complex project of this nature is highly dependent upon quality of detailed planning and vigor of execution as well as thorough, professional knowledge.

The subject of safe passage of ships in confined and congested waters has become in recent years a subject of considerable international as well as national interest, particularly with respect to vessels carrying hazardous cargoes. This paper contains important, relevant findings. Of particular interest is the principal finding of the trials, set forth in the third paragraph of the Summary, that steering control could be maintained in all three water depths as low as 1.5 knots, even with the engine stopped. It was further noted that maneuverability is improved when rpm is quickly increased (kicking ahead) and reduced when rpm is rapidly decreased. The last two sentences which follow deserve to be memorized: "Because of this, a prudent ship handler will navigate in tight quarters at the lowest safe speed. Then if required to increase speed he will gain control, rather than risk losing it if required to slow down."

It is recognized that significant beam and quartering winds and currents normally require additional ahead vessel speed to reduce a vessel’s deviation in heading with respect to its intended course. These values are readily calculated and allowed for. The important question of how much speed is required to maintain steering control of a large tanker driven by a fixed-pitch propeller has now been answered. It should be noted that the results of the trials of the *Esso Osaka* are conditioned particularly by its propeller type and propulsion machinery characteristics. The steam turbine, reduction-gear, fixed-pitch propeller propulsion system permitted operation at any desired low speed with minimum interruption of flow to the rudder. A variable-pitch propeller system could be expected to produce somewhat different results. Fixed-pitch propeller systems with various diesel and gas turbine drives inherently are incapable of continuous operation at low power and consequently must resort to intermittent operation or tug assistance where low vessel speed is required. Caution should therefore be exercised in applying the results of the *Esso Osaka* trials to other tankers which do not have the same type of propulsion system.

Mr. Crane, Exxon International, the companies, agencies, and persons who supported and participated in these trials have made a valuable contribution to the fields of hydrodynamics and marine safety.

Ronald W. Yeung, Member

This is a fine and timely paper on a subject of much common concern and controversy: the safe operation of VLCCs in shallow water. The author is to be commended for coordinating successfully a full-scale program of such a magnitude involving sponsors of such a multitude. Results from these full-scale trials will no doubt provide the much-needed data to validate existing computer models as well as to develop guidelines for the safe operations of tankers in shallow water. Of course, one must bear in mind that this paper discusses primarily the overall response of the vessel. Much analysis remains to be done in order to extract meaningful hydrodynamic coefficients from the trial data so that a tanker-handling simulator can be developed and future vessel and control-system design may be improved.

The effect of water depth on the dynamic stability of a tanker is a well-discussed topic in the recent literature. It seems fair to conclude that the trend reversal at medium water depth, as observed from these trials, conforms well with that predicted by experiments on tanker-type hulls (for example, Fujino [18]). (Additional references follow this discussion.) Thus it will be of interest if the author can compare the present trial data that are indicative of the dynamic stability of the vessel with either pretrial predictions based on model experiments directly or predictions using model-based computer simulation. The author has noted that such comparisons were not satisfactory for the case of *Esso Bernicia*. Is this the case for *Esso Osaka* or not?

It is gratifying to see that, as the water depth varies, the spiral-test and Z-maneuver results display trends consistent with each other. The author has expounded well on this point in relation to dynamic stability. To this discusser, it seems that an equally if not more revealing observation can be made from the crossing-turn results (Fig. 7). With the propeller shut off, the effect of the rudder is downplayed; the higher initial turning rate in medium depth compared with the other depths suggests an increase in maneuverability, thus a decrease in dynamic stability. Indeed, as the vessel slows down, the rudder develops so little lift that a "control fixed" situation is practically realized. The heading reversal toward the end is indicative of the presence of dynamic instability.

The final point this discusser would like to make is in regard to the author’s recommendation that the effect of irregular boundaries and bottom on a vessel’s maneuverability be studied by the use of large hydraulic models. This is a well-established route but is also known to be prohibitively expensive. It is worthwhile to call attention to the fact that analytical tools not available heretofore are now available for evaluating the effects of irregular boundaries. Figures 34 and 35 accompanying this discussion show the calculated unsteady hydrodynamic interaction between a tanker hull and a circular obstacle. The three-dimensional analytical model used is described by Yeung [19]. The effects of the hull geometry and the keel clearance are imbedded in the theory. Figure 34, taken from Tan [20], shows the time-history of the suction force and yaw moment experienced by a vessel as she moves near a circular island. The keel clearance to water-depth ratio $\delta$ is 0.1. These results show that as the diameter of the island approaches the ship length, the maximum suction force is almost the same as that for a straight bank located at the same separation distance. The transient bow-out moment in fact could be 40 percent higher than the steady-state value corresponding to the case of a straight bank. Figure 35 shows how sensitive the force and moment patterns are to the curvature of the obstacle. As the circular "island" thins out to a finite-length breakwater, the bow-out moment changes to a bow-in moment during the approach, followed by a strong repulsion and a bow-out moment as the midship passes the obstacle. It is obvious that the aforementioned interaction phenomenon is highly relevant to ship operation in areas with submerged shoals where problems of ship control and accidents are known to be common. With the advent of such powerful tool of analysis, it seems fitting that they should be adopted and improved in parallel with the more classical means proposed by the author. The computation cost for the two figures shown here totals less than the cost incurred at an average commercial testing basin in half a day.

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Fig. 34  Force and moment coefficient for interaction with a circular island

Fig. 35  Force and moment coefficient for interaction with an elliptical island perpendicular to path
This paper deservers the interest and appreciation of everybody in the profession, and especially of those of us who are concerned with scale-model testing and computer predictions of ship behavior in confined waters. For the first time now we have access to what appears to be reliable and consistent full-scale data. The discussor would certainly welcome an arrangement by which the Esso Osaka trials could be duplicated by free-sailing as well as captive tests with a large model in the new Maritime Dynamics Laboratory (MDL) at SSPA.

As a matter of interest it may be mentioned that the main dimensions of the Exxon tanker are very close to those of the Soeoland, for which shallow-water model results were presented at the 1978 Delft Symposium on Aspects of Navigability and in the International Shipbuilding Progress Journal. A comparison of nondimensional turning circle data is given in Table 13 of this discussion. The blank spaces should be filled in with data from further tests with free-sailing models.

In particular the Esso Osaka trials do support earlier findings from model tests on the existence of a range of depths of water in which the dynamic stability is lowered. The trend toward a larger hydrodynamic damping with a reduction of underkeel clearance is still unique. In computer simulation the aforementioned phenomena may well be included provided the nonlinear variations of forces with depth are properly described. This description requires tests with captive models.

Since the advent of screw propulsion, mariners have made use of the stern-to-port effect of a backing right-handed propeller. Due to the relatively small diameter and thrust of the propeller and the large inertia of a VLCC, that same effect will here only appear at low speeds or late in a stopping maneuver. The lateral thrust interference will be enhanced, again, by the ship's own mass. Since the review of that work in reference [15] has been supplemented by a more recent survey [21] (below), the increased characteristic time scale of ship maneuvers in shallow water is readily predicted by the theoretical model, which, simply stated, predicts the characteristic time to increase in shallow water in proportion to the length/beam ratio. The increased turning radius in shallow water has been predicted by Hess [22], and the very steep increase of this theoretical radius in very shallow water appears to be consistent with the sparse experimental data in Fig. 6. On the other hand, the theory is unable to account for nonlinear effects and, as a consequence of the neutral stability at an intermediate depth, the turning radius cannot be satisfactorily predicted in this regime.

The "apparent reversal" of dynamic stability noted in the spiral tests is consistent to some extent with the theory of Hess, but even more so with the analysis of Fujino [12] based on captive model tests. This represents a modest exception to the author's claim that this effect has not been observed in prior work.

The small decrease in headreach also is consistent with the increased longitudinal added mass which is predicted in shallow water, but this is a weak effect in view of the dominant role of the ship's own mass.

I would welcome some comments from the author regarding the practical implementation of these results. The increased turning diameter and response time in shallow water can be factored into simulation, but what can be done beyond this level? It is reassuring to find that the Esso Osaka could be maneuvered at speeds as low as 1.5 knots. On the other hand, the collision in deep water off Tobago last July was the most serious reminder of the fallibility in VLCC operations.

J. N. Newman, Member

The material which is summarized in this excellent paper has been awaited eagerly by workers in the field of ship maneuvering. The successful execution of these trials is a tribute not only to the author, but to all of the individuals and organizations which participated.

Ship maneuvering in shallow water has received a substantial amount of theoretical attention during the past decade, supported in large part by several grants from the National Science Foundation and promoted by discussions in SNAME Panel H-5. The review of that work in reference [15] has been supplemented by a more recent survey [21] (below).

There is an encouraging degree of agreement between the theoretical predictions and the results in this paper. The increased characteristic time scale of ship maneuvers in shallow water is readily predicted by the theoretical model, which, simply stated, predicts the characteristic time to increase in shallow water in proportion to the length/beam ratio. The increased turning radius in shallow water has been predicted by Hess [22], and the very steep increase of this theoretical radius in very shallow water appears to be consistent with the sparse experimental data in Fig. 6. On the other hand, the theory is unable to account for nonlinear effects and, as a consequence of the neutral stability at an intermediate depth, the turning radius cannot be satisfactorily predicted in this regime.

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Table 13 35-deg right rudder turning circle data (in metres)

<table>
<thead>
<tr>
<th></th>
<th>Advance at 90-deg Heading Change</th>
<th>Tactical Diam at 180-deg Heading Change</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$h/T$ = 1.2</td>
<td>$h/T$ = 1.2</td>
</tr>
<tr>
<td></td>
<td>4.2 2.3 1.5 1.3 1.2</td>
<td>4.2 2.3 1.5 1.3 1.2</td>
</tr>
<tr>
<td><strong>TT Esso Osaka trials</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L_{pp}$ = 325.0 m</td>
<td>1015</td>
<td>1180</td>
</tr>
<tr>
<td>$B = 53.00$ m</td>
<td></td>
<td>925</td>
</tr>
<tr>
<td>$T = 21.73$ m</td>
<td></td>
<td>1075</td>
</tr>
<tr>
<td><strong>MT Soeoland trials</strong></td>
<td>1160</td>
<td>990</td>
</tr>
<tr>
<td>$L_{pp} = 321.56$ m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B = 54.56$ m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T = 21.67$ m</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>MT Soeoland SSPA model</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(free-sailing 5-m model in MDL)</td>
<td>1005</td>
<td>1120</td>
</tr>
</tbody>
</table>

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profession must intensify its efforts to minimize the probability of such casualties.

Additional references


J. B. Hooft, Member

The Netherlands Ship Model Basin, like, I presume, many other organizations working on navigation studies, is indebted to the Society's responsive project mentioned in this paper. I would like to congratulate the author for the excellent discussion of this fascinating project and the skillful presentation and analysis of results he made.

Exact information on the real-life maneuvering performances of a tanker for a range of environmental conditions being now available, it will be possible to judge the results of the ship's maneuverability as described by several mathematical simulations. In this respect, I would like to emphasize that with the use of full-scale measurements the applicability of the mathematical model can be seriously considered. Not only have full-scale trials been performed of which most mathematical models are in reasonable agreement, but also such trials have been executed which define the ship's maneuverability much more accurately while supplying better criteria than have been supplied by existing mathematical models. I think this is one of the most important reasons why the project described is of such high value.

I disagree with the idea, expressed occasionally, that a mathematical model simulation can be developed by means of, for instance, system identification techniques, when a full description of the ship's maneuvers is at one's disposal. I especially dislike this approach since a very fine description of available maneuvers will be reached, possibly, while it may be doubted that such a description is applicable to other maneuvers since no proof of the extrapolation of the description is provided.

I therefore would recommend the development of a mathematical description based on all relevant hydrodynamic phenomena which play a role in those groups of maneuvers which have to be described by the mathematical simulation. The applicability of such a mathematical model has to be proved by comparing its results with the results attained from the full-scale measurements.

Also, I would like to join with the author in a study of the conditions of the maneuvers. He has at his disposal the results that have to be simulated and compared with the mathematical model. We will provide him the results of our calculations with the mathematical model available.

As a final remark, I would like to express my high estimation of the fiscal explanations with the very specific aspects of ship maneuverability in shallow water as presented by the author.

Eugene R. Miller, Jr., Member

This paper presents the results of a carefully conducted and successful set of full-scale maneuvering trials carried out under ideal conditions. The author and the sponsoring organizations are to be congratulated on their success. It is particularly noteworthy that the trial agenda included not only the normal definitive maneuvers, but also maneuvers which demonstrate the importance of hull, rudder, and propeller interactions which affect realistic operational maneuvers.

This discussion concerns the first recommendation of the paper. That is that the results of the trials be used to validate present-day procedures for developing maneuvering mathematical models by means of model tests with captive models. This is of great importance to us at Hydronautics, Incorporated, since we routinely develop such mathematical models by captive model tests using a large-amplitude horizontal planar motion mechanism. As a result, we would like to conduct a full set of captive-model tests in the three water depths, carry out computer simulations, and make the results available if the Maritime Administration would provide for the construction of a model. In due time this offer was accepted and we have built and just finished testing a model of the Esso Osaka. The model is built of fiberglass to a scale ratio of 44.78, which results in a model length of 23.81 ft (7.25 m). A model of the propeller was also constructed. This relatively large model size was chosen so that the hull, propeller, and rudder interactions would be free from overwhelming scale effects. It is our understanding that MarAd will make this hull and propeller model available to other laboratories interested in conducting similar tests.

We have just completed the tests and have not yet carried out a final set of simulations of all of the trial maneuvers. Some preliminary comments about the test results can be made. The stability derivatives from model tests show the same effects of water depth on directional stability as the trials: that is, a high degree of directional instability at $H/T = 1.8$, a small degree of directional instability at $H/T = 1.5$, and neutral stability in deep water. The asymmetric force and moment due to propeller rotation in stopping maneuvers were observed to increase significantly with reduction in water depth and these data when used in simulations of stopping maneuvers produced predictions in good agreement with the trials. The results of the simulations of the deepwater turning and Z-maneuvers, which are most complete at this time, show remarkably good agreement with the trial results. At the shallowest depth, the tactical diameter in a simulated 35-deg rudder turn was less than 10 percent larger than the trial result. The largest differences found so far between simulation predictions and the trial results is a tendency of the simulations to underpredict the first overshoot angle in the Z-maneuver at the shallowest water depth. Thus our preliminary conclusion is that captive-model tests with large models and the associated computer simulations give good qualitative agreement with the trial results and apparently acceptable quantitative agreement. The type and extent of corrections for scale effects, if such corrections are required, are not yet clear.

In any event, the results of these trials provide an outstanding opportunity to validate the procedures used to develop maneuvering mathematical models, and I am sure the laboratories involved in this type of work will not pass up the chance.

Haruzo Eda, Member

I would like to congratulate the author for completing such an extensive full-scale trial program in deep and shallow water. The results of the trials have an important impact on further development and improvement of computer simulation models to represent realistic ship maneuvering behavior.

We have been developing computer simulation capabilities of ship motions in deep and shallow water, mainly on the basis of captive model tests. Accordingly, I would like to point out an example of correlation between full-scale trials and computer simulation results. Let us compare the turning trajectories obtained in ship trials shown in Fig. 5 of the present paper (page 256) with those obtained in computer simulations for the case of the 80 000-dwt tanker shown in Fig. 3 of the preceding paper (page 231). There is an encouraging correlation of the shallow-water effect on the turning trajectory as demonstrated in these two figures. A substantial increase in turning diameter is shown in these figures for very shallow water depth ($D_o/H$
Thomas Sartor, Member

I appreciate Mr. Crane getting so many of these papers out—bringing a lot more theoretical material of value to us who are operating ships.

We recently were out running sea trials on the Nostra Pioneer. Bethlehem Steel was very cooperative with us on this, and we were trying to determine two things which relate to Mr. Crane’s work.

First of all, I notice all the excellent detail he had to check his current situation. On our turning circles, we did not. We requested and Bethlehem agreed to give us three complete circles on each of our turning circles, and the results, which were done by Radist, are now under evaluation. The intent was that the difference between these second and third loops in a circle could be utilized as a correction factor for the first loop in determining the drift, wind factor—things of that nature.

The second thing we did—and once again the results are not yet complete—was to utilize the sea data to compare with the Radist data. We wanted to determine whether the Loran-C data are sufficiently accurate for and (for ships that are already in operation) will enable us to run with, at a convenient time, at-sea trials, whenever the master finds it convenient to do so.

So these are two practical steps pertaining to turning circles that we are hoping for, but which we do not yet have answers for.

Once again, I certainly appreciate this opportunity to tell the author of the little thing we have done in comparison with the big thing he has done.

A. D. Fletcher, Visiting Professor

This latest paper from Mr. Crane provides yet another valuable contribution toward filling the gap in our knowledge of the maneuvering characteristics of ships in shallow water, and I would like to congratulate him and all those associated with the trials.

As one representative of users of the data and equations published by Mr. Crane and others working in this field, I would like to comment on our particular requirements, which are related largely to the operational specifications and expressions of effectiveness of aids to navigation.

Our approach to such problems is a probabilistic one and it involves the need to express such probabilities as a ship’s ability to maneuver within certain physical constraints, such as a channel or the constraint depth contours off a hazard. We are, therefore, concerned with establishing the possible effective beam (Fig. 1) and maneuvering envelope for each of a number of classes of ships operating under extreme environmental conditions. We need to be able to put numbers and probabilities on all the factors which contribute toward the evaluation of the effective beam in both shallow (h/T = 1.1) and deeper (h/T = >4) water.

I must, of course, agree with Professor Yeung’s point that analytical tools are now available which can handle irregularities in bottom and side boundaries. I feel, however, that as with the large hydraulic model, these mathematical tools can also be quite expensive to develop. This is especially true if taken to the degree necessary to treat the nature of irregularities that large hydraulic models easily handle. Also, as boundary conditions become more complex, the degree of difficulty in correlating analytical results with full-scale trial data becomes greater. Therefore, at this point we will be happy even to see simple correlations regarding maneuvers in uniform shallow water.

Professor Nordbin shares the project sponsors’ interest in having the trial results duplicated with predictions based on captive-model tests. In this connection, we are aware of the excellent results presently being obtained at SSFA in the area of the effects of side boundaries on ship maneuvers. In general, however, we believe that those organizations that are most active in developing model and analytical techniques should, if possible, take the initiative in this important correlation work.

Professor Newman asked for comments regarding practical implementation of our results. In fact, from the tanker operator’s point of view, the most important present implementation work are Advance to 10° Change of Heading and Advance to 0° Yaw Angle at the stern following the application of rudder, and I look forward to the possibility of comparing our earlier evaluations with the results of these trials.

Author’s Closure

Mr. Clark has pointed out the importance of having timehistories of system states throughout maneuvers. The full report of the present trials includes charts of these for most of the maneuvers, and data on magnetic disks are retained. I do not anticipate any problem in obtaining these upon request to the Maritime Administration. Certainly we encourage any work that might be done toward improving mathematical model-to-ship correlations. In view of Mr. Clark’s extensive experience with high-quality full-scale trials, his comments are indeed appreciated.

Mr. Sommet has suggested that we are now in a position to define the optimum procedure for certain maneuvers such as “back and fill” as are done in a turning basin. I agree, but must add that this may still be most easily done using a comprehensive mathematical model, possibly in a shiphandling simulator, or a large manned physical model. In either case, an important prerequisite is a good scale-effect study through careful comparisons of model and full-scale data.

Mr. Sommet’s second point, regarding making the final approach to berth stern-first, to allow a strong corrective rudder action control if it should subsequently be necessary to go ahead, is well appreciated. This practice is, of course, now used with VLCCs and ULCCs in ports such as Cape Antifer (Le Havre). Again, such maneuvers are best optimized using a comprehensive mathematical model or large models after their validation.

With regard to the stopping maneuvers of Fig. 9, their durations were 10.7 min in shallow water, 8.9 min in medium depth, and 8.7 min in deep water.

Mr. Lancaster has gone directly to the operational significance of the paper. For example, he emphasizes points about very slow-speed maneuvering, both with and without rpm, and warns that vessels with other configurations will have somewhat different responses. Certainly, his caution about a slow-speed diesel VLCC having a higher minimum maneuvering speed is very appropriate.

I must, of course, agree with Professor Yeung’s point that analytical tools are now available which can handle irregularities in bottom and side boundaries. I feel, however, that as with the large hydraulic model, these mathematical tools can also be quite expensive to develop. This is especially true if taken to the degree necessary to treat the nature of irregularities that large hydraulic models easily handle. Also, as boundary conditions become more complex, the degree of difficulty in correlating analytical results with full-scale trial data becomes greater. Therefore, at this point we will be happy even to see simple correlations regarding maneuvers in uniform shallow water.

will be in validating the comprehensive maneuvering math models that are the basis for modern shiphandling training simulators. It is only through such correlations that the necessary degree of confidence in the simulations can be given to the shiphandler trainees. Presently there is a continuous flow of deck officers through the several real-time simulator facilities dedicated to increasing the safety of ship maneuvers and reducing the possibility of casualties. In addition, the mathematical models which these trials are aimed at improving are the basis of shiphandling studies used in the design of approach channels, in the development of bridge maneuvering information, etc. All of these can in some way be considered practical implementation of the trial results.

As usual, I agree with Dr. Hooft’s comments and here I especially appreciate the interest he expresses in joining the study of scale effects and mathematical modeling of maneuvering and coursekeeping in general.

I am very happy to hear from Mr. Miller that the correlating captive-model and computer simulations of the *Esso Osaka* maneuvers are underway and apparently producing encouraging results. In this respect, it is important that both the water depth and rpm maneuver correlations be carried as far as possible. We cannot expect perfect agreements of predictions and full-scale trial results any more than we can expect direct model tests of resistance and propulsion to produce perfect answers. In both cases, logical corrections are required, and an exchange of details regarding these will help everyone.

Dr. Eda has noted some apparent disagreement between the sketches showing drift angles in the turning circle figures and in his own simulations of these maneuvers. I should note that, to date, no attempt has been made to analyze the drift angles in the *Esso Osaka* trials, and that the sketches are not precise in this regard. After receiving Dr. Eda’s comment, I did calculate the drift angle by using the Doppler-measured forward and lateral speed in two of the turning trial maneuvers. These showed very low drift angles in the shallow water cases, as Dr. Eda has predicted. In the recommended correlations between model and full-scale studies, I would certainly hope that detailed checks of important parameters such as drift angle would be made.

Mr. Sartor noted that in recent Farrell Lines trials, three complete circles were made in turning maneuvers. While this will give a good indication of mean set and drift due to water current in deep water, it is not certain that uniform set and drift will occur in shallow water as the ship heads at different angles to the current. Also, as shown by the current meter readings in the present trials, it is possible, especially in shallow water, that the water currents will be quite different at different depths. Finally, the type of correction made for turning circles cannot be made directly in the case of Z-maneuvers. We can intersperse turning trials with other trials, however, in an attempt to get some benefit from the turning circle correction data.

Regarding Mr. Sartor’s comments on the use of Loran-C, I would note that local calibrations of Loran-C can make it accurate enough for use in maneuvering trials. The first step is to determine the accuracy of coordinate transformations in the existing Loran-C system, locally.