NAVIGATION AND VESSEL INSPECTION CIRCULAR NO. 6-95
Electronic Version for Distribution on the World Wide Web
Subj: MANEUVERING STANDARDS

1. PURPOSE. The purpose of this circular is to call attention to International Maritime Organization (IMO) Resolution A.751(18) "Interim Standards for Ship Maneuvering", and Maritime Safety Committee (MSC) Circ.644 “Explanatory Notes".

2. DIRECTIVES AFFECTED None

3. BACKGROUND.

   a. Historically, marine industry design practice regarding maneuverability qualities of ships has been limited to meeting regulatory requirements for posting bridge information, rudder size, rudder turning rate, steering gear components, and bridge visibility. Frequently, little was done in the design stages to predict maneuvering capabilities and performance characteristics. Although the need for a ship to possess 'good' maneuvering qualities has long been recognized, those qualities were never defined or quantified. As larger tankers were constructed in the 1960's and 1970's, governing bodies and the public became concerned for the safety of these ships. Studies were given high priority in 1978 following the AMOCO CADIZ accident and passage of the Port and Tanker Safety Act of 1978. The studies have shown that collisions, rammings, and groundings account for more than 70% of all vessel accidents. Instances have been recounted in published technical literature of vessels with poor maneuvering characteristics, including a vessel prone to executing unexpected 360 degree turns.

   b. In response to the heightened concern over maneuverability, the IMO Sub-Committee on Design and Equipment established a Working Group on Maneuverability of Ships and Maneuvering Standards, to consider the issues. Over a period of several years, a series of resolutions and circulars were developed to address several key areas of ship controllability including standardized bridge information requirements, guidelines for estimating maneuvering performance during ship design, and minimum standards for maneuverability.

   c. In conjunction with the work of the IMO, the Coast Guard promulgated 33 CFR 164.11(k) requiring that the pilot who is not a member of the ship's crew be provided with current information on the ship's handling capabilities. Navigation and Vessel Inspection Circular (NVIC) 7-89 disseminates IMO Resolution A.601(15), "Provision and Display of Maneuvering Information on Board Ships", and MSC/Circ.389 "Interim Guidelines for Estimating Maneuvering Performance in Ship Design." IMO Resolution A.601(15) provides information about maneuvering conditions, and introduces standardized display formats. MSC/Circ.389 provides guidance to owners and designers on defining specific characteristics which quantify maneuverability and recommends the estimation of these characteristics for both the fully loaded and test conditions in deep water.

d. Although MSC/Circ.389 addressed the problem of defining maneuvering characteristics, and their estimation during design, no specific standards for performance were discussed. IMO Resolution A.751(l8) "Interim Standards for Ship Maneuvering" recommends maneuvering performance standards, and MCS/Circ.644 "Explanatory Notes" provides guidance for the application of those standards. This circular should be used in conjunction with NVIC 7-89 as complete guidance for specifying maneuvering performance, estimating maneuvering performance, measuring maneuvering performance during sea trials, and display of maneuvering information.

4. DISCUSSION.

a. IMO Resolution A.751(18), (enclosure (1)), recommends interim standards for ship maneuverability. They apply to all oceangoing ships of all rudder and propulsion types greater than 100m in length, and chemical and gas carriers, regardless of length, which are constructed after 1 July 1994. The interim standards are also applicable to ships constructed before 1 July 1994, which undergo either a major conversion as defined by 46 USC 2101(14a), or alterations or modifications which may influence maneuverability characteristics such as changes in rudder design, steering gear, fore and aft body hull form or plan form area, and propulsion/propeller systems.

b. The proposed standards are based on the understanding that the maneuverability of ships can be evaluated from observations and measurements made during sea trial maneuvers. The standards were selected so that they are simple, practical, and do not require a significant increase in time for sea trials. It is intended that maneuvering performance be incorporated during the design phase, and that the actual maneuvering characteristics of the ship be verified for compliance during sea trials. Compliance with the interim standards can be demonstrated in the following manner.

(1) "Scale model tests and/or computer predictions using mathematical models can be performed to predict compliance at the design stage. In this case full scale sea trials should be conducted to evaluate the results. The ship should then be considered to meet these standards regardless of full scale trial results, except where the administration determines that the prediction efforts were substandard and/or the ship performance is in substantial disagreement with these standards."

(2) "The compliance with the standards can be demonstrated based on the results of full scale trials conducted in accordance with the standards. If a ship is found in substantial disagreement with the interim standard, than the administration may require remedial action."

(3) Substantial disagreement should be verified on a case by case basis through comparison of tested performance against the criterion. This comparison should consider the magnitude of disagreement that is present, and the general maneuvering qualities believed to be impaired such as stopping ability, directional stability, and turning capability. The degree of suspected directional instability should be assessed through additional spiral and pull out tests.

c. MSC/Circ.644 "Explanatory Notes to the Interim Standards for Ship Maneuverability" is provided in enclosure (2). The explanatory notes are intended to provide guidance to the designer in the application of the standards, so that adequate design estimates and sea trial data may be collected. The collection of accurate sea trial data for later review is an important element of these standards. Comparisons of design predictions against sea trial data will be collected and reviewed by the IMO Design and Equipment Sub-Committee. The criteria may then be amended on the basis of the collected data before becoming a mandatory requirement at the end of five years. Consequently, it is highly recommended that Appendix 6 of MCS/Circ.644 "Explanatory Notes to the Interim Standards for Ship Maneuverability" be utilized to report the results of both design predictions, and sea trial data.

5. IMPLEMENTATION.

a. Owners of oceangoing ships greater than 100m in length, and chemical, and gas carriers, regardless of length, which are constructed after 1 July 1994, or ships constructed before 1 July 1994, which undergo either a major conversion as defined by 46 USC 2101(14a), or alterations or modifications which may influence maneuverability characteristics such as changes in rudder design, steering gear, fore and aft body hull form or plan form area, and propulsion/propeller systems, are urged to apply the standards contained in Resolution A.751(18) and ship designers are urged to use MSC/Circ.644 for guidance.

b. Officers in Charge, Marine Inspection (OCMIs) should stress the advantages of applying the interim standards as a way to improve vessel maneuvering characteristics, and safety against collision.

c. Owners of ships applying the standards proposed in IMO Resolution A.751(18) should contact the Marine Safety Center (MSC-1) during the initial design phase and before sea trials. A design report and sea trials plan should be submitted to MSC-1. The design report should summarize the design particulars, methodology used in estimating maneuvering performance, and the performance estimates. The sea trials plan should provide the sea trials agenda, location, schedule of instrumentation, and schedule of trials personnel. On completion of the sea trials, a report containing the data and comparing the design estimates to the sea trials results and criteria should be provided. If the results of the sea trials meet the criterion of the IMO Resolution, then a compliance letter will be issued stating that the vessel meets the criteria of IMO Resolution A.751(18). The owner should annotate the wheelhouse poster, and other applicable maneuvering information onboard the ship accordingly.

d. Compliance with the IMO resolution will be reviewed and noted during Coast Guard investigation of collisions, rammings and groundings. The Coast Guard will also note compliance with the IMO resolution during boardings of foreign flag and U.S. flag vessels.

e. OCMIs are encouraged to bring enclosures (1) and (2) to the attention of owners, operators, and designers in their zones.

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Enclosure (1) to NVIC 6--95

INTERNATIONAL MARITIME
ORGANIZATION

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RESOLUTION A.751(18)
adopted on 4 November 1993

INTERIM STANDARDS FOR SHIP MANEUVERABILITY

THE ASSEMBLY,

RECALLING Article 15(j) of the Convention on the International Maritime Organization concerning the functions of the Assembly in relation to regulations and guidelines' concerning maritime safety and the prevention and control of marine pollution from ships,

RECALLING FURTHER that by MSC/Circ.380. the Maritime Safety Committee approved interim guidelines for estimating maneuvering performance ,.in ship design, whereby Member Governments were invited to apply the guidelines on a trial basis so that they may be assessed in the light of practical experience gained with a view to their possible further development,

RECALLING ALSO resolutions A.160(ES.IV), A.209(VII) and A.501(15) ,concerning information on ship manoeuvring,

RECOGNIZING the manoeuvring capability of ships to be an important contribution to the safety of navigation,

BELIEVING that the development and implementation of standards for ship manoeuvrability, particularly to large ships and ships carrying dangerous goods in bulk, will improve maritime safety and enhance marine environment protection, HAVING CONSIDERED the recommendations made by the Maritime Safety Committee at its sixty-second session,

1. ADOPTS the Interim Standards for Ship Manoeuvrability, set out in the Annex to the present resolution;

2. RECOMMENDS Governments to encourage those responsible for the design, construction1 repair and operation of ships to apply the Standards;

3. INVITES Governments to collect data obtained by the application of the Standards and report them to the Organization;

4. REQUESTS the Maritime Safety Committee to keep the Standards under review on the basis of the information and data collected;

5. AUTHORIZES the Maritime Safety Committee to amend the Standards as necessary.

ANNEX

INTERIM STANDARDS FOR SHIP MANOEUVRABILITY

1 Principles

1.1 The standards should be used with the aim of improving ship manoeuvring performance and with the objective of avoiding building ships that do not comply with the criteria.

1.2 The standards contained in this document are based on the understanding that the manoeuvrability of ships can be evaluated from the characteristics of conventional trial manoeuvres. The following two methods can be used to demonstrate compliance with these standards:

.1 Scale model tests and/or computer predictions using mathematical models can be performed to predict compliance at the design stage. In this case full-scale trials should be conducted to validate these results. The ship should then be considered to meet these standards regardless of full-scale trial results, except where the Administration determines that the prediction efforts were substandard and/or the ship performance is in substantial disagreement with these standards:

.2 The compliance with the standards can be demonstrated based on the results of the full-scale trials conducted in accordance with the standards. If a ship is found in substantial disagreement with the interim standards, then the Administration may require remedial action.

1.3 The standards presented herein are considered interim for a period of 5 ~ from the date of their adoption by the Assembly. The standards and method of establishing compliance should be reviewed in the light of new information and the results of experience with the present standards and ongoing research and developments.

2 Application

2.1 The standards should be applied to ships of all rudder and propulsion types of 100 m in length and over, and chemical tankers and gas carriers regardless of the length, which are constructed on or after 1 July 1994.

2.2 In case ships referred to in paragraph 2.1 undergo repairs, alterations and modifications which in the opinion of the Administration may influence their manoeuvrability characteristics the continued compliance with the standards should be verified.

2.3 Whenever other ships, originally not subject to the standards, undergo repairs, alterations and modifications, which in the opinion of the Administration are of such an extent that the ship may be considered to be a new ship, then that ship should comply with these standards. Otherwise, if the repairs alterations and modifications in the opinion of the Administration may influence the manoeuvrability characteristics, it should be demonstrated that these characteristics do not lead to any deterioration of the manoeuvrability of the ship.

2.4 The standards should not be applied to the high speed craft as defined in the relevant Code.

3 Definitions

3.1 Geometry of the ship

.1 Length (L) is the length measured between the aft and forward perpendiculars:

.2 Midship point is the point on the centreline of a ship midway between the aft and forward perpendiculars,'
.3 Draught (Ta) is the draught at the aft perpendicular;
.4 Draught (Tf) is the draught at the forward perpendicular;
.5 Mean draught (Tm) is defined as Tm (Ta + Tf)/2.
3.2 Standard manoeuvres and associated terminology

Standard manoeuvres and associated terminology are as defined below:

.1 The test speed (V) used in the standards is a speed of at least 90% of the ship's speed corresponding to 85% of the maximum engine output.

.2 Turning circle manoeuvre is the manoeuvre to be performed to both starboard and port with 350 rudder angle or the maximum rudder angle permissible at the test speed, following a steady approach with zero yaw rate.

.3 Advance is the distance traveled in the direction of the original course by the midship point of a ship from the position at which the rudder order is given to the position at which the heading has changed 900 from the original course.

.4 Tactical diameter is the distance traveled by the midship point of a ship from the position at which the rudder order is given to the position at which the heading has changed 1800 from the original course. It is measured in a direction perpendicular to the original heading of the ship.

.5 Zig-zag test is the manoeuvre where a known amount of helm is applied alternately to either side when a known heading deviation from the original heading is reached.

.6 100/100 zig-zag test is performed by turning the rudder alternately by l0~ to either side following a heading deviation of l0~ from the original heading in accordance with the following procedure:

  .1 after a steady approach with zero yaw rate, the rudder is put over to l0~ to starboard/port (first execute);

  .2 when the heading has changed to 10. off the original heading$_1$ the rudder is reversed to l0~ to port/starboard (second execute);

  .3 after the rudder has been turned to port/starboard the ship will continue turning in the original direction with decreasing turning rate. In response to the rudder, the ship should then turn to port/starboard. When the ship has reached a heading of l0~ to port/starboard of the original course the rudder is again reversed to 10. to starboard/port (third execute).

.7 The first overshoot angle is the additional heading deviation experienced in the zig-zag test following the second execute.

.8 The second overshoot angle is the additional heading deviation experienced in the zig-zag test following the third execute.

.9 200/200 zig-zag test is performed using the procedure given in .6 above using 20~ rudder angles and 200 change of heading, instead of 100 rudder angles and l0~ change of heading, respectively.

.1.0 Full astern stopping test determines the track reach of a ship from the time an order for full astern is given until the ship stops in the water.

.11 Track reach is the distance along the path described by the midship point of a ship measured from the position at which an order for full astern is given to the position at which the ship stops in the water.

4 Standards

4.1 The standard manoeuvres should be performed without the use of any manoeuvring aids, which are not continuously and readily available in normal operation.

4.2 Conditions at which the standards apply

In order to evaluate the performance of a ship$_1$ manoeuvring trials should be conducted to both port and starboard and at conditions specified below:

.1 deep, unrestricted water;

.2 calm environment;

.3 full load, even keel condition;

.4 steady approach at the test speed.

4.3 Criteria

The manoeuvrability of the ship is considered satisfactory, if the following criteria are complied with:

.1 Turning ability

The advance should not exceed 4.5 ship lengths (L) and the tactical diameter should not exceed 5 ship lengths in the turning circle manoeuvre;

.2 Initial turning ability

With the application of l0~ rudder angle to port/starboard, the ship should not have traveled more than 2.5 ship lengths by the time the heading has changed by 10^0 from the original heading;

.3 Yaw checking and course keeping abilities

.1 The value of the first overshoot angle in the $10^0/10^0$ zig-zag test should not exceed:

- l0^0, if L/V is less than 10 seconds;
- 20^0, if LIV is 30 seconds or more; and
- (5 +.l/2 (L/V)) degrees, if L/V is 10 seconds or more but less than 30 seconds,

where L and V are expressed in m and m/s, respectively;

.2 The value of the second overshoot angle in the 100/100 zig-zag test should not exceed the above criterion values for the first overshoot by more than l5~;

.3 The value of the first overshoot angle in the 20~,200 zig-zag test should not exceed 25~;

.4 Stopping ability

The track reach in the full astern stopping test should not exceed 15 ship lengths. However, this value may be modified by the Administration where ships of large displacement make this criterion impracticable.

5 Additional considerations

5.1 In case the standard trials are conducted at a condition different from those specified in 4.2.3 necessary corrections should be made in accordance with the guidelines contained in the explanatory notes on the standards for ship manoeuvrability developed by the Organization.

5.2 Where standard manoeuvres indicate dynamic instability, alternative test may be conducted to define the degree of instability. Guidelines for alternative tests such as a spiral test or pull-out manoeuvre are included in the explanatory notes on the standards for ship manoeuvrability developed by the Organization.

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EXPLANATORY NOTES TO THE INTERIM STANDARDS FOR SHIP MANOEUVRABILITY

1 The Assembly, at its eighteenth session, adopted resolution A.751(18) -Interim Standards for Ship Manoeuvrability. In adopting the standards, the Assembly recognized the necessity of developing appropriate explanatory notes for the uniform interpretation, application and consistent evaluation of the standards during the interim period.

2 The Maritime Safety Committee, at its sixty-third session (15 to 25 May 1994), approved the Explanatory Notes to the Interim Standards for Ship Manoeuvrability (resolution A.751(18)), set out in the annex to the present circular, as prepared by the Sub-Committee on Ship Design and Equipment at its thirty-seventh session.

3 The Explanatory Notes are intended to provide Administrations with specific guidance so that adequate data may be collected by the Organization on the manoeuvrability of ships. It is the intent of the Maritime Safety Committee to fully evaluate these data with the purpose of reviewing and amending the Standards as necessary.

4 Member Governments are invited to use the Explanatory Notes when applying the Standards contained in resolution A.751(18), and to report the data obtained to the Organization using the form for reporting data contained in appendix 5 of the Explanatory Notes.

ANNEX

EXPLANATORY NOTES TO THE INTERIM STANDARDS FOR SHIP MANOEUVRABILITY

Contents

EXPLANATORY NOTES TO THE INTERIM STANDARDS FOR SHIP MANOEUVRABILITY

CHAPTER 1 - GENERAL PRINCIPLES

1.1 Philosophy and background

The purpose of this section is to provide guidance for the application of the Interim Standards for Ship Manoeuvrability (resolution A.751(18)) along with the general philosophy and background for the Standards.

Manoeuvring performance has traditionally received little attention during the design stages of a commercial ship. A primary reason has been the lack of manoeuvring performance standards for the ship designer to design to, and for regulatory authorities to enforce. Consequently some ships have been built with very poor manoeuvring qualities that have resulted in marine casualties and pollution. Designers have relied on the shiphandling abilities of human operators to compensate for any deficiencies in inherent manoeuvring qualities of the hull. The implementation of manoeuvring standards will ensure that ships are designed to a uniform standard, so that an undue burden is not imposed on shiphandlers in trying to compensate for deficiencies in inherent ship manoeuvrability.

IMO has been concerned with the safety implications of ships with poor manoeuvring characteristics since the meeting of the Sub-Committee on Ship Design and Equipment (DE) in 1958. MSClCirc.389 titled "Interim Guidelines for Estimating Manoeuvring Performance in Ship Design", dated 10 January 1985, encourages the integration of manoeuvrability requirements into the ship design process through the collection and systematic evaluation of ship manoeuvring data. Subsequently, the Assembly$_1$ at its fifteenth session in November 1987, adopted resolution A.501(l5), entitled "Provision and Display of Manoeuvring Information on board Ships". This process culminated at the eighteenth Assembly in November 1993, where "Interim Standards for Ship Manoeuvrability" were adopted by resolution A.751(18).

The Standards were selected so that they are simple, practical and do not require a significant increase in trials time or complexity over that in current trials practice. The Standards are based on the premise that the manoeuvrability of ships can be adequately judged from the results of typical ship trials manoeuvres. It is intended that the manoeuvring performance of a ship be designed to comply with the Standards during the design stage, and that the actual manoeuvring characteristics of the ship be verified for compliance by trials. Alternatively, the compliance with the Standards can be demonstrated based on the results of full-scale trials, although the Administration may require remedial action if the ship is found in substantial disagreement with the Standards. Upon completion of ship trials, the shipbuilder should examine the validity of the manoeuvrability prediction methods used during the design stage.

1.2 Manouvering characteristics

The “manoeuvring characteristics” addressed by the. IMO Interim standards for ship manoeuvrability are typical measures of performance quality and handling ability that are of direct nautical interest. Each can be reasonably well predicted at the design stage and measured or evaluated from simple trial-type manoeuvres.

1.2.1 Manoeuvring characteristics: general

In the following discussion, the assumption is made that the ship has normal actuators for the control of forward speed and heading (i.e., a stern propeller and a stern rudder). However, most of the definitions and conclusions also apply to ships with other types of control actuators.

In accepted terminology, questions concerning the manoeuvrability of a ship include the stability of steady-state motion with “fixed controls" as well as the time-dependent responses that result from the control actions used to maintain or modify steady motion, make the ship follow a prescribed path or initiate an emergency manoeuvre, etc. Some of these actions are considered to be especially characteristic of ship .manoeuvring performance and therefore should be required to meet a certain minimum standard. A ship operator may choose to ask for a higher standard in some respect, in which case it should be remembered that some requirements may be mutually incompatible within conventional designs. For similar reasons the formulation of the 'NO Interim standards for ship manoeuvrability has involved certain compromises.

1.2.2 Manoeuvring characteristics: some fundamentals

At a given engine output and rudder angle δ, the ship may take up a certain steady motion. In general, this will be a turning motion with constant yaw rate Ψ, speed V and drift angle β (bow-in). The radius of the turn is then defined by the following relationship, expressed in consistent units:

R = V / ⇁

This particular ship-rudder angle configuration is said to be "dynamically stable in a turn of radius R". Thus, a straight course may be viewed as part of a very wide circle with an infinite radius, corresponding to zero yaw rate.

Most ships. perhaps, are "dynamically stable on a straight course" (usually referred to as simply "dynamically stable") with the rudder in a neutral position close to midship. In the case of a single screw ship with a right-handed propeller, this neutral helm is typically of the order ✎$_0$ = -1$_0$ (i.e.. -1$_0$ to starboard). Other ships which are dynamically unstable. however, can only maintain a straight course by repeated use of rudder control. While some instability is fully acceptable, large instabilities should be avoided by suitable design of ship proportions and stern shape.

The motion of the ship is governed mainly by the propeller thrust and the hydrodynamic and mass forces acting on the hull. During a manoeuvre, the side force due to the rudder is often small compared to the other lateral forces. However, the introduced controlling moment is mostly sufficient to balance or overcome the resultant moment of these other forces. In a steady turn there is complete balance between all the forces and moments acting on the hull. Some of these forces seeming to "stabilize" and others to "destabilize" the motion. Thus the damping moment due to yaw, which always resists the turning, is stabilizing and the moment associated with the side force due to sway is destabilizing. Any small disturbance of the equilibrium attitude in the steady turn causes a change of the force and moment balance. If the ship is dynamically stable in the turn (or on a straight course) the net effect of this change will strive to restore the original turning (or straight) motion.

The general analytical criterion for dynamic stability may be formulated and evaluated with the appropriate coefficients of the mathematical model that describes the ship's motion. The criterion for dynamic stability on a straight course includes only four "linear stability derivatives" which, together with the center-of-gravity position, may be used ~o express the "dynamic stability lever". This lever denotes the longitudinal distance from the center-of-pressure of the side force due to pure sway (or sideslip) to the position of the resultant side force due to pure turning, including the mass force, for small deviations from the straight-line motion. If this distance is positive (in the direction of positive x, i.e.

towards the bow) the ship is stable. Obviously "captive tests" with a ship model in oblique towing and under the rotating arm will furnish results of immediate interest.
The value of the dynamic stability lever typically varies from 0.1L (where L is ship length) for a stable, fine form cargo liner to -0.1L for a full form wide-beam tanker. It is understood that a change of trim will have a marked effect mainly on the location of the center-of-pressure of the side force resulting from sway. This is easily seen that a ship with a stern trim, a common situation in ballast trial condition, is likely to be much more stable than it would be on an even draught.

Figure 1 gives an example of the equilibrium yaw-rate/rudder angle relation for a ship which is inherently dynamically unstable on a straight course. The yaw rate is shown in the non-dimensional form for turn path curvature discussed above. This diagram is often referred to as "the spiral loop curve" because it may be obtained from spiral tests with a ship or model. The dotted part of the curve can only be obtained from some kind of reverse spiral test. Wherever the slope is positive, which is indicated by a tangent sloping down to the right in the diagram, the equilibrium balance is unstable. A ship which is unstable on a straight course will be stable in a turn despite the rudder being fixed in the midship or neutral position. The curvature of this stable turn is called "the loop height" and may be obtained from the pullout manoeuvre. Loop height, width and slope at the origin may all be regarded as a measure of the instability.

If motion is not in an equilibrium turn, which is the general case of motion, there are not only unbalanced damping forces but also hydrodynamic forces associated with the added inertia in the flow of water around the hull. Therefore, if the rudder is left in a position the ship will search for a new stable equilibrium, indicated by the arrows and small circles shown in figure 1. If the rudder is shifted (put over “to the other side") the direction of the ship on the equilibrium turning curve is reversed and the original yaw tendency will be checked. By use of early counter-rudder it is fully possible to control the ship on a straight course with helm angles and yaw rates well within the loop.

The course-keeping ability or "directional stability" obviously depends on the performance of the closed loop system including not only the ship and rudder but also the course error sensor and control system. Therefore, the acceptable amount of inherent dynamic instability decreases as ship speed increases, covering more ship lengths in a given period of time. This results because a human helmsman will face a certain limit of conceptual capacity and response time. This fact is reflected in the IMO Interim standards for ship manoeuvrability where the criterion for the acceptable first overshoot in a zig-zag test includes a dependence on the ratio L/V, a factor characterizing the ship "time constant" and the time history of the process.

In terms of control engineering, the acceptable inherent instability may be expressed by the "phase margin" available in the open loop. If the rudder is oscillated with a given amplitude, ship heading also oscillates at the same frequency with a certain amplitude. Due to the inertia and damping in the ship dynamics and time delays in the steering engine, this amplitude will be smaller with increasing frequency, meaning the open loop response will lag further and further behind the rudder input. At some certain frequency, the "unit gain" frequency, the response to the counter-rudder is still large enough to check the heading swing before the oscillation diverges (i.e., the phase lag of the response must then be less than 180^0). If a manual helmsman takes over the heading control, closing the steering process loop, a further steering lag could result but, in fact, he will be able to anticipate the swing of the ship and thus introduce a certain "phase advance". Various studies suggest that this phase advance may be of the order of 10. to 20~. At present there is no straightforward method available for evaluating the phase margin from routine trial manoeuvres.

Obviously the course-keeping ability will depend not only upon the counter-rudder timing but also on how effectively the rudder can produce a yaw checking moment large enough to prevent excessive heading error amplitudes.. The magnitude of the overshoot angle alone is a poor measure for separating the opposing effects of instability and rudder effectiveness, additional characteristics should therefore be observed. So, for instance, "time to reach second execute", which is a measure of "initial turning ability", is shortened by both large instability and high rudder effectiveness.

It follows from the above that a large dynamic instability will favour a high "turning ability" whereas the large yaw damping, which contributes to a stable ship, will normally be accompanied by a larger turning radius. This is noted by the thin full-drawn curve for a stable ship included in figure 1.

Hard-over turning ability is mainly an asset when manoeuvring at slow speed in confined waters. However, a small advance and tactical diameter will be of value in case emergency collision avoidance manoeuvres at normal service speeds are required.

The "crash-stop" or "crash-astern" manoeuvre is mainly a test of engine functioning and propeller reversal. The stopping distance is essentially a function of the ratio of astern power to ship displacement. A test for the stopping distance from full speed has been included in the Standards in order to allow a. comparison with hard-over turning results in terms of initial speed drop and lateral deviations.

1.2..3 Manoeuvring characteristics: selected quality measures

The IMO Interim standards for ship manoeuvrability identify six significant qualities for the evaluation of ship manoeuvring characteristics. Each has been discussed above and is briefly defined below:

.1 Inherent dynamic stability: A ship is dynamically stable on a straight course if it, after a small disturbance, soon will settle on a new straight course without any corrective rudder. The resultant deviation from the original heading will depend on the degree of inherent stability and on the magnitude and duration of the disturbance.

.2 course-keeping ability: The course-keeping quality is a measure of the ability of the steered ship to maintain a straight path in a predetermined course direction without excessive oscillations of rudder or heading. In most cases, reasonable course control is still. possible where there exists an inherent dynamic instability of limited magnitude.

.3 Initial turning/course-changing ability: The initial turning ability is defined by the change-of-heading response to a moderate helm, in terms of heading deviation per unit distance sailed (the P number) or. in terms of the distance covered before realizing a certain heading deviation (such as the "time to second execute" demonstrated when entering the zig-zag manoeuvre).

.4 Yaw checking ability: The yaw checking ability of the ship is a measure of the response to counter-rudder applied in a certain state of turning, such as the heading overshoot reached before the yawing tendency has been canceled by the counter-rudder in a standard zig-zag manoeuvre.

.5 Turning ability: Turning ability is the measure of the ability to turn the ship using hard-over rudder. The result being a minimum "advance at 90. change of heading" and "tactical diameter" defined by the "transfer at l80^0 change of heading". Analysis of the final turning diameter is of additional interest.

.6 Stopping ability: Stopping ability is measured by the "track reach" and "time to dead in water" realized in a stop engine-full astern manoeuvre performed after a steady approach at full test speed. Lateral deviations are also of interest, but they are very sensitive to initial conditions and wind disturbances.

1.3 Tests required by the standards

1.3.1 Turning tests

A turning circle manoeuvre is to be performed to both starboard and port with 35~ rudder angle or the maximum design rudder angle permissible at the test speed. The rudder angle is executed following a steady approach with zero yaw rate. The essential information to be obtained from this manoeuvre is tactical diameter, advance, and transfer (see figure 2).

1.3.2 Zig-zag tests

A zig-zag test begins by applying a specified amount of rudder angle to an initially straight approach ("first execute"). The rudder angle is then alternately shifted to either side after a specified deviation from the ship's original heading is reached ("second execute" and following) (see figure 3).

Two kinds of zig-zag tests are included in the Standards, the $10^0/10^0$ and $20^0/20^0$ zig-zag tests. A $10^0/10^0$ zig-zag test uses rudder angles of 10^0 to either side following a heading deviation of 10^0 from the original course. A $20^0/20^0$ zig-zag test uses 20^0 rudder angles coupled with a 20^0 change of heading from the original course. The essential information to be obtained from these tests is the overshoot angles, initial turning time to second execute and the time to check yaw.

1.3.3 Stopping tests

A full astern stopping test is used to determine the track reach of a ship from the time an order for full astern is given until the ship is stopped dead in the water (see figure 4).

CHAPTER 2 - GUIDELINES FOR THE APPLICATION STANDARDS

2.1 Conditions at which the standards apply

2.1.1 General

Compliance with the manoeuvring criteria should be evaluated under the standard conditions in paragraph 4.2 of the Interim standards for ship manoeuvrability. The standard conditions provide a uniform and idealized basis against which the inherent manoeuvring performance of all ships may be assessed.

The Standards cannot be used to evaluate directly manoeuvring performance under non-standard, but often realistic, conditions'. The establishment of manoeuvrability standards for ships under different operating conditions is a complex task that deserves attention in the future. Research is currently under way to establish methods for accurately predicting and assessing manoeuvrability in non-standard operating conditions.

2.1.2 Deep, unrestricted water

Manoeuvrability of a ship is strongly affected by interaction with the bottom of the waterway, banks and passing vessels. Trials' should therefore be conducted preferably in deep, unconfined but sheltered waters. The water depth should exceed four times the mean draught of the ship.

2.1.3 Full load and even keel condition

The Standards apply to the full load and even keel condition. The term "fully loaded" refers to the situation where the ship is loaded to its summer load line draught (referred to hereafter as "full load draught"). This draught is chosen based on the general understanding that the poorest manoeuvring performance of a ship occurs at this draught. The full load draught, however, is not based on hydrodynamic considerations but rather statutory and classification society requirements for scantlings, freeboard and stability. The result being that the final full load draught might not be known or may be changed as a design develops.

Where it is impractical to conduct trials at full load because of ship type, trials should be conducted as close to full load draught and zero trim as possible. Special attention should also be given to: ensuring that sufficient propeller immersion exists in the trial 'condition.'

Where trials are conducted in conditions' other than full load, manoeuvring characteristics should be predicted for, trial and full load conditions using a reliable method (i.e. model tests or reliable' 'computers simulation) that ensures satisfactory extrapolation of trial' results to'. the full load condition. It rests with the designer/owner to demonstrate compliance at the final full load condition.

2.1.4 Metacentric height

The Standards apply to a situation where the ship is loaded to the minimum metacentric height for which it is designed at the full load draught.

2.1.5 Calm environment

Trials should be held in the calmest weather conditions possible. Wind, waves and current can significantly affect trial results, having a more pronounced effect on smaller ships. The environmental conditions should be accurately recorded before and after trials so that corrections may be applied. Specific environmental guidelines are outlined in 2.2.1.2.1.

2.1.6 Steady approach at the test speed

The required test speed is defined in paragraph 3.2.1 of the Interim standards for ship manoeuvrability.

2.2 Guidance for required trials and validation

2.2.1 Test procedures

2.2.1.1 General

The test procedures given in the following guidelines were established to support the application of the manoeuvring standards by providing to shipyards and other institutions standard procedures for the testing trials of new ships, or for later trials made to supplement data on manoeuvrability. This guidance includes trial procedures that need to be performed in order to provide sufficient data for assessing ship manoeuvring behavior against the defined criteria.

2.2.1.2 Test conditions

2.2.1.2.1 Environment

Manoeuvring trials should be performed in the calmest possible weather conditions. The geographical position of the trial is preferably in a deep sea, sheltered area where accurate positioning fixing is possible. Trials should be conducted in conditions within the following limits:

.1 Deep unrestricted water: more than 4 times the mean draught.

.2 Wind: not to exceed Beaufort 5.

.3 Wave: not to exceed sea state 4.

.4 Current: uniform only.

Correction may need to be applied to the test results following the guidance contained in 3.4.2.

2.2.1.2.2 Loading

The ship should preferably be loaded to the full load draught and even keel, however, a 5% deviation from that draught may be allowed and trim may deviate from-even keel up to 5% of the full load draught.

Alternatively, the ship may be in a ballast condition with a minimum of trim, and sufficient propeller immersion.

2.2.1.2.3 Ship speed

The test speed is defined in paragraph 3.2.1 of the Interim standards.

2.2.1.2.4 Heading

Preferably head to the wind during the approach run.

2.2.1.2.5 Engine

Engine control setting to be kept constant during the trial if not otherwise stated in following procedures.

2.2.1.2.6 Approach run

The above-mentioned conditions must be fulfilled for at least two minutes preceding the test. The ship is running at test speed up wind with minimum rudder to keep its course.

2.2.1.3 Turning circle manoeuvre

Trials shall be made to port and to starboard using maximum rudder angle without changing engine control setting from the initial speed. The following general procedure is recommended:

.1 The ship is brought to a steady course and speed according to the specific approach condition.

.2 The recording of data starts.

.3 The manoeuvre is started by ordering the rudder to the maximum rudder angle. Rudder and engine controls are kept constant during the turn.

.4 The turn continues until 360^0 change of heading has been completed. It is, however, recommended that in order to fully assess environmental effects a 720^0 turn be completed (paragraph 3.4.2 refers).

.5 Recording of data is stopped and the manoeuvre is terminated.

2.2.1.4 Zig-zag manoeuvre

The given rudder and change of heading angle for the following procedure is 10^0. This value can be replaced for alternative or combined zig-zag manoeuvres by other angles such as 20^0 for the other required zig-zag test. Trials should be made to both port and starboard. The following general procedure is recommended:

.1 The ship is brought to a steady course and speed according to the specific approach condition.

.2 The recording of data starts.

.3 The rudder is ordered to 10^0 to starboard/port.

.4 When the heading has changed by 10^0 off the base course, the rudder is shifted to 10^0 to port/starboard. The ship’s yaw will be checked and a turn in the opposite direction (port/starboard) will begin. The ship will continue in the turn and the original heading will be crossed.

.5 When the heading is 10^0 port/starboard off the base course, the rudder is reversed as before.

.6 The procedure is repeated until the ship heading has passed the base course no less than two times.

.7 Recording of data is stopped and the manoeuvre is terminated.

2.2.1.5 Stopping test

Full astern is applied and the rudder maintained at midship throughout this test. The following general procedure is recommended:

.1 The ship is brought to a steady course and speed according to the specific approach condition.

.2 The recording of data starts.

.3 The manoeuvre is started by giving a stop order. The full astern engine order is applied.

.4 Data recording stops and the manoeuvre is terminated when the ship is stopped dead in the water.

2.2.2 Recording

For each trial, a summary of the principal manoeuvring information should be provided in order to assess the behavior of the ship.

Continuous recording of data should be either manual or automatic using analog or digital acquisition units. In case of manual recording, a regular sound/light signal for synchronization is advisable.

2.2.2.1 Ship's particulars

Prior to trials, draughts forward and aft should be read in order to calculate displacement, longitudinal center of gravity, draughts and metacentric height. In addition the geometry, projected areas and steering particulars should be known. The disposition of the engine, propeller, rudder, thruster and other device characteristics should be stated with operating condition.

2.2.2.2 Environment

The following environmental data should be recorded before each trial:

.1 Water depth.

.2 Waves: The sea state should be noted. If there is a swell, note period' and direction.

.3 Current: The trials should be conducted in a v.11 surveyed area and the condition of the current noted from relevant hydrographic data. Correlation shall be made with the tide.

.4 Weather: Weather conditions, including visibility, should be observed and noted.

2.2.Z.3 Trial related data

The following data as applicable for each test should be measured and recorded during each test at appropriate intervals of not more than 20 s:

Position
Heading
Speed
Rudder angle and rate of movement
Propeller speed of revolution
Propeller pitch
Wind speed

A time signal should be provided for the synchronization of all recordings. specific events should be timed, such as trial starting-point, engine/helm change, significant changes in any parameter such as crossing ship course, rudder to zero or engine reversal in operating condition such as ship speed and shaft/propeller direction.

2.2.2.4 Presentation of data

The recordings should be analyzed to give plots and values for significant parameters of the trial. Sample recording forms are given in appendix 6. The manoeuvring criteria of the Standards should be evaluated from these values. Data should also be presented as in appendix 2 of resolution A.601(15) for turning and stopping manoeuvres.

CHAPTER 3 - PREDICTION GUIDANCE

3.1 General

To be able to assess the manoeuvring performance of a new vessel at the design stage, it is necessary to predict the vessel's manoeuvring behavior on the basis of main dimensions, lines drawings and other relevant information available at the design stage.

A variety of methods for prediction of manoeuvring behavior at the design stage exists, varying in the accuracy of the predicted manoeuvres and the cost of performing the prediction. In practice most of the predictions at the design stage have been based on three methods.

The first and simplest method is to base the prediction on experience and existing data, assuming that the manoeuvring characteristics of the new ship will be close to those of similar existing ships.

The second method Is to base the prediction on results from model tests. At the time these notes were written, model tests must be considered the most reliable prediction method. However, it may be said that traditionally the requirements with regard to accuracy have been somewhat more lenient in this area than in other areas of ship model testing. The reason for this has simply been the absence of manouvering standards The feedback of full-scale trial results has generally been less regular in this area than in the case of speed trials. Consequently the correlation basis for manoeuvrability is therefore of a somewhat lower standard, particularly for hull forms that may present a problem with regard to steering and manoeuvring characteristics. It is expected that this situation will improve very rapidly when it becomes generally known that a standard for ship manoeuvrability is going to be introduced. Model tests are described in section 3.2.

The third method is to base the prediction on results from calculation/simulation using a mathematical model. The numerical values of the characteristic coefficients appearing in this mathematical model are largely based on the analysis of the results of so-called captive scale model tests, derived from force measurements on models of varying forms. It may be said that many of the mathematical models in existence give reasonably accurate results for conventional not too full hull forms. Such hull forms seldom present problems with regard to steering and manoeuvring. Applied to the ships that are poor in the manoeuvrability database, existing mathematical models seem to achieve a lower level of reliability. In such cases it is recommended that special captive model tests be performed for the new design. As in the case of model tests an improvement in reliability is expected for mathematical models in the near future. Mathematical models are described in section 3.3.

3.2 Model tests

There are two commonly used model test methods available for prediction of manoeuvring characteristics. One method employs a free-running model moving in response to specified control input (i.e. helm and propeller); the tests duplicate the full-scale trial manoeuvres and so provide direct results for the manoeuvring characteristics. The other method makes use of force measurements on a "captive" model[1] forced to move in a particular manner with controls fixed; the analysis of the measurements provides the coefficients of a mathematical model, which may be used for the prediction of the ship response to any control input.

3.2.1 Manoeuvring test with free-running model

The most direct method of predicting the manoeuvring behavior of a ship is to perform representative manoeuvres with a scale model.

To reduce costs by avoiding the manufacture of a special model for manoeuvring tests, such tests may be carried out with the same model employed for -resistance and self-propulsion tests. Generally it means that a relatively large model will be used for the manoeuvring tests, which is also favorable with regard to reducing scale effects of the results.

The large offshore, seakeeping and manoeuvring basins are well suited for manoeuvring tests with free-running models provided they have the necessary acquisition and data processing equipment. In many cases, conventional towing tanks are wide enough to allow the performance of the $10^0/10^0$ zig-zag test. Alternatively. tests with a free-running model can be conducted on a lake. In this case measuring equipment must be installed and the tests will be dependent on weather conditions.

Both laboratory and open-air tests with free-running models suffer from scale effects, even if these effects to a certain extent will be reduced by using a large model for the tests. Sometimes it has been attempted to compensate for scale effects by means of an air propeller on board the model. Another improvement is to make the drive motor of the ship model simulate the characteristics of the main engine of the ship with regard to propeller loading.

Manoeuvres such as turning circle, zig-zag and spiral tests are carried out with the free-running model, and the results can be compared directly with the standard of manoeuvrability.

More recently, efforts have been made at deriving the coefficients of mathematical models from tests with free-running models. The mathematical model is then used for predicting the manoeuvring characteristics of the ship. Parameter identification methods have been used and this procedure has been combined with oblique towing and propulsion tests to provide some of the coefficients

3.2.2 Manoeuvring tests with captive model

Captive model tests include oblique-towing tests in long narrow tanks as well as "circling" tests in rotating-arm facilities. but in particular such tests are performed by the use of a Planar Motion Mechanism (PMM) system capable of producing any kind of motion by combining static or oscillatory modes of drift and yaw. Generally, it may be said that captive model tests suffer from scale effects similar to those of the free-running tests, but corrections are more easily introduced in the analysis of the results.

In using captive model tests due account of the effect of roll during manoeuvring should be taken.

The PMM has its origin in devices operating in the vertical plane and used for submarine testing. The PMM makes it possible to conduct manoeuvring tests in a conventional long and narrow towing tank. The basic principle is to conduct various simpler parts of more complex complete manoeuvres. By analysis of the forces measured on the model the manoeuvring behavior is broken down into its basic elements, the hydrodynamic coefficients. - The hydrodynamic coefficients are entered into a computer based mathematical. model and the results of the standard manoeuvres are predicted by means of this mathematical model.

A rotating arm facility consists of a circular basin, spanned by an arm from the center to the circumference. The model is mounted on this arm and moved in a circle, varying the diameter for each test. The hydrodynamic coefficients related to ship turning as well as to the combination of turning and drift will be determined by this method. Additional tests often have to be conducted in a towing tank in order to-determine hydrodynamic coefficients related to ship drift. As in the case of the PMM the manoeuvring characteristics of the ship are then predicted. by means of a mathematical model using the coefficients derived from the measurements. as input.

3.2.3 Model test condition

The Standards are applicable to the full load condition of the ship. The model tests should therefore be performed for this condition. For many ships the delivery trials will be made at a load condition different from full load. It will then be necessary to assess the full load manoeuvring characteristics of the ship on the basis of the results of manoeuvring trials performed at a condition different from full load. To make this assessment as reliable as possible the model tests should also be carried out for the trial condition, meaning that this condition must be specified at the time of performing the model tests. The assumption will be that when there is an acceptable agreement between model test results and ship trial results in the trial condition, the model test results for the loaded condition will then be a reliable basis for assessing the manoeuvring characteristics of the ship.

3.3 Mathematical model

A "mathematical model" is 8 set of equations which can be used to describe the dynamics of a manoeuvring ship. In this section, the method used to predict the manoeuvring performance of a ship at full load for comparison with the Standards is explained.

The following details of the mathematical model are indicated:

(1) when and where to use
(2) how-to use
(3) accuracy level of predicted results

3.3.1 Application of the mathematical model

In general, the manoeuvring performance of the ship must be checked by a sea trial to determine whether it satisfies the manoeuvring standards or not. The Standards are regulated in full load condition from the viewpoints of marine safety. consequently it is desired that the sea trial for any ship be carried out in full load condition. This may be a difficult proposition for ships like a dry cargo ship, for which the sea trial is usually carried out in ballast or heavy ballast conditions from the practical point of view.

In such cases, it will be required to predict the manoeuvring performance in full load condition by means of some method that uses the results of the sea trial. As an alternative to scale model tests, usually conducted during the ship design phase, a numerical simulation using a mathematical model is a us full method for predicting ship manoeuvring performance. in full load condition.

3.3.2 Prediction method using a mathematical model

There are many types of mathematical models for predicting ship manoeuvrability, and in general, each one of them has merits and demerits for application from the point of accuracy. Therefore it would be very difficult to pick out and select any one method as the best mathematical model. It is a well-known fact that there are still some problems to be solved, and it is required in the near future to develop a more accurate method for predicting ship manoeuvrability. But it may be possible to predict the manoeuvrability for the conventional ship's form with certain accuracy from the practical point of view using some mathematical models which have already been published.

3.4 Corrections from non-standard trial conditions

3.4.1 Loading condition

In the case for predicting manoeuvrability of a ship in full load condition using the mathematical model through the sea trial results in ballast or heavy ballast condition, the following two methods are used in current practice.

Option 1:

-The manoeuvrinq performance in full load condition can be obtained from the criteria of measured performance during the sea trial in ballast condition (T) and the interaction factor between the criteria of manoeuvrability in full load condition and in a trial condition (F/B), that is as given below:

$$R = TF/B$$

where,

B: the estimated performance in the condition of sea trial based on the numerical simulation using the mathematical model or on the model test.

F: the estimated performance in full load condition based on the numerical simulation using the mathematical model or on the model test.

T: the measured performance during the sea trial.

R: the performance of the ship in full load condition.

Option 2:

The manoeuvring performance in the condition of sea trial such as ballast or heavy ballast are predicted by the method shown in appendix 2, and the predicted results must be checked with the results of the sea trial.

Afterwards it should be confirmed that both results agree well with each other. The performance in full load condition may be obtained by means of the same method using the mathematical model.

3.4.2 Environmental conditions

Ship manoeuvrability can be significantly affected by the immediate environment such as wind, waves, and current. Environmental forces can cause reduced course keeping stability or complete loss of the ability to maintain a desired course. They can also cause increased resistance to a ship's forward motion, with consequent demand for additional power to achieve a given speed.

When the ratio of wind velocity to ship speed is large, wind has an appreciable effect on ship control. The ship may be unstable in wind from some directions. Waves can also have significant effect on course-keeping and manoeuvring. It has been shown that for large wave heights a ship may behave quite erratically and, in certain situations, can lose course stability..

Ocean current affects manoeuvrability in a manner somewhat different from that of wind. The effect of current is usually treated by using the relative velocity between the ship and the water. Local surface current velocities in the open ocean are generally modest and close to constant in the horizontal plane.

Therefore, trials shall be performed in the calmest weather conditions possible. In the case that the minimum weather conditions for the criteria requirements are not applied, the trial results should be corrected.

Generally, it is easy to account for the effect of constant current. The turning circle test results may be used to measure the magnitude and direction of current. The ship's track, heading and the elapsed time should be recorded until at least. a 720^0 change of heading has been completed. The data obtained after ships heading change 180. are used to estimate magnitude and direction of the current. Position (x_{1i}, y_{1i}, t_{1i}) and (x_{2i}, y_{2i}, t_{2i}) in figure 5 are the positions of the ship measured after a heading rotation of 360^0. By defining the local current velocity $\underline{V}_i$ for any two corresponding positions as

$$\underline{V}_i = \frac{(x_{2i} - x_{1i},\ y_{2i} - y_{1i})}{(t_{2i} - t_{1i})} ;$$

the estimated current velocity can be obtained from the following equation:

$$\underline{V}_c = \frac{1}{n} \sum_{i=1}^{n} \underline{V}_i = \frac{1}{n} \sum_{i=1}^{n} \frac{(x_{2i} - x_{1i},\ y_{2i} - y_{1i})}{(t_{2i} - t_{1i})} .$$

If the constant time interval, $\delta t = (t_{2i} - t_{1i})$, is used this equation can be simplified and written:

$$\underline{V}_c = \frac{1}{n\delta t} \left(\sum_{i=1}^{n} x_{2i} - \sum_{i=1}^{n} x_{1i},\ \sum_{i=1}^{n} y_{2i} - \sum_{i=1}^{n} y_{1i} \right) .$$

Actually, the above vector, $\underline{V}_C$ obtained from a 720^0 turning test will also include the effect of wind and waves.

The magnitude of the current velocity and the root mean square of the current velocities can be obtained from the equations:

$$V_c = | \underline{V}_c |$$

$$V_c(\mathrm{RMS}) = \left[\frac{1}{n} \sum_{i=1}^{n} | \underline{V}_i - \underline{V}_c |^2 \right]^{1/2}$$

V_C(RMS) represents the non-uniformity of V_i which may be induced from wind, waves, and non-uniform current.

All trajectories obtained from the sea trials should be corrected as follows:

$$\underline{x}'(t) = \underline{x}(t) - \underline{V}_C t$$

where $\underline{x}$ (t) is the measured position vector and $\underline{x}'$(t) is the corrected one of the ship and $\underline{x}'(t) = \underline{x}(t)$ at t=0

3.5 Uncertainties

3.5.1 Accuracy of model test results

In most cases, the model will turn out to be more stable than the ship due to scale effects. This problem seems to be less serious when employing a large model. Consequently, to reduce this effect model scale ratios comparable to that considered acceptable for resistance and self-propulsion tests should be specified for manoeuvring tests that use a free-running model. Captive model tests can achieve satisfactory results with smaller scale models.

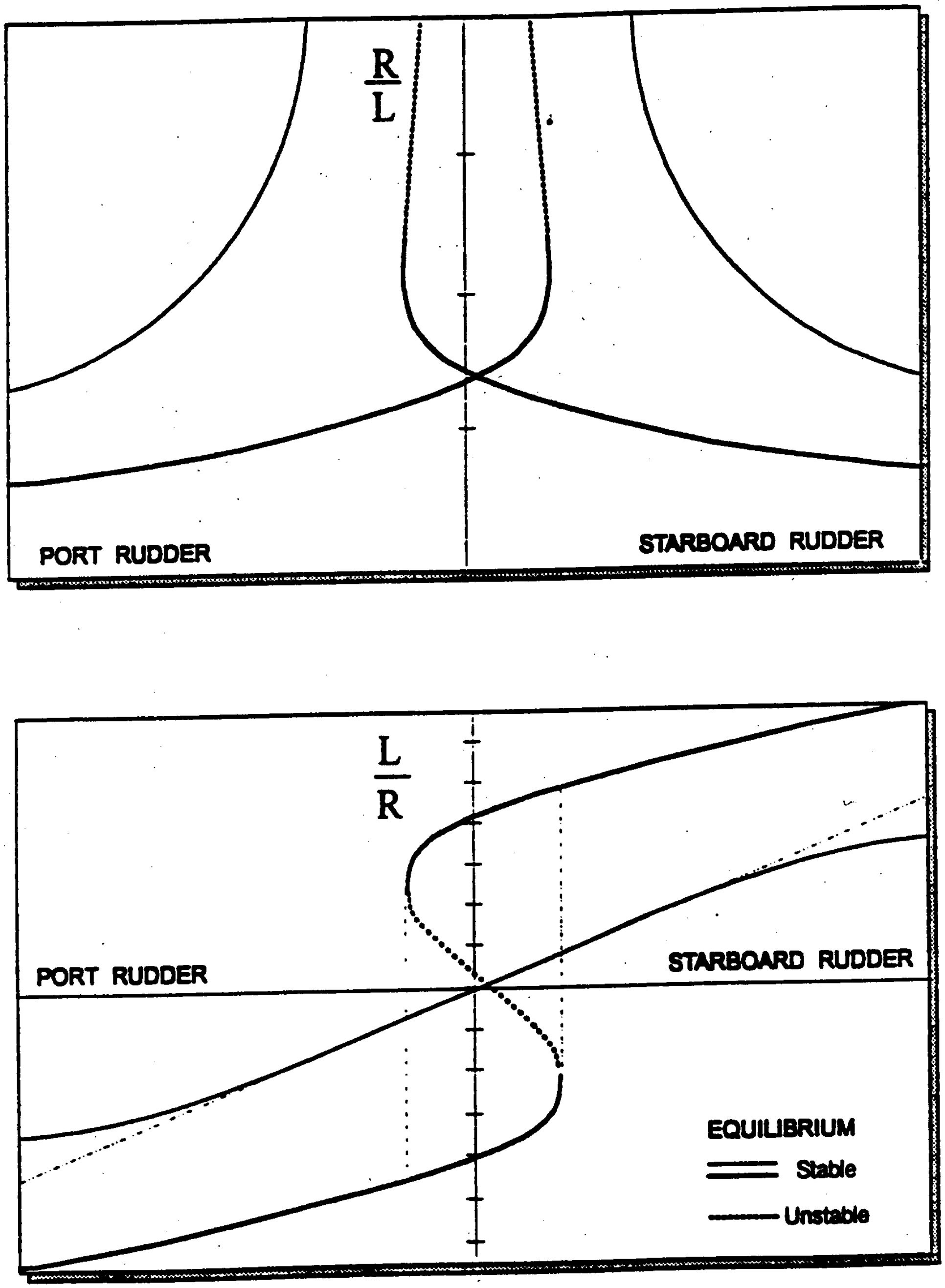
While the correlation data currently available are insufficient to give reliable values for the accuracy of manoeuvring model test results$_1$ it is the intent of the Standards to promote the collection of adequate correlation data during the interim period.

3.5.2 Accuracy of predicted results using the mathematical model

The mathematical model that can be used for the prediction of the manoeuvring performance depends on the type and amount of prepared data.

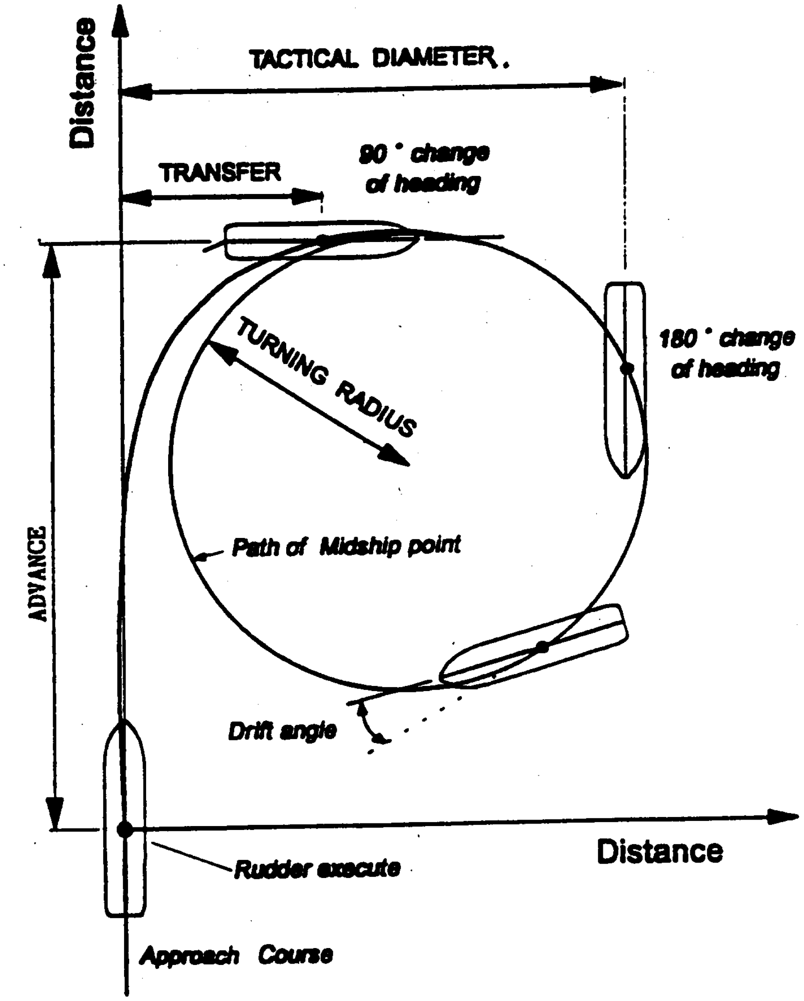
If there is no available data, under assumptions that resistance and self-propulsion factors are known, a set of approximate formulae for estimation of the derivatives and coefficients in the mathematical model will become necessary to predict the ship's manoeuvrability.

If there is enough experimental and accumulated data, it is desirable to use a detailed mathematical model based, on this data. In most cases the available data is not sufficient and a mathematical model can be obtained by a proper combination of different parts derived from experimental data and those obtained by the estimated formulae.



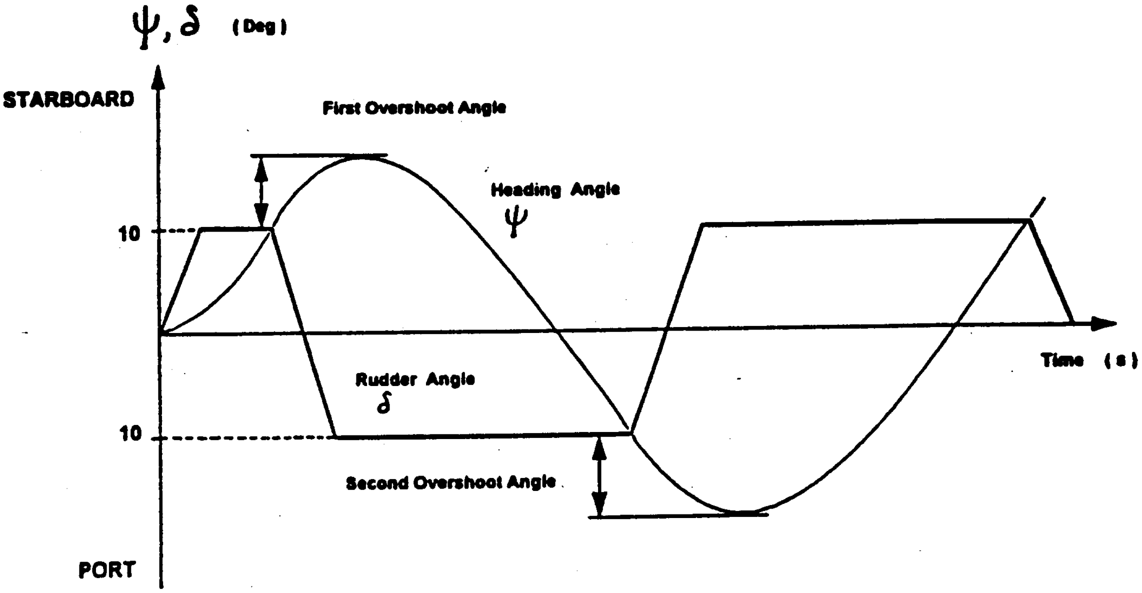
THE EQUILIBRIUM YAW RATE/RUDDER ANGLE RELATION

FIGURE 1



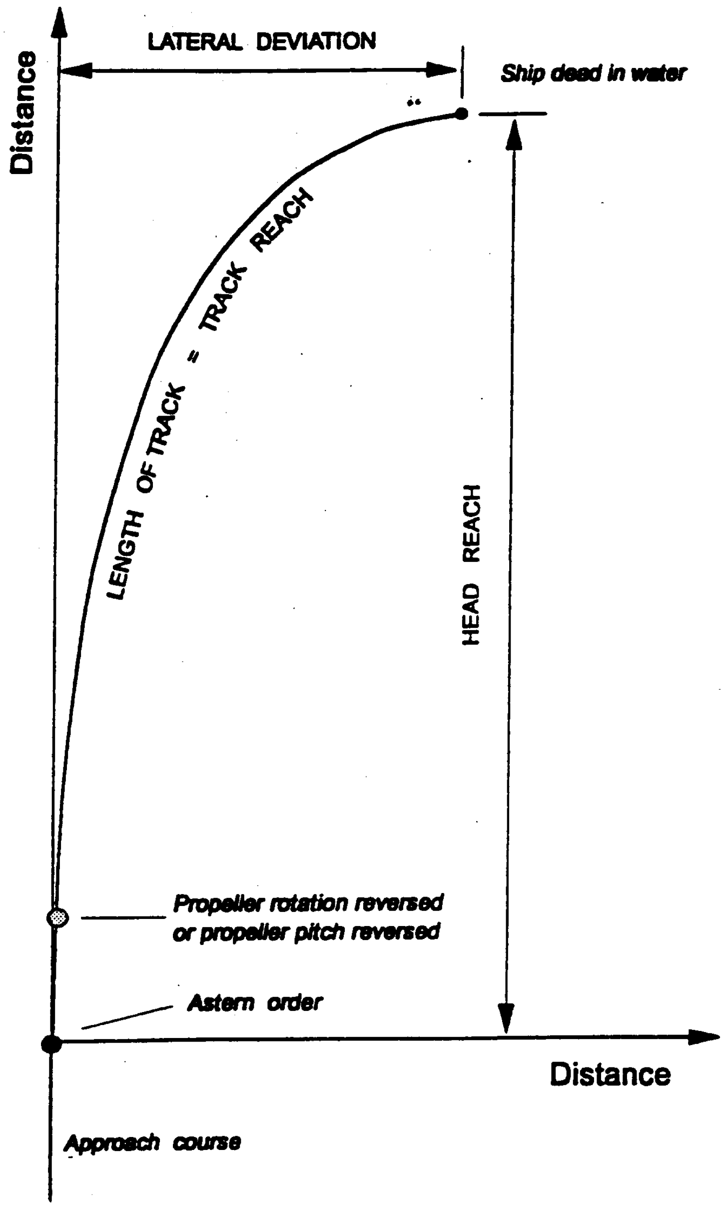
DEFINITIONS USED ON TURNING CIRCLE TEST

FIGURE 2



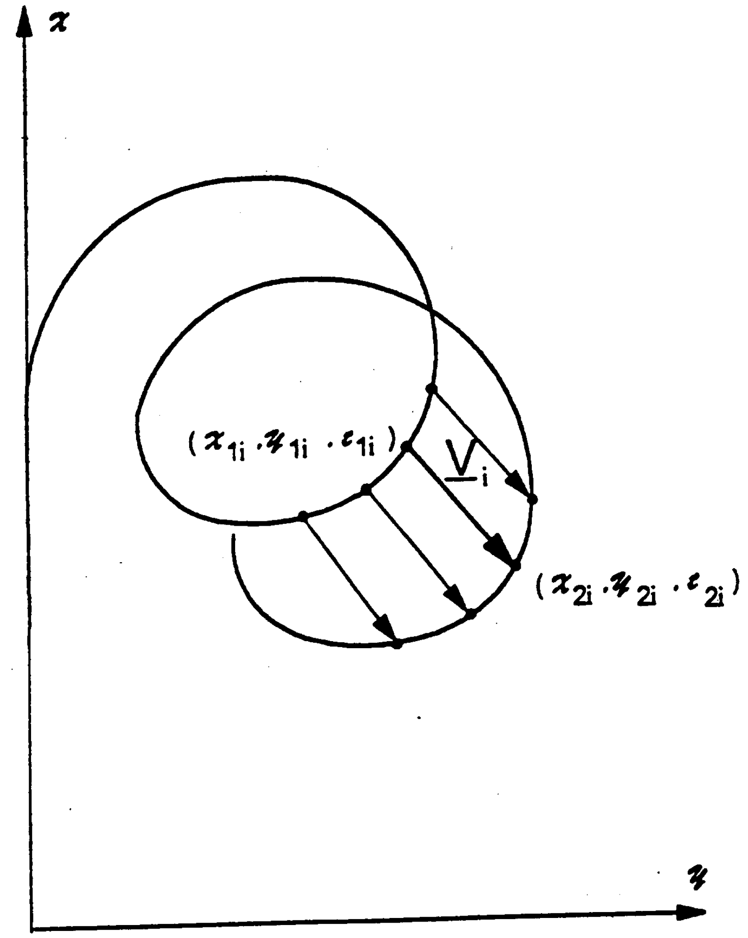
ZIG-ZA; 10°/10°TEST

FIGURE 3



DEFINITIONS USED IN STOPPING TEST

FIGURE 4



TURNING TRAJECTORY IN WIND, WAVES AND CURRENT

FIGURE 5

APPENDIX 1 - NOMENCLATURE

A.1.l Nomenclature and reference systems

The manoeuvres of a surface ship may be seen to take place in the x_0y_0-plane of a right-handed system of axes $0_0(x_0y_0z_0)$ "fixed in space", the z_0-axis of which is pointing downwards in the direction of gravity. For the present discussion let the origin of this system coincide with the position at time t = 0 of the midship point 0 of the ship, and let the x_0-axis be pointing in the direction of ship's heading at the same moment. the y_0-axis pointing to starboard. The future orientation of the ship in this system is given by its heading angle ψ, its angle of pitch θ, and its angle of roll Φ. (See figure Al-l.)

In calm conditions with no tide or current ship speed through water (V) equals the speed over the ground. and the progress along the ship track is equal to the time integral

$$\int V dt.$$

This distance may conveniently be expressed by the number of ship-lengths sailed, i.e. by the non-dimensional time

$$t' = \int_0^t (V/L)dt.$$

In general the ship's heading deviates from the direction of the speed vector by the sideslip or drift angle β. The advance and transfer parallel to and at right angles to the original line of course (and ideal line of approach) are given by the integrals

$$X_0(t) = \int_0^t V\cos(\psi-\beta)dt$$

$$Y_0(t) = \int_0^t V\sin(\psi-\beta)dt.$$

Mathematical models of ship dynamics involve expressions for the forces acting an the hull. usually separated in their components along the axes of a system O(xyz) moving with the body. The full six-degrees-of-freedom motion of the ship may be defined by the three components of linear velocities (u,v,w) along the body axes, and by the three components of angular velocities (p.q.r) around these axes. Again. for the present discussion it is sufficient to consider the surface ship, moving with forward velocity U and sway velocity v in the O(xy) plane. and turning with yaw velocity r around the s-axis normal to that plane. On these assumptions the speed $V = (u^2+v^2)^{1/2}$, the drift angle is $\beta = -\tan^{-1}(v/u)$ and the yaw rate is equal to the time rate of change of heading angle ψ, i.e.

$$r = \frac{d}{dt}\psi = \psi.$$

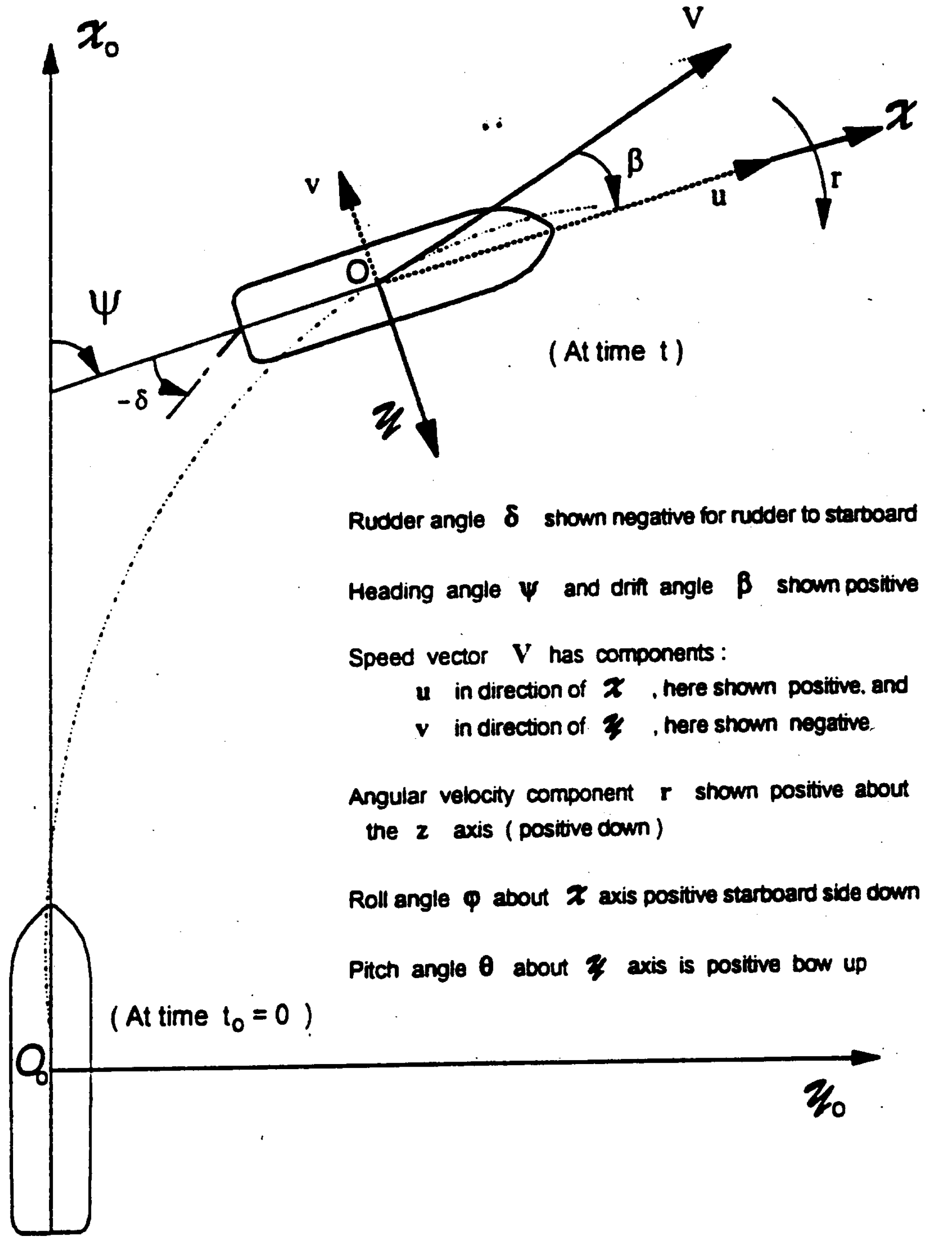
The non-dimensional yaw rate in terms of change of heading (in radians) per ship length sailed is

$$r' = \frac{d}{dt'}(\psi) = \psi' = (L/V)\psi$$

which is also seen to be the non-dimensional measure of the instantaneous curvature of the path of this ship LIR.

Many ships will experience a substantial rolling velocity and roll angle during a turning manoeuvre, and it is understood that the mathematical model used to predict the manoeuvring characteristics should then include the more stringent expressions as appropriate.

Further information can b. found in section 3.2 of the Interim standards for ship manoeuvrability



Rudder angle δ shown negative for rudder to starboard

Heading angle ψ and drift angle β shown positive

Speed vector V has components :
u in direction of x , here shown positive, and
v in direction of y , here shown negative.

Angular velocity component r shown positive about the z axis (positive down)

Roll angle φ about x axis positive starboard side down

Pitch angle θ about y axis is positive bow up

SURFACE SHIP WITH BODY AXES O(xyz) MANOEUVRING WITHIN
SPACE-FIXED INERTIAL FRAME WITH AXES $O_o(x_oy_oz_o)$

FIGURE A1-1

APPENDIX 2 - GENERAL VIEW OF PREDICTION OF MANOEUVRING PERFORMANCE

A mathematical model of the ship manoeuvring motion can be used as one of the effective methods to check whether a ship satisfies the manoeuvrability standards or not, by a performance prediction at the full load condition and from the results of the sea trial in a condition such as ballast.

Existing mathematical models of ship manoeuvring motion are classified into two types. One of the models is called a 'response model', which expresses a relationship between input as the control and output as its manoeuvring motion. The other model is called a ‘hydrodynamic force model', which based on the hydrodynamic forces that include the mutual interferences. By changing the relevant force derivatives and interference coefficients composed of a hydrodynamic force model, the manoeuvring characteristics due to a change in the ship's form of loading condition can be estimated.

Furthermore, a hydrodynamic force model is helpful for understanding the relationship between manoeuvring performance and ship form than a response model from the viewpoint of design. Considering these situations, this Appendix shows the prediction method using a hydrodynamic force model. Certainly. the kind of mathematical model suitable for prediction of the performance depends on the kind of available data. Presently, there are many kinds of mathematical models.

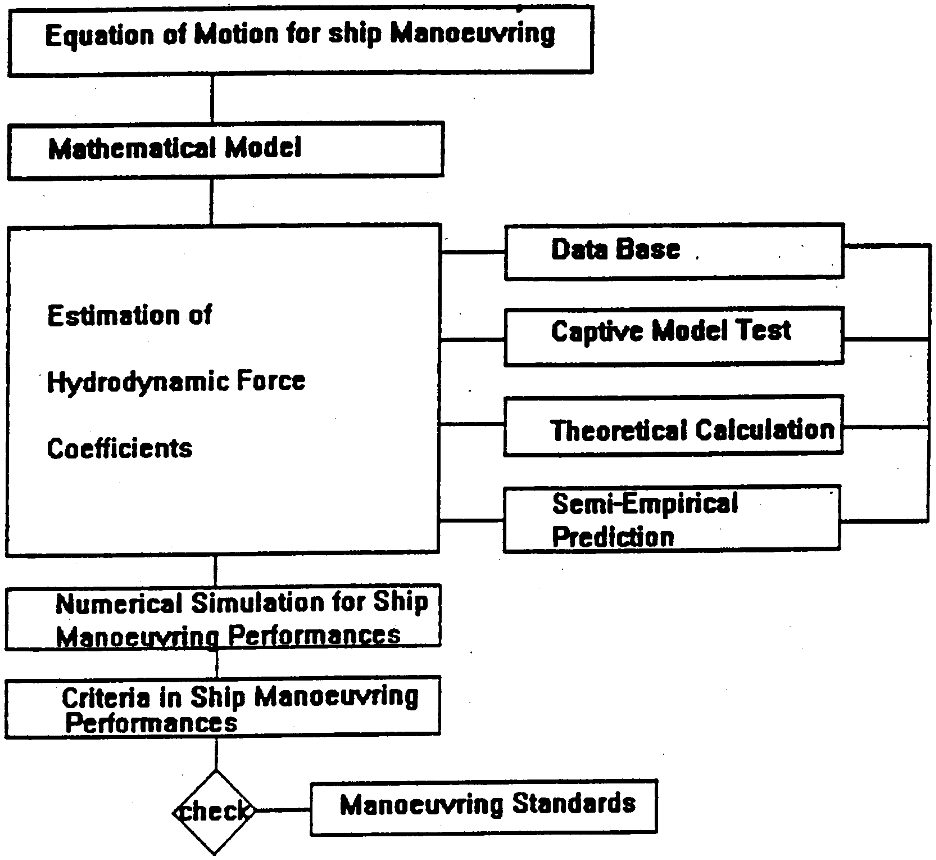
In figure A2-l, the flow chart of prediction method of ship manoeuvring performance using a hydrodynamic force model is shown. There are in general various expressions of a hydrodynamic force model in current practice, though their fundamental ideas based on hydrodynamic considerations have little difference. Concerning the hydrodynamic force acting on a ship in manoeuvring motion, they are usually expressed as a polynomial term of motion variables such as the surge, sway and angular yaw velocities.

The most important and difficult work in performance prediction is to estimate such derivatives and parameters of these expressions to compose an equation of a ship manoeuvring motion. These hydrodynamic force coefficients and derivatives may usually be estimated by the method shown in figure A2-l.

The coefficients and derivatives can be estimated by the model test directly, by data based on the data accumulated in the past. by theoretical calculation and semi-empirical formulae based on any of these methods. There is also an example that uses approximate formulae for estimation derived from a combination of theoretical calculation and empirical formulae based on the accumulated data. The derivatives which are coefficients of hydrodynamic forces acting on a ship's hull, propeller and rudder are estimated from such parameters as ship length, breadth, mean draught, trim and the block coefficient. Change of derivatives due to a change in the load condition may be easily estimated from the changes in draught and trim.

As mentioned above, accuracy of manoeuvring performance predicted by a hydrodynamic force model depends on accuracy of estimated results by hydrodynamic forces which constitutes the equation of a ship manoeuvring motion. Estimating the hydrodynamic derivatives and coefficients will be important to raise accuracy as a whole while keeping. consistency of relative accuracy among various hydrodynamic forces.

A stage in which theoretical calculations can provide all of the necessary hydrodynamic forces with sufficient accuracy has not yet been reached. Particularly, non-linear hydrodynamic forces and mutual interferences are difficult to estimate with sufficient accuracy by pure theoretical calculations. Thus, empirical formulae and databases are often used, or incorporated into theoretical calculations.



FLOW CHART FOR PREDICTION OF SHIP
MANOEUVRING PERFORMANCE

FIGURE A2-1

APPENDIX 3 - STOPPING ABILITY OF VERY LARGE SHIPS

It is stated in the Interim standards for ship manoeuvrability that the track reach in the. full astern stopping test may be modified from 15 ship lengths[1] at the discretion of the Administration, where ship size and form make the criterion impracticable. The following example and information given in tables A3-1, 2 and 3 indicate that the discretion of the Administration is only likely to be required in the case of large tankers.

The behavior of a ship during a stopping manoeuvre is extremely complicated. However, a fairly simple mathematical model can be used to demonstrate the important aspects which affect the stopping ability of a ship. For any ship the longest stopping distance can be assumed to result when the ship travels in a straight line along the original course, after the astern order is given. In reality the ship will either veer off to port or starboard and travel along a curved track, resulting in a shorter track reach, due to increased hull drag.

To calculate the stopping distance on a straight path a number of assumptions must be made.

1. The resistance of the hull is proportional to the square of the ship speed.
2. The astern thrust is constant throughout the stopping manoeuvre, and equal to the astern thrust generated by. the propeller when the ship eventually stops dead in the water.
3. The propeller is reversed as rapidly as possible after the astern order is given.

An expression for the stopping distance along a straight track, in ship lengths, can be written in the form:

$$S = A \log_e (1 + B) + C,$$

where:

S : is the stopping distance, in ship lengths.

A : is a coefficient dependent upon the mass of the ship divided by its resistance coefficient.

R is a coefficient dependent on the ratio of the ship resistance immediately before the stopping manoeuvre, to the astern thrust when the ship is dead in the water.

C : is a coefficient dependent upon the product of the time taken to achieve the astern thrust and the initial speed of the ship.

The value of the coefficient A is entirely due to the type of ship and the shape of its hull. Typical values of A are shown in table A3-1.

The value of the coefficient B is controlled by the amount of astern power which is available from the power plant. with diesel machinery, the astern power available is usually about 85% of the ahead power, whereas with steam turbine machinery this figure could be as low as 40%.

Table A3-1

Ship Type	Coefficient
Cargo ship	5-8
Passenger/car ferry	8-9
Gas carrier	10-11
Products tanker	12-13
VLCC	14-16

Accordingly the value of the coefficient B is smaller if a large amount of astern power and hence astern thrust, is available. Typical values of the coefficient B are given in table A3-2.

Table A3-2

Type of Machinery	Percentage Power	Coefficient B	Log (1+B)
Diesel	85%	0.6 - 1.0	0.5 - 0.7
Steam turbine	40%	1.0 - 1.5	0.7 - 0.9

The value of the coefficient C is half the distance traveled, in ship lengths, by the ship, whilst the engine is reversed and full astern thrust is developed. The value of C will be larger for smaller ships and typical values are given in table A3-3.

Table A3-3

Ship Length (meters)	Time to Achieve Astern Thrust (s)	Ship Speed (Knots)	Coefficient C
100	60	15	2.3
200	60	15	1.1
300	60	15	0.8

If the time taken to achieve the astern thrust is longer then 60 seconds, as assumed in table A3-3, or if the ship speed is greater than 15 knots, then the values of the coefficient C will increase pro rata.

Although all the values given for the coefficients A, B and C may only be considered as typical values for illustrative purposes, they indicate that large ships may have difficulty satisfying the adopted stopping ability criterion of 15 ship lengths.

Consider a steam turbine propelled VLCC of 300 meters length, traveling at 15 knots, and assume that it takes 1 minute to develop full-astern thrust in a stopping manoeuvre. Then from tables A3-1, 2 and 3 we get

$A = 16$,
$B = 1.5$, and
$C = 0.8$

Using the formula for stopping distance S, given above, then

$$S = 16 \log_e (1 + 1.5) + 0.8 = 15.5 \text{ ship lengths,}$$

which exceeds the stopping ability criterion of 15 ship lengths.

In all cases the value of A is inherent in the shape of the hull and so cannot be changed unless resistance is significantly increased. The value of B can only be reduced by incorporating more astern power in the engine, an option which is unrealistic for a steam turbine powered ship. The value of C would become larger if more than one minute was taken to reverse the engines, from the astern order to the time when the full-astern thrust is developed.

APPENDIX 4 - ADDITIONAL MANOEUVRES

A.4 Additional methods to assess course keeping ability

The standards note that additional testing may be used to further investigate a dynamic stability problem identified by the standard trial manoeuvres. This appendix briefly discusses additional trials that may be used to evaluate a ship ~s manoeuvring characteristics.

The standards are used to evaluate course-keeping ability based on the overshoot angles resulting from the 10.110. zig-zag manoeuvre. The zig-zag manoeuvre was chosen for reasons of simplicity and expediency in conducting trials. However, where more detailed analysis of dynamic stability is required some form of spiral manoeuvre should be conducted as an additional measure. A direct or reverse spiral manoeuvre may be conducted, as recommended in MSC/Circ.389. The spiral and pullout manoeuvres have historically been recommended by various trial codes as measures that provide the comprehensive information necessary for reliably evaluating course-keeping ability. The direct spiral manoeuvre is generally time consuming and weather sensitive. A relatively new trial, the simplified spiral, can be used to quickly evaluate key points of the spiral loop curve. DE 35/INF.14 provides a correlation between acceptance criteria for the spiral loop width versus the overshoot angle in the 10^0 / 10^0 zig-zag manoeuvre. Another new trial uses a very small zig-zag manoeuvre to evaluate the dynamic instability of the vessel.

A.4.l Spiral manoeuvres

A.4.l.l Direct spiral manoeuvre

The direct spiral manoeuvre is an orderly sequence of turning circle tests to obtain a steady turning rate versus rudder angle relation (see figure A4-2).

Should there be reasons to expect the ship to be dynamically unstable, or only marginally stable, a direct spiral test will give additional information. This is a time-consuming test to perform especially for large and slow ships. A significant amount of time is needed for the ship to obtain a steady rate of change of heading after each rudder angle change. Also, the test is very sensitive to weather conditions.

In the case where dynamic instability is detected with other trials or is expected, a direct spiral test can provide more detailed information about the degree of instability that exists. While this test can be time consuming and sensitive to weather conditions, it yields information about the yaw rate/rudder angle relation that cannot be measured b~ any other test.

The direct spiral is a turning circle manoeuvre in which. various steady state yaw rate/rudder angle values are measured by making incremental rudder changes throughout a circling manoeuvre. Adequate time must be allowed for the ship to reach a steady yaw rate so that false indications of instability are avoided.

In cases where the ship is dynamically unstable it will appear that it is still turning steadily in the original direction although the rudder is now slightly deflected to the opposite side. At a certain stage the yaw rate will abruptly change to the other side and the yaw rate versus rudder angle relation will now be defined by a separate curve. Upon completion of the test the results will display the characteristic spiral loop as presented in figure A4-3.

A direct spiral manoeuvre can be conducted using the following general procedure:

.1 The ship is brought to a steady course and speed according to the specific initial condition.

.2 The recording of data starts.

.3 The rudder is turned about 15 degrees and held until the yaw rate remains constant for approximately one minute.

.4 The rudder angle is then decreased in approximately 5 degree increments. At each increment the rudder is held fixed until a steady yaw rate is obtained, measured and then decreased again.

.5 This is repeated for different rudder angles starting from large angles to both port and starboard.

.6 When a sufficient number of points is defined, data recording stops.

A.4.l.2 Reverse spiral manoeuvre

The reverse spiral test may provide a more rapid procedure than the direct spiral test to define the instability loop as well as the unstable branch of the yaw rate versus rudder angle relationship indicated by the dotted curve as shown in figure A4-2. In the reverse spiral test the ship is steered to obtain a constant yaw rate, the mean rudder angle required to produce this yaw rate is measured and the yaw rate versus rudder angle plot is created. Points on the curve of yaw rate versus rudder angle may be taken in any order.

This trial requires a properly calibrated rate of turn indicator and an accurate rudder angle indicator. Accuracy can be improved if continuous recording of rate of turn and rudder angle is available for the analysis. Alternatively the test may be performed using a conventional autopilot. If manual steering is used, the instantaneous rate of turn should be visually displayed to the helmsman.

A.4.l.3 Simplified spiral manoeuvre

The simplified spiral reduces the complexity of the spiral manoeuvre. The simplified spiral consists of three points which can be easily measured at the end of the turning circle test. The first point is a measurement of the steady state yaw rate at the maximum rudder angle. To measure the second point, the rudder is returned to the neutral position and the steady state yaw rate is measured. If the ship returns to zero yaw rate the ship is stable and the manoeuvre may be terminated. Alternatively, the third point is reached by placing the rudder in the direction opposite of the original rudder angle to an angle equal to half the allowable loop width. The allowable loop width may be defined as:

0 degrees	for	LIV < 9	seconds
-3 + l/3(L/V)	for	9 < L/V < 45	seconds
12 degrees	for	45 < L/V	seconds

When the rudder is placed at half the allowable loop width and the ship continues to turn in the direction opposite to that of the rudder angle$_1$ then the ship is unstable beyond the acceptable limit.

A.4.2 Pull-out manoeuvre

After the completion of the turning circle test the rudder is returned to the midship position and kept there until a steady turning rate is obtained. This test gives a simple indication of a ship's dynamic stability on a straight course. If the ship is stable, the rate of turn will decay to zero for turns to both port and starboard. If the. ship is unstable, then the rate of turn will reduce to some residual rate of turn (see figure A4-l). The residual rates of turn to port and starboard indicate the magnitude of instability at the neutral rudder angle. Normally, pull-out manoeuvres are performed in connection with the turning circle, zig-zag, or initial turning tests, but they may be carried out separately.

A.4.3 Very small zig-zag manoeuvre.

The shortcomings of the spiral and $l0^0/l0^0$ zig-zag manoeuvres may be overcome by a variation of the zig-zag manoeuvre that quite closely approximates the behaviour of a ship being steered t6 maintain a straight course. This zig-zag is referred to as a Very Small Zig Zag (VSZZ), which can be expressed using the usual nomenclature, as $0^0/5^0$ zig-sag, where ψ is 0 degrees and δ is 5 degrees.

VSZZs characterized by $0^0/5^0$, are believed to be the most useful type, for the following two reasons.

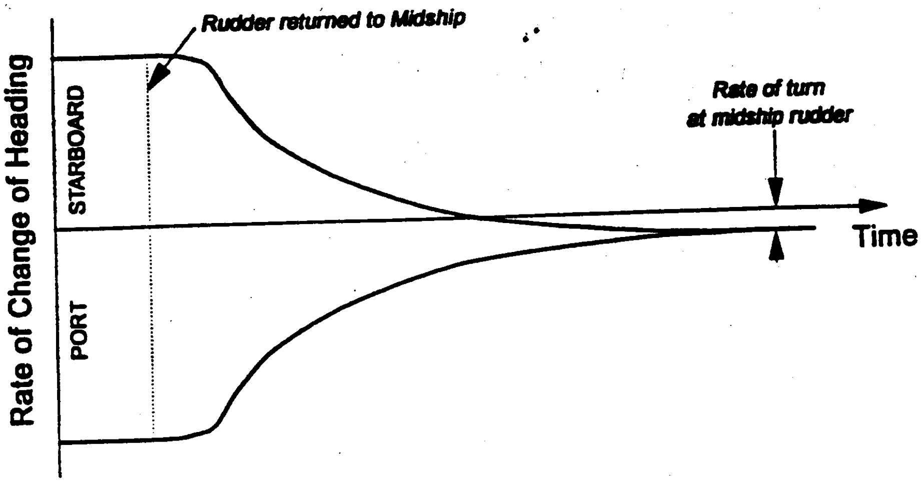
(1) A human helmsman can conduct VSZZs by evaluating the instant at which to move the wheel while sighting over the bow, which he can do more accurately than by watching a conventional compass.

(2) A conventional autopilot could be used to conduct VSZZs by setting a large proportional gain and the differential gain to zero.

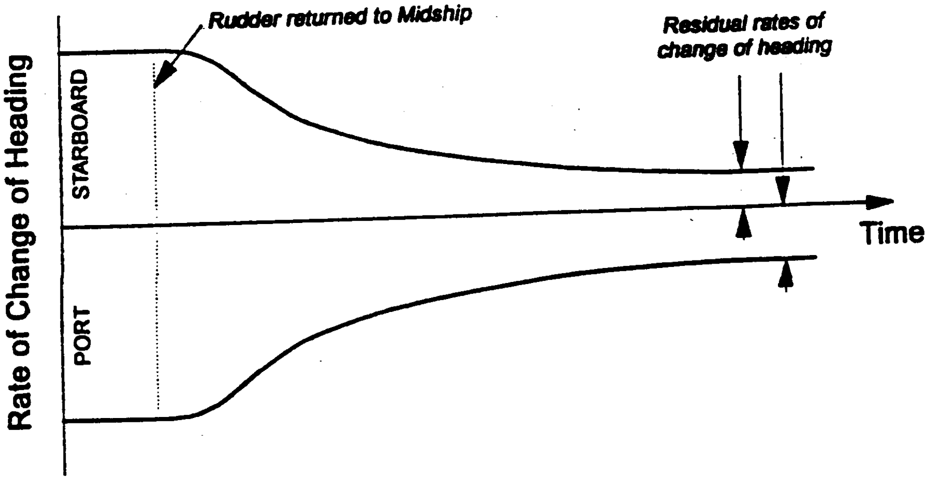
There is a small but essential difference between $0^0/5^0$ VSZZs and more conventional similar zig-zags, such as $1^0/5^0$ zig-zag. A $0^0/5^0$ zig-zag must be initialized with a non-zero rate-of-turn. In reality, this happens naturally in the case of inherently unstable ships.

A VSZZ consists of a larger number of cycles than a conventional zig-tag, perhaps 20 overshoots or so, rather than the conventional two or three, and interest focuses on the value of the overshoot in long term. The minimum criterion for course-keeping is expressed in terms of the limit-cycle overshoot angle for $0^0/5^0$ VSZZs, and is a function of length to speed ratio.

STABLE SHIP

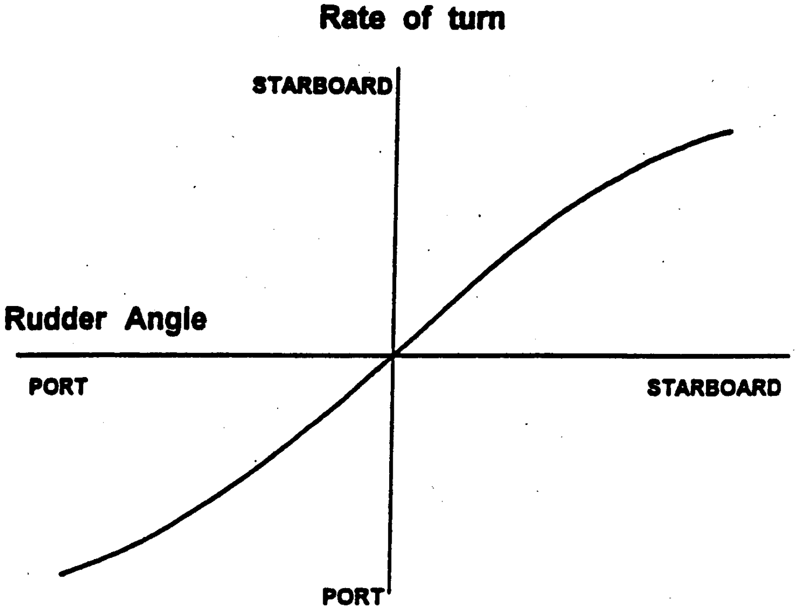


UNSTABLE SHIP



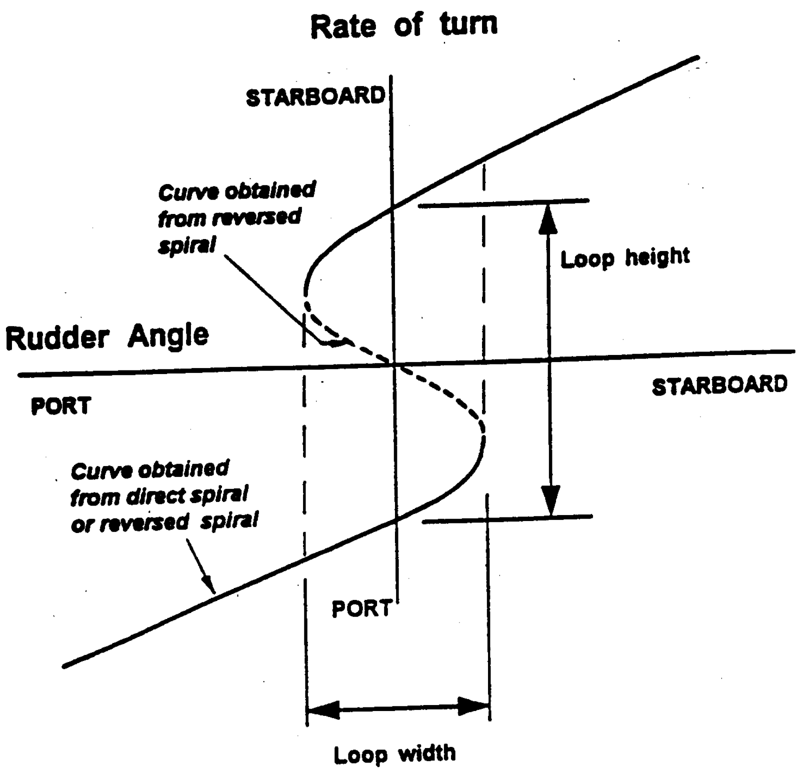
PRESENTATION OF PULL-OUT TEST RESULTS

FIGURE A4-1



PRESENTATION OF SPIRAL TEST RESULTS FOR STABLE SHIP

FIGURE A4-2



PRESENTATION OF SPIRAL TEST RESULTS FOR UNSTABLE SHIP

FIGURE A4-3

APPENDIX 5 - BACKGROUND AND BIBLIOGRAPHY

A.5.l Background data

MSC/Circ.389 invited Member Governments to submit ship manoeuvrability data for use in ship design and for establishing manoeuvrability standards. In response, ship trials data and other manoeuvring information were submitted to the DE Sub-Committee by Member Governments. The data, along with other available information, were incorporated into a ship manoeuvring database to facilitate analysis for establishing the manoeuvring standards. The Working Group on Manoeuvrability considered collation papers submitted by the correspondence group (DE 351413, DE 34/413) and submissions by Canada (DE 31/3/3), China (DE 35/411), Finland (DE 31/INF.2, DE 3lIINF.3), Germany (DE/317, DE/316, DE 33/7, DE 26/6), Italy (DE •32/INF.2). Japan (DE 35IINF.14, DE 34/IN F.2, DE 33/INF.8, DE/308, DE1329, DE/323, DE XXII/8/3, DE 28/4/1, DE 3211NF.S, DE 30/4, DE 30/INF.10, DE 29/INF.3, DE 29/INF.4, DE 33/4), the Netherlands (DE.31/3), Norway (DE 35/4/4, DE 34/4/2), Poland (DE/270, DE 2715/3), Sweden (DE 34/4/4), the USSR (DE/294, DE/326), the United Kingdom (DE XI/10, DE 32/4, DE 31/INF.5, DE/59, DE 33/4/1), the United States (DE 34/4/1, DE/300, DE/319, DE/307, DE/314, DE XX/6/l, DE 25/5/1, DE 31/3/1, DE 31/3Y2) and reports of the Working Group on Manoeuvrability (DE 35/WP.4, DE 34/4, DE 34/WP.7, DE XXIV/5 and DE 25/5, DE 25/WP.6). Other sources of data and information that were also examined in establishing the manoeuvring Standards are included under "References for Background Data".

A.5.2 Bibliography

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APPENDIX 6 - FORM FOR REPORTING MANOEUVRING DATA TO IMO

Administration: ____________________ **Reference No *** ☐

SHIP DATA: **(FULL LOAD CONDITION)**

Ship Type *		L/V	sec
L/B	B/T	C_B	
Rudder Type *			
Total Rudder Area / LT		Number of Rudders	
Propeller Type *			
No of propellers			
Engine Type *			

TRIALS DATA: **(ENVIRONMENTAL CONDITION)**

Water depth / trial draught	
Wind: Beaufort Number	
Wave: Sea State	

MANOEUVRING DATA:

Loading Condition: Tested at Full Load ☐ Tested at Partial Load and Corrected ☐

	TEST RESULTS			IMO CRITERIA
Turning Circle:	PORT	STBD		
Advance			Ship Lengths	4.5
Tactical Diameter			Ship Lengths	5
Zig-Zag:				
10 deg/10 deg	PORT	STBD		
1st Overshoot Angle			deg	*
2nd Overshoot Angle			deg	*
20 deg/20 deg	PORT	STBD		
1st Overshoot Angle			deg	25
Initial Turning:	PORT	STBD		
Distance to turn 10 deg with 10 deg rudder			Ship Lengths	2.5
Stopping Distance:				
Track Reach			Ship Lengths	15

REMARKS: ____________________

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* see notes on the reverse of the page

Form for reporting manoeuvring data to IMO

Notes:

1 Reference no. assigned by the Administration for internal uge.

2 Ship type such as container ship, tanker, gas carrier, ro-ro ship, passenger ship, car carrier, bulk carrier, etc.

3 Rudder type such as full spade, semi-spade, high lift, etc.

4 Propeller type such as fixed pitch, controllable pitch. with/without nozzle, etc.

5 Engine type such as diesel, steam turbine, gas turbine, diesel-electric, etc.

6 IMO criteria for $10^0/10^0$ zig-zag test vary with LIV. Refer to paragraphs 4.3.3.1 and 4.3.3.2 of the Interim Standards for Ship Manoeuvrability (IMO Assembly resolution A.751(18), annex).