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FREE-RUNNING MODEL TECHNIQUES FOR THE EVALUATION OF SHIP-HANDLING QUALITIES

by

S. C. Gover

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ABSTRACT

The concept of "definitive maneuvers" has been introduced as the basic framework for establishing a system for evaluating handling qualities. The particular maneuvers selected for this purpose are the spiral, overshoot, and turning circle. This report describes model test methods used at the David Taylor Model Basin from definitive maneuvers.

INTRODUCTION

In many respects the present paper is an extension of one entitled "Handling Quality Criteria for Surface Ships",[1] which was presented at the 2 May 1959 meeting of the Chesapeake Section of the Society of Naval Architects and Marine Engineers. Material shown in quotation marks are from the foregoing paper unless otherwise identified by reference marks. The principal difference between the papers is that the present one emphasizes the function of free-running model tests in the evaluation of handling qualities.

"It may be stated that the broad objective in the field of stability and control of ships is to achieve the best stability and maneuverability characteristics commensurate with other design requirements. It is not always obvious, however, what is categorically the "best" as in some other fields of naval architecture. Many of the previous attempts to define these elusive qualities have been highly subjective and wrapped up in the lore of the experienced ship operators. Furthermore, judgments are usually made after delivery and long term use of a ship rather than on the basis of predetermined goals."

"The researchers have traditionally employed indices, derivatives, and hydrodynamic parameters to analyze stability and control characteristics. These methods may serve a very useful purpose as analytical tools and undoubtedly contribute to the overall picture. Their weakness lies in their use as figures of merit since they usually lead to qualitative interpretations such as "acceptable" or "unacceptable". Furthermore, a profound knowledge of mathematics and systems analysis of the type found only among the highly specialized is required to fully understand the implications of such analyses. The operators, on the other hand, are concerned more intimately with ship behavior as it really exists in point of full-scale time and environmental forcing functions. The operators are the customers and must live with the ship long after the design has left the drafting table and research laboratory. Thus to establish an effective system for defining handling qualities, it is necessary to bridge this gap to enable a meeting of the minds of the researcher, designer, and operator."

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[1] References are list on page 15.

This report utilizes the concept of definitive maneuvers as the basic framework for a system of rating handling qualities. General procedures for selected maneuvers of this type are described. A description is then given of how these maneuvers are adapted to suit the facilities and instrumentation at the Taylor Model Basin. The methods outlined in this report are also used to evaluate handling qualities of submarines, both surfaced and submerged, in the horizontal plane of motions.

CONCEPT OF DEFINITIVE MANEUVERS

"The term "definitive maneuvers" has been adopted to describe a class of maneuvers designed solely to reveal objective or numerical measures of specific handling qualities. Some of these maneuvers may resemble operational maneuvers. It is highly desirable if this is the case since the numerical measures derived from the definitive maneuver will then have a more direct significance to the operator. There are two general types of definitive maneuvers, those which define inherent qualities of a ship resulting from its hydrodynamic design and are independent of the man or control mechanisms in the loop; and those which define qualities associated with the complete ship-control system and are dependent of the man or control mechanisms in the loop; and those which define qualities associated with the complete ship-control system and are dependent on the responses of the man, automatic control equipment, and control linkages in the loop."

"Maneuvers which define inherent qualities are considered preferable because they directly provide specific numerical measures from a single maneuver of a given type. Also, these measures are indicative of the maximum potentialities of the ship system without qualification as to the efficiency of the operator in executing the maneuver. On the other hand, maneuvers which define qualities associated with the complete system are much more cumbersome and time consuming. Such a maneuver must be repeated many times with several operators, possessing varying degrees of skill, to furnish data which then must be statistically analyzed to obtain the desired figures of merit. Nevertheless, there are cases where the latter type of maneuver must be used if certain handling qualities are to be directly manifested."

"The qualities associated with course-keeping are illustrative of a case where the statistical approach might be used. These qualities result from an interplay between the ship system consisting of the man or automatic control, the directional stability of the ship, the rudder effectiveness, and the control mechanism characteristics, and the external disturbances provided by currents, wind, and waves. Since the whole ship system is involved, appropriate numerical measures can be obtained only by conducting statistical-type course-keeping maneuvers."

"Numerical measures pertaining to the inherent directional stability of a ship can be simply obtained by conducting a single spiral maneuver of the type attributable to Dieudonné.[2] Thus, if it is assumed that the ship with the best directional stability characteristics potentially will have the best course-keeping qualities, the numerical measures from the spiral maneuver can be used in lieu of those from the statistical course-keeping maneuver. Up to the present time, it has been necessary to make this assumption since most full-scale surface ships have not been available for properly conducted course-keeping tests. The only other alternative for providing course-keeping data would be to use simulator techniques similar to those used to evaluate performance of submarines. Unfortunately, neither hydrodynamic data nor well-developed techniques are available yet to support such studies with surface ships."

"To gain a fuller appreciation of the concept and purpose of definitive maneuvers, it is helpful to temporarily forget the existence of other analytical methods and detailed approaches used to solve stability and control problems. If this is done it can be readily seen that the end product desired from stability and control studies points to those kinds of handling qualities that are of interest to the ship operators. Furthermore, the emphasis should be on treating these qualities in a quantitative sense if there is to be any hope of achieving progressive improvements on future ships. As a matter of orientation, it is desirable to consider descriptively the kinds of qualities of interest. The following is a list, which is by no means all-inclusive, of kinds of handling qualities that the operators should reasonably expect from a surface ship:

1. The ability to maintain course with a small amount of heading error, course error, and rudder activity.

2. The ability to initiate a course change rapidly.

3. The ability to check a course change rapidly with small overshoots in heading angle and width of path.

4. The ability to execute an efficient steady-turning maneuver with small tactical diameter, advance, and transfer.

5. The ability to accelerate and decelerate rapidly yet retaining good control.

6. The ability to maneuver in and out of harbors ahead and astern at slow speeds without tug assistance."

"The quantitative measures obtained from definitive maneuvers which are used to describe qualities of the kinds given in the foregoing list are discussed in the next section. It is pertinent to the concept of definitive maneuvers, however, that such numbers be expressed dimensionally in terms of real time and distance. In this manner, the numbers can be maintained within the perspective of the operators. In addition, they will serve as a better basis for specifications since they can be checked directly in acceptance trails. If it is desired, however, to utilize these numbers in analyses involving different-sized ships, the dimensional values can be converted into nondimensional ones by the use of appropriate normalizing factors."

"On the basis of the preceding considerations, a given maneuver can be classified as a definitive maneuver if it has the following characteristics:

1. It can actually be performed by a full-scale ship and is not merely a laboratory or analytical response technique.

2. It has salient features which can be expressed as quantitative measures of specific handling qualities of the type that lead to objective standards and finally to specifications which must be met prior to the acceptance of a ship.

3. If possible, it should accomplish its purpose with a minimum of specialized instrumentation and without using a disproportionate amount of full-scale trial time."

DESCRIPTION OF SELECTED MANEUVERS

"A wide variety of maneuvers have been used in the past as definitive maneuvers and other might conceivably be used in the future. Obviously, many of these maneuvers involve similar modes of performance and to this extent overlap each other in defining certain types of handling qualities. Consequently, in selecting standard definitive maneuvers, one can go from one extreme by considering too few maneuvers and perhaps overlooking some important handling qualities to the other extreme by utilizing too many and thus overburden trial schedules and produce excessive amounts of data. In the present stage of development of handling quality criteria, the conservative approach would be to select more instead of less than the required minimum number of representative maneuvers. In this manner, there would be less risk of overlooking some handling qualities that might become important in the future and the opportunity to conduct trials on a given ship may not again present itself. In any event, the number of maneuvers conducted on any given set of trials will be compounded by the range of speeds (forward and backing) as well as other pertinent conditions. A thorough coverage of operational conditions should be considered in establishing handling quality criteria. In is unwise at this stage of development to place too much credence on handling qualities of a single type. This point has been confirmed by recent experiences with naval-type surface ships. For years, the maneuverability of naval ships was evaluated solely on basis of steady-turning tests. However, within the last few years it was found that some of the ships which had excellent turning characteristics had poor and, at least in one case, unacceptable directional stability characteristics. As the result of these findings, spiral tests to define directional stability characteristics have now become as standard with naval ships as the traditional turning tests."

"The development of facilities, instrumentation, and techniques which are necessary for detailed treatment of the subject of stability and control of surface ships has been relatively slow. In addition, full-scale surface ships have been made available for only limited programs to evaluate maneuverability. Consequently, whatever data are available have been obtained from essentially three types of definitive maneuvers, spirals, overshoots, and turning circles. Each of these three types of maneuvers is discussed in terms of the purpose of the maneuver, the procedure followed in carrying out the maneuver, the numerical measures derived from it, and the significance of the numerical measures."

SPIRALS

"The spiral is a definitive maneuver which is intended to provide quanitative measures of the inherent directional stability characteristics of a ship. These characteristics can be used to impute course-keeping potentialities. The maneuver can be conducted in a variety of ways with full-scale ships, free-running models, and analog computers utilizing hydrodynamic force and moment data derived from captive model tests. An attractive feature of the maneuver for full-scale tests is that it can usually be carried out with the ship's own instrumentation. The basic maneuver, which can be carried out when sea room is not at a premium, is conducted as follows:

1. The propeller speed is adjusted to an rpm corresponding to a predetermined speed (either ahead or astern). Once a steady rpm is achieved, the throttle settings are not changed for the balance of the maneuver.

2. The rudder is manipulated as necessary until a "practically" straight course has been obtained and held for one minute.

3. The rudder is then deflected to about 15 degrees right and held until the rate of change of heading as indicated by the gyro compass and a stop-watch remains constant for one minute. The rudder angle is then decreased by 5 degrees and held again until the rate of change of heading remains constant for one minute. The procedure is repeated until the rudder has coverd a range of from 15 degrees on one side to

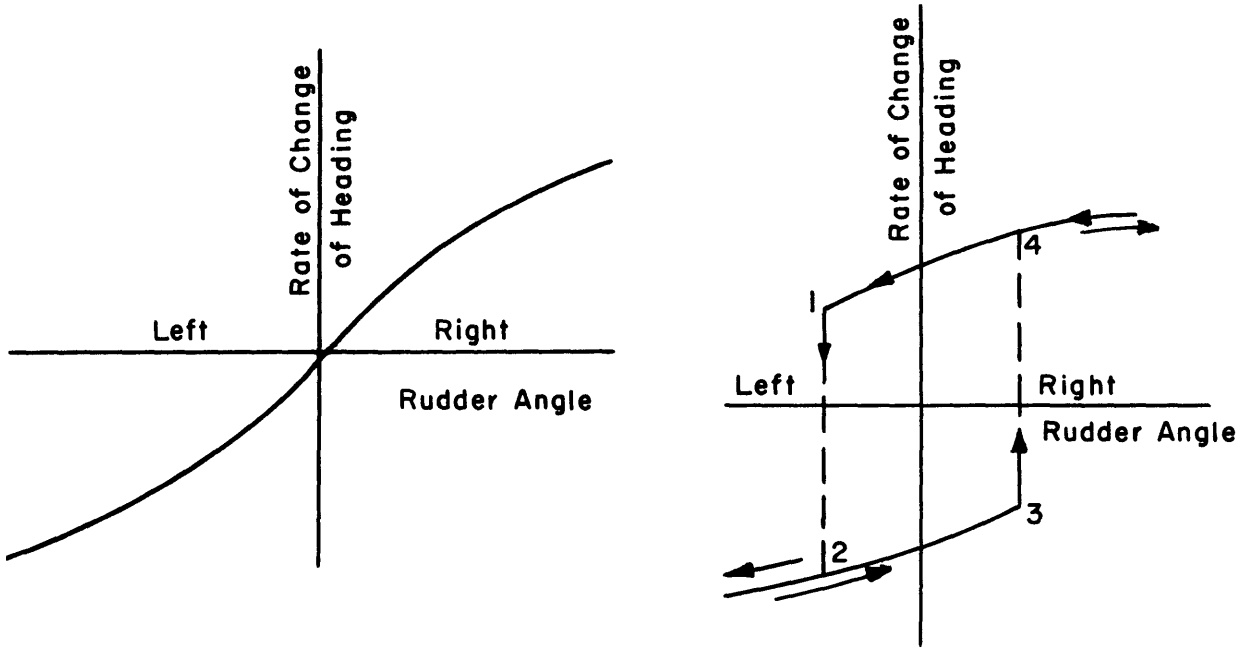
15 degrees on the other side and back again to 15 degrees on the first side. For 5 degrees on either side of zero or neutral rudder angle, the intervals are taken in one degree steps."

Inasmuch as even maneuvering basins do not have enough room to make continuous spiral meneuvers, a technique has been developed for synthesizing spirals with 20-foot models in the 50-foot wide towing basin at the Taylor Model Basin. If we refer to the description of the full-scale spiral maneuver it is noted that it is really a succession of steady turns with first decremental and the incremental rudder changes. Since the transition from one turning rate to the other forms no part of the record it is necessary only to insure that the model is turning at a rate (not necessarily steady) equivalent to that obtained at the preceding rudder angle when the particular rudder angle is set.

In order to obtain indication of steady turning rates in the narrow basin it has been necessary to use a rate gyro with remote recording on the towing carriage. Path data are of no significance in spiral tests and are not recorded.

Maximum backing power on the propellers and manual assistance from helpers along the basin walls are often needed to prevent the models from colliding with the wave breakers along the sides of the basin. This is particularly true when testing single-screw models which tend to swing to starboard when backing hard.

Whether the spirals are conducted either according to the general or the modified procedure, "The numerical measures obtained from the spiral maneuver are the steady rates of change of heading versus rudder angles. A plot of these variables is indicative of the inherent characteristics of the ship. If the plot is a single continuous curve going from right rudder to left rudder, as shown in Figure la, the ship is said to be directionally stable. If, however, the plot consists of two branches joined together to form a "hysteresis" loop, as shown in Figure lb, the ship is said to be directionally unstable. In addition, the size of the loop (height and width) can be used as a numerical measure of the degree of instability; the larger the loop, the more unstable the ship. The width of the loop is also a fairly direct indication of probable course-keeping ability since it defines the envelope of rudder angles which must be employed to keep the ship from swinging from port to starboard. Unfortunately, the spiral technique as presently used does not define the degree of stability for stable ships. The slope of the rate curve at the origin seems to be indicative of degree of stability for directionally stable ships. Also, the time required for the turning rate to decrease to zero when the rudder is returned to zero or neutral angle may provide a numerical measure of degree of stability. Further analysis of these techniques is required to establish these relationships, however, and it may develop that a supplementary definitive maneuver may be needed in the case of directionally stable ships."



(a) Stable Ship (b.) Unstable Ship

Figure 1 - Typical Curves from Spiral Maneuvers

OVERSHOOT

"The overshoot is a definitive maneuver which is intended to provide quantitative measures of the inherent effectiveness of the rudder in making changes in heading or width of path. The kinds of handling qualities revealed by this maneuver are typified by the ability to initiate course changes and ability to check course changes during transient maneuvers. The maneuver can be conducted with full-scale ships, free-running models, and analog computers. The numerical measures pertaining to the heading changes can be obtained with the ship's own instrumentation. Numerical measures associated with width of path, however, will require either much more elaborate equipment than is generally available for most ships or testing on a range with triangulation facilities."

'The overshoot maneuver is shown diagrammatically in Figure 2. It can be seen that if the maneuver is continued through several cycles it results in the well-known zig-zag maneuver. A typical procedure for conducting overshoot tests is as follows:

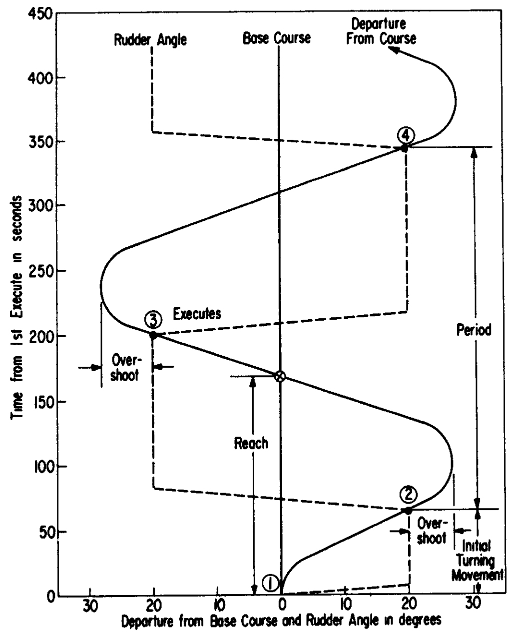


Figure 2 - Diagram of Overshoot Maneuver

1. The propeller speed is adjusted to an rpm corresponding to a predetermined speed and when a steady rpm is achieved, the throttle settings are not changed for the balance of the maneuver.

2. The rudder is manipulated as necessary until a "practically" straight course has been obtained and held for one minute.

3. After steady conditions on straight course have been established, the initial heading shown on the ships gyro compass is noted. The rudder is then deflected at maximum rate to a predetermined angle, say 20 degrees, and held until a predetermined execute change of heading angle, say 20 degrees, is reached.

4. At this point, the rudder is deflected at maximum rate to an opposite (checking) angle of 20 degrees and held until the ship passes through its initial course.

5. If a zig-zag is to be completed, the maneuver is continued until a second execute of 20 degrees to the other side is reached. Whereupon, the rudder is again deflected rapidly to an angle of 20 degrees in the first direction. This cycle is repeated through 3rd and 4th executes and so on.

"The primary numerical measures obtained from the overshoot maneuver are the time to reach execute change of heading angle, overshoot heading angle, and overshoot width of path. The zig-zag maneuver provides the additional measures of reach and period which are perhaps more significant for frequency response analyses than establishment of handling qualities.

The time to reach execute is a direct numerical measure of ability to rapidly initiate changes in course. The heading and path-width overshoots are measures of course-checking ability and are indicative of the amount of anticipation and latitude of error that the helmsman is permitted if he is to remain within tolerable limits of the maneuver.

TURNING CIRCLES

"The turning circle is a definitive maneuver which is intended to provide quantitative measures of the effectiveness of the rudder in producing steady-turning characteristics. The turning circle is the oldest, most familiar, and most widely used of the definitive maneuvers. The handling qualities defined by this maneuver are generally considered to be more important to naval than most sea-going merchant ship applications. The maneuver can be conducted with full-scale ships, free-running models, and ultimately with analog computers. As with the other maneuvers, some of the desired numerical measures can be obtained with the ship's own instrumentation in open sea. However measures pertaining to path data will require either much more elaborate ship-borne equipment or testing on a range with triangulation facilities."

"Although the turning circle maneuver is familiar to most naval architects, it is shown diagrammatically in Figure 3 for purposes of completeness. The standard procedure for the conduct of such maneuvers is as follows:

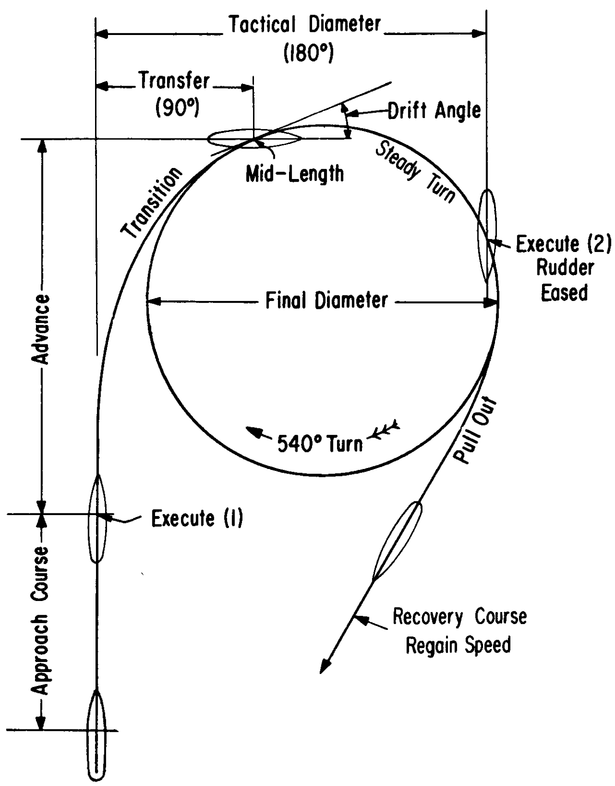


Figure 3 - Diagram of Turning Circle Maneuver

1. The propeller speed is adjusted to an rpm corresponding to a predetermined speed and when a steady rpm is achieved, the throttle settings are not changed for the balance of the maneuver.

2. The rudder is manipulated as necessary until a "practically" straight course has been obtained and held for one minute.

3. After steady conditions on straight course have been established, the initial heading on the ship's gyro compass is noted. The rudder is then laid to a predetermined angle, say 35 degrees, and held until a change of heading of generally at least 540 degrees has occurred at which point the maneuver is terminated."

"The numerical measures obtained from the turning circle tests are the tactical and steady-turning diameter, advance, transfer, times to change heading 90 to 180 degrees, and loss of speed in turning. All of these measures should be taken into consideration in defining handling qualities associated with this type of maneuver."

The model turning tests are essentially the same as for full scale except that the turn is limited to 180 degrees and pull-out data are not obtained at present. The added 360 degrees used in the full-scale turning circles is for the purpose of obtaining drift corrections which are not needed in model tests. Pull-out data may be readily obtained in the new Maneuvering Basin. Path data for the model turning circles are now derived from the traces of timed flashing lights in the models photographed by three overhead cameras whose fields cover the J-basin maneuvering area. In the new basin it is expected that the overhead cameras will be supplanted later by an automatic tracking system.

DESCRIPTION OF EQUIPMENT

The primary quantities needed to evaluate the three definitive maneuvers are rudder angle, heading, rate of change of heading (turning rate), speed, and path. The following description applies to tests of surface-ship models made in the J-basin at TMB. It is to be remembered that power, control commands, and recording signals are transmitted to and from the model by means of flexible cables suspended over the center of the model. Data from the transducers in the model are recorded on two-channel Brown Recorders. A report on model equipment for the new basin is in preparation.[3]

RUDDER ANGLE

A servo-type rudder dynamometer is used on the model for positioning the rudder and for measuring rudder forces. An output signal from the rudder dynamometer is transmitted back to the towing carriage where it is recorded. A frequent check on the calibration of the system is made by reading the quadrant indicator on the dynamometer between runs.

HEADING

The heading is measured by the Doelcam Model 2002-1 directional gyro. The gyro is caged in between each run and is uncaged just as the run is about to commence. Since the expected drift is 0.25 degree per minute, the error introduced during the course of the run is small and correction is seldom necessary during the course of the recorded portion of the run. A Humphrey Model FG01-0203 gyro has been obtained for use in the radio-controlled and free-running submerged models.

TURNING RATE

The turning rate, or rate of change of heading, is measured by means of a Minneapolis-Honeywell Type JG7005A10 rate gryo. It has been found that rates in excess of 15 degrees per second have been encountered. A Humphrey Model RG03-0117-1 gyro with a range up to 20 degrees per second has been procured for the new basin and is being proof-tested in the cable-controlled model.

ROLL AND PITCH

Roll and pitch motions in turns are sensed by a Minneapolis-Honeywell Vertical Gyro Type GG33B-2.

SPEED

For most maneuvering tests, the speed is obtained by adjusting the model speed to match that of the towing carriage during the straight line approach run. Since the loss of speed in turning may amount to 50 percent or more, the speed in the transient and steady turn is calculated from timed-light traces on the photographic plates.

PATH

The path swept out by a ship making a maneuver is of great importance to the conning officer. However, the path of a ship is not usually recorded except on a trial course where triangulation facilities are available or in rare cases in which inertial navigation equipment is installed. Reasonably good path data may be obtained on ships with Dead Reckoning Tracer equipment. In day to day operations tracking is done by navigational fixes when in restricted waters.

In the J-basin three overhead cameras cover the area ordinarily used for turning tests. However, it is not practicable to confine overshoot maneuvers to this limited area of the basin and path data are not obtained except in unusual cases. Twenty-foot models which cannot execute 20-degree overshoots in the straight part of the basin have poor maneuvering characteristics. When automatic tracking equipment is installed in the Maneuvering Basin, path data will be recorded as standard procedure.

CORRELATION OF FULL-SCALE AND MODEL TESTS

Although it is beyond the scope of this report to treat the subject of model-full scale correlation, it is pertinent perhaps to make a few observations in this respect to check the validity of the model test procedures. Sufficient tests of different kinds of ships have been made to establish confidence that the handling qualities of ships can be readily predicted by means of free-running model tests which have been conducted in accordance with the methods and procedures used at the Taylor Model Basin. Since all three definitive maneuvers are practicable for model tests, the steering, maneuvering, and turning qualities of new designs can be readily characterized and corrected, if need be, before construction of the ship is started.

Spiral tests of both stable and unstable ships and models have been made and no case has been encountered in which the model did not properly predict either the presence or absence of a loop in the turning rate curve or the relative size of a loop if one was present. The trend has been for the model loop to be slight smaller than the ship loop. Thus the prediction is conservative and there is little hope that the ship might be more stable than indicated by model.

The method used for determining the turning rate of ships by stop-watch and compass is probably not accurate to better than about 0.05 degree per second. Since the heights of the loop for all but one ship have been less than 0.5 degree per second, (0.25 in one direction) it is not practicable to expect agreement to much better than 20 percent, even if the model prediction was perfect.

About the same degree of accuracy is all that can be expected of the width of the loop for no attempt is usually made to determine the crossover rudder angle to closer than one degree (if that) and the maximum width of loop for all but one case was less than 8 degrees (4 degrees each side of zero).

There have been some inconsistencies in the correlation of overshoots particularly in the time to perform various phases of the maneuver. However, these inconsistencies have not assumed a definite pattern indicating scale effect but rather seem to reflect the accumulated errors of the many factors affecting the overshoot maneuver. The principal results of the overshoot maneuver have been consistent; a quick response by the model is confirmed by a quick response by the ship, a large overshoot by the model by a large overshoot by the ship. Comparison of full-scale and model times to reach execute and overshoot angles vary over a range of about ±15 percent.

Turning circles were made with 3 ships and models for which spirals and overshoots were available. None of the models were run after the ship trials to represent the trial conditions exactly, consequently, there are varying degrees of differences in loading between ship and model. In spite of this, the difference between the tactical diameter of the ships and models were 3.5, 7.5, and 16.5 percent. The latter case showed the largest differences between ship and model in the spirals and overshoots also. When time permits a correlation test will be made on that model.

The principal known scale effect is found in turning circles at large rudder angles and high speeds where rudder breakdown or stall sometimes occurs. In most cases observed, the model rudder stalls very sharply and there is a discontinuity in the curve of tactical diameter versus rudder angle. The more gradual stalling of the ship rudder at high Reynolds number sometimes makes it difficult to determine whether the phenomenon is actually a stall or merely an increase in tactical diameter due to change in trim and wave making. Recently there was an exception to the foregoing in which the ship suffered very definite rudder breakdown which did not occur in the preliminary model tests. This anomaly has not been investigated at the present time but is expected to be carried out in the coming months.

By means of the three foregoing definitive maneuvers the model tests predicted the handling qualities, i.e., steering, maneuvering, and turning characteristics, for the ships being designed. The full-scale trials of the ships confirmed that the model tests predicted the ship characteristics quantitatively as well as qualitatively.

CONCLUSIONS AND RECOMMENDATIONS

Tests carried out at the Taylor Model Basin have shown that the "definitive maneuvers" concept is a valuable means of improving ship designs, providing operational data, and establishing performance criteria. The maneuvers, being common to both models and ships, provide a meeting ground for researchers, designers, and operators. Many of the maneuvers can be carried out in model basins not having special maneuvering tanks thus enabling a greater participation in this phase of "tankery"

It is recommended that a greater emphasis be placed on the development of newer and improved model techniques in an effort to gain a firmer understanding not only of the status of handling qualities of existing ships, but for the purpose of achieving optimum handling qualities in future ships. Model tests can play a major role in this respect by utilizing research designs where the emphasis will be on optimum stability and control to the exclusion, if necessary, of other characteristics. In this manner, the various points of diminishing returns can be defined with reasonable clarity.

ACKNOWLEDGMENTS

The author is grateful to Mr. Morton Gertler of the Stability and Control Division of the DavidTaylor Model Basin for guidance, suggestions, and support in development of the "definitive maneuver" procedures and to the members of the Model Dynamic Trials Section who have carried out the experimental work with free-running models.

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2. Ships – Maneuverability – Model tests

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