NAVY DEPARTMENT
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# THE EFFECT OF THRUST DIRECTION AND POSITION ON THE STEERING OF SHIPS

by



K.E. Schoenherr, Dr. Eng.

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PERSONNEL


The discussion presented in this report is the work of Dr. K.E. Schoenherr, of the David Taylor Model Basin staff, and the report was written by him. The calculations were made by H.L. Pond of the Taylor Model Basin staff.

# THE EFFECT OF THRUST DIRECTION AND POSITION ON THE STEERING OF SHIPS

## ABSTRACT

The position of the shaft lines in a twin-screw ship and the position and direction in which thrust is exerted by the wing propellers in a ship relative to the center of gravity of the vessel is discussed in a general way.

In the application of this reasoning to the design of a submarine with a single steering rudder, it is shown that varying the direction and position of the thrust from two propellers with reference to the center of gravity affects the steering in only a minor degree.

In an extreme case, it is calculated that if the two shafts were parallel to the centerline, and if one propeller were driving by itself with the other propeller coasting, the rudder angle necessary to keep the vessel on its course would be negligible.

## INTRODUCTION

The question is frequently raised as to the effect of the position and direction of the shaft lines on the steering and maneuvering of a vessel with wing propellers. So far as known, there is no published literature containing an extended discussion of this feature, although there are a number of references which mention it briefly.

This matter has come up recently in connection with the design of certain submarines, and this opportunity has been taken to set down the general considerations of the problem as they apply to all single-rudder ships with wing propellers, and to supplement them with a brief discussion which applies to the design of a submarine.

Sufficient time has not been available to make an extended study or a complete analysis, but it is hoped that with this report as a basis, it may be possible to collect data from various sources and to place them in better form at some time in the future, with an analysis which will cover all the situations normally encountered in naval architecture.

It is an old rule of ship design, the origin of which is unknown, to run the shaft lines of a twin-screw vessel, when projected on a horizontal plane, either parallel to the axis of the vessel or converging so that fore-and-aft they intersect at a point on the centerline of the vessel ahead of the bow. The reason for this, whether consciously or unconsciously applied, is the fact that by bringing the intersection of the shaft lines sufficiently far forward, the moment of the thrust of each wing propeller, measured about a vertical line through the center of gravity of the vessel as a whole, is then sufficient to produce some steering effect by the use of the propellers alone (1).* This is a safety feature of great value since it is

*Numbers in parentheses indicate references on page 7 of this report.

possible thereby to steer a vessel back to port even after its rudder has been carried away.

This characteristic has its disadvantages in case one engine is out of commission or one propeller is lost and the ship must be driven by the remaining propeller. The greater the moment of the thrust on one wing shaft under these conditions, the greater will be the action to turn the vessel out of its straight course, requiring the application of a constant rudder angle to hold it on a given course.

It has been proved by experience, on a large number of vessels of varying types, that neither the position nor the direction of the shaft line with reference to the center of gravity of a ship has much effect upon the steady running or the steering of the ship, provided of course that these positions and angles are kept within reasonable limits, and that the propeller thrusts on the port and starboard shafts are balanced.

The position and direction of a shaft line in any ship are generally dictated by the size of the propeller and of the propelling machinery, and by the clearances which it is desired to maintain for the propeller outside the ship and for the machinery inside it. On many vessels this has resulted in shafts placed at large angles to the ship's axis in the horizontal plane, so that the shaft lines have intersected well aft of the bow; on some vessels they have even intersected aft of the center of gravity.

In destroyers it frequently happens that, because of the fore-and-aft position of the machinery with one engine ahead of the other, the shaft lines are not symmetrical with respect to the ship's axis and they do not even intersect in that axis, when projected on a horizontal plane. In submarines it has almost invariably been necessary to place the shaft line or lines well *below* the center of gravity of the vessel, or to place them at such an angle that the moment of the thrust about a horizontal transverse axis through the center of gravity is quite large. Under these conditions it might be expected that controllability in the vertical place would be unsatisfactory when the vessel was submerged, but no particular difficulties have been experienced because of this feature, and it is rarely necessary to consider it in the design of a new submarine.

## GENERAL CONSIDERATIONS

In general the turning motion of a ship consists of a motion of translation of the center of gravity and a motion of rotation about the center of gravity. This motion is the result of the action of forces and couples acting at any instant on the ship.

### THE FIRST STAGE OF THE MOTION

Assume that a twin-screw ship is progressing in a straight line and that suddenly power is lost on one of the engines, permitting the propeller to "coast," or causing it to stop. The conditions are then as shown in Figure 1. Inertia will carry

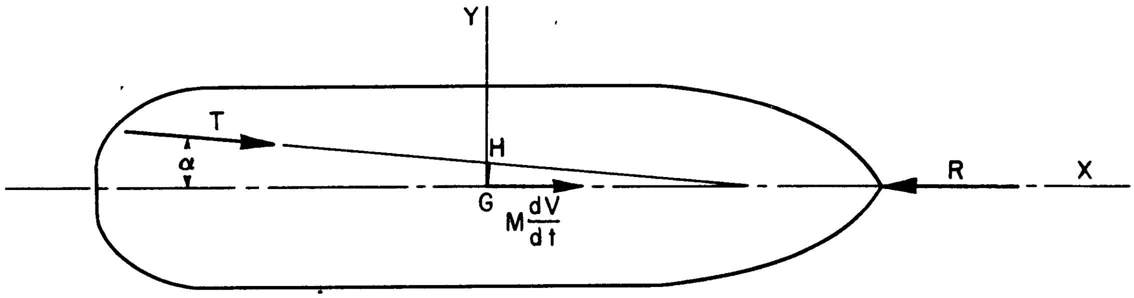


Figure 1 - Diagram Showing the First Stage of the Turning Motion

- $T$ is the propeller thrust
- $\overline{GH}$ is the moment arm of $T$ about the longitudinal center of gravity
- $R$ is the ship resistance
- $M$ is the mass of ship and entrained water
- $V$ is the ship speed
- $t$ is the time

the ship forward along its original line of travel, the resistance will slow the ship down, and the couple of the unbalanced thrust will turn the vessel to starboard unless opposing rudder is given.

THE SECOND STAGE OF THE MOTION

In the second stage of the motion, as shown in Figure 2, the ship is still progressing in the original direction along the $X$-axis but is moving crab-fashion with an angle of deviation $\delta$. The resistance no longer acts along the centerline of the ship but along a line $\overline{RLK}$ as shown. The angle $\beta$ between the direction of $R$ and the centerline of the ship and the point L where $R$ meets the centerline of the ship are unknown,

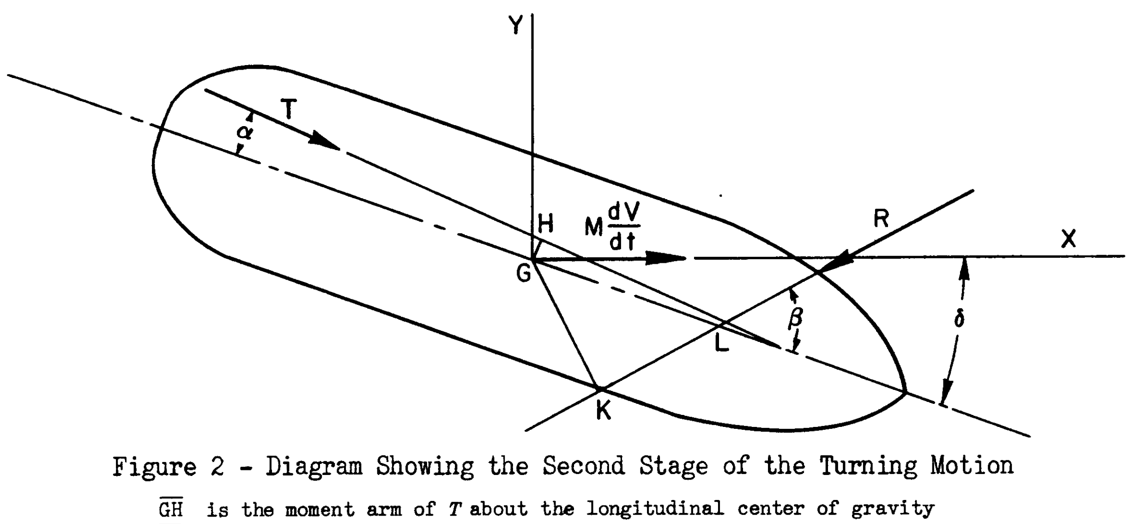


Figure 2 - Diagram Showing the Second Stage of the Turning Motion

- $\overline{GH}$ is the moment arm of $T$ about the longitudinal center of gravity
- $\overline{GK}$ is the moment arm of $R$ about the longitudinal center of gravity
- $M$ is the mass of ship and entrained water
- $\delta$ is the angle of deviation between $M\frac{dv}{dt}$ and centerline of the ship
- $T$ is the propeller thrust
- $R$ is the ship resistance
- $V$ is the ship speed
- $t$ is the time

but from experience it is known that the situation is approximately as illustrated. In addition to the couple of the thrust $T$, a new couple is acting, formed by the resistance $R$ which during this stage of the motion acts to increase the angle $\delta$. There exists now also a large transverse force component $R_Y$ which, combined with the transverse component of the thrust $T$, starts to move the ship at right angles to the original line of travel.

## THE THIRD STAGE OF THE MOTION

In this stage the ship is traveling on a curved path as shown in Figure 3. The pressure distribution on the hull has altered completely as the result of the curvature of the flow lines, causing the direction, magnitude, and point of attack of the resistance $R$ to be approximately as shown in Figure 3. The couple of the resistance force $R \times \overline{GK}$ now opposes the couple of the propeller thrust $T \times \overline{GH}$. Sooner or later the angle $\delta$ reaches a steady value and steady turning conditions are reached.

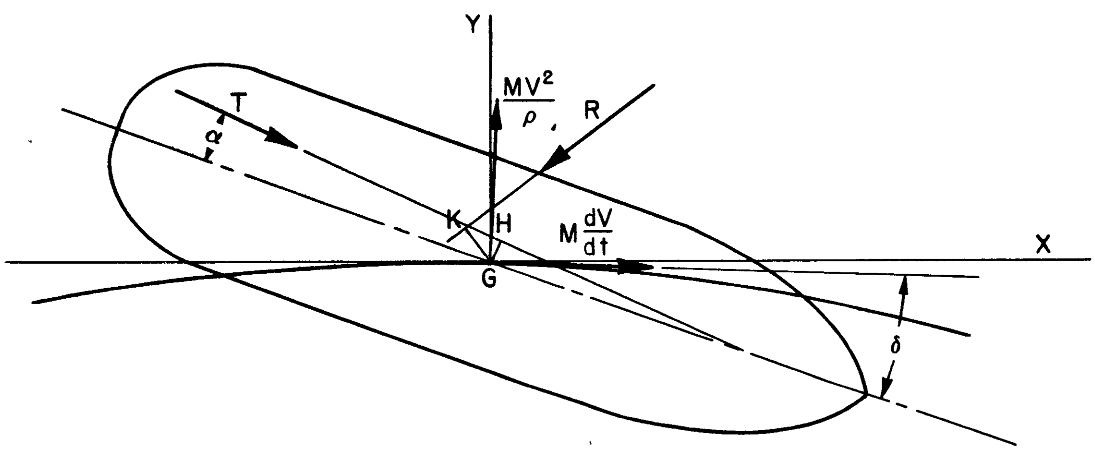


Figure 3 - Diagram Showing the Third Stage of the Turning Motion

$\overline{GH}$ is the moment arm of $T$ about the longitudinal center of gravity
$\overline{GK}$ is the moment arm of $R$ about the longitudinal center of gravity
$M$ is the mass of ship and entrained water
$\rho$ is the radius of curvature of the path
$\delta$ is the angle of deviation between $M\frac{dv}{dt}$ and centerline of the ship
$T$ is the propeller thrust
$R$ is the ship resistance
$V$ is the ship speed
$t$ is the time

## APPLICATION TO THE STEERING PERFORMANCE OF A TWIN-SCREW SUBMARINE

The preceding treatment is general. For steady motion, the problem may be put on a numerical basis by calculating the rudder angle necessary to nullify the turning couple due to the unbalanced thrust of one wing propeller. This is done here for a submarine, in which it was desired to change the shaft lines without influencing adversely the steering behavior of the vessel.

The original shaft lines, when extended, intersected the centerline of the vessel at a point 26.0 per cent of the length from the bow, as shown in Figure 4. The proposed shaft lines, when extended, intersected the centerline much farther aft,

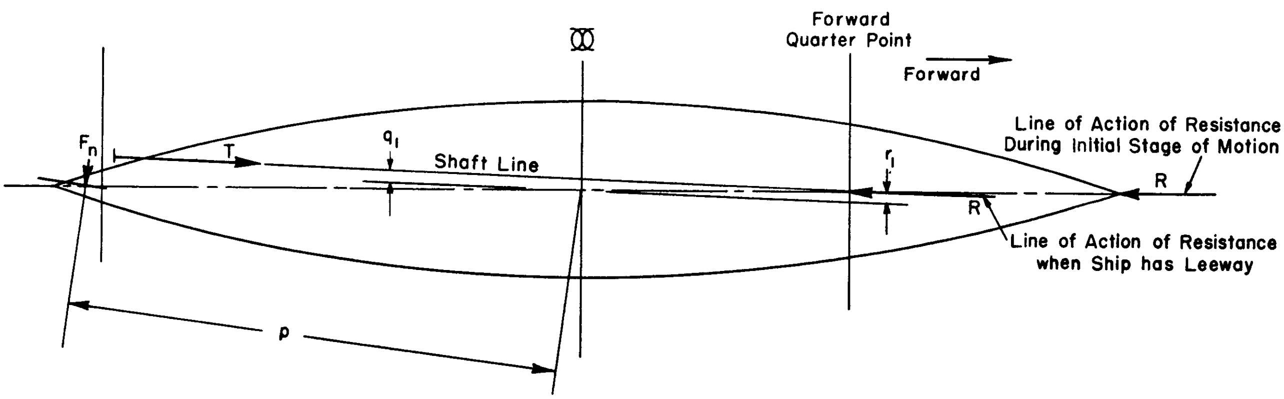


Figure 4 - Diagram Showing Original Shaft Lines and Positions of Forces and Lever Arms

$T$ is the propeller thrust
$q_1$ is the moment arm of $T$ about the longitudinal center of gravity (assumed at Station 10)
$F_n$ is the normal rudder force
$p$ is the moment arm of $F_n$ about the longitudinal center of gravity
$R$ is the ship resistance
$r_1$ is the moment arm of $R$ when the ship has leeway

as indicated in Figure 5. This change would have moved the point of application of the propeller thrust from a point well forward of the center of gravity to a point somewhat abaft the center of gravity.

For the purpose of setting up a numerical example, it may be assumed that the speed is 15 knots, and that the resistance of the submarine at this speed is 25,600 pounds. If this resistance is overcome by thrust on the port shaft alone, assuming that the starboard propeller coasts and interposes no resistance, the turning couple for the original shaft installation about the center of gravity is 56,900 pound-feet, acting clockwise as in Figures 4 and 5. To keep the vessel on her course, sufficient left rudder must be given so that the rudder force $F_n$ multiplied by the lever arm $p$ in Figure 4 is equal to 56,900 pound-feet. The lever arm $p$ is approximately 143 feet so that the required rudder force $F_n$ is 400 pounds. Using Joessel's formula for rudder force as a function of the angle, the required rudder angle is 0.15 degrees.

In the proposed new shaft installation, the shafts intersected at a point 6.2 per cent of the length aft of the center of gravity. Again assuming that the port propeller is driving and that the starboard propeller interposes no resistance, the couple about the center of gravity set up by the thrust on the port propeller is 26,500 pound-feet, acting counterclockwise in Figure 5. To counteract this couple, it is found by a calculation similar to that in the previous paragraph that the rudder angle must be 0.07 degrees right rudder.

The preceding discussion is only a first approximation because the couple set up by the leeward motion of the vessel has been neglected. To take account of

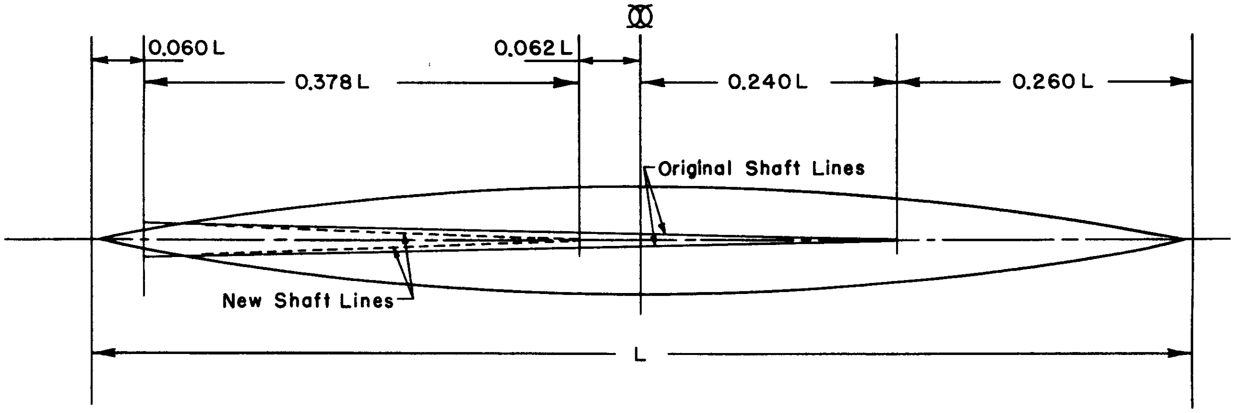


Figure 5 - Location of Original and Proposed Shaft Lines

this the leeway angle of the ship resulting from the action of the transverse components of the thrust and the rudder force was calculated by data given in EMB Report 109 (2). This angle was found to be approximately 0.6 degrees for both the original and the proposed shaft installations.

From experimental data on rudders and hydrofoils, it is known that for small angles of attack the center of pressure lies approximately at the quarter-chord point. Making the assumption that this holds also for the underwater body of a ship, the couple set up by the ship resistance is found to be 20,600 pound-feet, acting counterclockwise. The combined torque of propeller thrust and resistance for the original shaft lines is therefore 56,900 minus 20,600, or 36,300 pound-feet, and for the new shaft lines it is 26,500 plus 20,600, or 47,100 pound-feet.

Repeating the calculation for the rudder angles, using the total torque values, it is found that the required rudder angle to keep the ship on her course with the original shaft lines is approximately 0.1 degree left rudder and with the new shaft lines approximately 0.12 degree right rudder. The leeway angles for the two cases are of the same magnitude for all practical purposes and act in the same direction, namely, approximately 1/2 degree to starboard.

The magnitudes of the calculated values indicated that the proposed change in shaft lines would have little effect on the steering or operation of the vessels at sea, and the design office was so advised.

## APPLICATION TO THE CASE OF A SUBMARINE WITH TWO SHAFTS PARALLEL TO THE CENTERLINE

As a rather extreme case, it may be assumed that the two shafts, as relocated, are to be placed parallel to the centerline of the submarine, 5.66 feet distant, and that the steering situation with one propeller out of commission is to be investigated.

Assuming as before that the speed of the submarine is 15 knots, that the resistance and the thrust are both 25,600 pounds, and that the idle propeller coasts and interposes no resistance, the turning couple for the working shaft about the center of gravity is 144,900 pound-feet. To keep the vessel moving ahead, sufficient rudder movement must be exerted by the rudder to balance this thrust moment. With a rudder lever arm of 143 feet, the lateral force exerted by the rudder is 1013 pounds. The rudder angle, to keep the vessel on its course, derived in the same way as in the preceding section, is still of the order of only 0.5 degree.

## GENERAL STEERING PROBLEMS WITH OFFSET THRUST

In many actual cases, of course, the non-working propeller may not be in position to coast and to interpose no resistance; it may be jammed and the negative thrust developed by it may be quite large. The number of possible cases with twin-screw and multiple-screw ships is legion, and it is difficult to pick out a representative one for illustration here.

As a general rule, it may be stated, however, that if the situation requires the crippled vessel to carry not more than 10 degrees of rudder, the increase in resistance to be expected from the rudder angle alone is of the order of only 1 or 2 per cent.* Under these conditions, of course, the one propeller of a twin-screw vessel remaining in commission will be rather severely overloaded, and there will be a further loss in power from this source.

To show what can be done in the way of handling a ship with an excessive offset of propeller thrust, there is the record of a quadruple-screw heavy cruiser which limped back to port on one ***outboard*** shaft, with the propellers on all the remaining three shafts jammed. Despite the fact that this outboard shaft ***diverged*** forward, with a large moment about the vertical axis through the center of gravity, the cruiser was able to make 7 or 8 knots with 5 to 10 degrees rudder and to hold "a fairly steady course." After the three jammed propellers had been removed, this ship made an overseas voyage of several thousand miles on the ***one outboard propeller*** only!

## REFERENCES

(1) "Principles of Naval Architecture," edited by Rossell and Chapman, published by Society of Naval Architects and Marine Engineers, 1939, Vol. II, Chap. IV, page 219.

(2) "Report of Test on Model of USS LANGLEY to Determine Leeway Due to Wind," EMB Report 109, January 1925.

* Derived from tests of Model 2285, representing the PATOKA class of U.S. Navy oilers, made at the U.S. Experimental Model Basin.