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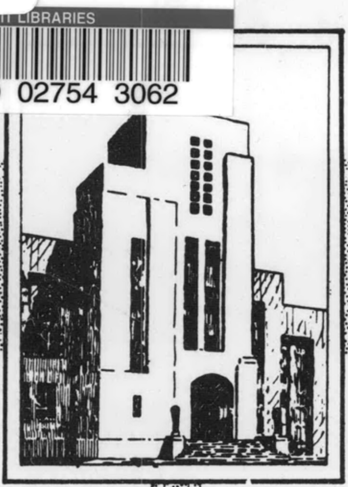

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PRELIMINARY ANALYSIS OF MANUAL AND AUTOMATIC STEERING OF A DIRECTIONALLY UNSTABLE MODEL WHICH EXHIBITS A LOOP

by

A. G. Strandhagen, Ph.D.

[redacted]

HYDROMECHANICS LABORATORY
RESEARCH AND DEVELOPMENT REPORT

October 1958 Report 1280

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ABSTRACT

The relatively large nonpreferential rates of change of heading at small rudder angles experienced by directionally unstable ships can be controlled and repressed either manually or with some types of automatic control if loop characteristics from spiral experiments are known. With information of this kind, it is then possible to efficiently control the motion of a model on the straight approach to a turning maneuver in a J-basin. Moreover, with additional experimental data, studies of this kind may be extended to include the case of steering of ships in canals.

INTRODUCTION

From the standpoint of achieving the best course-keeping qualities, it is desirable that ships be inherently directionally stable. Many of the ships in existence, however, are directionally unstable. Others still in the design stage undoubtedly will have insufficient stability because of the many concessions that are made to other requirements. Experience has shown that it is difficult to maintain straight course with small rates of change of heading with directionally unstable ships. In fact, by trial and error methods, it usually takes considerable practice even by experienced operators to achieve acceptable performance.

The course-keeping problem with directionally unstable ships is also a matter of great concern at the David Taylor Model Basin in connection with model turning experiments. To carry out this type of experiment properly, the model should be made to approach the beginning of a turn with a zero rate of change of heading. This is extremely difficult to do within the limitations of the length and width of the J-Basin. Furthermore, limitations of scheduled time make the use of trial and error methods of control extremely impractical. To provide more suitable procedures, a study was initiated under the Fundamental Hydromechanics Research Program to investigate the best methods of control on straight course of models exhibiting a loop as a result of spiral maneuvers. The present report is concerned with a group of exploratory studies of this nature carried out on the Analog Computer Facility at the Taylor Model Basin.

The studies described in this report indicate that testing time can be shortened and steering control improved if, following an initial disturbance, the responsive rate of change of heading is limited to values within the loop. This can be accomplished by a corrective rudder manipulation followed with a particular rudder sequence executed at proper times. A rudder procedure of this kind will quickly yield a near-zero rate of change of heading so that a model is properly oriented for a turning experiment.

GENERAL CONSIDERATIONS

The difficulty in steering may be noted by reference to Figure 1 which shows the steady-state reponses of both a directionally unstable and a directionally stable model. Suppose a corrective rudder setting $\delta_r < \delta_1$ is estimated by a steersman. Then the rate of change of heading r' for a directionally unstable model as compared with a directionally stable model is not only larger in magnitude but is also nonpreferential. Consequently, additional corrective measures to counter this unexpected large magnitude and possible opposite sense of rate of change of heading often leads to more unexpected excursions in rate of change of heading. Before the model is finally brought under control both the time of operation and also the length of approach to a maneuvering experiment has thus increased beyond expectation. It is clear that any studies to diminish both of these undesirable observations would be of benefit to a steersman of the model as well as for the full-scale ship.

EQUATIONS OF MOTION

To arrive at definite quantitative conclusions, it is necessary to assume a particular model of a surface ship which is directionally unstable on a straight course.

It has been shown that the equations of motion in a horizontal plane, neglecting both the loss of forward speed and roll, may be written as follows:[1]

$$\begin{aligned} -a_1\dot{\beta}' &= c_1\beta + d_1r' + P(\beta,r',\delta_r) + e_1 \\ -b_2\dot{r}' &= c_2\beta + d_2r' + Q(\beta,r',\delta_r) + e_2 \end{aligned} \qquad [1]$$

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[1] Strandhagen, A. G., "Analytical Determination of a Loop Associated with Directionally Unstable Ships," David Taylor Model Basin Report 1274 (October 1958)

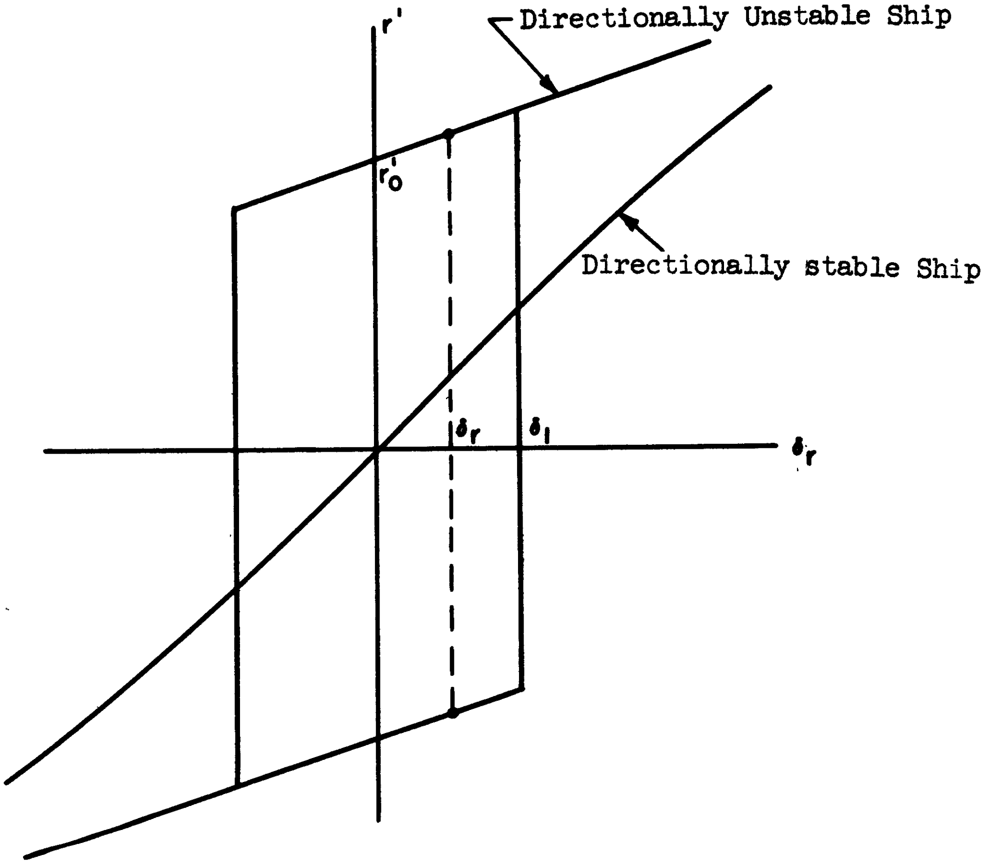


Figure 1 - Steady-State Comparisons

where: $a_1 = + m_y{}', \quad b_2 = I'$

$$c_1 = Y_\beta{}'(0,0,0) + \delta_r Y_{\beta\delta_r}{}'(0,0,0) + \tfrac{1}{2}\,\delta_r{}^2 Y_{\beta\delta_r\delta_r}{}'(0,0,0) + \cdots$$

$$d_1 = Y_r{}'(0,0,0) - m_x{}' + \delta_r Y_{r\delta_r}{}'(0,0,0) + \tfrac{1}{2}\,\delta_r{}^2 Y_{r\delta_r\delta_r}{}'(0,0,0) + \cdots$$

$$c_2 = N_\beta{}'(0,0,0) + \delta_r N_{\beta\delta_r}{}'(0,0,0) + \tfrac{1}{2}\,\delta_r{}^2 N_{\beta\delta_r\delta_r}{}'(0,0,0) + \cdots$$

$$d_2 = N_r{}'(0,0,0) + \delta_r N_{r\delta_r}{}'(0,0,0) + \tfrac{1}{2}\,\delta_r{}^2 N_{r\delta_r\delta_r}{}'(0,0,0) + \cdots$$

$$e_1 = \delta_r Y_{\delta_r}{}'(0,0,0) + \tfrac{1}{2}\,\delta_r{}^2 Y_{\delta_r\delta_r}{}'(0,0,0) + \cdots$$

$$e_2 = \delta_r N_{\delta_r}{}'(0,0,0) + \tfrac{1}{2}\,\delta_r{}^2 N_{\delta_r\delta_r}{}'(0,0,0) + \cdots$$

$$\begin{aligned} P(\beta,r',\delta_r) = {} & \tfrac{1}{2}\left[(r')^2 Y_{rr}{}'(0,0,0) + \beta^2 Y_{\beta\beta}{}'(0,0,0)\right] + \beta r' Y_{r\beta}{}'(0,0,0) \\ & + 1/6\left[(r')^3 Y_{rrr}{}'(0,0,0) + \beta^3 Y_{\beta\beta\beta}{}'(0,0,0)\right] \\ & + r'\beta\delta_r Y_{r\beta\delta_r}{}'(0,0,0) + \tfrac{1}{2}\left[(r')^2\beta Y_{rr\beta}{}'(0,0,0)\right. \\ & + \beta^2 r' Y_{r\beta\beta}(0,0,0) + r'\delta_r{}^2 Y_{r\delta_r\delta_r}{}'(0,0,0) \\ & \left. + (r')^2\delta_r Y_{rr\delta_r}{}'(0,0,0)\right] \end{aligned}$$

$$\begin{aligned} Q(\beta,r',\delta_r) = {} & \tfrac{1}{2}\left[(r')^2 N_{rr}{}'(0,0,0) + \beta^2 N_{\beta\beta}{}'(0,0,0)\right] + \beta r' N_{r\beta}{}'(0,0,0) \\ & + 1/6\left[(r')^3 N_{rrr}{}'(0,0,0) + \beta^3 N_{\beta\beta\beta}{}'(0,0,0)\right] \\ & + r'\beta\delta_r N_{r\beta\delta_r}{}'(0,0,0) + \tfrac{1}{2}\left[(r')^2\beta N_{rr\beta}{}'(0,0,0)\right. \\ & + \beta^2 r' N_{r\beta\beta}{}'(0,0,0) + r'\delta_r{}^2 N_{r\delta_r\delta_r}{}'(0,0,0) \\ & \left. + (r')^2\delta_r N_{rr\delta_r}{}'(0,C,0)\right] \end{aligned}$$

Equations [1] are general and valid for all surface ships moving in a horizontal plane. However, to arrive at quantitative results it is assumed that nondimensional force Y' and moment N' of a particular directionally unstable ship are as follows:

$$\begin{aligned} Y'(\beta, r', \delta_r) = {} & 0.33690\beta + 3.76182\beta^3 - 0.15953r' + m_x'r' \\ & -0.34667(r')^3 - 0.25518\beta(r')^2 + 9.72997\beta(r')^4 \\ & -30.09455\beta^3(r')^2 + 0.00029\beta\delta_r - 0.00309\beta\delta_r(r')^2 \\ & -0.00135\delta_r \end{aligned} \qquad [2]$$

$$\begin{aligned} N'(\beta, r', \delta_r) = {} & 0.11688\beta + 0.71098\beta^3 - 0.02659r' - 0.2838(r')^3 \\ & -0.78747\beta(r')^2 + 4.77658\beta(r')^4 - 8.90912\beta^3(r')^2 \\ & + 0.0006\delta_r - 0.0001\delta_r r' + 0.00143\beta\delta_r(r')^2 \end{aligned} \qquad [3]$$

With the aid of Equations [2] and [3], Equations [1] take the following form:

$$\begin{aligned} -\dot{\beta}' = {} & 0.82372\beta + 9.19756\beta^3 + 0.00071\beta\delta_r - 0.39005r' \\ & -0.84760(r')^3 - 0.62391(r')^2\beta - 0.00330\delta_r \\ -\dot{r}' = {} & -4.870004\beta - 29.62524\beta^3 + 32.81151(r')^2\beta + 1.10793r' \\ & + 11.825095(r')^3 + 0.00417r'\delta_r - 0.02500\delta_r \end{aligned} \qquad [4]$$

The steady-turning state will be obtained if both $\dot{\beta}'$ and $\dot{r}'$ are set equal to zero. The DTMB Analog Computer was used to solve Equation [4], and the steady-state results are shown in Figure 2. The following interesting items which provide the motivation for the exploratory studies contained in the next section are noted (let $\delta_1 = 5.8$ degrees):

1. If the rudder is laid over to the amount $\delta_r > \delta_1$, the rate of change of heading will be unique in magnitude and sense of direction.

2. If the rudder is laid over such that $0 < \delta_r < \delta_1$ the rate of change is no longer unique because there exists two different magnitudes and senses of direction. The sense of the direction of rate of change of heading will depend upon the sense of initial impulse which the analog computer shows so easily and convincingly.

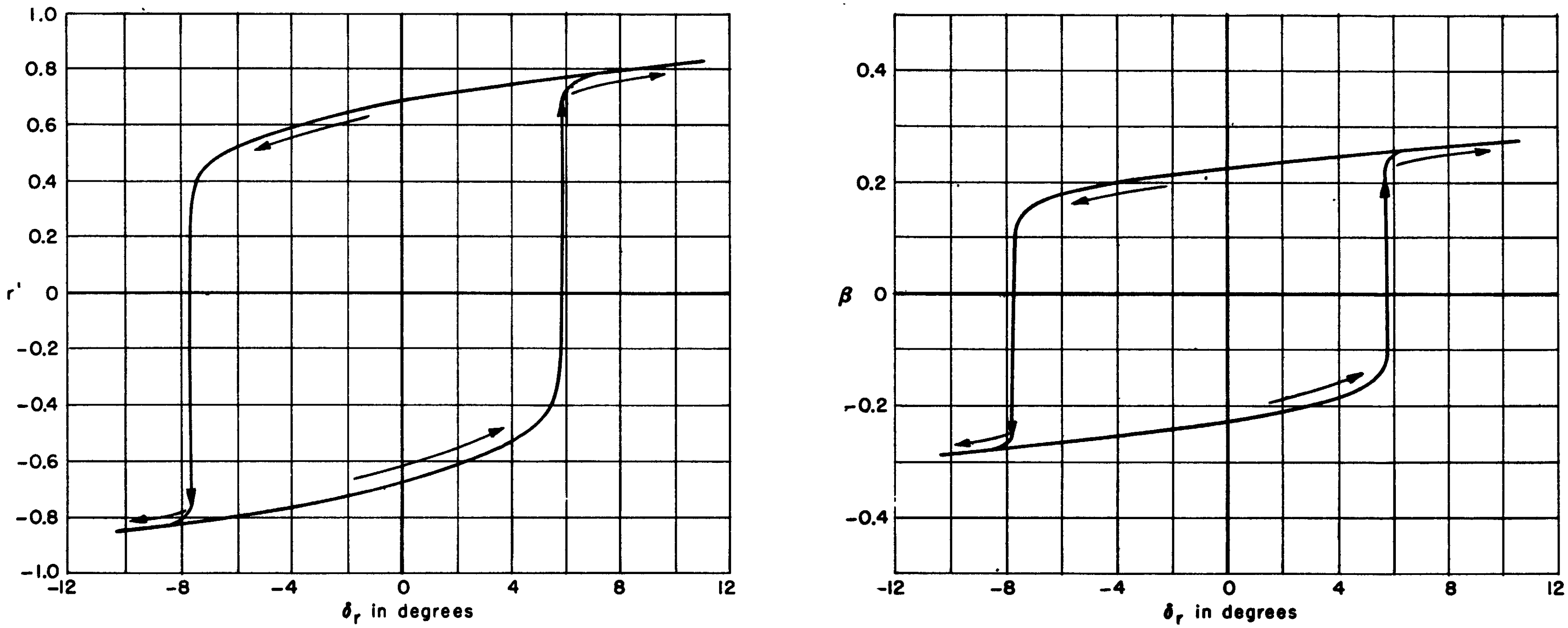


Figure 2 – Dieudonné Loop

3. In a similar manner, identical conclusions for the behavior of β for various settings of rudder angle δ_r can be demonstrated.

Thus it follows that when a model with rudder amidships is tested in a basin, an initial disturbance produced by a reflected wave from a basin wall may cause the model to turn against its rudder which in turn leads to unpredictable course-keeping. This unexpected and undesired rate of change of heading calls for additional rudder movements which again may or may not be appropriate either in magnitude or sense of direction. Thus it is evident that when the model has approached the execute position in a J-basin, it may possess an undesirable finite rate of change of heading which should have been zero in a properly performed turning experiment.

The exploratory studies in this report should assist the operator of model experiments with several useful steering guides.

SOLUTIONS OF EQUATIONS OF MOTION ON DTMB ANALOG COMPUTER

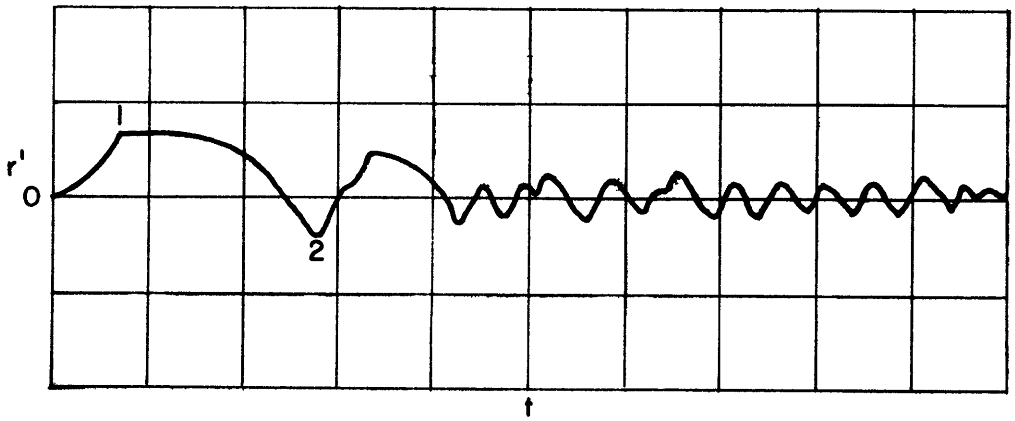
Before proceeding with specific cases, it is to be noted in Figure 2 that a steady rate of change of heading, $r_o' = \pm 0.68$, is attained at zero rudder angle when the model is disturbed by an external impulse. This value of r_o' is used as a basis of comparison in the following cases:

RUDDER OPERATED MANUALLY

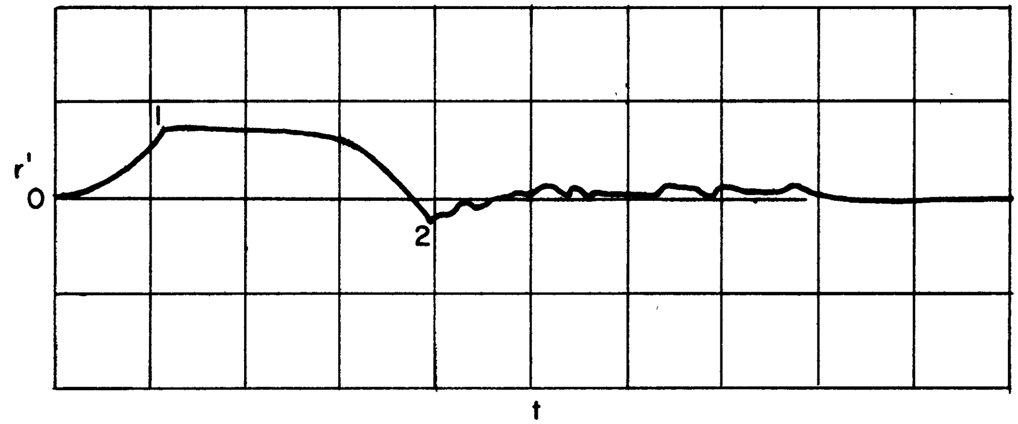
Case I. $\delta_r = 7.5$ degrees, $r' < r_o'/2$, (Figure 3a)

Suppose the directionally unstable model is proceeding along a straight course with rudder amidships and is suddenly disturbed by an external impulse. If sufficient time is allowed, the rate of change of heading will become steady at a nondimensional value of ±0.68, where the signs indicate two possible directions arising from two possible external impulse directions.

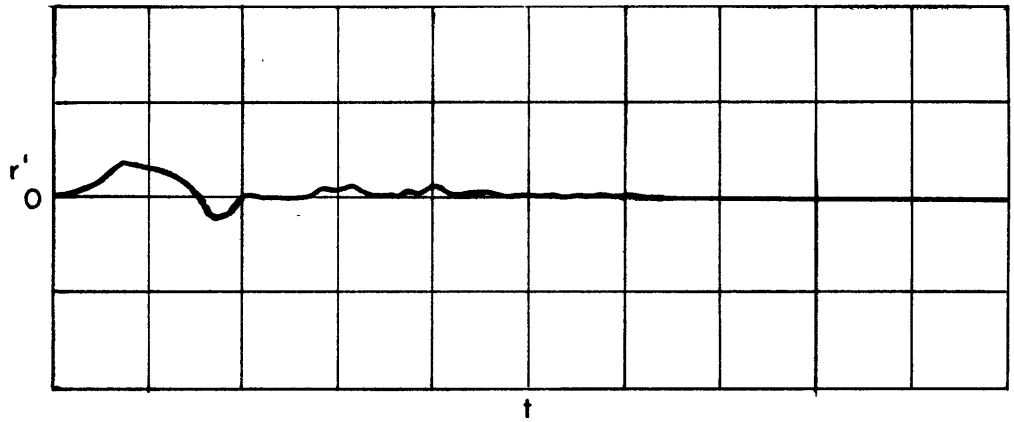
If instead of allowing the rate of change of heading to develop the steady value of say $r_o' = +0.68$, the steersman checks the rate at $r' \simeq r_o'/2$ with an opposing rudder angle of -7.5 degrees, the rate then tends to diminish and becomes negative. When $r' = r_o'/4$, a positively directed rudder angle of 7.5 degrees is applied. This sequence then produces an increasing rate of



(a) Case I



(b) Case II



(c) Case III

Figure 3 - Typical Time Histories with Rudder Controlled Manually

change which passes through zero at which time a rudder angle of -7.5 degrees is applied. A rudder angle of ±7.5 degrees is manipulated in sequence thereafter whenever the rate is approximately zero. Figure 3a shows that the rate of change of heading does not tend to zero with this particular rudder sequence and upper bound on r'. Thus this model could not be oriented properly to execute a turning maneuver.

Case II. $\delta_r = 7.5$ degrees, $r' < r_o'/2$, (Figure 3b)

This case is somewhat similar to Case I and differs only after the first execute of rudder angle of -7.5 degrees. Thereafter all subsequent rudder angles are ±4 degrees. Figure 3b shows a rate of change of heading which is approximately zero, and therefore this rudder sequence is satisfactory insofar as improved steering is concerned.

Case III. $\delta_r = 5.0$ degrees, $r' = r_o'/4$, (Figure 3c)

This case is similar to both Cases I and II but the rudder angle is restricted to ±5 degrees and the r' is checked at $r_o'/4$. It is to be noted that both δ_r and r' are within the boundaries of the loop shown in Figure 2. Figure 3c shows considerable improvement over Cases I and II with regard to excursions in r' and also with regard to attaining a zero rate of change of heading in considerably less time.

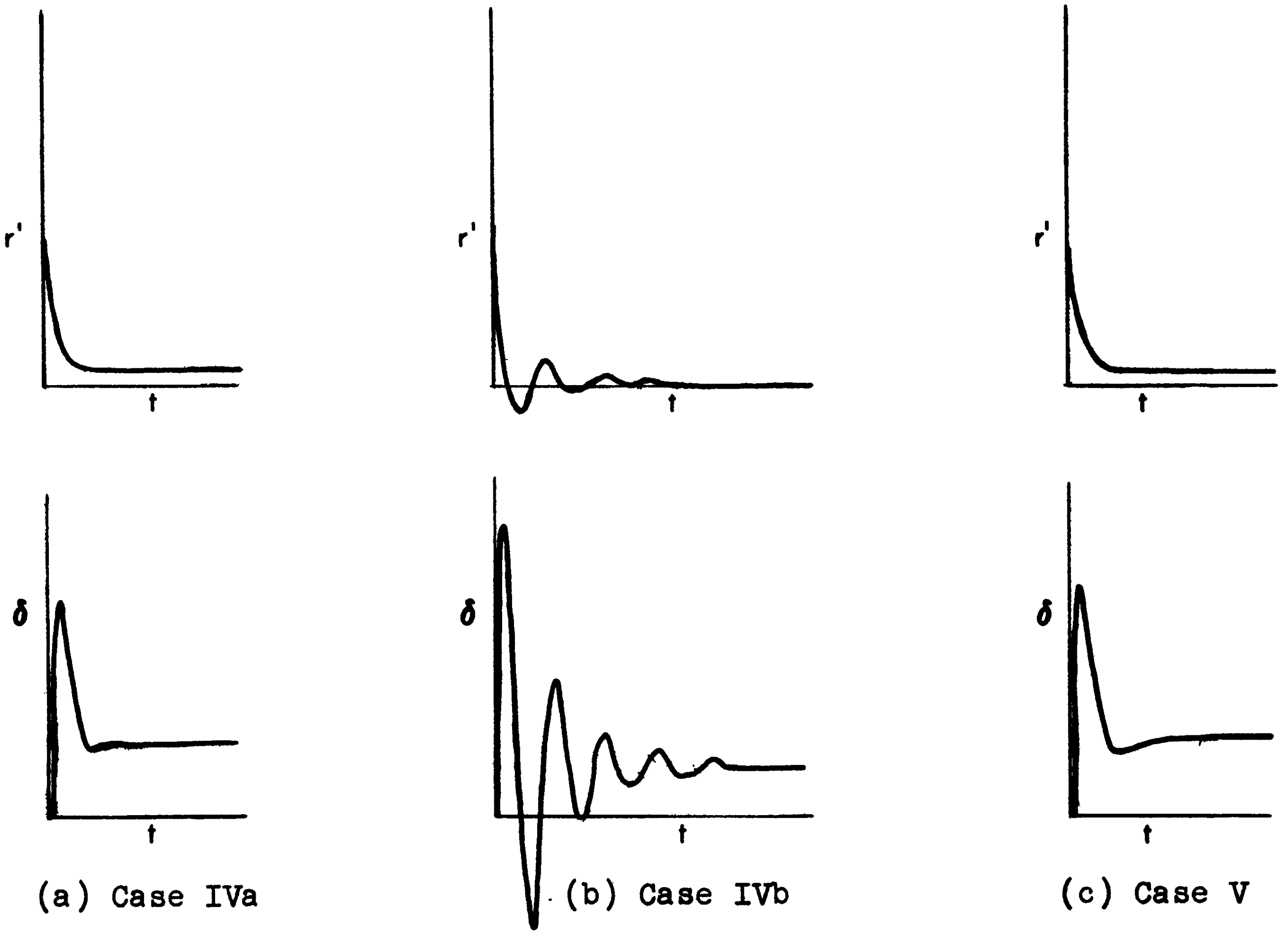
It may be concluded from an analysis of the various cases involving manual control that when δ_r and r' are confined within the boundaries of a loop, a zero rate of change of heading may be attained quickly, and the model will become properly oriented for a turning maneuver. Rudder sequences of the type discussed in Case III with the bound on $r' = r_o'/4$ appear to have been observed by a trial and error procedure by steersmen.

AUTOMATIC CONTROLS

In this series of preliminary studies the rudder angle δ_r is assumed to be governed by the following equation:

$$\delta_r(t) = - a\beta - Br' - C(D\delta_r/dt) \qquad [5]$$

in which δ_r is a function of the instantaneous values of r' and the rate of rudder application $d\delta_r/dt$. Figure 4 illustrates three possible control equations which may form the basis of



(a) Case IVa

(b) Case IVb

(c) Case V

Figure 4 - Typical Time Histories with Rudder Controlled Automatically

further studies for directionally unstable ships.

Case IVa. A = 0, B = 50, C = 1, (Figure 4a)

In this case, r' tends to a finite value which is not zero. This type of control would of course be unsatisfactory if one is interested in obtaining a zero rate of change of heading after the model is disturbed by an external impulse.

Case IVb. A = 0, B = 100, C = 2, (Figure 4b)

Following an initial external disturbance, this case shows that the rate of change of heading tends to zero and, therefore, is satisfactory as a control equation.

Case V. A = 50, B = 50, C = 1, (Figure 4c)

Again following an initial disturbance, r' approaches a finite value which is not zero. Therefore, with constants chosen for A, B, C, this control would be unsatisfactory. However, this case was not studied sufficiently with respect to various combinations of constants which would yield a zero rate of change of heading.

Case VI. A = 0, B = 75, C = 1

This case is similar to Case V in which the constant B has been increased from 50 to 75. A control of this type shows that the rate of change of heading tends to zero, and differs from zero by a very small amount. In some cases this control would be satisfactory.

SUMMARY

An analog computer analysis of the course-keeping behavior of a directionally unstable model reveals the following:

1. The rate of change of heading of the model can be restored to zero if, after an initial disturbance, the steersman

applies corrective rudder action when the rate is about one-half the steady rate attained by the model with zero rudder angle. It is necessary, however, to use other additional rudder sequences to attain this zero rate. In any event, the model can be controlled so that it can enter the approach to a turning experiment satisfactorily. The magnitudes of the rudder angle and rate of change of heading involved in the sequence must lie within the bounds of a loop previously determined for this model.

2. The model can be more efficiently controlled with an automatic steering device whose equation is of the type discussed in Case VI.

3. It may be possible to apply an analysis similar to that given in this report to the case of steering in restricted channels. However, this would require experimental data of a type not obtainable with existing facilities.

ACKNOWLEDGMENTS

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