MODELLING THE BEHAVIOR OF THE HELMSMAN STEERING A SHIP

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Abstract

A supertanker can be considered as a nonlinear system which responds very slowly to changes in the rudder position. Moreover this type of ships is often unstable in loaded condition, i.e. it has a tendency to start turning either to the left or to the right. These properties make the supertanker very hard to handle.

In order to model the helmsman's behavior, a number of tests has been performed using a ship maneuvering simulator. The trained subjects had to steer a 200,000 tons tanker along a varying course. The results obtained from these trials are encouraging. A discussion of the further research is given.

1. Introduction

Most of the investigations concerned with the behavior of the human operator as a controller have been executed with reference to pilots of aircraft or spacecraft; some work has been done on the control of submarines. The human operator as a controller of surface ships, however, did not get very much attention until recently.

In the Netherlands in 1968 the Institute TNO for Mechanical Construction (TNO-IWECO) at Delft built a ship maneuvering simulator [1] in order to study among other things ship maneuverability, the design of nautical instruments and the training of ship crews. In the same year Stuurman [2] executed a series of trials in which he showed that for small ships the control behavior of the helmsman could very well approximated by means of a Describing Function Model. He also found evidence that for larger ships a nonlinear model probably would give a more realistic description of the helmsman's behavior.

In consult with TNO-IWECO it was decided to continue the work of Stuurman as a joint activity of the Shipbuilding Laboratory of the Delft University of Technology and the Man-Machine Systems Group. Special emphasis was to be laid on modelling the helmsman of a supertanker with the following goals in mind: To provide data on which the maneuvers of this type of ships under human control can be predicted in a number of situations as well as to enable an evaluation of the employment of a human pilot. The results of some preliminary experiments have been reported at last year's Annual Conference on Manual Control [3].

2 Ship dynamics

The dynamics of a ship depend not only on the properties of the ship itself but also on the topology of the surrounding water. The motions of a ship in the horizontal plane can be described by a set of nonlinear differential equations. These equations describe the translations of the ship in a direction corresponding to the longitudinal axis of the ship and in a direction perpendicular to this axis as well as the rotation about a vertical axis through the center of gravity. Fig. 1 gives an indication of the variables concerned.

In 1957, Nomoto [4] showed that for a ship sailing at constant speed the relation between rudder angle δ and rate of turn r can be described by means of a second order linear differential equation. For most of the smaller ships this equation gives an adequate description of the ship's behavior in a number of standard maneuvers. For a supertanker, however, it was found that the behavior was essentially nonlinear. Based on full scale trials, Bech [5] proposed to extend Nomoto's equation with a nonlinear term. This leads to the following relation [6]:

$$T_1T_2\,\ddot{r}(t)+(T_1+T_2)\dot{r}(t)+a_1r(t)+a_2[r(t)]^3=K[T_3\,\dot{\delta}(t)+\delta(t)], \qquad (1)$$

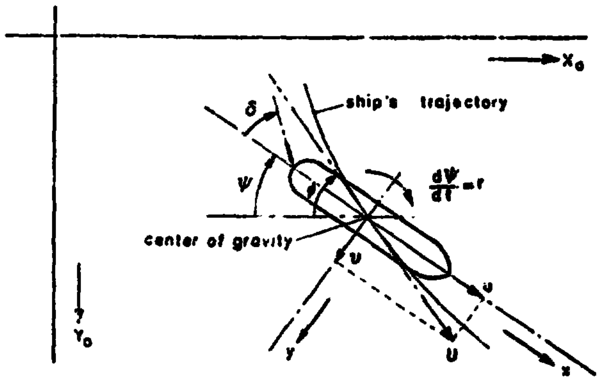

FIGURE 1:

The quantities involved in the description of the ship's maneuvers.

where $r(t) = d\psi(t)/dt$ is the rate of turn, $\psi(t)$ is the heading angle, $\delta(t)$ is the rudder angle, and where the quantities a_1, a_2, T_1, T_2, T_3 and K are constants. These constants are dependent on the hydrodynamic properties of the ship, which are for instance related to speed, load condition and possible restrictions in the surrounding water.

In this study a particular ship viz. a 220,000 tons deadweight tanker in loaded condition has been chosen. The principal data of the ship were: Length = 310.00 m; Breadth = 47.16 m; Depth = 24.50 m; Draft = 18.90 m; Displacement = 238,000 m^3 and Froude number = 0.14. The constants in Eq. (1) for this ship have been determined by Glansdorp [6;7], they are given in Table 1. If a stationary situation is considered, that is, $\ddot{r}(t) = 0$, $\dot{r}(t) = 0$, $\dot{\delta}(t) = 0$, then Eq. (1) changes into:

$$a_1 r + a_2 r^3 = K\delta. \qquad (2)$$

TABLE 1:

Constants in the equation describing the relation between the rudder angle and the rate of turn for the supertanker, in deep and still water; the speed considered is 7.72 m/sec.

constants	dimension	numerical values	
		fully loaded	ballasted
a_1		-1	1
a_2	sec^2/rad^2	60,000	16,200
T_1	sec	250	80
T_2	sec	10	3
T_3	sec	20	6
K	sec^{-1}	-0.0434	-0.0471

Fig. 2 represents Eq. (2) ; this static characteristic is given for the ship in fully loaded and ballasted condition. The ship is course unstable in loaded condition; it has a natural tendency to deviate from the straight course and to start turning either in one direction or the other.

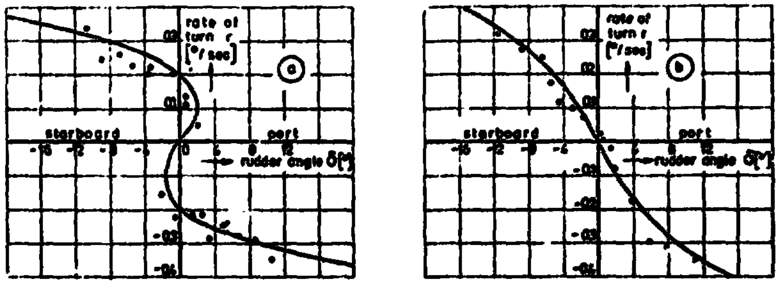

FIGURE 2:

Relation between the rudder angle δ and the rate of turn r in the stationary state for the ship considered in this investigation as found by Glansdorp [7] (a: loaded condition; b: ballasted condition).

3 The maneuvering simulator

The simulator consists of a wheelhouse which has the same appearance as that of a real sea-going vessel. The fore part of the ship, the sea and a coastline are displayed on a screen in front of the wheelhouse. The total angle of vision of the helmsman is 120°. The image of the fore part of the ship is static, it is produced by two slide projectors which have a fixed position. The coast line is generated by means of a point light source and a movable model with three degrees of freedom simulating two translations and one rotation in the horizontal plane. A blockdiagram of the system, including the helmsman, is given in Fig. 3.

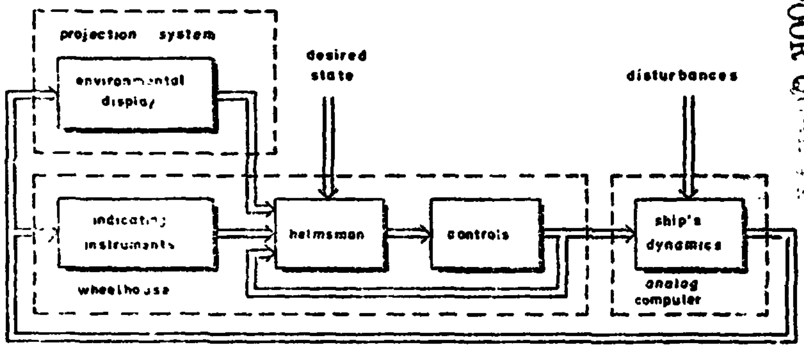

FIGURE 3:
Blockdiagram of the TNO simulator.

On an analog computer the dynamics of the ship to be simulated, including the characteristics of thrust engine and rudder engine, can be programmed. The computer yields the signals which control the environmental display system and also the instruments such as compass, rudder position indicator, log, etc. The helmsman has the same controls at his disposal for maneuvering as on a real ship viz. the wheel, which gives the input to the rudder engine, and the telegraph to the engine, which governs the speed of the propeller. External disturbances simulating the effects of wind, waves and currents can also be introduced into the model on the analog computer.

4 The experiments

In the experiments described here, the simulator has been used as a supertanker at full sea in fully loaded condition as well as in ballasted condition, moving at a constant speed. The analog computer was programmed according to Eq. (1) based on the constants given by Glansdorp as indicated in Table 1. The rudder engine was also included in the simulation; its dynamics have been chosen according to the Eqs (3) and (4).

$$T_4 \dot{\delta}(t) + \delta(t) = \delta_d(t); \quad (3)$$

$$|\dot{\delta}(t)| \leq M, \quad (4)$$

where $\delta_d(t)$ is the position of the steering wheel or the desired rudder angle; where T_4 is a time constant of 1 sec and where the quantity M is the maximal value of the rotation speed of the rudder (0.045 rad/sec).

The subjects were four trainees of the School of Navigation at Rotterdam. They were studying for the rank of first or second mate after having been at sea for several years. All four trainees were experienced in steering conventional cargo ships; only one of them (subject A) had sailed on tankers up to 90,000 tons dead weight. Their task consisted of following a straight course for about half an hour, or of following a preprogrammed but unpredictable course which changed between +2° and -2° around a certain nominal course for about fourty minutes. This prescribed course acted as a forcing function for the man-supertanker system. Because it is not a realistic situation to follow a continuously changing course, a binary signal was chosen. The construction of the binary test signal was based on the idea that with the experiments to be executed also linear models of the helmsman's behavior might be investigated.

Therefore the input signal (desired course) was constructed in such a way that about 70 percent of the input's energy was concentrated at only four frequencies. The amplitude of the binary signal was equal to the two degrees earlier mentioned. The four sinusoidal components were the third, fifth, eight and thirteenth harmonics of a sinusoid with a period of forty minutes; the phase at the initial point was chosen at random.

TABLE 2: Summary of the tests performed.

DATE / TIME	1972 April 25	1972 April 26	1972 May 2	1972 May 3
7.00pm	Subject A 1 loaded cond. course chang.	Subject C 7 loaded cond. course chang.	Subject A 13 ball. cond. course chang.	Subject D 19 ** loaded cond. course chang.
8.00pm	Subject B 2 loaded cond. course keep.	Subject D 8 loaded cond. course chang.	Subject B 14 loaded cond. course chang.	Subject C 20 loaded cond. course chang.
	Subject A 3 loaded cond. course keep.	Subject C 9 loaded cond. course keep.	Subject A 15 loaded cond. course keep.	Subject D 21 loaded cond. course keep.
9.00pm	Subject B 4 loaded cond. course chang.	Subject D 10 loaded cond. course keep.	Subject B 16 loaded cond. course keep.	Subject C 22 loaded cond. course keep.
	Subject A 5 ball. cond. course keep.	Subject C 11 ** loaded cond. course keep.	Subject A 17 loaded cond. course keep.	Subject D 23 loaded cond. course keep.
10.00pm	Subject B 6 ball. cond. course keep.	Subject D 12 *** loaded cond. course chang.	Subject B 18 * loaded cond. course keep.	Subject C 24 * loaded cond. course keep.

* With disturbances due to waves.

** With rate of turn indicator.

*** Due to a want of time this run could not be performed.

In Table 2 a summary of the tests is given. During the experiments the compass as well as the rudder angle indicator were used. Three tests have been executed in which also the rate of turn indicator was used. With the exception of two trials no external disturbances simulating ship motions originating from wind, waves and currents were introduced; these external disturbances were generated by means of a digital computer and consisted of the sum of 23 sinusoids simulating the motions of the fully loaded tanker in a following sea with long crested waves. These waves were considered to originate from a wind with a force of eight to nine Beaufort.

During the tests the following signals were recorded on magnetic tape:

- The desired course $\psi_d(t)$.
- The course of the ship $\psi(t)$.
- The desired rudder angle $\delta_d(t)$.
- The rudder angle $\delta(t)$.
- The rate of turn $r(t) = \dot{\psi}(t)$.

5 Modelling the helmsman's behavior

In the Figs 4 through 6 some examples are given of the time histories of the desired course $\psi_d(t)$; the course of the ship $\psi(t)$; the desired rudder angle $\delta_d(t)$; the rudder angle $\delta(t)$, and finally the rate of turn $r(t)$ as recorded during the tests. In all cases the records show that the helmsman generates a rudder angle $\delta(t)$ as output which consists of discrete steps. Hence the records indicate that a linear model to describe the helmsman's behavior will not fit the data very well. To check this presumption, the ratio between the energy not located at the four frequencies mentioned before and the total energy of the signal considered has been calculated. The Table 3 shows the results for the four subjects, each having performed two runs of forty minutes. From the table it can be concluded that the remnant energy, in particular of the desired rudder angle $\delta_d(t)$, is that high in most of the runs observed, that it does not seem appropriate to focus the attention on linear descriptions of the helmsman's behavior

Subject	A		B		C		D	
Run	1	2	1	2	1	2	1	2
$\psi_d(t)$	28.0	28.6	29.3	28.0	29.0	28.6	28.3	28.8
$\psi(t)$	10.3	21.6	7.8	27.7	50.1	19.5	1.7	26.6
$\delta_d(t)$	88.7	88.0	90.9	94.3	78.2	85.9	78.1	87.9
$\delta(t)$	86.2	86.0	88.8	91.3	77.6	84.7	77.1	86.5
$r(t)$	48.8	47.9	49.5	52.9	70.0	53.2	35.0	56.1

TABLE 3:

Survey of the remnant energy in the signals observed for eight tests with four subjects: Loaded condition; without rate of turn indicator; without disturbances.

any longer. It suggests that the helmsman bases his decisions on when to move and how much to move the wheel on some criterion which is, for instance, a function of the heading angle $\psi(t)$; the rate of turn $r(t)$; the position of the rudder $\delta(t)$, and, of course, the desired angle $\psi_d(t)$.

By the compass the course $\psi(t)$ is displayed to the helmsman; while in the case that no rate of turn indicator is used, it is assumed that the helmsman estimates the rate of turn $r(t)$ directly from the time history of the course $\psi(t)$. Based on the records obtained by preliminary tests as well as on the records shown in the Figs 4, 5 and 6 a model for the helmsman's behavior is proposed which states that if the absolute value of a quantity $s(t)$ which is defined as:

$$s(t) = [\psi(t) - \psi_d(t)] + c_1\dot{\psi}(t) \qquad (5)$$

exceeds a certain threshold value d_1, the helmsman moves the steering wheel into a position δ_d (t) according to Eq. (6):

$$\delta_d^*(t) = a\psi_e(t) + b\dot{\psi}(t) + c[\psi_e(t)]^3 + d \text{ sign } \psi_e(t). \qquad (6)$$

In this equation the quantity $\psi_e(t) = \psi(t) - \psi_d(t)$, and the quantities $\psi(t)$, $\psi_d(t)$ and $\dot{\psi}(t)$ are the values of these variables at the moment that the threshold value is exceeded. As a result of this action, the quantity $|s(t)|$ wil decrease; if now $|s(t)|$ becomes less than a second threshold value d_2, it is assumed that

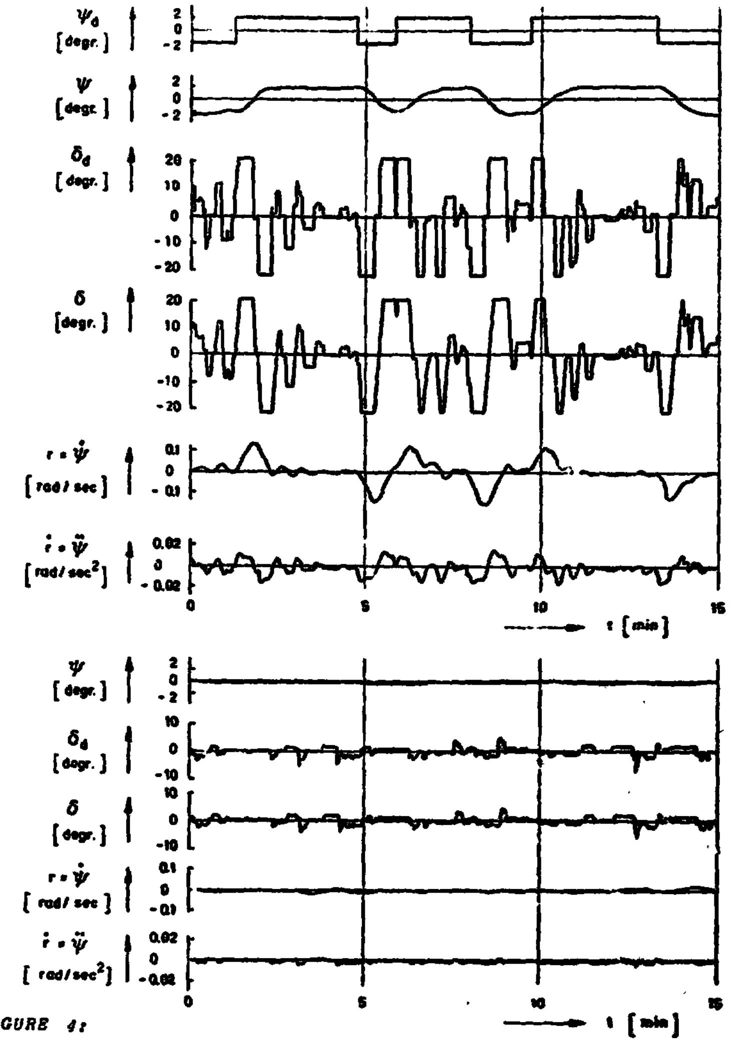

FIGURE 4:

Example of the time histories of the desired course $\psi_d(t)$; the course of the ship $\psi(t)$; the desired rudder angle $\delta_d(t)$; the rudder angle $\delta(t)$; the rate of turn $r(t)$, and the derivative of the rate of turn with respect to the time $\dot{r}(t)$: subject A; without rate of turn indicator; without disturbances; loaded condition.

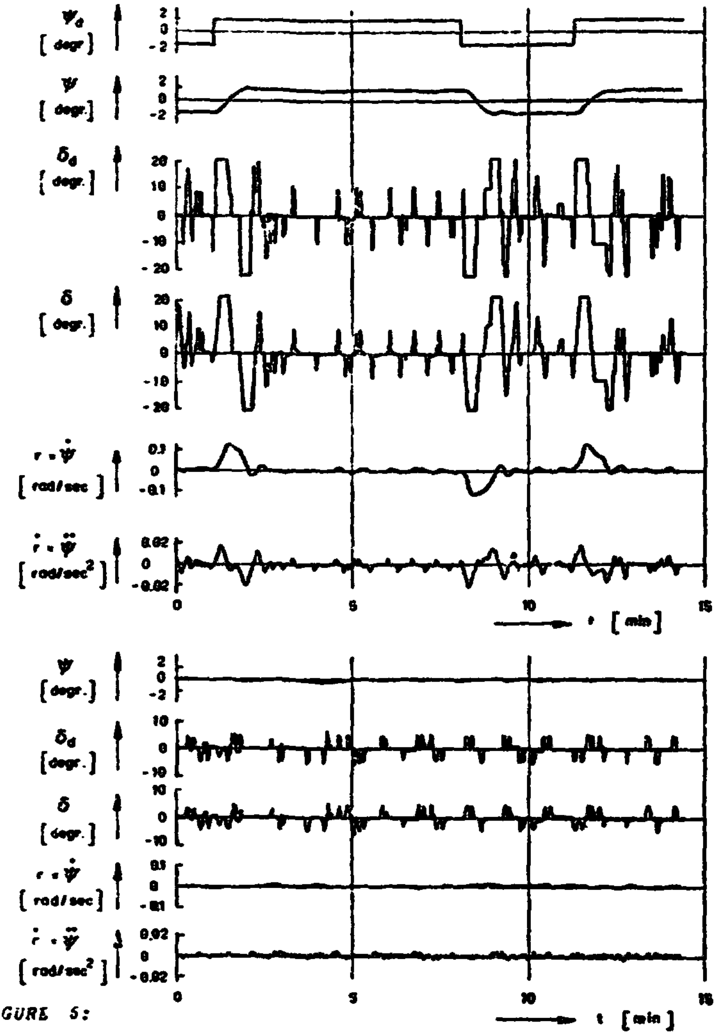

FIGURE 5:

Example of the time histories of the desired course $\psi_d(t)$; the course of the ship $\psi(t)$; th· desired rudder angle $\delta_d(t)$; the rudder angle $\delta(t)$; the rate of tu. [illegible] t), and the derivative of the rate of turn with respect to [illegible] e $\dot{r}(t)$: Subject B; without rate of turn indicator; without [illegible] ances; loaded condition.

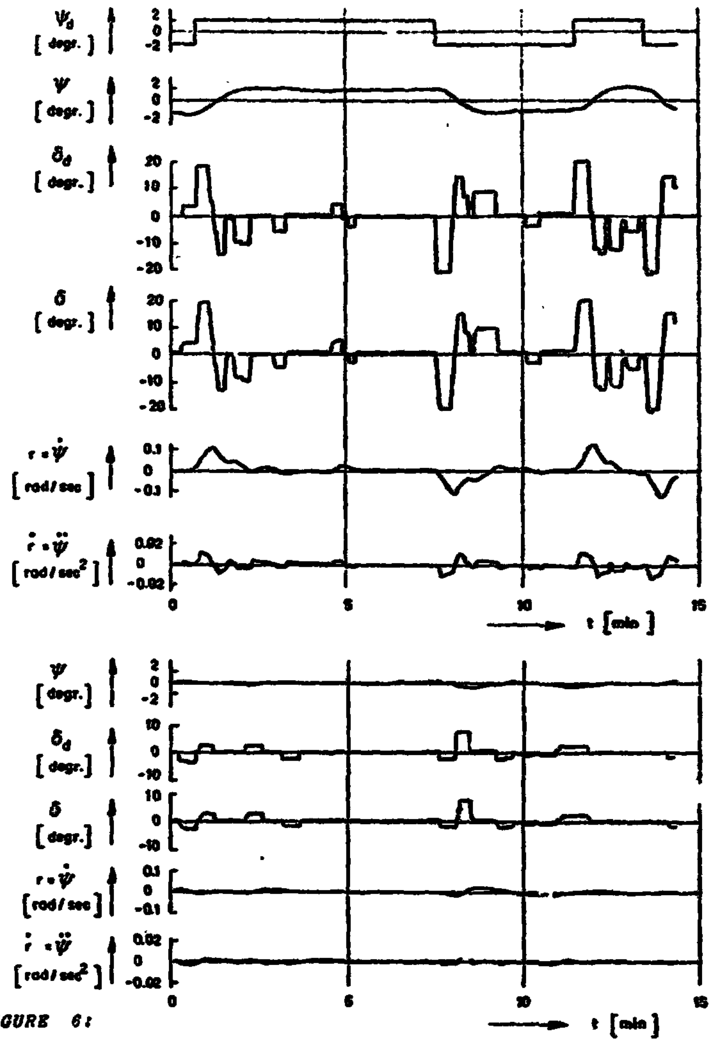

FIGURE 6:

Example of the time histories of the desired course $\psi_d(t)$; the course of the ship $\psi(t)$; the desired rudder angle $\delta_d(t)$; the rudder angle $\delta(t)$; the rate of turn r(t), and the derivative of the rate of turn with respect to the time $\dot{r}(t)$: Subject D; without rate of turn indicator; without disturbances; loaded condition.

the helmsman moves the rudder again into zero position.

6. Parameter Estimation

The parameters a, b, c, d, c_1, d_1 and d_2 can be estimated by minimizing a quantity J_1 defined as:

$$J_1 = \frac{1}{T}\int_0^T [\varepsilon(t)]^2\,dt, \tag{7}$$

where the signal $\varepsilon(t)$ represents the difference between the human operator output $\delta_d(t)$ and the model output $\delta_d^*(t)$. The minimal value of the quantity J_1 can be found by partial differentiation of this quantity with respect to each of the unknown parameters and by setting the result equal to zero. This yields as many equations as there are unknown parameters. Because there does not exist a simple analytical relation between the input and the output of the model of the helmsman it is not possible to solve the equations just-mentioned in a simple way. Furthermore, it should be noted that if a model with given parameters should be inserted into the control loop instead of the helmsman, this would lead to another time history for the quantities $\delta_d(t)$, $\phi(t)$ and $r(t)$. So, in order to get an unbiased estimate of the parameters in the human operator model, a comparison should be made between the output of the helmsman and the output of thu model, where this model is also part of a closed loop system with the ship's model (See Fig. 7). The parameters can be found by means of a direct search method minimizing the quantity J_1 with respect to the model parameters. With the help of Eq. (7) the quantity E_1 can be defined:

$$E_1 = \frac{J_1}{\frac{1}{T}\int_0^T [\delta_d(t)]^2\,dt} = \frac{\int_0^T [\varepsilon(t)]^2\,dt}{\int_0^T [\delta_d(t)]^2\,dt}. \tag{8}$$

The quantity E_1 indicates how well the model output approximates the actual output of the helmsman.

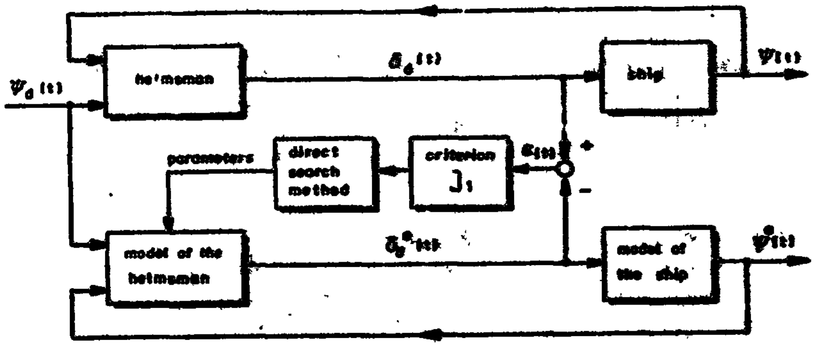

FIGURE 7:

Application of an error criterion in such a way that unbiased parameters can be obtained for a model of a system in a closed loop.

The correspondence between the time histories of the actual course of the ship $\psi(t)$ steered by the helmsman and those of the ship model $\psi^*(t)$ steered by the model of the helmsman's behavior can be expressed by the quantity E_2, defined as:

$$E_2 = \frac{\int_0^T [\psi(t)-\psi^*(t)]^2\,dt}{\int_0^T [\psi(t)]^2\,dt}. \tag{9}$$

7 Results

Based on the data of one test, in which the subject had been instructed to steer a ship in loaded condition along a straight course for a period of 25 minutes, the parameters of a series of simple models have been estimated according to the parameter estimation method just-mentioned. The first model was a linear one; later models were based on the Eqs (5) and (6), be it that the nonlinear terms in Eq.(6) were neglected. The results with these simple models, however, were very poor, and did not give any indication how to modify the model used in order to get a better result. Therefore, the task of the helmsman, which during these tests was to keep a ship in loaded condition on a straight course, was changed into the task of following a certain unpredictable but well defined course. In this case, again the parameters were estimated, and now the results were much better; they even led to a direction in which the structure of the model had to be changed. Finally, the model as given by the Eqs (5) and (6) was obtained.

The Table 4 shows the values of the model parameters as well as the values of the quantities E_1 and E_2 calculated from four tests executed by the four subjects A, B, C and D (See Table 2). The Figs 8 and 9 show some typical time histories of the actual signals $\psi_d(t)$, $\psi(t)$ and $\delta_d(t)$ compared with the model outputs $\psi^*(t)$ and $\delta_d^*(t)$. Some remarks with respect to the results obtained can be made.

- Although a remarkable difference in the steering behavior of the subjects exists (See the Figs 4, 5 and 6), the difference of the parameters among the different subjects is rather small.
- In particular for the subjects A and D the model fits the test results fairly well.
- Although the output of the model of the helmsman's behavior does not always resemble the actual output very well the course of the ship generated by the model experiment fits extremely well.
- In a few cases, for instance the test with subject C, the optimization of the parameters by minimizing the quantity J_1, was difficult. The problem was to find the absolute minimum of the quantity J_1 in stead of a local minimum

TABLE 4:

Summary of the parameters of the model given by the Eqs (5) and (6) and the quantities E_1 and E_2.

Subject	A	B	C	D
Date	1972 May 2	1972 May 2	1972 May 3	1972 May 3
Test nr	15	14	20	21
a	3.5	1.9	6.2	2.0
b [sec.]	176.9	155.0	210.0	230.5
c [degr.$^{-2}$]	0.0	0.1	-0.1	0.1
d [degr.]	1.7	1.0	1.0	1.5
c_1 [sec.]	20.3	30.0	22.5	30.0
d_1 [degr.]	-5.0	0.2	0.3	0.2
d_2 [degr.]	-5.0	0.1	0.2	0.0
E_1 [%]	40.1	70.9	43.4	32.8
E_2 [%]	8.7	--	--	3.1

Further research

Until now, only the parameters of the model have been estimated for four subjects steering a fully loaded tanker along a prescribed course changing at certain moments from +2 degrees to -2 degrees and back. Also some tests were performed with a tanker in ballasted condition and with disturbances (simulating for instance the motions originating from seawaves) acting on the ship, but at this moment parameters have not yet been estimated. Some of these tests, in particular those with the ship sailing in open sea with rather high waves, showed that fairly dangerous situations can occur when the helmsman is not well trained.

The further research is focussed on the following points which may be of importance in developing a useful model in order to be able to predict the behavior of a ship under human control.

- A study of the influence of the task to be executed by the subjects on the structure of the model of the helmsman's

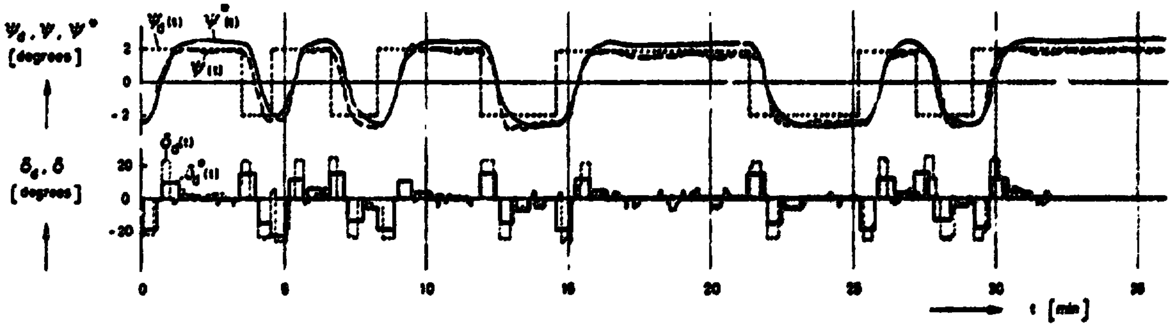

FIGURE 8: Typical time histories of the actual signals $\psi_d(t)$, $\psi(t)$ and $\delta_d(t)$ compared with the model outputs $\psi^*(t)$ and $\delta_d^*(t)$: Subject A; loaded condition; without rate of turn indicator.

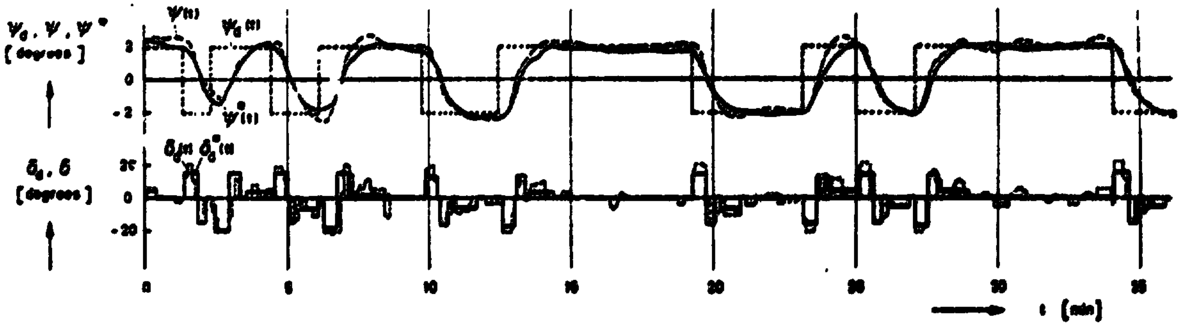

FIGURE 9: Typical time histories of the actual signals $\psi_d(t)$, $\psi(t)$ and $\delta_d(t)$ compared with the model outputs $\psi^*(t)$ and $\delta_d^*(t)$: Subject D; loaded condition; without rate of turn indicator.

behavior and on the parameters belonging to the model.

- A study of the influence of the ship dynamics on the structure of this model and on the model parameters.
- A study of the influence of the disturbances acting on the ship on the structure of this model and on the model parameters.
- The physiological and psychological interpretation of the model parameters.

A large number of experiments with the TNO ship maneuvering simulator have been planned in the middle of 1973. The experiments have been set up in such a way that about ten subjects will have to steer a large number of ships with different dynamics. In characterizing these ships with reference to their dynamics, three groups can be distinguished, i.e.:

- Course stable ships with a more or less linear relation between rudder angle δ and rate of turn r (see Fig. 10a).
- Course stable ships with a nonlinear relation between rudder angle δ and rate of turn r (dead zone) (see Fig.10 b).
- Course unstable ships with a nonlinear relation between rudder angle δ and rate of turn r (see Fig. 10c).

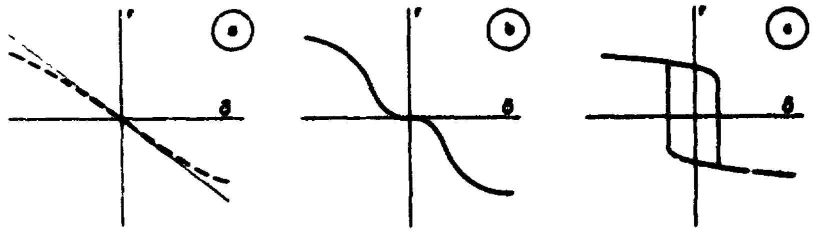

FIGURE 10:

The relation between rudder angle δ and rate of turn r for the three classes of ships.

A second aspect of the maneuvering dynamics of ships is the time constant. Each of the three classes of ships mentioned before will be used in combination with three time constants viz. 10, 50 and 250 sec. In this way the whole area of possible ships is covered. During the tests first-mentioned no disturbances acting on the ship (wind, waves) will be taken into account. In the beginning of 1974 some additional trials will be executed in order to check the influence of disturbances acting on the ship on the structure of the model of the helmsman's behavior and on the parameters belonging to the model.

9 Acknowledgements

The authors gratefully acknowledge the contribution of C.C. Glansdorp of the Shipbuilding Laboratory of the Delft University of Technology. They are also greatly indebted to TNO-IWECO for providing the facilities to do the experiments. The special thanks go to the staff of the TNO-IWECO simulator group for their contributions in the preparation as well as in the execution of the trials. Finally, the authors would like to express their gratitude to the subjects from the School of Navigation at Rotterdam for their wholehearted cooperation.

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HUMAN OPERATOR PERFORMANCE IN A SIMULATED AAA TASK

by

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Sheldon Baron

To be presented at the Ninth Annual Conference on Manual Control

ABSTRACT

Human operator performance in a simulated anti-aircraft artillery (AAA) task is explored as a function of system and environmental parameters. Operator responses to repeated fly-bys are analysed to provide trajectories of both mean response and of response variability. Both the mean and the variability of the response are shown to change with changes in experimental variables, and comparison of experimental data and theoretical data obtained from the human operator model indicate that performance changes can be related to changes in the human's ability to obtain and process information. In addition, it appears that the human predicts the future course of the target to a limited extent. Modification to the human operator model to account for this type of behavior are suggested.