MODELLING THE HUMAN OPERATOR OF SLOWLY RESPONDING SYSTEMS USING LINEAR MODELS.

N79-17492

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1. Introduction

From the forties onwards, much attention has been paid to manual control problems. A number of useful models such as the cross-over model [1, 2], and the optimal control model [3] have been developed. The very large part, however, of these studies, is concerned with the control of relatively fastly responding systems, e.g. aircraft and cars, of which the time constants are of the same order as the time constants of the human neuro-muscular system.
Since about ten years, there is a tendency to focus more and more the attention on the analysis of human behavior in the supervision of automated systems [4]. More than in the manual control of fastly responding systems, in the supervision of large scale systems are monitoring and failure detection, state estimation, prediction and decision making important aspects of human behavior, on which many investigations will have to be done. Also psychological factors such as attention, motivation, play an important role in the study of supervisory control.
For this reason, describing function techniques, which have proved to be useful in studying problems on manual control of fastly responding systems, are likely not very suitable to the study of problems with slowly responding systems. It should be noted, that a clear distinction between manual and supervisory control cannot be made. Just as in the case of manual control the human supervisor is part of a closed-loop: he receives information about the system, and at discrete times he changes the set-points of the automatic controllers or even switches over from automatic to manual control. In the manual control of a scalar, slowly responding system it is observed that the human operator behaves in a discrete way [5, 6]: A helmsman of a large ship like a supertanker does not change the rudder position continuously but only at discrete times. The slowly responding character of these ships will be experienced as a kind of supervisory control of a scalar system. Although monitoring, state estimation and decision making are important in this situation and also many psychological factors influence the helmsman's behavior, it will be shown in this paper that the describing function techniques still can be useful in analyzing the control behavior of the helmsman steering a large ship.

2. Experiments

Tests with a maneuvering simulator have been used to analyze the helmsman's control behavior [6]. This simulator is extensively described by Brummer and Van Wijk [7]. In general, the helmsman's task may be considered to be a pursuit tracking task, where the input signal or test signal (the headings ordered) consists of a series of steps of randomly chosen amplitudes and durations. The ordered heading $\psi_d(t)$ has been displayed by means of an alphanumerical display, the actual heading $\psi(t)$ has been presented by means of a compass as normally done.
A time history of the test signal, the subjects had to attempt to follow, is shown in Fig. 1.

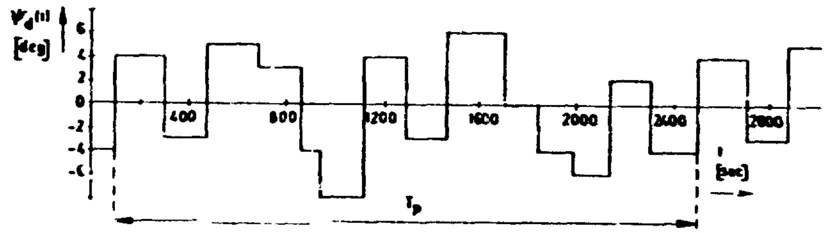

Figure 1 : Time history of the test signal.

The signal is periodic. A test consisted just of one period of forty minutes with a randomly chosen starting point. The choice of this test duration was based on the experience that making the tests too long, the subjects become less motivated at the end of the test, whereas the observation time must be long enough to obtain reliable estimates of the model parameters. Tests have been performed using the signal with the amplitudes as shown in Fig. 1, and with amplitudes twice as large as shown. In the first case the signal is indicated by TS S, in the last case by TS L.

To control the ship's rudder position $\delta(t)$ a steering wheel was provided of which the position is denoted by $\delta_d(t)$.
To simulate the ship's behavior a model describing the dynamics of the ship has to be chosen. A simple model, suitable for this purpose is the following one [8]:

$$T_s\,\ddot{\psi}(t) + a_1\dot{\psi}(t) + a_2\,[\dot{\psi}(t)]^3 = K_s\,\delta(t). \qquad (1)$$

The model consists of a nonlinear first order differential equation in the rate of turn $\dot{\psi}(t)$. The coefficient T_s is related to the ship's moment of inertia with respect to a vertical axis through the center of mass; the coefficient K_s is related to the effective moment which can be exerted on the ship's hull by the rudder; and finally the coefficients a_1 and a_2 are related to the damping. When a_1 is smaller than zero, the ship is directionally unstable, which means that it starts turning to either starboard or port when the rudder is kept amidships. To simulate the steering gear, a first order differential equation has been used, where the rudder angular velocity is limited. In this way the following equations are obtained:

$$T_\delta \ \dot{\delta}(t) + \delta(t) = \delta_d(t) \ ; \qquad (2a)$$

$$|\dot{\delta}(t)| < \dot{\delta}_m , \qquad (2b)$$

where T_δ is a time constant, and $\dot{\delta}_m$ is the maximum rudder angular velocity.

In this paper, tests with two very large ships, e.g. supertankers, are analyzed. The parameters of these ships with respect to the model (Eqs 1 and 2) are listed in Table 1.

Table 1 : The parameters of the model used to simulate the ships.

Ship	parameters model					
	T_s	K_s	a_1	a_2	T_δ	$\dot{\delta}_m$
	sec	sec^{-1}	-	$(\frac{sec}{deg})^2$	sec	$\frac{deg}{sec}$
I	250	-.05	1	5	1	3
II	250	-.05	-1	5	1	3

During these tests no disturbances, such as waves or wind effects, have been introduced in the simulations. That means that the ships were sailing in calm sea.
Four subjects, trainees of the School of Navigation at Amsterdam, were used to analyze the helmsman's behavior. They are indicated by S1, S2, S3 and S4, respectively. None of them was very experienced in steering ships larger than 10,000 tons. To become familiar with the dynamic behavior of large ships, each subject controlled about one hour the unstable ship before starting the experiments.

3. Analysis of the experiments

To identify the helmsman's describing function with respect to each test, several methods are available, which can be divided into two main groups [9]

- Methods without a-priori knowledge.
- Methods with a certain a-priori knowledge.

In the case that no a-priori knowledge about the system to be identified is available, the identification should be achieved on the basis of general methods such as the determination of Bode or Nyquist plots from the analysis of deterministic test signals or spectral density functions of stochastic processes.

For instance, in a closed loop, the human operator describing function denoted by $H(\nu)$ can be determined by the following well-known relation:

$$H(\nu) = \frac{S_{uy}(\nu)}{S_{ue}(\nu)} , \qquad (3)$$

where $S_{uy}(\nu)$ and $S_{ue}(\nu)$ are the cross-spectral density functions with respect to the system input $u(t)$, the human operator output $y(t)$ and the error signal $e(t)$, being the difference between system input and controlled element output.
The coherency spectrum, defined as:

$$\Gamma_{uy}(\nu) = \left[\frac{|S_{uy}(\nu)|^2}{S_{uu}(\nu)\ S_{yy}(\nu)}\right]^{1/2} . \qquad (4)$$

indicates to which extent the signals $u(t)$ and $y(t)$ are linearly correlated. In Fig. 2 an estimated squared coherency spectrum $\Gamma^2_{\psi_d \delta_d}(\nu)$ of a test with the stable ship is shown.

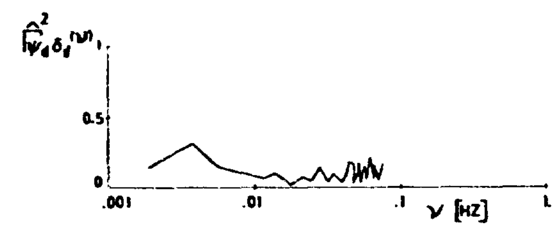

Figure 2 : Estimated squared coherency spectrum $\hat{\Gamma}^2_{\psi_d\delta_d}(\nu)$ of a test with the stable ship.
Subject: S1; Testsignal: TS 5.

From this figure, it can be seen that the coherency between the signals $\psi_d(t)$ and $\delta_d(t)$ is rather small, which means that $\delta_d(t)$ is more or less uncorrelated with $\psi_d(t)$ in the frequency range shown. This result corresponds with the fact that for each test the estimated spectral density functions $\hat{S}_{\psi_d\psi_d}(\nu)$ and $\hat{S}_{\psi_e\psi_e}(\nu)$, as well as the estimated cross spectrum $|\hat{S}_{\psi_d\psi_e}(\nu)|$ show only very slight differences in the frequency range observed [6].
Based on these results it can be concluded that the feed back loop does not contain components with frequencies higher then about .01 Hz. It should be noted that the region of interest is only the low frequency range. However, only a few data points can be estimated in this range, since the number and position of data points are determined by the duration of a test, the observation time [10]. This means that the test durations were too short to obtain reliable estimates of the spectra and also of the helmsman's describing function at low frequencies.

When a-priori knowledge is available, for instance the structure of the describing function, the parameters can be determined. Of course, the model obtained in this way should describe the helmsman's control behavior in the frequency range where the spectral analyses of the records did not provide the desired information: the low frequency range. Starting with the simplest human operator model, given by McRuer [1]

$$H_h(j\omega) = K_h \frac{T_1\, j\omega + 1}{T_2\, j\omega + 1}\, e^{-j\omega\tau} \qquad (5)$$

taking into account, that slowly responding systems are considered, Eq. (5) can be simplified to Eq. (6):

$$H_h(j\omega) = K_h \frac{T_1\, j\omega + 1}{T_2\, j\omega + 1}, \qquad (6)$$

where the time delay has been neglected because of the slowly responding character of the ship. By assuming that the cross-over model may be applied, it follows that (neglecting again the time-delay)

$$H_h(j\omega).H_s(j\omega) = K_h \frac{(T_1\, j\omega + 1)}{(T_2\, j\omega + 1)} \cdot \frac{K_s}{j\omega(T_s\, j\omega + 1)} = \frac{K}{j\omega} \qquad (7)$$

where the dynamic behavior of the ship has been approximated by Nomoto's first order model [11]. Hence

$$H_h(j\omega) = K_h\,(T_1\, j\omega + 1). \qquad (8)$$

Comparing thi model with the linear model used by Stuurman [12]

$$H_h(j\omega) = K_h \frac{(T_1\, j\omega + 1)}{(T_2\, j\omega + 1)}, \qquad (6)$$

it may be expected that the model based on the cross-over model (Eq. 8) has a rather large part of its output power at higher frequencies. To investigate the influence of the lag term both models have been used to analyze the helmsman's control behavior.

The parameters of the two linear models (Eqs 6 and 8) were estimated as shown in Fig. 3. The upper loop represents the experimental loop with the maneuvering simulator, the lower loop is a simulation of ship and helmsman on a hybrid computer. This method to estimate unbiased model parameters was chosen to be able to analyze also the usefulness of other models, including non-linear models [6].

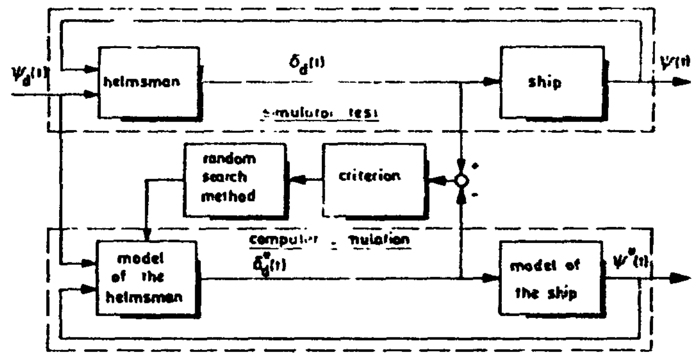

Figure 3 : Estimation of the parameters of the helmsman's odels.

The criterion applie. to optimize the model parameters was the following one:

$$E_{|\delta|} = \frac{\int_0^T \left| \delta_d(t) - \delta_d^*(t) \right| dt}{\int_0^T \left| \delta_d(t) \right| dt} \cdot 100\% . \qquad (9)$$

This criterion was preferred to a quadratic criterion

$$E_{\delta}2 = \frac{\int_0^T \left[\delta_d(t) - \delta_d^*(t) \right]^2 dt}{\int_0^T \left[\delta_d(t) \right]^2 dt} \cdot 100\% \qquad (10)$$

as it was expected that the absolute value criterion could be calculated more accurately on the hybrid computer than the quadratic criterion due to the accuracy of the analogue components. However, in literature mostly a quadratic criterion is used, which enables a direct computation of the unknown parameters, if no time-delays are involved [9]. To be able to compare the results to be obtained by minimizing $E_{|\delta|}$ with data given in literature, also E_δ 2 has been calculated.
Besides the quantity $E_{|\delta|}$ and $E_\delta 2$, also the following quantities have been computed:

$$E_{\psi}2 = \frac{\int_0^T \left[\psi(t) - \psi^*(t) \right]^2 dt}{\int_0^T \left[\psi(t) \right]^2 dt} \cdot 100\% , \qquad (11)$$

and

$$E_{|\psi|} = \frac{\int_0^T \left| \psi(t) - \psi^*(t) \right| dt}{\int_0^T \left| \psi(t) \right| dt} \cdot 100\% . \qquad (12).$$

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The last two quantities indicate the correspondance between the time histories of the actual heading of the ship $\psi(t)$ steered by the helmsman and those generated by the ship model $\psi^*(t)$ steered by the model of the helmsman.

4. Results

In the Tables 2 and 3 the results of the parameter optimization with the two models are given. These tables provide information about the parameter values determined and the criterion values related to these parameters.
In Fig. 4 some typical time histories are shown of the heading $\psi(t)$ and the steering wheel position $\delta_d(t)$ as well as of the output of the linear model with three parameters (Eq. 5) $\delta_d^*(t)$ and that of the ship model $\psi^*(t)$.

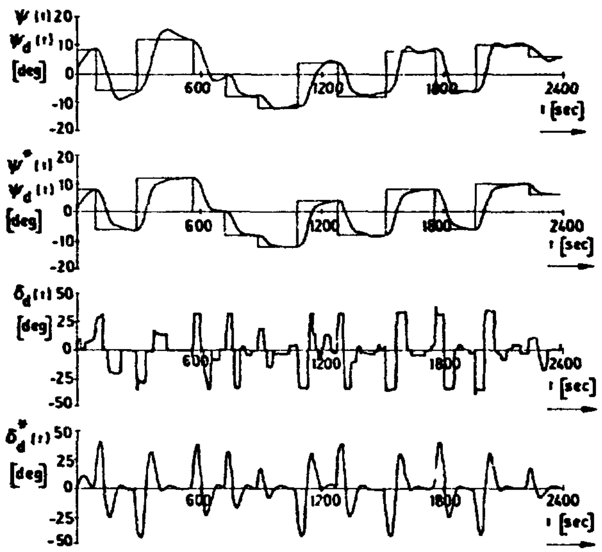

Figure 4 : Typical time histories of the actual signals $\psi_d(t)$, $\psi(t)$ and $\delta_d(t)$ compared with the output of the three parameter model $\delta_d^*(t)$ and the output of the ship model $\psi^*(t)$:
Subject S1; stable ship; TS L.

Table 2 : Results of the parameter optimization with the two parameter model (Eq. 8).

test conditions			parameter values		criterion values			
			K_h	T_I	$E_{\|\delta\|}$	E_{δ^2}	$E_{\|\psi\|}$	E_{ψ^2}
Ship	TS	Subj.	-	sec	%	%	%	%
I	S	S1	4.8	32.8	83	60	19	4
		S1	1.2	98.5	88	81	49	26
		S3	3.8	31.6	86	73	-	-
		S4	3.7	41.9	85	68	18	5
	L	S1	5.0	29.5	65	42	-	-
		S1	5.4	28.5	77	58	19	5
		S2	3.8	31.5	73	51	25	8
		S3	3.7	26.5	77	60	33	13
		S3	2.3	43.1	75	57	23	6
II	S	S1	4.5	33.1	69	52	22	6
		S1	5.5	28.1	81	56	32	14
		S2	3.2	45.0	84	72	23	8
		S2	1.6	142.8	95	87	42	21
	L	S1	4.9	33.7	73	56	-	-
		S2	1.0	104.6	85	77	36	15
		S2	1.0	132.7	93	82	-	-

Table 3 : Results of the parameter optimization with the three parameter model (Eq. 6).

test conditions			parameter values			criterion values			
			K_h	T_1	T_2	$E_{\|\delta\|}$	E_{δ^2}	$E_{\|\psi\|}$	E_{ψ^2}
Ship	TS	Subj.	-	sec	sec	%	%	%	%
I	S	S1	5.5	46.2	8.1	74	46	19	4
		S1	2.8	89.4	21.6	75	61	32	11
		S3	6.5	73.2	19.6	76	61	-	-
		S4	4.5	64.3	9.1	78	59	20	6
	L	S1	4.3	48.3	11.3	49	22	-	-
		S1	8.2	46.7	13.4	55	30	16	4
		S2	5.1	49.6	11.8	56	30	13	2
		S3	4.1	46.9	11.2	67	46	14	3
		S3	3.1	69.4	19.1	64	43	14	3
II	S	S1	5.1	43.2	6.2	60	38	18	4
		S1	5.9	37.6	7.8	71	43	30	13
		S2	3.2	67.8	18.8	62	42	21	6
		S2	2.6	136.9	23.8	81	67	37	15
	L	S1	4.6	53.9	11.9	59	35	-	-
		S2	1.9	94.9	21.5	74	57	15	3
		S2	2.1	106.8	31.2	75	50	-	-

To interprete these results in terms of the cross-over model, it is necessary to linearize the nonlinear ship model. To this end the mean value and the variance of the rate of turn for each of the tests are computed. The results of these computations are shown in Table 4.

Table 4 : Computed mean value and variance of the ship's rate of turn for each test.

test conditions			mean value	variance
Ship	TS	Subj.	deg/sec	$(deg/sec)^2$
I	S	S1	.0034	.0046
		S1	-.0025	.0024
		S3	-.0025	.0030
		S4	-.0002	.0040
	L	S1	-.0041	.0116
		S1	.0029	.0092
		S2	.0015	.0130
		S3	.0014	.0141
		S3	-.0031	.0122
II	S	S1	.0045	.0060
		S1	-.0036	.0052
		S2	-.0007	.0046
		S2	-.0045	.0025
	L	S1	-.0035	.0138
		S2	-.0040	.0130
		S2	-.0020	.0095

From this table it was concluded that the rate of turn was such small during all the experiments that the influence of the nonlinear term of the ship model, $a_2[\dot{\psi}(t)]^3$, can be neglected without making too large errors.
Also the dynamics of the steering gear are nonlinear. However, by linearizing this behavior a first order system is obtained, of which the time constant can be estimated to be three through four seconds. This time constant is small in relation to the ship time constant T_s. Hence, the influence of the steering gear on the stability of the system helmsman-ship will be small too. A more exact estimation of the time constant has not been executed for this reason.
Based on the parameter values given in the Tables 2 and 3, and the linearized ship model the cross-over frequencies and the phase margins have been determined for each test by means of Bode plots. The results are shown in Table 5.

Table 5 : The cross-over frequencies and the phase margins with respect to the two helmsman's models.

test conditions			two param. model		three param. model	
Ship	TS	Subj.	ω_c rad/sec	ϕ deg	ω_c rad/sec	ϕ deg
I	S	S1	.03	53	.05	50
		S1	.03	79	.05	35
		S3	.03	51	.08	31
		S4	.02	51	.05	54
	L	S1	.03	42	.04	45
		S1	.03	49	.05	38
		S2	.03	50	.05	42
		S3	.03	46	.04	44
		S3	.02	52	.04	39
II	S	S1	.03	37	.04	42
		S1	.03	32	.04	33
		S2	.03	44	.04	27
		S2	.05	77	.05	24
	L	S1	.03	37	.05	34
		S2	.02	52	.03	30
		S2	.02	58	.04	20

5. Discussion and conclusions

The structure of the model has been based on data given in literature, in particular McRuer's cross-over model. According to this model the helmsman adapts his control behavior to the controlled element dynamics in such a way that the necessary conditions required for a good closed loop response are fulfilled, that means that the closed loop system has to be stable and well-damped with a high amplitude ratio of the open loop frequency response $|H_h H_s|$ for frequencies of the input bandwidth and a low amplitude ratio outside this range.
From Table 5 it can be concluded that for each of the two models these requirements are fulfilled: all the parameters found correspond to a stable and mostly well-damped system, even in the case of the unstable ship.
In the literature on automatic steering of ships, a large number of studies can be found on the design of autopilots. Koyama [13] used a controller with a transfer function equal to three parameter helmsman's model (Eq. 6) to control an unstable ship, with a time constant of about 269 sec. He has found that for T_1 = 100 sec, T_2 = 12.5 sec, and K_h between 1 and 4 sec, a stable closed loop response is obtained, of which the performance is very acceptable in a wide range of ship speeds. In accordance with the cross-over model the parameter values found (Table 3) agree very well with the values given by Koyama.

The criterion values with respect to the steering wheel position, $E_{|\delta|}$ and $E_\delta 2$, indicate how well in terms of these criteria the models describe the helmsman's control behavior. From the Tables 2 and 3, it can be concluded that the two parameter model yields a much poorer description than the three parameter model. The criterion values $E_\delta 2$ with respect to the latter range from 30 until 60%, with an average of about 45%, with only a few exceptions. This means that this model provides a rather poor average description of the helmsman's control behavior.
In particular in the case of the three parameter model, the correspondance between the heading of the ship as steered by the model closely approximates the heading of the ship as steered by the helmsman. The criterion values $E_\psi 2$ are less than 10%, with a few exceptions. Although the output of the model of the helmsman's behavior sometimes differs from the actual output, the heading of the ship generated by the model is invariably a good fit due to the very low pass filtering properties of the ships.

Summarizing the following conclusions can be drawn:

- To identify the helmsman's describing function at very low frequencies, the test duration must be very long; however, after about 45 minutes the subjects are getting tired, and unwanted effects will occur. Hence, the identification of the helmsman's describing function by means of e.g. spectral analysis is not possible in the situation studied in this paper.
- The results obtained show that the cross-over model can be useful in the analysis of human behavior in controlling slowly responding systems.
- The description of the helmsman's control behavior by means of a model consisting of a gain and a lead term is poor; by adding a lag term a better description can be obtained.
- The heading of the ship steered by the two parameter model matches the heading of the ship steered by the helmsman rather well. In the case of the three parameter model a good description has been achieved.

6. Acknowledgement

The author gratefully acknowledge the contribution of Mr. J.F. Zegwaard of the Hybrid Computer Centre, who executed the model optimizations on the hybrid computer, and the valuable assistance in data processing of Mr. R.E. Schermerhorn.

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