Determination of Linear and Nonlinear Ship Steering Dynamics Using System Identification

Källström, Claes; Åström, Karl Johan

1979

Document Version:
Publisher's PDF, also known as Version of record

Link to publication

Citation for published version (APA):
Källström, C., & Åström, K. J. (1979). *Determination of Linear and Nonlinear Ship Steering Dynamics Using System Identification*. (Research Reports TFRT-3155). Department of Automatic Control, Lund Institute of Technology (LTH).

Total number of authors:
2

LUND UNIVERSITY

PO Box 117
221 00 Lund
+46 46-222 00 00

CODEN: LUTFD2/(TFRT-3155)/1-024/(1979)

DETERMINATION OF LINEAR AND NONLINEAR SHIP STEERING DYNAMICS USING SYSTEM IDENTIFICATION

FINAL REPORT STU PROJECT 77-5766

K. J. ÅSTRÖM
C. G. KÄLLSTRÖM

DEPARTMENT OF AUTOMATIC CONTROL
LUND INSTITUTE OF TECHNOLOGY
SEPTEMBER 1979

Contents

Dokumentutgivare
Lund Institute of Technology
Dept of Automatic Control

Handläggare
K J Åström

Författare
K J Åström
C G Källström

Dokumentnamn
Report

Dokumentbeteckning
LUTFD2/(TFRT-3155)/1-024/(1979)

Utgivningsdatum
Sept 1979

Ärendebeteckning
STU 77-5766

10T4

Dokumenttitel och undertitel

Determination of linear and nonlinear ship steering dynamics using system identification.

Referat (sammandrag)

Methods for determining linear and nonlinear shipsteering dynamics using physical models based on hydrodynamics in combination with parameter estimation methods are discussed. Experiences from a large number of experiments on full scale ships and scale models are reviewed.

Referat skrivet av
Authors

Förslag till ytterligare nyckelord
System identification, Maximum likelihood, Output error.

Klassifikationssystem och -klass(er)
50T0

Indextermer (ange källa)
52T0

Omfång
24 pages

Övriga bibliografiska uppgifter
56T2

Språk
English

Sekretessuppgifter
60T0

ISSN
60T4

ISBN
60T6

Dokumentet kan erhållas från
Department of Automatic Control
Lund Institute of Technology
Box 725, S-220 07 Lund 7, Sweden

Mottagarens uppgifter
62T4

Pris
66T0

SIS-
DB 1

DOKUMENTDATABLAD enligt SIS 62 10 12

Blankett LU 11:25 1976–07

UPPGIFTER I DOKUMENTDATABLADET

Nedanstående uppgifter motsvaras av ledtext i blanketten. Beteckningarna består av radgångsnummer och tabuleringsläge (T-läge). De anger startläge, dvs var textrad normalt skall börja.

04T0
DOKUMENTUTGIVARE
ISSUING ORGANIZATION

Fullständigt namn för den organisation (motsv) som utgivit dokumentet (uppgiften kan vara förtryckt).

04T4, 04T6
DOKUMENTNAMN OCH -BETECKNING
DOCUMENT NAME AND REF.NO.

Dokumentnamn anger dokumentets typ och ändamål och då dokumentet har ett dokumentnamn utsätts detta (med versaler). Exempel: PM, RAPPORT, KOMPENDIUM, BESKRIVNING, INSTRUKTION, UTREDNING, ANBUD, STANDARD. Dokumentnamnet följs av en dokumentbeteckning som anger dokumentets plats i en serie, t ex rapportnummer, protokollnummer. Är dokumentet i första hand framställt för spridning utanför den egna organisationen bör beteckningen utformas så att utgivande institution kan identifieras med uppgift om enbart dokumentbeteckningen.

Exempel härpå är rapportnumrering enligt amerikansk nationell standard (ANSI Z39-23) och det av ISO tillämpade beteckningssystemet för dokument i olika utvecklingsskeden.

06T0
HANDLÄGGARE

Person som sakbearbetar ärendet hos dokumentutgivaren.

06T4
UTGIVNINGSDATUM
DATE OF ISSUE

Dokumentbladet förses med dokumentets utgivningsdatum. Datum skall anges enligt SIS 01 02 11, dvs numeriskt i ordningen år, månad, dag (exempel 1975-07-03) eller alfanumeriskt med de tre första bokstäverna av månadens namn (exempel Aug 1975).

06T6
ÄRENDEBETECKNING
PROJECT NO. ETC

Exempel på ärendebeteckning är diarienummer, projektnummer, kontonummer, kort sakord eller annan beteckning som hänför sig till det i dokumentet behandlade ärendet ("sak").

08T0
FÖRFATTARE
AUTHOR(S)/CORPORATE AUTHORS

I första hand anges dokumentets författare. Vid kollektivt författarskap (t ex kommitté) anges för dokumentet ansvarigt organ. Även projektledare, redaktör eller annan "handläggare" kan anges. Namn bör anges i följden (1) hela förnamn (2) efternamn. Titel erfordras ej.

10T0
(RESERV)

Fältet (motsv v2 i standardiserad brevblankett) kan utnyttjas då flera författarnamn förekommer. Fältet kan även användas för namn och adress på mottagare av dokumentdatabladet, t ex dokumentationscentral.

10T4
ANSLAGSGIVARE
SPONSORING ORGANIZATION

Fältet (motsv h2 i standardiserad brevblankett) bör reserveras för namn och postadress på anslagsgivare eller annan institution som i egenskap av finansierande organ (för ett projekt) åberopas i dokumentet.

18T0
DOKUMENTTITEL OCH UNDERTITEL
DOCUMENT TITLE AND SUBTITLE

Fältet används för dokumentets titel och (ev) undertitel. Antalet bilagor anges inom parentes efter den första titeluppgiften. Tituppgifterna får ej förkortas eller på annat sätt förändras, men de kan kompletteras med exempelvis översättning till engelska.

26T0
REFERAT (SAMMANDRAG)
ABSTRACT

Texten i fältet skall bestå av ett sammandrag av dokumentets innehåll. Nyckelord skall understrykas.

Det bör uppmärksammas att sammandraget bör kunna återges i reproduktion på kort i format A6L eller i förminskning. Detta motiverar att referatet skrivs med början i tabuleringsläget T2. (Vid början i TO iakttas en radlängd av högst 125 mm).

Anm: ISO 214 - Documentation - Abstracts ger ledning vid utformning och redigering av referat.

42T0
REFERAT (SAMMANDRAG) SKRIVET AV
ABSTRACT WRITTEN BY

Det förutsätts att sammandraget i första hand skrivs av dokumentets författare. Härvid anges "förf" i rutan. Om annan än författaren är ansvarig för referatet (sammandraget) kan initial och efternamn eller enbart initialer anges.

44T0
FÖRSLAG TILL (YTTERLIGARE) NYCKELORD
KEY WORDS

Med nyckelord avses ord som författaren finner bäst karaktäriserar innehållet i det refererade dokumentet. Antalet nyckelord bör vara minst 5 och högst 15.

55T0
KLASSIFIKATIONSSYSTEM OCH KLASS(ER)
CLASSIFICATION SYSTEM AND CLASS(ES)

I fältet anges beteckningar för dokumentets ämnesinnehåll enligt något klassifikationssystem.

52T0
INDEXTERMER
INDEX TERMS

Härmed avses innehållsbeskrivande termer om de hämtats från en kontrollerande vokabulär (tesaurus). Indextermerna kan avvika från nyckelorden (jfr 44T0) som kan fritt väljas. Den tesaurus eller motsv från vilken indextermerna har hämtats skall anges efter sista indextermen.

56T2
ÖVRIGA BIBLIOGRAFISKA UPPGIFTER

Uppgifterna kan avse impressum (förlagsort, förlag, utgivningstid, tryckeri etc), upplaga, serietillhörighet och liknande.

56T0
OMFÅNG
NUMBER OF PAGES

Uppgiften anges med antal sidor i det refererade dokumentet inkl bilagor, förekommande (särpaginerade) bilagor.

58T0
SPRÅK
LANGUAGE

Dokumentets språk i det fall det är annat än svenska.

60T0
SEKRETESSUPPGIFTER
SECURITY CLASSIFICATION

Uppgift om begränsad tillgänglighet hos dokumentet med hänsyn till sekretess och andra av myndighet (genom lagstiftning eller på annat sätt) eller av dokumentutgivaren gjorda inskränkningar.

60T4
ISSN

International Standard Serial Number. Anges endast för serier åsatt ISSN.

60T6
ISBN

International Standard Book Number. Anges endast för dokument med åsatt ISBN.

62T0
DOKUMENTET KAN ERHÅLLAS FRÅN
DISTRIBUTION BY

Namn och (om möjligt) postadress på distributör av det refererade dokumentet.

62T4
MOTTAGARENS UPPGIFTER
RECIPIENT'S NOTES

Fält som kan disponeras av mottagaren.

66T0
PRIS

Priset anges i svenska kronor såvida ej dokumentets spridning motiverar annan valuta.

För att möjliggöra maskinell läsning av text i dokumentdatabladet har teckensnitt ORC-B använts vid ifyllning av förlageblanketten. Teckensnittet behandlas i SIS 66 22 42 (under arbete 1976).

1. INTRODUCTION

The project was a continuation of earlier work, Åström and Källström (1973, 1976), Åström et al (1975), Norrbin et al (1977), aimed at applying system identification methods to determination of ship steering dynamics. In the earlier work the feasibility of using system identification to determine linear ship steering dynamics was demonstrated.

The first goal of this project was to apply the linear methods to more experimental data. This gave interesting insights both for the input-output models and for the structural models. The new applications also gave good insights into the influence of sensor resolution and the possibilities of modeling disturbances. This line of research has also been taken up by other groups, Tiano (1976), Tiano and Volta (1978), and Ohtsu et al (1979). Their findings essentially confirm our results that an ARMAX model is a convenient tool for modeling ship steering dynamics.

The second goal of this project was to explore the possibilities of estimating nonlinear models. This has also been done successfully. Several nonlinear model structures have been explored. A Taylor series expansion of the nonlinearities is commonly used in ship hydrodynamics. It was originally attempted to estimate the coefficients of the Taylor series expansion. This was met with great difficulties because of the strong interdependence of the parameters. It was therefore decided to use models where the coefficients had natural physical interpretations. Nonlinear models of different complexity which describe the cross-flow drag were derived by Dr Nils H Norrbin of SSPA. In Norrbin's models the nonlinearities are represented with only a few parameters which simplifies the estimation problem. These models have been fitted to the data using an approximative maximum likelihood method. It has been demonstrated that drastic improvements can be achieved by including the nonlinearities, in particular for motions where the angle of attach is large. The nonlinear models have also been applied to a large number of real experiments.

The third goal of the project was to establish good procedures for using the system identification methods in a routine manner. The results of a large number of calculations on different experiments have been evaluated and guidelines for experiments have been established.

The work has been done in close collaboration with SSPA (Dr Nils H Norrbin and Mr Lennart Byström). The nonlinear hydrodynamic models were developed by Dr Norrbin. The estimation methods and the software were developed at LTH. The software were transferred to SSPA. Parameter estimation for different experiments was carried out at SSPA and LTH. We had regular meetings to discuss the results and exchange experiences. Twenty-five experiments performed with 12 different ships were analysed. The methods were also applied to 7 tests performed with 2 free-sailing scale-models.

The project could largely be done according to the original plans. There were some unexpected results due to poor resolution of the sensors in one of the experiments. When applying Akaike's test to determine the complexity of the linear models it was found that the data sometimes picked up high order dynamics, sometimes round-off errors, and sometimes wave disturbances depending on the experimental conditions and the precision of the sensors. The nonlinear parameter estimation was more time-consuming than originally anticipated. Several different model structures had to be tried before good results could be obtained.

We believe that it is safe to say that the method developed is a reliable tool for determination of ship steering dynamics. As suggestions for further work it would be of interest to make a major revision of the multivariable estimation program (LISPID). Based on our current experiences there are several useful modifications that could be made. The revision of LISPID is, however, an effort that requires a manyear or two. It would also be of interest to do some further work on the nonlinear estimation schemes. Perhaps the most interesting continuation would be to do further work on modeling of wave disturbances and their interaction on ship steering dynamics. This is an area where the theoretical models available are based on many unverified assumptions. Some of our experiments indicate that useful information can be obtained by applying system identification to experimental data.

2. MODEL STRUCTURES

The equations describing a free-sailing ship in deep and unrestricted waters are well known (Norrbin 1960, 1970). It is commonly assumed that the influence of heave, roll, and pitch motions into the motion in the horizontal plane can be neglected. This is true at least for large ships such as supertankers.

Equations of Motion

To describe the equations of motion a co-ordinate system fixed to the ship with the x- and y-axes as shown in Fig. 1 and the z-axis pointing downwards is introduced. The projections of the total ship speed V on the x- and y-axes are called the surge velocity u and the sway velocity v. The turning rate is denoted r and the heading and rudder angles are denoted ψ and δ.

The equations for the horizontal motion are obtained from Newton's laws expressing conservation of linear and angular momentum:

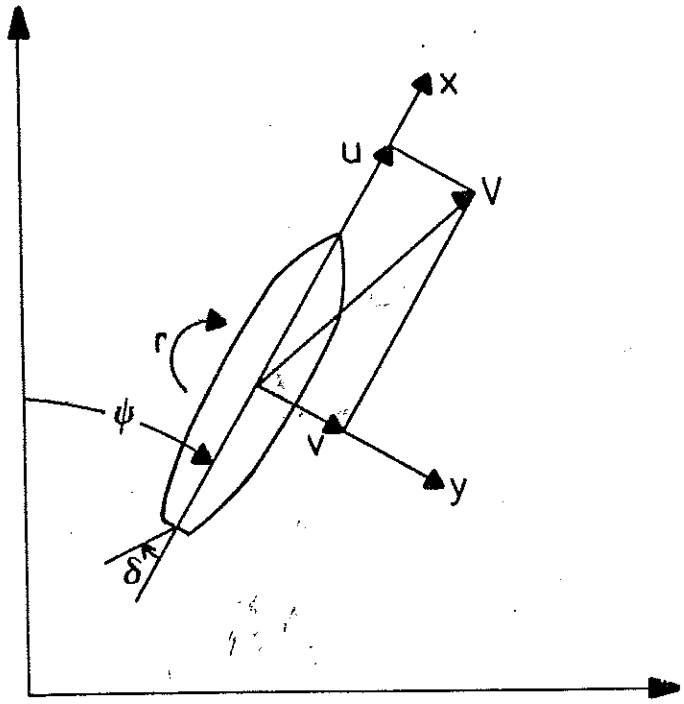

Fig. 1 - Ship with co-ordinate system for equations of motion.

$$
\begin{aligned}
m(\dot{u} - vr - x_G r^2) &= X \\
m(\dot{v} + ur + x_G \dot{r}) &= Y \\
I_z \dot{r} + m x_G (\dot{v} + ur) &= N
\end{aligned}
\tag{1}
$$

where X and Y are the components of the hydrodynamic forces on the x-axis and y-axis, N is the z-component of the hydrodynamic moments, m is the mass of the ship, Iz is the moment of inertia about the z-axis, and x_G is the x co-ordinate of the centre of gravity.

Hydrodynamic Forces and Moments

The hydrodynamic forces X and Y and the hydrodynamic moment N of (1) are complicated functions of the ship motion. Abkowitz (1964) suggested the following functional form

$$
\begin{aligned}
X &= X(u, v, r, \delta, \dot{u}, \dot{v}, \dot{r}) \\
Y &= Y(u, v, r, \delta, \dot{u}, \dot{v}, \dot{r}) \\
N &= N(u, v, r, \delta, \dot{u}, \dot{v}, \dot{r})
\end{aligned}
\tag{2}
$$

and approximated the functions with Taylor series expansions about the steady state condition $u = u_0$ and $v = r = \delta = \dot{u} = \dot{v} = \dot{r} = 0$. The derivatives of X, Y, and N are called hydrodynamic derivatives.

A drawback with the Taylor expansions of (2) is that the high-order terms have no physical interpretations. Norrbin (1970) has developed other expressions for the hydrodynamic forces and moments, where the high-order terms have physical interpretations.

Linear Models

Linearization of the equations of motion (1) about the stationary solution $u = u_0$, $v = r = \delta = 0$, gives

$$
\begin{pmatrix} m' - Y'_{\dot{v}} & L(m' x'_G - Y'_{\dot{r}}) \\ m' x'_G - N'_{\dot{v}} & L(I'_z - N'_{\dot{r}}) \end{pmatrix}
\begin{pmatrix} \dot{v} \\ \dot{r} \end{pmatrix} =
$$

$$
= \begin{pmatrix} \frac{V}{L} Y'_v & V(Y'_r - m') \\ \frac{V}{L} N'_v & V(N'_r - m' x'_G) \end{pmatrix}
\begin{pmatrix} v \\ r \end{pmatrix} +
\begin{pmatrix} \frac{V^2}{L} Y'_\delta \\ \frac{V^2}{L} N'_\delta \end{pmatrix} \delta
\tag{3}
$$

where the X-equation has been omitted. In this equation the first order hydrodynamic derivatives have been normalized by using the length L of the ship as length unit, L/V as time unit, and $\sigma L^3/2$ as mass unit, where σ is the density of the water.

It follows from (3) that the transfer function relating yaw rate to rudder angle is given by

$$G_{r\delta}(s) = K \frac{(s + 1/T_3)}{(s + 1/T_1)(s + 1/T_2)} \tag{4}$$

and that the transfer function relating sway velocity to rudder angle is

$$G_{v\delta}(s) = K_v \frac{(s + 1/T_{3v})}{(s + 1/T_1)(s + 1/T_2)} . \tag{5}$$

Nomoto and co-workers (1957) proposed the following approximation of (4)

$$G_{r\delta}(s) = \frac{K}{(s + 1/T)} , \qquad T = T_1 + T_2 - T_3, \tag{6}$$

which is called Nomoto's model.

Since the data is normally sampled it would also be natural to estimate the parameters of the difference equation model

$$A(q^{-1})y(t) = B(q^{-1})u(t-1) + \lambda C(q^{-1})e(t), \tag{7}$$

where A, B, and C are polynomials in the shift operator and $\{e(t)\}$ is a sequence of random variables which represents the combined effect of disturbances and measurement errors. A model like (7) can for example be obtained by sampling a continuous time model (4) or (6) with rational disturbances.

Nonlinear Models

The linearized models work well if the yaw rate and the sway velocity are small. If this is not the case nonlinear models must be used. There are nonlinear models of different complexity. A simple model suitable for system identification was derived in Norrbin (1976). In this model a nonlinear force $Cf_Y(v,r)$ and a nonlinear moment $Cf_N(v,r)$ were added to the right-hand side of the linear model (3). The functions f_Y and f_N represent the cross-flow drag and can be determined from hydrodynamic theory. See Norrbin (1976). Norrbin's model is attractive from the point of view of system identification because it only introduces one parameter, the effective cross-flow drag coefficient C, to be estimated.

The ship speed can change significantly during large manoeuvres. By using the measured value of the ship speed V at each sampling event instead of the mean value the influences of the speed variations can be reduced. It is also possible to include the X-equation in the model used. Since this equation is nonlinear principally, the identification technique must be modified. Blanke (1978) has applied frequency response analysis to determine a nonlinear speed equation.

Disturbances

A ship is influenced by wind, waves, and currents, which appear as disturbances in the equations of motion. There is a substantial literature on disturbances. See Etkin (1961), Comstock (1967), Zuidweg (1970), van Berlekom, Trägårdh, and Dellhag (1974), and Price and Bishop (1974). In a simplified analysis the influence of disturbances can be handled by adding forces and moments generated by wind, waves, and currents to the equations of motion (1). See Källström (1979).

Summary

The parameters of the different models outlined in this section have been estimated by system identification techniques. The parametrizations chosen for the different models are given in Åström and co-workers (1975) and Källström (1979). The experimental data were analysed using the program packages LISPID (Källström, Essebo, and Åström, 1976; Källström, 1978a) and IDPAC (Wieslander, 1976).

3. EXPERIMENTS

At LTH system identification has been applied to data from full scale experiments performed with two cargo ships and four tankers. Seventeen experiments corresponding to a total time of 15 h have been analysed. The data contain over 6000 samples. A few examples of the identification results are given in this section. The detailed results can be found in Källström (1977a, 1977b, 1977c, 1978b, and 1978c).

Several summaries of the results and experiences obtained at SSPA and LTH by applying system identification to determine ship steering dynamics have been published. See Åström and Källström (1972, 1973, 1976), Åström and co-workers (1974, 1975), Norrbin and co-workers (1977), Byström and Källström (1978), Källström and Åström (1979), and Källström (1979).

The *Sea Scout*

The *Sea Scout* is an oil tanker of 255 000 tdw. Three experiments E1 - E3 performed in ballast condition have been analysed (Källström, 1977c). A detailed description of the experiments is given in Källström (1974).

The ML estimates of the parameters of Nomoto's model obtained are summarized in Table 1. The prediction interval T_p is equal to the sampling period T_s in the ML procedure. This table shows that the values obtained in the different experiments do not differ much. It also appears that it is no big difference between the parameters obtained when estimating discrete time or continuous time models. A typical input-output record is shown in Fig. 2. The output error method gives estimates that differ substantially from the ML method. The estimates $K' = -0.82$, -0.37, -0.14 and $T' = 1.79$, 4.17, and 0.88 were obtained for the different experiments.

	Initial esti-mates	E 1		E 2		E 3	
		T_p = 10 s		T_p = 5 s		T_p = 5 s	
		continuous time	discrete time	continuous time	discrete time	continuous time	discrete time
K'	-0.56	-1.04	-1.08	-0.94	-1.01	-0.94	-1.02
T'	1.31	1.37	1.33	1.64	1.43	1.43	1.20

Table 1 - Results of ML identifications of Nomoto's model to the *Sea Scout* experiments.

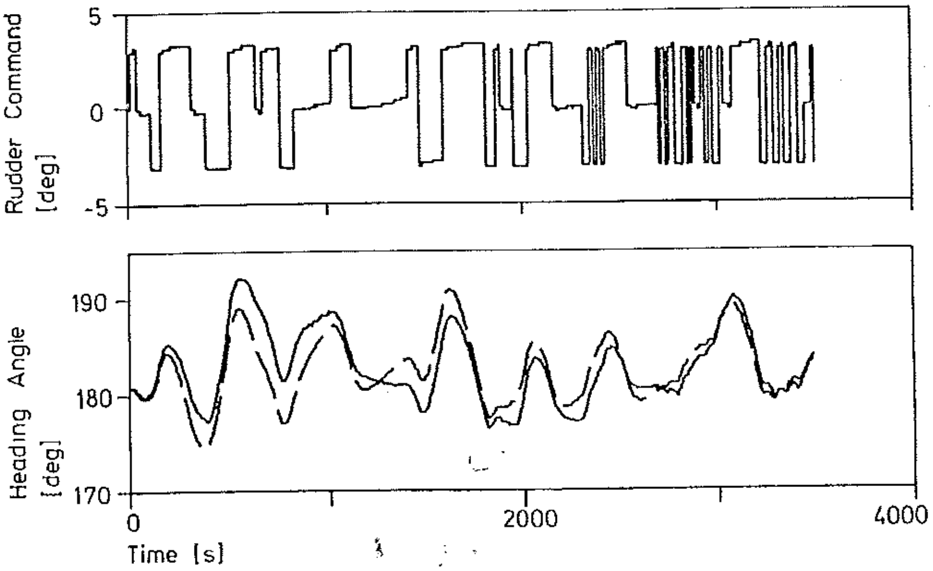

Fig. 2 - Result of ML identification ($T_p = 10$ s) using LISPID to data from experiment E1 with the *Sea Scout*. The continuous line is measurements and the dashed line is the output of the deterministic model.

The *Sea Swift*

The *Sea Swift* is a sister ship to the *Sea Scout*. Four experiments E1 - E4 performed at full draught have been analysed (Källström, 1978b). The experiments are described in detail by Källström (1975).

The linear model (3) was fitted to the data by output error and prediction error methods with $T_p = 10$, 20, 30, and 40 s. Poor estimates of the hydrodynamic derivatives were usually obtained when the output error method and the prediction error method with $T_p = 10$ s were applied. The results were improved by increasing the prediction horizon. The value $T_p = 30$ s and $T_p = 40$ s was very small. The results of prediction error identifications with $T_p = 40$ s are summarized in Table 2.

The different models of Table 2 were investigated further. It was found that the performances of the models did not differ much. Figure 3 shows the result obtained when the model from experiment E2 in Table 2 was simulated to the rudder commands from experiment E4.

	Initial estim.	E 1	E 2	E 3	E 4
Y'_v	-0.01422	-0.02754	-0.01988	-0.02451	-0.02244
$Y'_r - m'$	-0.01152	-0.01586	-0.01507	-0.01656	-0.01556
N'_v	-0.00738	-0.00042	-0.00079	-0.00044	-0.00003
$N'_r - m'x'_G$	-0.00301	-0.00011	-0.00029	-0.00016	0.00009
Y'_δ	0.00298	0.00141	0.00147	0.00184	0.00088
N'_δ	-0.00140	-0.00067	-0.00069	-0.00087	-0.00041
K'	-0.82	-0.39	-0.41	-0.50	-0.24
K'_v	0.10	0.05	0.05	0.06	0.03
T'_1	-3.09	-14.79	-8.04	-15.34	-15.66
T'_2	0.39	0.95	1.04	1.02	1.31
T'_3	1.00	1.05	1.38	1.17	1.32
T'_{3v}	0.20	0.23	0.23	0.22	0.24

Table 2 - Results of prediction error identifications ($T_p = 40$ s) to the *Sea Swift* experiments.

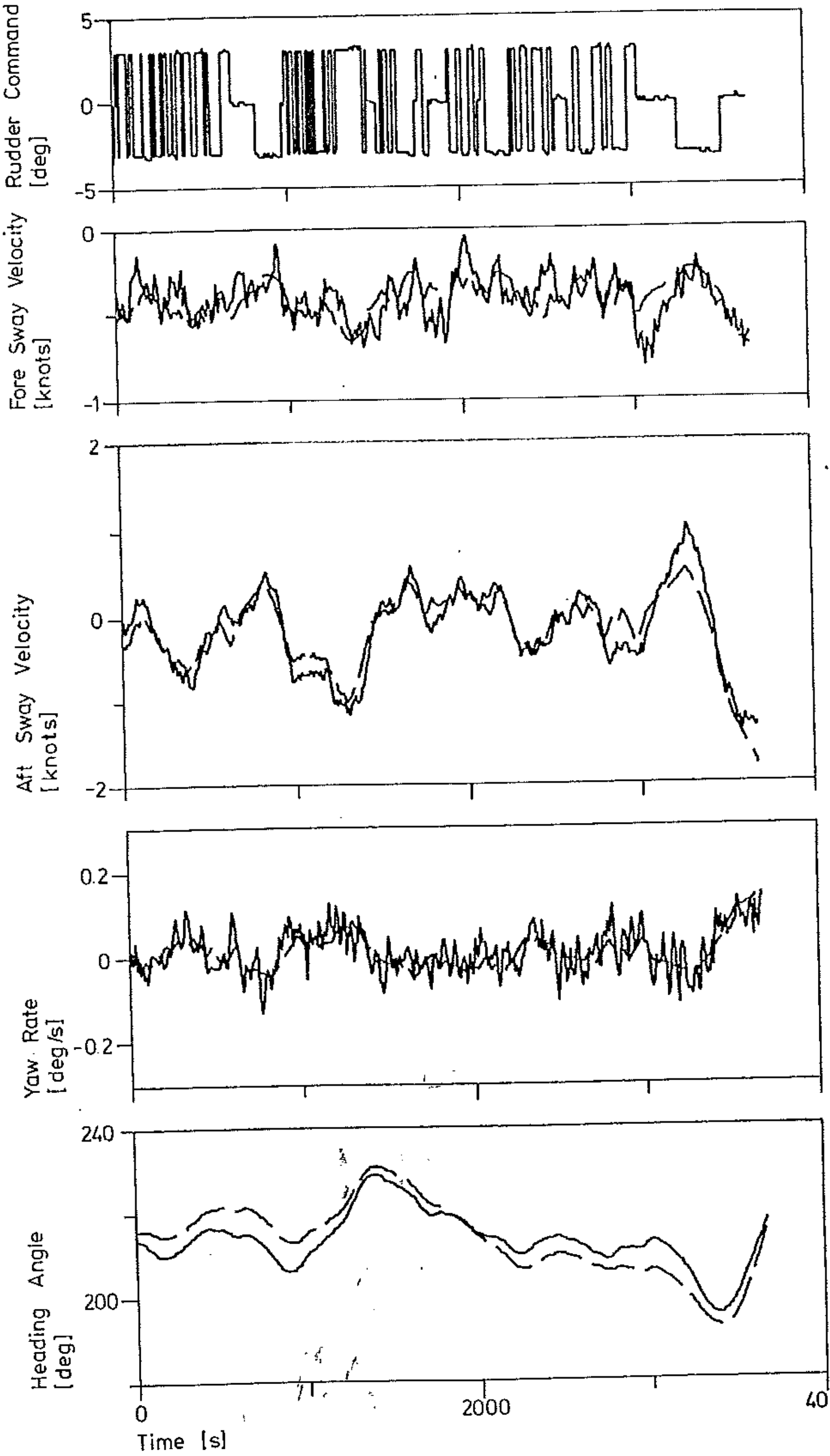

Fig. 3 - Simulation of the prediction error model ($T_p = 40$ s) obtained from experiment E2 with the *Sea Swift* to the rudder commands from experiment E4. The continuous lines are measurements and the dashed lines are model outputs.

The *Sea Stratus*

Four experiments E1 - E4 were performed with the oil tanker *Sea Stratus* of 356 000 tdw. They are described by Källström (1976). The detailed identification results are given in Källström (1978c).

The results obtained by fitting linear and nonlinear models to experiment E2, which is a $5^{o}/5^{o}$ zig-zag test, are summarized in Table 3. A prediction interval T_p of 60 s was chosen. The estimates of the linear and the nonlinear models were close. The effective cross-flow drag coefficient C was estimated to 0.63. The value of C' is expected to be approximately 0.7 for a tanker. The result obtained with the nonlinear model is shown in Fig. 4.

	Initial estim.	Linear	Non-linear
Y'_v	-0.00687	-0.02121	-0.02037
$Y'_r - m'$	-0.00724	-0.01010	-0.01065
N'_v	-0.00254	-0.00258	-0.00300
$N'_r - m'x'_G$	-0.00161	-0.00144	-0.00138
Y'_δ	0.00201	0.00203	0.00206
N'_δ	-0.00095	-0.00096	-0.00097
C	0.7	-	0.63
K'	-1.00	-1.01	-1.03
K'_v	0.12	0.12	0.13
T'_1	-4.88	9.36	-11.08
T'_2	0.43	0.37	0.36
T'_3	1.32	0.61	0.61
T'_{3v}	0.19	0.15	0.15

Table 3 - Results of prediction error identifications ($T_p = 60$ s) to the *Sea Stratus* experiment E2.

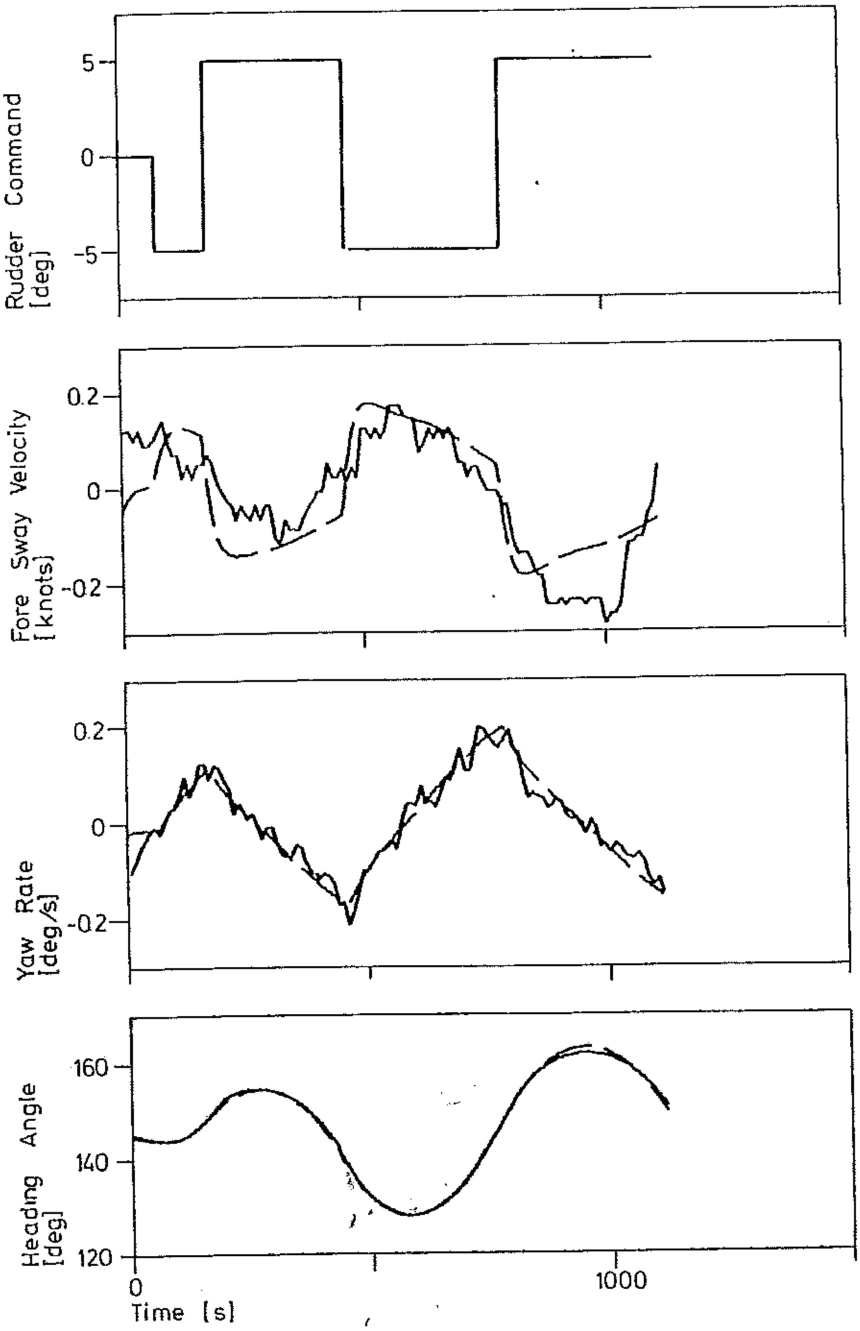

Fig. 4 - Result of prediction error identification ($T_p = 60$ s) to data from experiment E2 with the *Sea Stratus*. The continuous lines are measurements and the dashed lines are the outputs of the deterministic model.

The *Compass Island*

Experiments found in the literature will be used in this section. Three $20^{o}/20^{o}$ zig-zag tests were analysed (Källström, 1977b). The rudder angles, the sway velocities, the yaw rates, and the heading angles from the experiments were obtained from graphs in Morse and Price (1961). The *Compass Island* experiments were performed using an inertial navigation system which gave measurements with hith precision and good resolution. Naturally a lot of the precision inherent in the data were, however, lost when the graphs were digitized.

The results of fitting linear and nonlinear models to the data with the ML method are summarized in Table 4. An illustration of the results is given in Fig. 5.

Poor estimates of the hydrodynamic derivatives were in general obtained when the linear model was used, although the fit between the model outputs and the measurements was good. The estimates were improved significantly when the nonlinear model was fitted to the data. Reasonable values of the effective cross-flow drag coefficient C were obtained.

	Initial estimates	E 1		E 2		E 3	
		Linear	Nonlinear	Linear	Nonlinear	Linear	Nonlinear
Y'_v	-0.01160	-0.01313	-0.00892	-0.05502	-0.04886	-0.02428	-0.01487
$Y'_r - m'$	-0.00526	-0.00844	-0.00817	-0.02175	-0.02090	-0.01005	-0.00875
N'_v	-0.00291	-0.00009	-0.00075	0.00273	-0.00010	0.00117	-0.00123
$N'_r - m'x'_G$	-0.00184	-0.00106	-0.00100	0.00052	-0.00022	-0.00021	-0.00062
Y'_δ	0.00278	0.00218	0.00240	0.00140	0.00169	0.00130	0.00178
N'_δ	-0.00133	-0.00105	-0.00115	-0.00067	-0.00081	-0.00062	-0.00085
C	0.7	-	0.35	-	0.46	-	0.79
K'	-1.65	-1.28	-1.42	-	-1.00	-	-1.04
K'_v	0.21	0.17	0.18	-	0.12	-	0.13
T'_1	5.70	1.15	7.09	} complex poles	4.51	} complex poles	-13.54
T'_2	0.37	0.85	0.64		0.33		0.60
T'_3	0.89	1.18	1.50	0.32	0.32	0.72	0.90
T'_{3v}	0.22	0.19	0.19	0.10	0.09	0.19	0.20

Table 4 - Results of ML identifications ($T_p = 6$ s) to the *Compass Island* experiments.

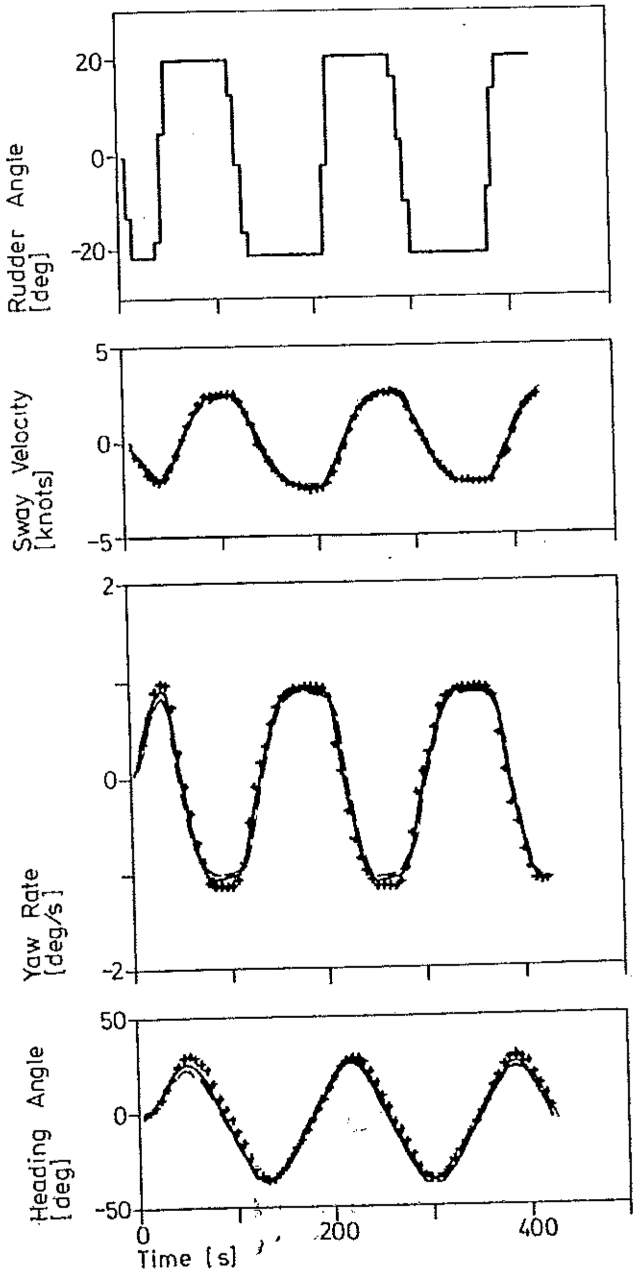

Fig. 5 - Results of ML identifications ($T_p = 6$ s) to data from experiment E3 with the *Compass Island*. The dashed lines are the outputs from the linear, deterministic model, the continuous lines are the outputs from the nonlinear deterministic model, and the dots are measurements.

4. SUMMARY OF EXPERIENCES

Experiments performed at different load, speed, and weather conditions were analysed. It was found that system identification methods are useful for determination of ship steering dynamics. A valuable insight into experimental design, model structures, and properties of different identification methods was also obtained.

Identification Methods

The output error method gave occasionally reasonable results, but poor parameter estimates were obtained in most cases. Reasonable results could, however, be obtained with the output error method for experiments performed under very nice weather conditions. The same conclusion was reached in Norrbin and co-workers (1977) based on experiments performed with a small tanker. In Byström and Källström (1978) it was found that satisfactory results were obtained by the output error method when a scale model test was analysed. This is natural because the experiment was made under ideal conditions in an indoor tank.

The prediction error method was superior to the output error method, but it is essential to choose an appropriate time horizon. Prediction horizons between 10 and 60 s were suitable for the tankers, but 6 s was sufficient for the *Compass Island*. Experiments performed under different weather conditions with wind speeds between 0 and 14 m/s were analysed. Good results were obtained by the prediction error method.

Model Structures

Different continuous time models were explored using LISPID. Hydrodynamic derivatives were estimated by fitting linear and nonlinear models. The analysis of a $5^{\circ}/5^{\circ}$ zig-zag test showed that reasonable estimates were obtained from a linear model. However, the results were improved slightly by fitting a nonlinear model. The nonlinearities in the model were crucial when $20^{\circ}/20^{\circ}$ zig-zag tests were analysed. The other experiments were designed to determine the linear ship steering dynamics only. Therefore good results were obtained by fitting linear models.

A continuous time model containing parameters of the transfer function relating heading to rudder angle was also explored using LISPID. The results were compared with the results of fitting a discrete time model using IDPAC. The results from LISPID and IDPAC did not differ much, when the parameters of Nomoto's model were determined. Very few problems were encountered. It was difficult to determine the parameters of a third-order transfer function. Attempts to fit a discrete time system gave models for round-off noise or wave disturbances depending on the experimental conditions. Good results were sometimes obtained by fitting a continuous time model provided that the resolution of the heading measurement was sufficient.

Experiments

Different types of experiments were analysed. The identification results from open loop and closed loop tests were compared. It was found that the results did not differ much. The open loop experiments were either zig-zag tests or experiments with a PRBS as rudder perturbations. Since the rudder input contains mainly one frequency during a zig-zag test, a PRBS experiment, where many frequencies are included, is preferable. However, the zig-zag tests proved to be very useful to determine the effective cross-flow drag coefficient of the nonlinear model. It was found that accurate measurements were essential in order to obtain good parameter estimates.

Recommended Procedure

The following procedure is recommended to determine ship steering dynamics from full scale experiments. First a linear model is estimated from data obtained under closed loop control. Perturbations can be introduced as changes in the heading reference to the ordinary autopilot. The frequency of the perturbation signal should be chosen in such a way that the ship is properly excited in the frequency range of interest. Long experiments can be performed since only small deviations from the desired heading are made. It is advantageous if the experiments are performed under nice weather conditions. If possible the experiments should be made in head seas in order to encounter as high wave frequencies as possible. Otherwise the wave disturbances can significantly influence the results obtained when the data are analysed and it may be necessary to model the waves as oscillatory disturbances. Determination of nonlinear models requires experiments where the nonlinear forces are substantial. Appropriate experiments are 20°/20°, or possibly 10°/10°, zig-zag tests. It could also be considered to design experiments which are even better suited to estimate nonlinear models. It is suitable, although not necessary, to first determine a linear model from a closed loop experiment and then estimate only the effective cross-flow drag coefficient from the zig-zag tests.

5. ACKNOWLEDGEMENTS

The valuable collaboration with the Swedish State Shipbuilding Experimental Tank (SSPA) in Gothenburg is gratefully acknowledged. We thank Nils H Norrbin and Lennart Byström for many interesting discussions on ship steering dynamics.

We would also like to express our gratitude to the Salén Shipping Companies, Stockholm, and to Kockums, Malmö, for their positive attitude to this type of research. A special thank to Leif Sten, Johannes Eriksson, and Nils-Eric Thorell, Kockums Automation.

This work was supported by the Swedish Board of Technical Development (STU) under contract No 77-5766.

The manuscript has been expertly typed by Ms Eva Dagnegård. The figures are drawn by Ms Britt-Marie Carlsson.

6. REFERENCES

Abkowitz, M A (1964):
Lectures on ship hydrodynamics, steering and maneuverability. Report No Hy-5, Lyngby, Denmark.

Åström, K J, and C G Källström (1972):
Identification and modelling of ship dynamics. Report TFRT-7015, Dept of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Åström, K J, and C G Källström (1973):
Application of system identification techniques to the determination of ship dynamics. Proc 3rd IFAC Symposium on Identification and System Parameter Estimation, pp 415-424, the Hague/Delft, The Netherlands.

Åström, K J, N H Norrbin, C G Källström, and L Byström (1974):
The identification of linear ship steering dynamics using maximum likelihood parameter estimation. Report 1920-1, SSPA, Gothenburg, Sweden.

Åström, K J, C G Källström, N H Norrbin, and L Byström (1975):
The identification of linear ship steering dynamics using maximum likelihood parameter estimation. Publ No 75, SSPA, Gothenburg, Sweden.

Åström, K J, and C G Källström (1976):
Identification of ship steering dynamics. *Automatica* 12, 9.

van Berlekom, W B, P Trägårdh, and A Dellhag (1974):
Large tankers - wind coefficients and speed loss due to wind and sea. *Trans Royal Institution of Naval Architects* 117, 41, London, 1975.

Blanke, M (1978):
On identification of nonlinear speed equation from full scale trails. Proc 5th Ship Control Systems Symposium, Vol 6, Annapolis, Maryland, USA.

Byström, L, and C G Källström (1978):
System identification of linear and nonlinear ship steering dynamics. Proc 5th Ship Control Systems Symposium, Vol 3, paper J2 2-1, Annapolis, Maryland, USA.

Comstock, J P (Editor) (1967):
Principles of Naval Architecture. Society of Naval Architects and Marine Engineers, New York.

Etkin, B (1961):
Theory of the flight of airplanes in isotropic turbulence; review and extension. UTIA Report No 72, Institute of Aerophysics, University of Toronto, Toronto, Canada.

Källström, C G (1974):
The *Sea Scout* experiments, October 1973. Report TFRT-7063, Dept of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Källström, C G (1975):
The *Sea Swift* experiments, October 1974. Report TFRT-7078, Dept of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Källström, C G (1976):
The *Sea Stratus* experiments, April 1976. Dept of Automatic Control, Lund Institute of Technology, Lund, Sweden, Report CODEN: LUTFD2/(TFRT-7110)/1-587/(1976).

Källström, C G, T Essebo, and K J Åström (1976):
A computer program for maximum likelihood identification of linear, multivariable stochastic systems. Proc 4th IFAC Symposium on Identification and System Parameter Estimation, Vol 2, pp 508-521, Tbilisi, USSR.

Källström, C G (1977a):
Identification of the linear steering dynamics of the *Sea Splendour*. Dept of Automatic Control, Lund Institute of Technology, Lund, Sweden, Report CODEN: LUTFD2/(TFRT-7129)/1-085/(1977).

Källström, C G (1977b):
Determination of linear and nonlinear steering models for the USS *Compass Island*. Dept of Automatic Control, Lund Institute of Technology, Lund, Sweden, Report CODEN: LUTFD2/(TFRT-7130)/1-099/(1977).

Källström, C G (1977c):
Identification of the steering dynamics of the *Sea Scout*. Dept of Automatic Control, Lund Institute of Technology, Lund, Sweden, Report CODEN: LUTFD2/(TFRT-7131)/1-137/(1977).

Källström, C G (1978a):
LISPID - user's manual. Dept of Automatic Control, Lund Institute of Technology, Lund, Sweden, Report CODEN: LUTFD2/(TFRT-7147)/1-147/(1978).

Källström, C G (1978b):
Identification of the steering dynamics of the *Sea Swift*. Dept of Automatic Control, Lund Institute of Technology, Lund, Sweden, Report CODEN: LUTFD2/(TFRT-7155)/1-175/(1978).

Källström, C G (1978c):
Identification of the steering dynamics of the *Sea Stratus*. Dept of Automatic Control, Lund Institute of Technology, Lund, Sweden, Report CODEN: LUTFD2/(TFRT-7157)/1-218/(1978).

Källström, C G (1979):
Identification and adaptive control applied to ship steering. Thesis, Dept of Automatic Control, Lund Institute of Technology, Lund, Sweden, CODEN: LUTFD2/(TFRT-1018)/1-192/(1979).

Källström, C G, and K J Åström (1979):
Experiences of system identification applied to ship steering dynamics. 5th IFAC Symposium on Identification and System Parameter Estimation, Darmstadt, West Germany.

Morse, R V, and D Price (1961): Maneuvering characteristics of the *Mariner* class ship in calm seas. Report GJ-2223-1019, Sperry Gyroscope Company, New York.

Nomoto, K, T Taguchi, K Honda, and S Hirano (1957):
On the steering qualities of ships. *International Shipbuilding Progress* 4, No 35, 354.

Norrbin, N H (1960):
A study of course keeping and manoeuvring performance. Proc 1st Symposium on Ship Maneuverability, Washington.

Norrbin, N H (1970):
Theory and observations on the use of a mathematical model for ship manoeuvring in deep and confined waters. Proc 8th Symposium on Naval Hydrodynamics, Pasadena, California, USA.

Norrbin, N H (1976):
Om en kvasi-stationär integral för icke-linjär dämpning i fartygs girmanöver. Internal PM B187, SSPA, Gothenburg, Sweden (in Swedish).

Norrbin, N H, L Byström, K J Åström, and C G Källström (1977):
Further studies of parameter identification of linear and nonlinear ship steering dynamics. Report 1920-6, SSPA, Gothenburg, Sweden.

Ohtsu, K, M Horigome, and G Kitagawa (1979):
A new ship's auto pilot design through a stochastic model. *Automatica* 15, 255.

Price, W G, and R E D Bishop (1974):
Probabilistic Theory of Ship Dynamics. Chapman and Hall, London.

Tiano, A (1976):
Identification and control of the ship steering process. Proc 2nd IFAC/IFIP Symposium on Ship Operation Automation, pp 573-580, Washington.

Tiano, A, and E Volta (1978):
Application of the identification techniques to the ship system. Proc 7th IFAC Triennial World Congress, pp 1583-1588, Helsinki.

Wieslander, J (1976):
IDPAC - user's guide. Report TFRT-3099, Dept of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Zuidweg, J K (1970):
Automatic guidance of ships as a control problem. Thesis, Technische Hogeschool, Delft, The Netherlands.