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Determination of Linear and Nonlinear Ship Steering Dynamics Using System Identification

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DETERMINATION OF LINEAR AND NONLINEAR SHIP STEERING DYNAMICS USING SYSTEM IDENTIFICATION

FINAL REPORT STU PROJECT 77-5766

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Contents

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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
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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 re-
search has also been taken up by other groups, Tiano (1976),
Tiano and Volta (1978), and Ohtsu et al (1979). Their find-
ings 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 possi-
bilities of estimating nonlinear models. This has also been
done successfully. Several nonlinear model structures have
been explored. A Taylor series expansion of the nonlinear-
ities is commonly used in ship hydrodynamics. It was orig-
inally 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 coeffici-
ents 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 non-
linearities, 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 proce-
dures for using the system identification methods in a
routine manner. The results of a large number of calcula-
tions on different experiments have been evaluated and guide-
lines 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 hydro-
dynamic 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 expe-
riences. 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 reso-
lution of the sensors in one of the experiments. When apply-
ing 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 antici-
pated. 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 dynam-
ics. 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 theo-
retical models available are based on many unverified assump-
tions. Some of our experiments indicate that useful informa-
tion 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 pro-
jections 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:

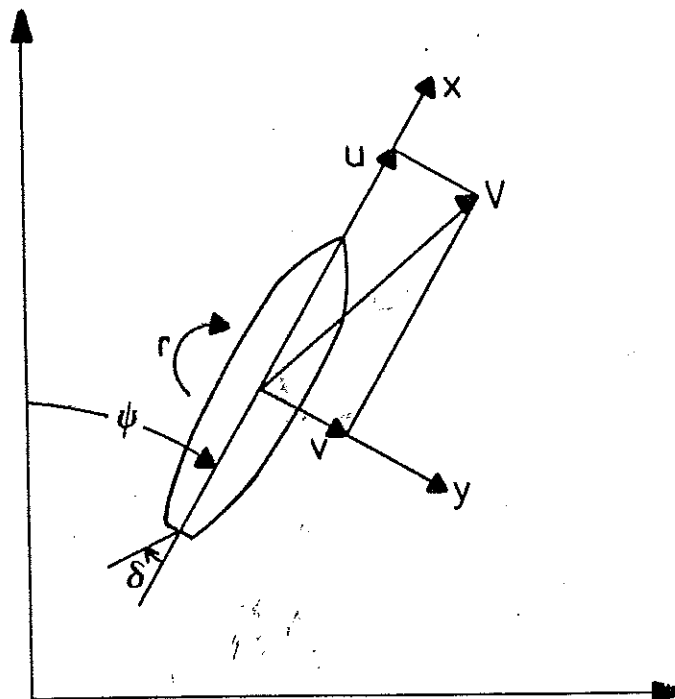Fig. 1 - Ship with co-ordinate system for
         equations of motion.

$$m(\dot{u} - vr - x_G r^2) = X$$

$$m(\dot{v} + ur + x_G \dot{r}) = Y \tag{1}$$

$$I_z \dot{r} + mx_G(\dot{v} + ur) = N$$

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

$$X = X(u,v,r,\delta,\dot{u},\dot{v},\dot{r})$$

$$Y = Y(u,v,r,\delta,\dot{u},\dot{v},\dot{r}) \tag{2}$$

$$N = N(u,v,r,\delta,\dot{u},\dot{v},\dot{r})$$

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

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

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

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

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

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

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

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

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

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

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

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), By-
ström 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 expe-
riments 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 inter-
val T_p is equal to the sampling period T_s in the ML proce-
dure. 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 ob-
tained 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 sub-
stantially 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 $T_p = 10$ s		E 2 $T_p = 5$ s		E 3 $T_p = 5$ 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.
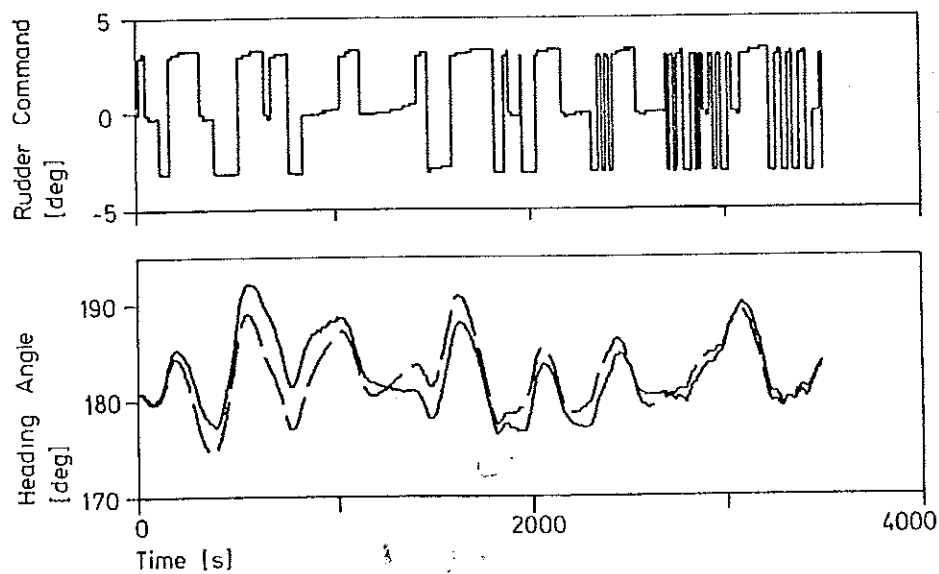

Fig. 2 - Result of ML identification ($T_p = 10$ s) using LISPID to data from experiment E1 with the *Sea Scout*. The continuous line is measurements and the dashed line is the output of the deterministic model.

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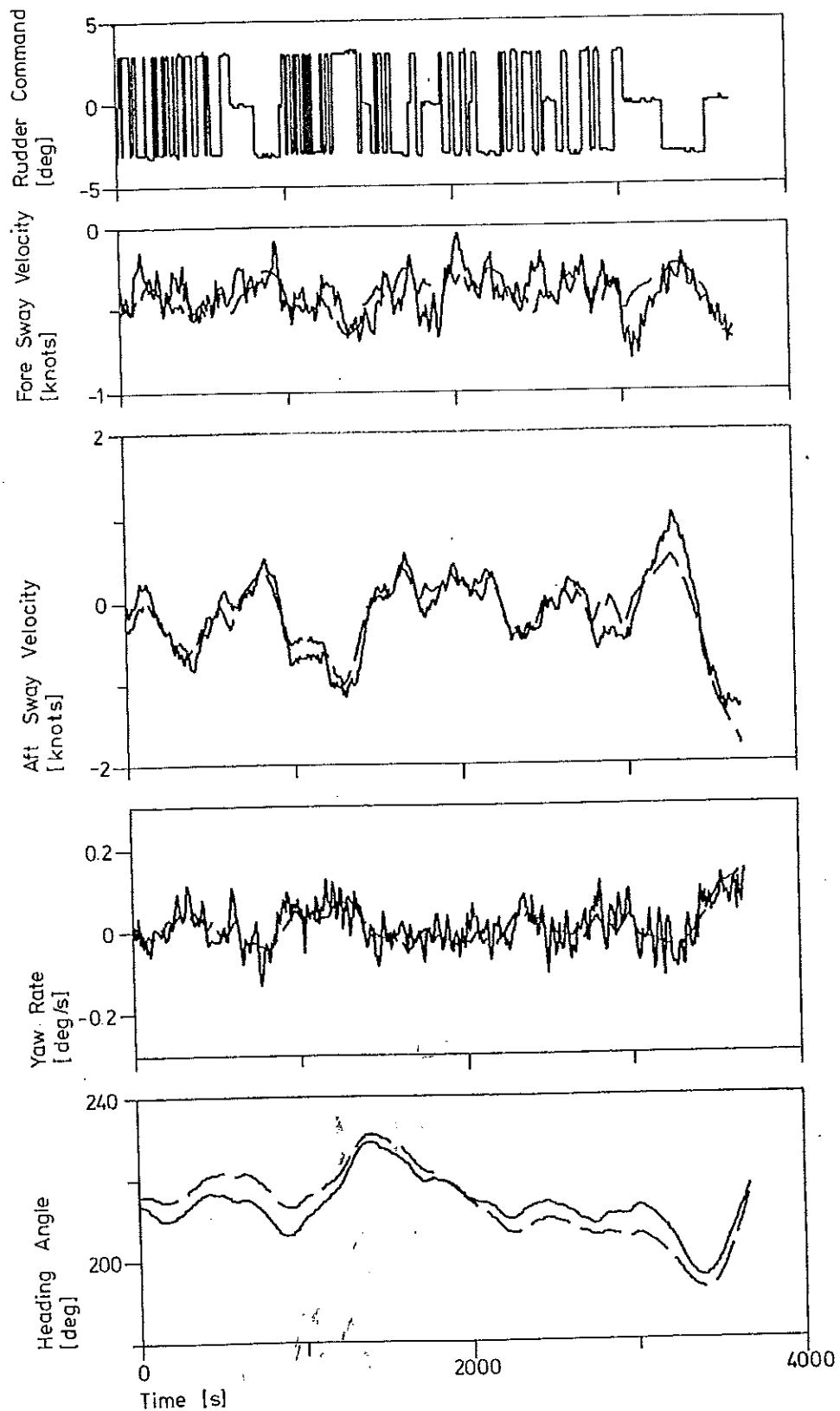
Fig. 3 - Simulation of the prediction error model $(T_p = 40 \text{ s})$
obtained from experiment E2 with the *Sea Swift* to
the rudder commands from experiment E4. The con-
tinuous lines are measurements and the dashed
lines are model outputs.

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 $5^\circ/5^\circ$ 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

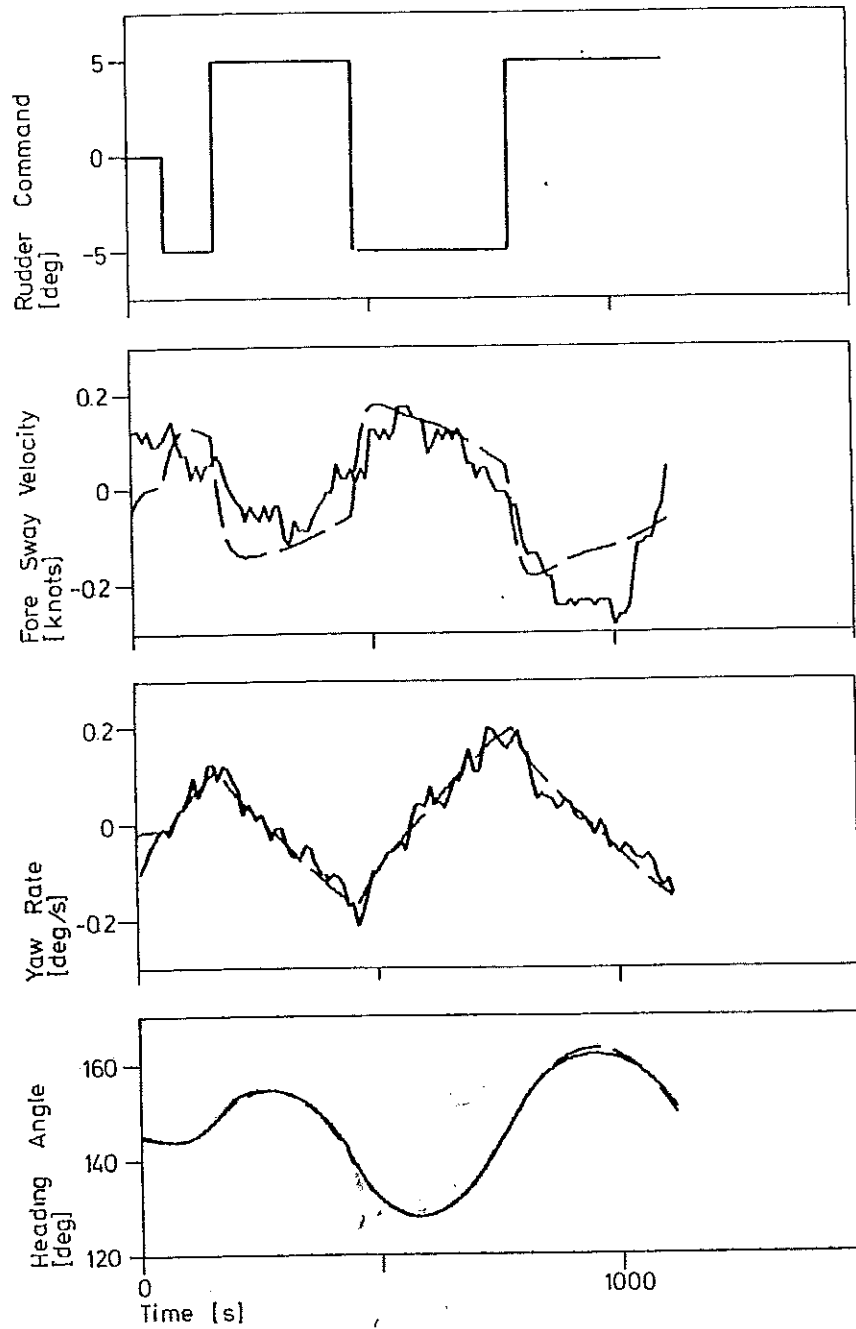Table 3 - Results of prediction error identifications ($T_p = 60$ s) to the *Sea Stratus* experiment E2.

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°/20° 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
$N'_r - m' \times '_G$	-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.
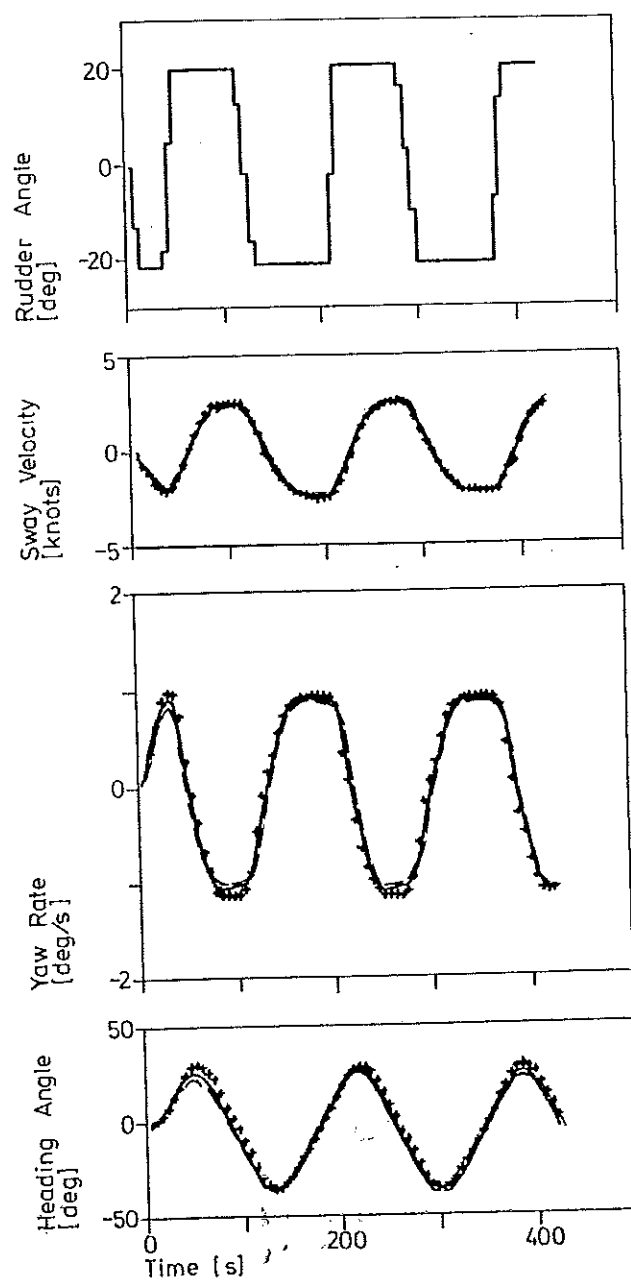
Fig. 5 — Results of ML identifications
(T_p = 6 s) to data from experi-
ment E3 with the *Compass Island*.
The dashed lines are the outputs
from the linear, deterministic
model, the continuous lines are
the outputs from the nonlinear
deterministic model, and the
dots are measurements.

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 experi-
mental design, model structures, and properties of differ-
ent identification methods was also obtained.

Identification Methods

The output error method gave occasionally reasonable re-
sults, 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 experi-
ments performed with a small tanker. In Byström and Käll-
ström (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°/5° 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°/20° 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 trans-
fer 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 identi-
fication 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 coeffici-
ent of the nonlinear model. It was found that accurate mea-
surements 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 fre-
quency 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 $20^{o}/20^{o}$, or possib-
ly $10^{o}/10^{o}$, 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 expe-
riment and then estimate only the effective cross-flow drag
coefficient from the zig-zag tests.

5. ACKNOWLEDGEMENTS

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